GUIDELINES FOR RECYCLED AGGREGATE IN MALTA

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ABSTRACT

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Recycling of construction and demolition waste (C&DW) is one of the solutions for dealing with the local waste disposal problem. Waste disposal fees have increased drastically in the past year and recycling reduces the majority of waste to be dumped at a landfill. Also, circa 86% of total waste collected for land filling is C&DW, so recycling can definitely be a major contribution to achieving EU targets. No local standards or guidelines for recycling of C&DW for contractors, structural engineers, architects or other stakeholders exist as yet.

This dissertation discusses how different classification schemes are used internationally and how the quality of recycled concrete aggregates (RCA) varies from conventional ones. Local case studies are assessed to comprehend types and amounts of C&DW. Testing on typical RCA have aided in the setting or modification of existing foreign limits for use in particular local applications. Since no recycling plant exists locally, the available machinery at a typical local factory was used for processing the aggregates.

The drafting of local proposed guidelines include best practices from countries well-experienced in processing of RA and also the limits set for tests to be carried out on representative samples of processed aggregates. A classification scheme is proposed and the material tested is graded according to this scheme, and treated as a product for potential use in even high grade structural applications, depending on the grade it is classified with. Applications for the material tested are then proposed as part of the conclusions. Data not included in the guidelines, due to the limited time available or lack of local information, merits for future research and completion of the guidelines.

Keywords: GUIDELINES, CLASSIFICATION, RECYCLED CONCRETE AGGREGATE, CONSTRUCTION AND DEMOLITION WASTE.

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CHAPTER 1: INTRODUCTION

1.1 Scope of study

"'Waste' – A resource in the wrong place"

(Air Force Centre for Environmental Excellence, A.F.C.E.E., 1999)

The need to manage waste locally in a more efficient manner has been in discussion throughout the years, especially since our accession in the EU. The basic objectives of current EU waste policy are to prevent waste and promote reuse, recycling and recovery so as to reduce the negative environmental impact (Car, Gretzmacher, Willing and Zerz, 2008). When considering the life cycle of a building material, the choice of how to handle the waste should be considered on the basis of having the least carbon footprint. Figure 1.1 clearly depicts that land filling should be the last resort, since it has the highest impact on the environment.

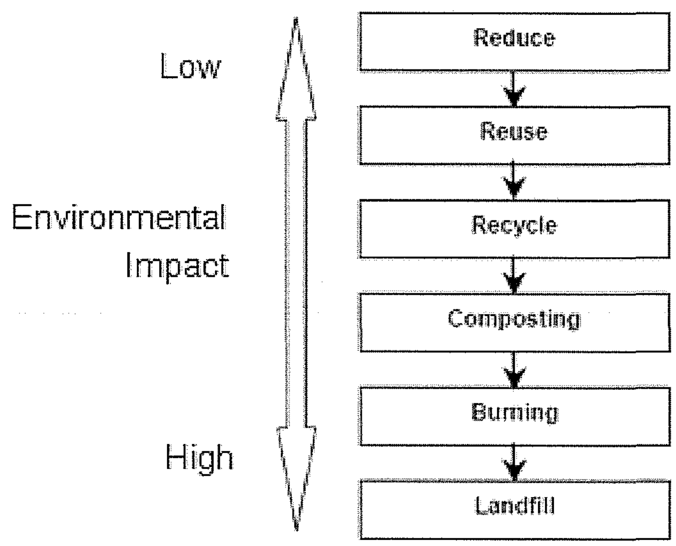

Figure 1.1: Waste management options Hierarchy. Source: A.F.C.E.E. (2005), p7

The Waste Management Strategy for Malta emphasizes the need to deal with the problem through its proposals of handling Construction and Demolition waste (C&DW). The main objective of this study is to provide a draft guideline for handling operations and recycling of high-quality recycled construction materials from non-hazardous mineral and mixed C&DW [1], as raw materials.

1.2 Local disposal of non-hazardous mineral waste

National Statistics Office of Malta [NSO] (2010) records that non-hazardous mineral waste reached an estimated annual average of 86% percent of the total waste managed between 2002 and 2008. Up to a few years back, there were three main ways of how this type of waste could be disposed of: land-filling, quarry rehabilitation and disposal at sea (table 1.1).

Tonnes

Year	Quarry Sites Controlled by WasteServ Malta Ltd.	Privately Managed Quarry Sites	Disposal at Sea	Total Amount of Waste Disposed
2004	2,177,861	372,238	210,404	2,760,503
2005	1,185,174	776,875	357,942	2,319,991
2006	865,713	1,191,580	329,426	2,386,719
2007	981,789	562,267	146,205	1,690,261
2008	427,905	355,281	300,360	1,083,546

Note: These amounts are classified under EWC code 17 01 07 (Mixtures of concrete, bricks, tiles and ceramics other than those mentioned in 17 01 06)

Note: Figures are subject to revision

Source: WasteServ Malta Ltd.; MEPA

Table 1.1: Amount of non-hazardous mineral waste disposed at quarry sites or at sea
Source: NSO (2010), p. 3, table 2

This significant drop in waste disposal in public landfills can be noticed in Table 1.2.

[1] Non-hazardous mineral waste is composed of rocks, stone aggregates, sand, concrete, ceramics and tiles, gypsum among other materials, generated by construction, demolition and excavation works (NSO, 2009). Mixed C&DW comprises of this fraction of mineral waste, the hazardous fraction, and other materials such as glass, metals, plastics and so on which can be reused as raw materials.

tonnes

Waste streams	2000	2001	2002	2003	2004	2005	2006	2007
Municipal solid waste	140,157	149,269	163,278	163,131	164,312	165,259	167,002	177,528
Debris material	1,252,159	989,700	1,342,826	577,063	38,092	11,328	4,503	5,512
Commercial/industrial	26,766	25,804	25,597	28,516	24,624	18,506	17,037	18,831
Mixed trade municipal	51,354	48,310	43,994	56,591	53,235	48,670	51,198	67,829
Mixed waste	14,966	19,916	15,969	13,756	9,423	8,816	7,516	8,802
Special waste	419	2	5	757	77	36	0	0
Total	**1,485,821**	**1,233,000**	**1,591,669**	**839,814**	**289,762**	**252,614**	**247,256**	**278,502**

Source: WasteServ Malta Ltd.
Note: Figures are subject to revision

Table 1.2: Amount of waste disposed in public landfills
Source: NSO (2009), p. 2, table 2, 2009

The sudden decrease in debris material [1] is a result of local disposal operations for non-hazardous mineral waste being managed in approved facilities and not in the Maghtab or Qortin dump sites, since May 2003 (MRRA, 2009a). The use of landfills for disposal of excavation and C&D waste is being limited in order to achieve the European targets for reuse, recycling and other material recovery, which is a minimum of overall 70% by weight by 2020 (MRRA, 2009b) according to the EU directive 2008/98/EC. This target is aimed to produce high-quality construction products with the necessary, minimal processing. Hence, since C&DW owes to a substantial part of waste material collected locally, it is only reasonable that implementing strategies for reuse or recycling will help reach this target.

It is important to note that the 86% is rather high when compared to other countries. Table 1.3 is an extract from a compilation by Tam et al. (2008). If Malta were included, it would rank as having the highest C&DW from total waste generated. However, Tam reports these figures from different sources and possibly different methods of calculating these percentages are used (section 1.6), hence these can only be considered as approximations for comparison reasons.

[1] Debris Material is composed of the following waste streams: street-cleaning waste; construction and demolition waste; rock excavation waste (NSO, 2009).

Country	Proportion of construction waste to total waste	C&D waste recycled (%)
Australia	44	51
Brazil	15	8
Denmark	25-50	80
Finland	14	40
France	25	20-30
Germany	19	40-60
Hong Kong	38	-
Japan	36	65
Italy	30	10
Netherlands	26	75
Norway	30	7
Spain	70	17
UK	More than 50	40
USA	29	25
Among various types of construction solid waste, concrete forms the most significant element with about 75% from construction sites, 70% from demolition sites 40% from general civil work, 70% from renovation work		

Table 1.3: Comparison of C&DW in different countries.
Source: Tam et al. (2008), p2, Table 1.1

1.3 Rise in landfill disposal fees

One of the most debated issues this past year has been that of the drastic increase in local landfill fees, based on the 'polluter pays' principle, where waste disposal at the Ta' Zwejra engineered landfill has increased from €0.91 to €20 per tonne. This has come into effect on the 1st of June 2010. This twenty-fold increase has thus, applied also to C&DW hauled to the landfills. On the other hand, the fee to dump recycled waste at the Sant'Antnin recycling plant has dropped from 77c to 50c a tonne (Grech, 2010). Table 1.4 shows how waste disposed in non-hazardous public landfills has decreased suddenly the last few years. The fee has been enforced to pressure the public into thinking twice on whether the waste generated can be reduced, re-used or recycled instead of being dumped hence it is probable that disposal at landfills shall decrease even further, as has happened in foreign countries (section 1.7).

Tonnes

EWC Chapter	EWC Chapter Description	2004	2005	2006	2007	2008
1	Waste resulting from exploration, mining, quarrying, physical and chemical treatment of minerals	168	0	0	0	0
17	Construction and demolition waste (including excavated soil from contaminated sites)	30,355	8,834	4,047	5,024	9,147

Table 1.4: Waste disposed in non-hazardous public landfills with European Waste Catalogue (EWC) references. Source: NSO (2010), p 2, extract from table 1

This new disposal levy is one of the recommendations for better management of C&D waste in the local waste management strategy. It was suggested in 2008, as part of a Twinning Project MT05-IB-EN-01 (Car et al, 2008), Recycling of Construction and Demolition Waste in Malta, between Malta and the Austrian Federal Environment Agency. Another recommendation is that of writing standards and guidelines for recycled building materials (MRRA, 2009a), which is in fact the intention of this dissertation.

1.4 Promotion of guidelines and public awareness

EN standards are the only local source for reference on basic use of recycled aggregates in concrete, the main reason is because no collection site or private company to specifically collect, separate and process the material into a certified product, exists as yet.

There are five barriers which one usually encounters in trying to promote the use of such guidelines (A.F.C.E.E., 1999):

i. The newness of doing it
ii. Limited diversion markets
iii. Limited market awareness
iv. Perceived higher cost due to transportation and processing
v. Perceived requirement for additional job-site space

In order to find a party interested in managing such a business, much research and effort is needed. Reasons for encouraging recycling of C&DW and convincing such parties that having such resources locally, is of sustainable benefit to our Maltese community are the following:

i. Conservation of natural resources and reduction of our dependency on virgin materials
ii. Realisation of the discomfort of having to live with what one discards
iii. Control of volumes of waste disposal at landfill and possibly transportation costs, depending on location of recycling plant and project where RA is to be used
iv. Compliance with policy, legislation and regulation on waste management
v. Elimination of illegal dumping and associated negative impacts on landscape

vi. Possible cheaper costs with diversion of C&DW rather than land filling
vii. Possible reduction in use of energy in material/aggregate production
viii. Exemption from future aggregate levies that may be introduced
ix. Conformity with any Green building rating systems such as LEED and BREEAM, that may be introduced locally

(Foras Áiseanna Saothair [F.A.S.] & Construction Industry Federation [C.I.F.], 2002; The cement sustainability initiative [CSI], 2009)

Once the people concerned comprehend the implication of such benefits, the demand for recycling of building materials will be a motivation for the realisation of such companies. Figure 1.2 confirms that the public is showing an interest in separation of domestic waste materials such as plastic, paper, glass and metal for recycling/reuse and reflects how the trend is increasing. This clearly indicates that public awareness and concern is improving and it is the author's belief there is a great potential for this happening with C&DW also.

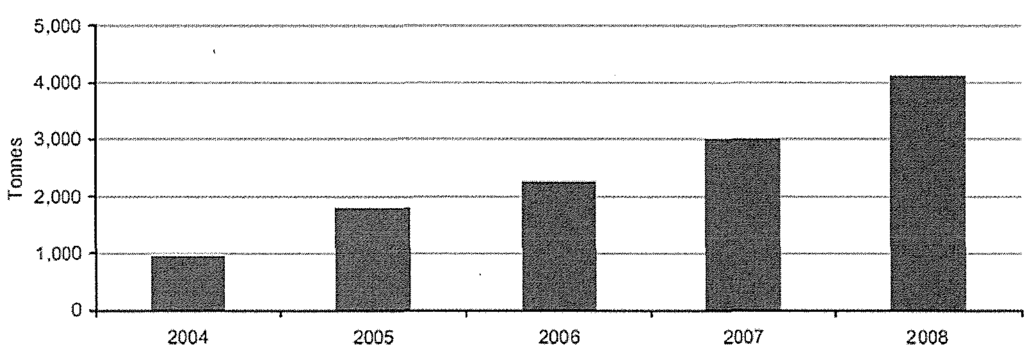

Figure 1.2: Chart showing waste collected from bring-in sites from 2004 to 2008
Source: NSO (2010), p. 6, chart 2

Even though some cases of reuse of non-hazardous inert building material for filling and base road applications have in fact been carried out throughout the years, no records are being kept for public consideration. Hence, several literatures has been reviewed in this script, to assess how foreign countries have been benefitting from such recycling processes these past years and hence, how this can happen in Malta too. Legislation against fly-tipping, levies for disposals in landfills and rehabilitation of quarries have been the first step towards achieving this goal so far.

1.5 Waste statistics from Foreign Countries

It is important to note that there exist variations in calculations methods of waste targets achieved and the availability of data makes cross-country comparison difficult at the present time (CSI, 2009). This is because definitions usually vary[1]. CSI has also noticed that some countries exclude civil engineering projects from building construction statistics. However, the most is made out of what data is available and there exist several reports with percentages showing progress throughout the years, especially for countries well-experienced in recycling.

Sonigo et al. (2010) report an overall 47% recycling rate for all the 27 member states in the EU. Figure 1.3 shows how the different countries rank, with Denmark, Estonia, Germany, Ireland and the Netherlands at the front and other countries, including Malta, with no data available. The current information on the website of European Quality Association for Recycling [EQAR] states that in a recycling quota of more than 70% was reported for Austria, Denmark, Germany and the Netherlands and hence the EU target mentioned in section 1.2 is being reached.

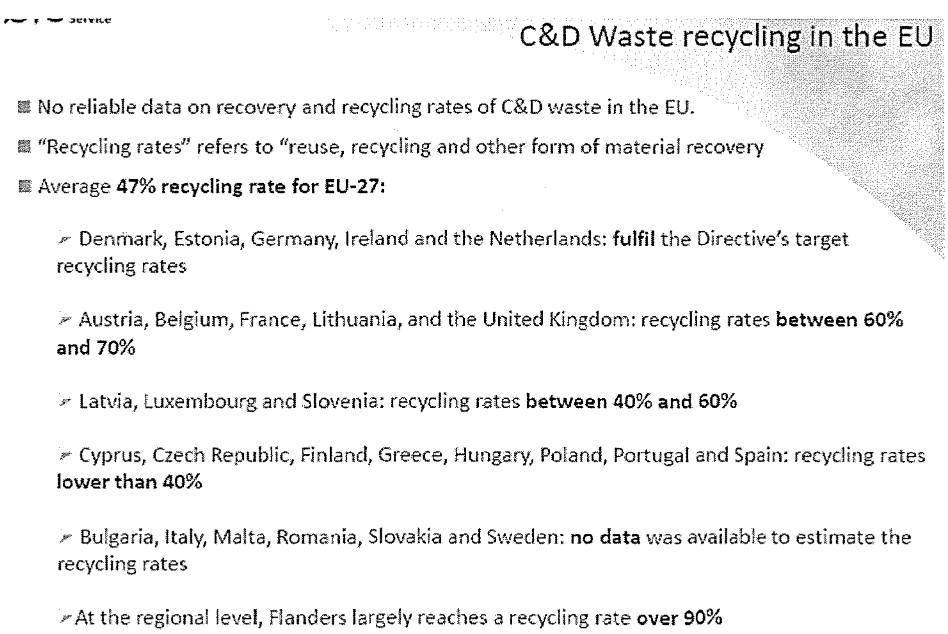

Figure 1.3: Recycling percentages in different EU coutnries. Source: Sonigo et al. (2010), p7

[1] For example, in general, C&DW recovery rates refer to waste that is diverted from landfill however some countries include excavated soil whereas others do not (CSI, 2009).

CSI (2009) goes a step further and compares Europe with the United States and Japan stating that Europe is at 30% while the US is at 82% and Japan 80% (Table 1.5). This is a clear example of how percentages may vary since the 30% stated in this report (2009) varies from the 47% stated in Sonigo et al.'s presentation (2010), just mentioned.

Material	Recycling rates		
	Europe (%)	US (%)	Japan (%)
Concrete/C&DW	30	82	80
Aluminium beverage cans	58	52	93
Aluminium in buildings	96	Not available	90
Glass containers	61	22	90
Lead acid batteries	95	99	99

Table 1.5: Recycling rates in Europe, USA and Japan. Source: CSI, 2009, p16

1.6 Recycled aggregate as a product, not a waste

The mission of E.P.R.A (European Platform for Recycled Aggregates)[1] is to achieve the best use of recycled aggregates for the highest applications possible (U.E.P.G., 2008). One of the activities carried out by F.I.R.[2] for the national associations of recycling companies is to encourage the market to recognise this material as a product and not a waste (F.I.R., 2003). This label otherwise continues to enhance the problems of construction recycled materials maintaining a negative image with the 'waste' connotation and also, the increased costs imposed in the areas of analyses and administration due to the waste legislation.

Figure 1.4 shows a flow chart provided by WRAP (2005) clearing showing the steps involved for accepting and processing of inert waste as a certified product with CE marking.

[1] EPRA is launched by the U.E.P.G. (Union Européenne des Producteurs de Granulats also known as European Aggregate Association [EAA]) and the F.I.R. (Fédération Internationale du Recyclage also known as International Recycling Federation),

[2] F.I.R. is the representative of the European Recycling Industry of C&DW (U.E.P.G., 2008)

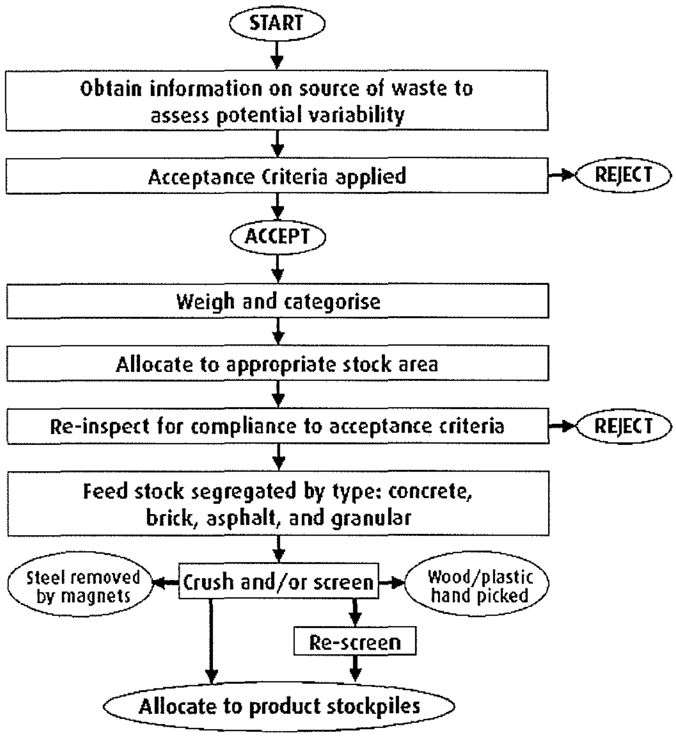

Figure 1.4: Flow chart for acceptance and processing of inert waste
Source: W.R.A.P., 2005, Annex A

1.7 Market for Recycled Aggregates and Industry Profitability

Several reports show how recycling aggregate has had an economic advantage once put on the market (with sufficient demand and supply), when compared to virgin aggregate or other building materials. For example, some US states have estimated savings of up to 50% to 60% and recycling is less costly than disposal in Germany, Holland and Denmark (CSI, 2009). CSI (2009) reports that the cost of sorting and selling concrete waste from a construction site to a recycler (or even paying a fee for collection) can often be cheaper than the cost of sending waste to and paying the fees for the landfill. Costs of use of demolition materials might even be cheaper than new materials. Recycling costs depend greatly on the sorting and processing methods used. However, countries without the required recycling infrastructure and abundant natural resources, recycling might be more expensive.

Figure 1.5 shows how the production of aggregates (natural, recycled and manufactured) varied with different European countries in 2006.

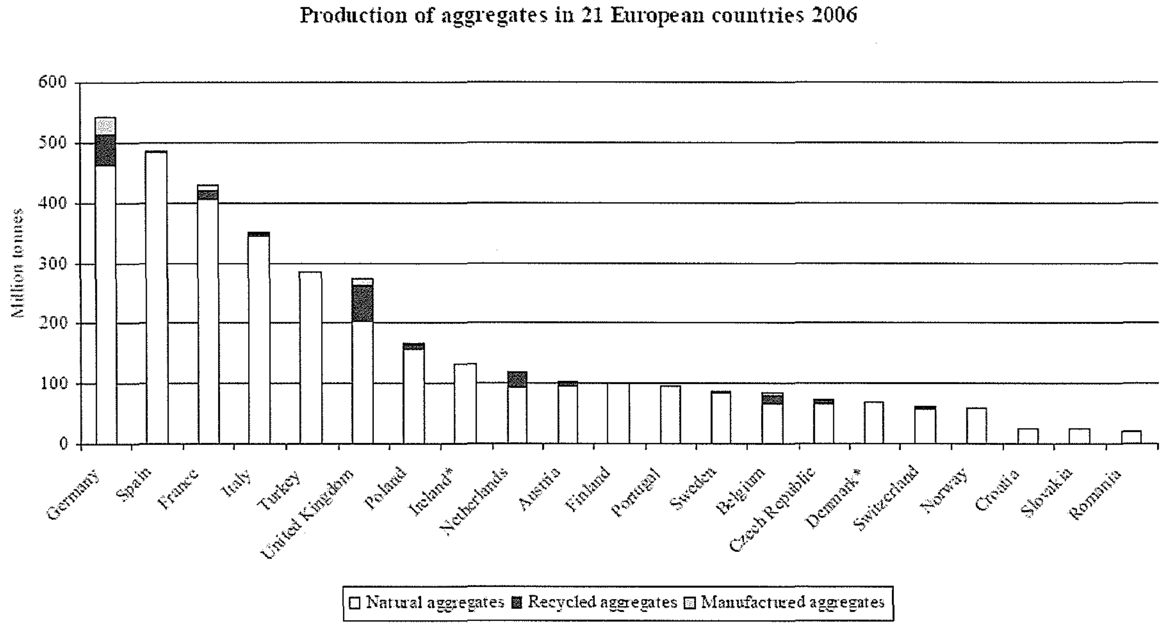

Figure 1.5: Production of recycled and secondary aggregates in European countries in 2006 Note that Malta is not included here. Source: J.R.C. (2008), p. 161, figure 7

CSI (2009) reports how industry studies in Europe have shown a variation in the comparable profit margin. Figure 1.6 compares production, logistics and tipping fee costs.

In Paris, market price for recycled materials is cheaper than natural materials and also a larger profit margin can be observed. There is lack of natural aggregate and high demand for RA. Also the recycling market is driven by the civil works companies who benefit from the recycling processes (CSI, 2009). If NA is exhausted locally, this could become a possible scenario. Similarly, in Rotterdam, the profit margin for recycled materials is high but this is more due to the selling price (CSI, 2009) despite the higher production costs involved for recycled materials. It is also important to note how the exempted TGAP[1] plays a significant role to the overall savings.

[1] General tax on polluting activities (TGAP) establishes a system of tax exemptions on enterprises making use of RA from building demolition will not be subject to the general tax on polluting activities on the aggregates.
Source: www.ilonewsletters.com/Newsletters/Detail.aspx?g=e023f026-03ec-da11-8a10-00065bfd3168

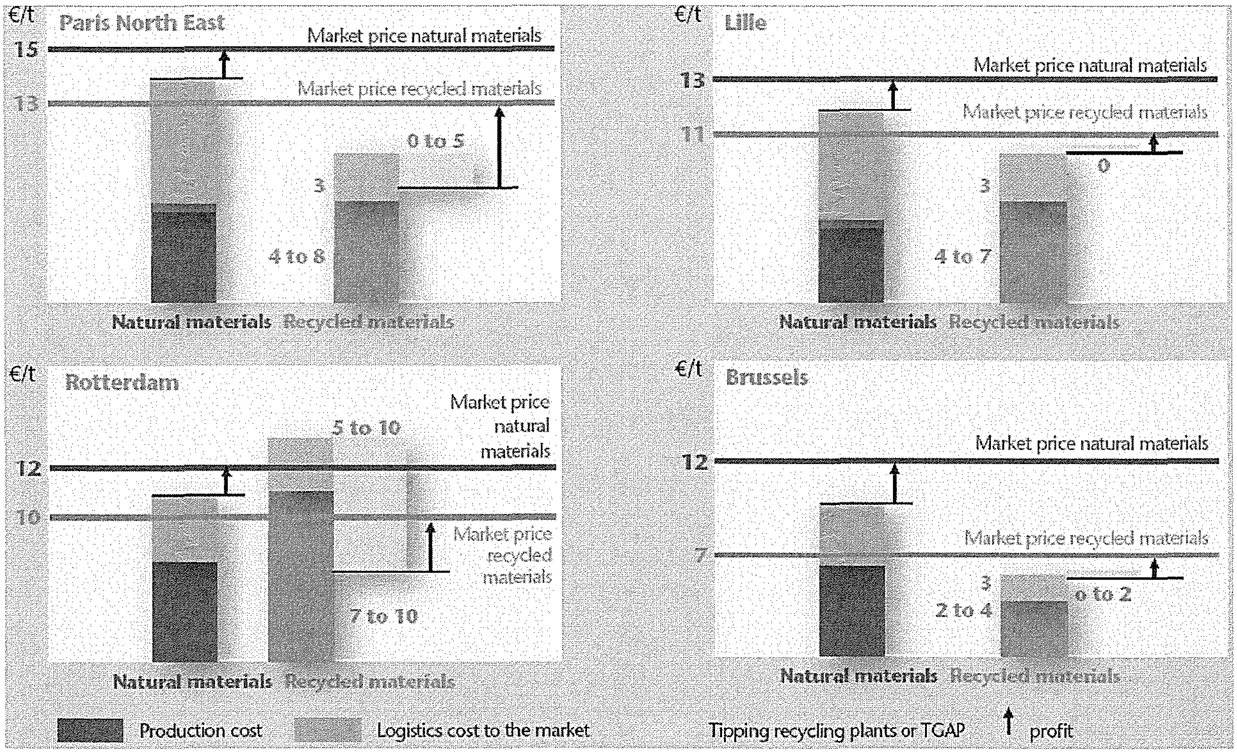

Figure 1.6: Investigations of profit margins with recycled materials. Source: CSI (2009), p18

In Brussels, C&D companies have dropped the market price to find solutions for the waste since there are scarce dumping sites (CSI, 2009). This is an unfortunate result which might become a problem locally due to lack of good practice in waste management. In Lille, the abundance of quarries (CSI, 2009) makes the higher production costs a limiting factor.

U.E.P.G. (2008b) has published a report investigating the effect of environmental taxes and charging fees for management of C&DW on particular countries. It was concluded that the aggregate levy increased environmental awareness and has led to social pressure to use these recyclable materials as a resource. In fact organisations such as WRAP have carried out intensive and numerous research programmes to investigate and exploit the potential of all kinds of recyclable materials. However, the elasticity of demand needs to be considered carefully before introducing a tax, since it determines how sensitive producers and consumers will be to a change in price.

1.8 Adopting a Waste Management Plan for local Construction and Demolition Waste

Figure 1.7 is a clear run-through of efficient best practices in adopting a waste management plan for C&D for A.F.C.E.E., which can be used for any project. This dissertation explores mostly steps 2, 3 and 4 of this flowchart.

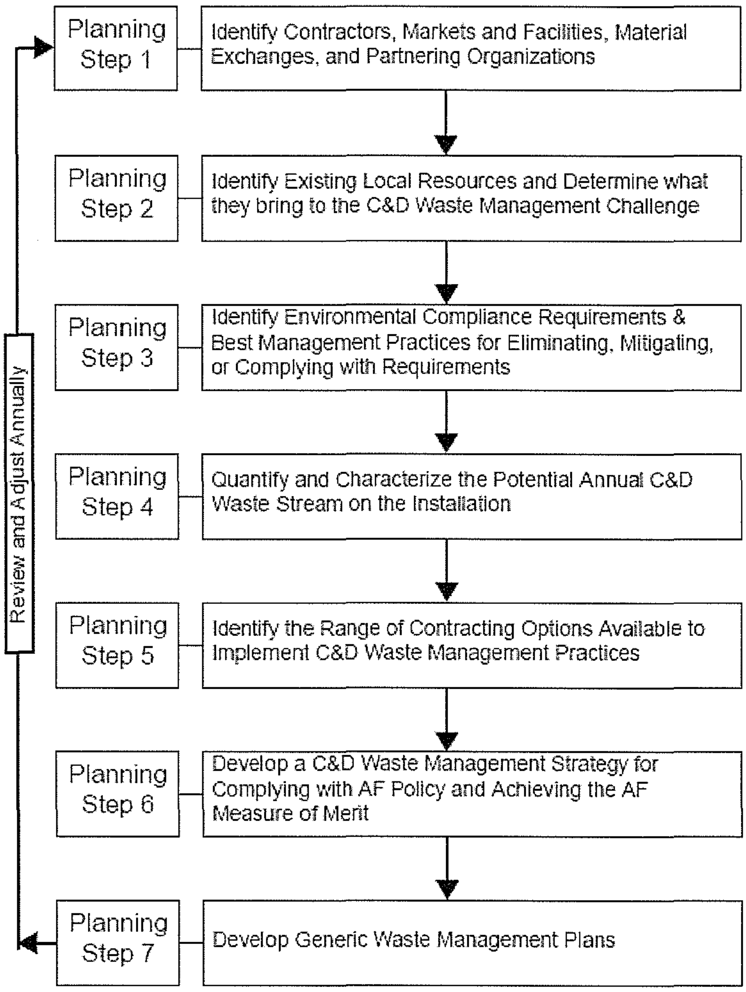

Figure 1.7: The seven-step Construction and Demolition Waste Management Project Planning
Source: A.F.C.E.E. (1999) p13

1.9 Methodology used and structure of dissertation

Chapter 2: An overview of Recycled Concrete Aggregate (RCA)

This chapter is an overview of how the properties and quality of recycled concrete aggregate (RCA) varies from conventional aggregate. Local and foreign results are assessed to comprehend the difference. Strategies for better handling and processing of material, in experienced foreign countries, to certify RCA as a product is also reviewed. Literature and best practice from overseas was a key priority.

Chapter 3: International Classification schemes for RCA

This chapter is an overview of how the limit values specified by foreign countries affect the choice of application for RCA or for a mix of this with other types of RA. Differences in criteria required for structural concrete are discussed. Interpretation of values is used to modify (where necessary) limits for local use to be included in the proposed local guidelines.

Chapter 4: Waste Generation Inventory: Local case studies

This chapter gives an overview of types and amounts of building-related waste generated from typical common local (public and residential) buildings. The processing of the RCA tested in this dissertation was carried out with machinery at a typical Concrete Factory, usually used for NA, since no recycling plant exists as yet. To broaden the spectrum of RCA used to derive conclusions for the Proposed Guidelines, results from tests carried out on RCA from a bridge are also used. An account of the processing of the material from the beginning of its life to testing for grading purposes is given. Conclusions derived and observations from processing of material are used for the drafting of the Proposed Guidelines as discussed in Chapter 7. Use of returned fresh concrete as a waste material is also mentioned. Finally, results of experiments carried out on local NA (original aggregate in any RCA) is compared to NA and RCA in Hong Kong and its quality assessed with the methodology used by Tam et al in section 3.2.

Chapter 5: Experimental Methodology

This chapter outlines the methodology and approach used for derivation of limits to be used in the proposed local guidelines discussed in Chapter 7.

Chapter 6: Discussion of results

This chapter discusses results derived from experiments and desk-work exercises performed in previous chapters. Each section discusses a different property which was tested and how, if necessary, the limit being proposed was modified to suit local needs.

Chapter 7: Proposed Local Guidelines for RA in Malta

This chapter discusses the structure and content of the guidelines proposed in Appendix G, as a result of the research carried out in this dissertation. The limitations of the guidelines being proposed and the use of the guideline to determine applications for the material tested and discussed in Chapter 6, follows.

Chapter 8: Conclusions and Future Research

The applications for RCA tested in this dissertation are derived using the Proposed Local Guidelines, with additional reference to more specific applications in Appendix K. Conclusions from desk-work exercises are also discussed followed by proposals for future research for completion of any sections missing in the proposed guidelines due to lack of information.

CHAPTER 2:

AN OVERVIEW OF RECYCLED CONCRETE AGGREGATE (RCA)

This chapter is an overview of how the properties and quality of recycled concrete aggregate (RCA) varies from conventional aggregate. Local and foreign results are assessed to comprehend the difference. Strategies for better handling and processing of material, in experienced foreign countries, to certify RCA as a product, is also reviewed.

2.1 Definitions

Appendix A lists definitions [1] which vary as encountered in literature reviewed from foreign countries and as used in this dissertation (not necessarily from literature reviewed).

2.2 Function of aggregate in concrete

The properties of aggregates (natural, secondary or recycled) affect the quality, durability and structural performance of the concrete. Aggregates may be considered to be the building medium, existing as loose material, bonded together into a cohesive whole by means of cement paste (Neville, 1995, p.108). Since they form at least three-quarters of the volume of concrete (Neville, 1995) they are expected to have an important influence on the concrete's properties when freshly set or hardened. Recycled aggregate (RA) has the same function as natural (conventional) aggregate (NA). Hence, the first step towards producing recycled aggregate concrete (RAC) of good quality is to assess the properties of the recycled aggregate (RA).

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[1] It should be noted that many definitions, although referring to the same article, are sometimes misinterpreted or are not fully defined. This leads to uncertainties when calculating say, waste amounts. These altered definitions are often a result of translation errors or else of different practices occurring in individual countries.

2.3 Substitution of Conventional Aggregate (NA) with Recycled Aggregate (RA)

Approximately 30% of the total volume of C&DW in Europe (850 million tonnes) is diverted to recycling while the remaining 70% is disposed of in landfills (Fischer & Werge, 2009, p. 25; Unweltbundesamt 2008). Several foreign countries already process good quality RA from the mineral fraction of the waste stream on the market.

In recent years, several attempts have been made to determine a way to classify all possible types of RA for recycling purposes. When RA passes the required tests, its application can be chosen according to its quality. It shall be discussed later on in Chapter 3 how standards have been amended for use of recycled aggregates in applications which are also structural.

Even though use of RA in lieu of conventional aggregate is still in research phase locally, some attempts have been made to test its feasibility in road works. For example, in 2007, glass collected from bring-in sites were recycled and incorporated as crushed waste in the sub-base layer underneath the asphalt in a road in Naxxar (personal communication with Mr. Briffa from Transport Malta). Ameen (2007) reports that the subsoil layer, about 6 to 8 inches thick, consisted of 20% gravel and broken glass which did not cause a greater cut hazard than NA.

Locally, building contractors try to reduce waste generation especially since the waste disposal fee was increased. There are no local guidelines on the percentage replacement with NA and so any recycled inert material is not used other than for bulk filling, screed, road sub-base or minor concrete works which are not documented. Also, some concrete factories make use of any extra block work not used on site for casting large blocks used for dwarf walls separating stockpiles of NA (personal communication with Nicholas Attard, foreman at Blokrete) (figure 2.1).

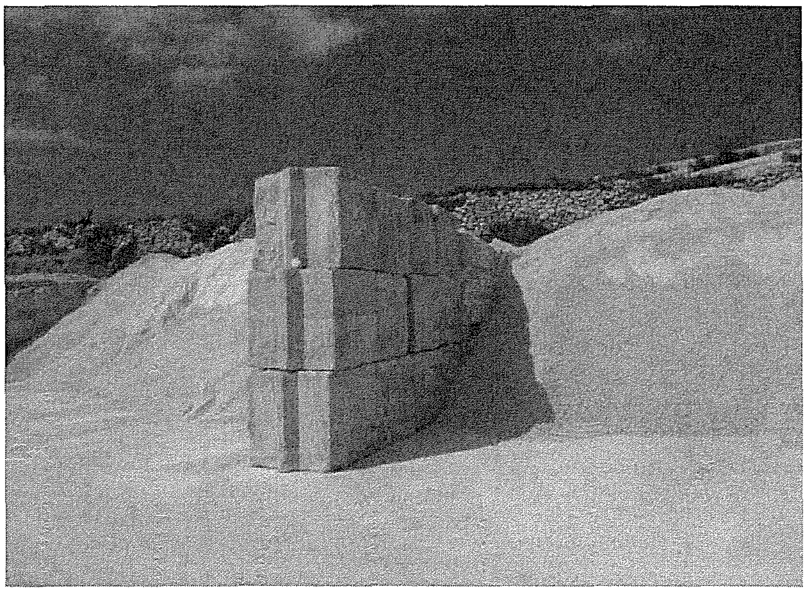


Figure 2.1: Dwarf walls made from recycled block work separating stockpiles of NA. Photo taken by author (2011)

Olorusongo (1999) reports that RA has been used in construction since the end of World War II with use of demolished concrete pavement as RA in stabilizing base courses for road construction (as cited in Rahman, 2009). It has since then gained popularity worldwide with countries such as Austria, UK, Netherlands and Germany being at the forefront in producing guidelines for efficient use of RA. Recycled concrete aggregate is the most popular type of RA.

2.4 Quality of Recycled Concrete Aggregate (RCA)

2.4.1 Reasons for the reduction in quality

a) Weak interfacial zone: When demolished concrete is crushed, a certain amount of cement paste from the original concrete remains attached to stone particles (figure 2.2). Tam et al. (2008, p71) cite that the different mineralogy and microstructure existing between aggregate and mortar in demolished concrete has direct influence on the properties of RAC.

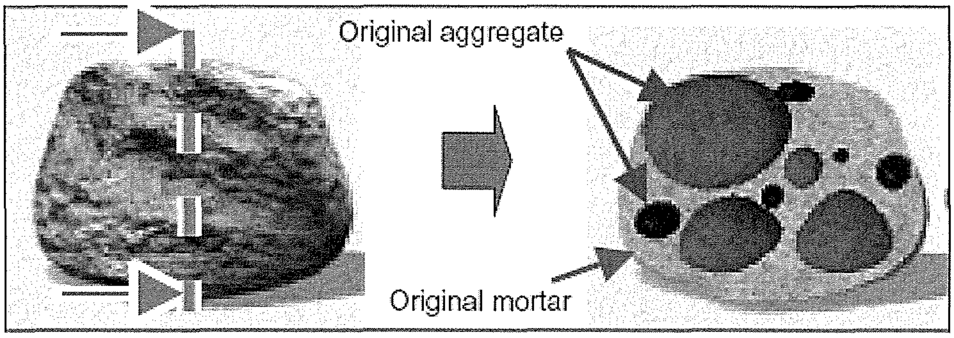


Figure 2.2: Section through recycled coarse concrete aggregate
Source: Dosho (2007), Sustainable concrete as waste recycling, p. 49, figure 4

This attached mortar at the interfacial zone (ITZ), is the main reason for the lower quality of RCA compared to NA (Malešev et al, 2010). In concrete with NA there is just one ITZ while in RAC, there are two: the interface between the original aggregate and adhesion mortar (old ITZ) and the interface between the adhesion mortar and new mortar (new ITZ) (figure 2.3). Ryu (2002) and Otsuki et al, (2003) believe that the adhered mortar from the original concrete plays an important role in determining the performance of RCA concrete, particularly with respect to permeability and strength (as cited in Dhir et al, 2007).

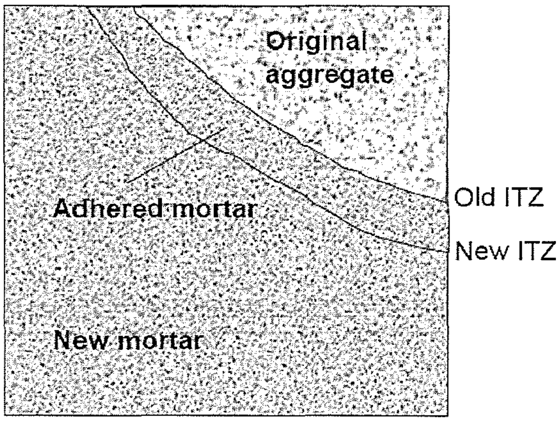


Figure 2.3: Concept of old and new interfacial transition zones
Source: Ryu, (2002), used in WRAP (2007) p. 18, fig 5

b) High porosity of RA: Attached cement makes the RCA more porous and thus less resistant to mechanical action in comparison with natural aggregate.

c) Transverse cracks generated: When RA is processed (crushed, sieved, cleaned) cracks and fissures may form within the structure of the aggregate rendering it susceptible to permeation - diffusion and absorption of fluids (Tam et al, 2008).

d) High impurity levels: Depending on exposure conditions and life span of structure from which concrete is to be recycled, impurity levels (such as of chlorides and sulfates) may be high.

e) Poor grading: Too harsh or too many fines in the particle size distribution cause problems with increased water demand and hence modifications are required for the water/cement ratios used.

f) Variations in quality: Quality of demolished concrete varies from site to site. Mixing of aggregate suitable for high grade applications, with inferior aggregates, leads to the reduction in quality of the whole mix.

g) Processing: The expenses, time and degree of processing and effort put into refining the aggregate affects its final quality.

2.4.2 Typical processing of RCA

One of the countries most advanced with recycling of concrete is the Netherlands. Figure 2.4 shows the typical processes (sieving, hand picking, separation by air and magnets, crushing, washing) involved for aggregate of CE marking. It is generally produced by two-stage crushing of waste concrete then screening followed by removal of contaminants (Malešev, Radonjanin, & Marinković, 2010).

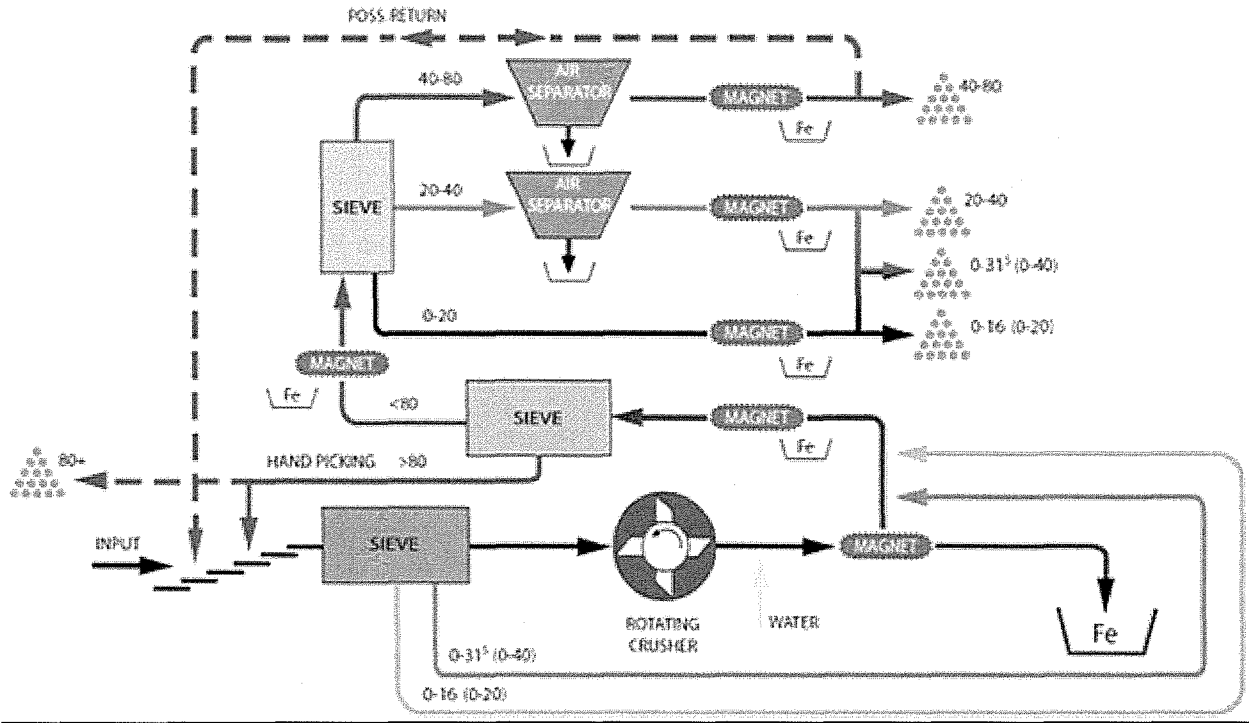


Figure 2.4: C&DW recycling process in the Netherlands
Source: http://www.bentumrecycling.nl/uk/brc_c&dwrecyclingschema.htm

2.4.3 Emerging technologies for improvement of RCA quality

2.4.3.1 Separation of mortar from aggregate

Since the main factor reducing quality of RCA is the mortar attached to it, techniques have been developed in Japan to help reduce this problem by separating the cement mortar from the aggregate and much as possible to achieve a quality almost as good as conventional aggregate.

Different techniques are listed in Table 2.1 on the next page.

Method	Details of the method
Heating and grinding	Makes the hardened cement paste which adheres to concrete waste soften by heating concrete waste to about 300 degrees. After that parts of the hardened cement paste adhered to original aggregate in the concrete mass can then be separated by a grind process resulting in clean original aggregate from the concrete waste.
Screw grinding	Uses a shaft screw consisting of an intermediate part and an exhaust part with a warping cone to remove mortar adhered to the aggregate's surface
Mechanical grinding	Uses a drum body which finely separates partition boards with same-sized holes. The steel balls can move horizontally and vertically by rolling the drum. The quality of aggregate can be improved in narrowing the inside space by using the partition boards.
Gravity concentration	After processing with a jaw crusher, an impact crusher and an improvement rod mill, aggregate of over 8 mm are divided into RCA and mortar particles. Aggregate with sizes less than 8 mm are divided into two types: recycled fine aggregate of sizes 5 mm and 5-8 mm. The wet gravity concentration machine is used to move: i) light weight things such as mortar particle and wood waste upward ii) heavy-weight things such as aggregate grain downward

Table 2.1: Japanese techniques to separate cement from aggregate to improve RCA quality
Source: Tam et al. (2008) p. 61

2.4.3.2 Electrical decomposition

Break down of concrete or rocks can be done by applying a high shear force with a shock wave. At present, there are high initial outlay costs and also environmental impacts when using electricity. (CSI, 2009)

2.4.3.3 Mechanical and thermal energy

The University of Delft (Netherlands), together with TNO, is working on a novel closed-cycle construction concept whereby concrete rubble and masonry debris are separated back into coarse and fine aggregates and cement stone. This is done by using mechanical and thermal energy supplied by the combustible fraction of C&DW (CSI, 2009).

Another type of thermal treatment is used by Barra (1996) (as cited in Gutiérrez et al, 2004). This includes a treatment of soaking the RCA for two hours (enough for mortar to become saturated and not the original aggregate) and drying at high temperatures of 500°C. Evaporation of water at this temperature causes stresses in the mortar which facilitates its removal with a rubber hammer or scratching the surface. Material is then passed through 4mm sieve and mortar content can be weighed and quantified.

2.4.3.4 Treatment in acidic environment

Tam et al (2008) suggest the pre-soaking treatment method (PSTM). This involves soaking the RCA in acidic conditions to detach the cement from the aggregate. Hydrochloric acid (HCl) proved to give better results than phosphoric or sulfuric acid. As a result water absorption decreased significantly. Yagishita et al (1994) (as cited in Gutiérrez et al, 2004) emphasise that HCl cannot be used with limestone because acid attacks this kind of natural aggregate. Further investigation would be necessary to see which type of acid, if any, would be suitable for local coralline limestone.

2.4.4 Combined and individual waste sources

Aggregate from a centralised recycling plant is a mix of aggregates from different sources, which means that any high quality aggregate is classified at a lower quality when used in combination with more inferior material. Mobile crushers (figure 2.5) can be used effectively from site to site and material collected separately to solve this problem

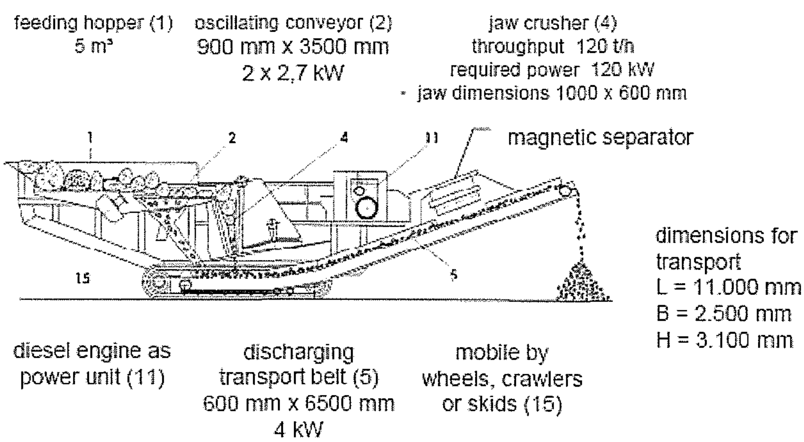


Figure 2.5: Mobile crusher in Germany. Source: Mueller (2007), slide 34

One centralised trial recycling plant for processed demolition concrete was initiated in Hong Kong between 2002 and 2005. There is a crisis since all land fills are expected to be exhausted within the next few years, a probable future scenario in Malta. The urgency there has been realised and this is one of the initiatives to deal with the problem. In all there exist 265 registered recycling organisations none of which recycled C&DW, in 2008. Several investigations were carried out with contractors to discuss the possibility of expanding with RA. Tam et al (2008) summarise the pros and cons discussed. Major issues were time, space and extra resources required for RA processing. When, in the future a recycling plant for aggregates might be implemented locally the options explored by different countries and their mistakes and resolutions should be taken into consideration to implement the most feasible solution at the start. Since space is a problem locally, having a mobile crusher might have its benefits, however if to be used on a large scale, it might be too slow a process since its size would need to be limited to ease mobility.

An exercise has been carried out by Tam et al (2008) whereby correlation equations are derived between the different geometrical, physical and mechanical properties wherever possible, using Linear Regression Analysis. The savings in time and resources in carrying out all these tests are tremendous when correlation equations can be used to find the result of one property from another. This increases efficiency to evaluate RA quality and grade. Having the bare minimum of tests required for classification is a motivation for it to be carried out in the first place.

2.5 Properties of RCA

2.5.1 Foreign criteria for classification of RCA based on aggregate properties

The properties deemed essential for the classification of RCA according to different standards, are summarised in table 2.2 on the next page. Chapter 3 discusses the individual properties. Some properties are based on standards of the country itself, while others are based on BS or the newer EN version. It is important to note that not all the data gathered was from the original source due to the author's limited access to international standards[1]. However citations are from reliable sources (foreign University papers or recognised organisations) as indicated.

[1] There is a probability that updated data in the mentioned standards/guidelines or further relevant data exist, which the author did not come across, for example, limits for frost resistance for which only those used for UK, Germany and Austria could be found.

Reference			Belgian (NBN) standard as cited in Tam et al. (2008, p 46-47)	German (DIN) standard as cited in Mueller (2007), Tam et al (2008)	Hong Kong Building Depart. (2003) APP-129	Spanish (EHE) standard as cited in Gutiérrez et al (2004)	RILEM (1994)	Japanese standard as cited in Mueller (2007), Tam et al (2008)	British Standards (BSI 1987, 1992, 2002a,b,d, 2006a,b)	Proposal by Tam et al, Hong Kong (2008, p 98)	Austrian Der Österreichische Baustoff-Recycling Verband (2007)	Dhir et al (2007) for WRAP
Number of grades for classifying RA, High grade			2 grades GBSB-I, GBSB-II	4 grades 1, 2, 3, 4	2 grades 20P, 25D - 35D	1 grade	3 grades I, II, III	3 grades RA-L, RA-M, RA-H	2 grades RA, RCA	6 grades A to F	4 grades I, II, III, IV	3 grades A, B, C
Recycled Aggregate properties	Geometrical	Particle size distribution		✓	✓ BS 882				✓ EN 12620	✓ BS 882/ASTM	✓	
		Particle shape		✓	✓ Flakiness Index			✓	✓ FI, BS 882 cl 4.2	✓ Flakiness Index		
	Mechanical and physical	Dry Density kgm^{-3}	✓ NBN B11-255	✓ DIN 4226-100	✓ BS 812-2 Particle density	✓ UNE 83134:98	✓	✓	✓ EN 206-1 cl 3.1.25	✓ BS 812-2 Particle density		✓
		Water absorption (%)	✓ NBN B11-255, after 24 hrs	✓after 10 mins	✓ BS 812-2	✓ UNE 83134:98		✓	✓ BS 882 (24h) BS 8007 cl 6.2.2	✓ TAWA (until constant mass)	✓	✓
		TFV			✓ BS 812-111				✓ BS 882, Table 2	✓		
		AIV							✓ BS 882, Table 2	✓		
		LA				✓ UNE-EN 1097-2:99		✓ abrasion	✓ BS 8500-2 cl 4.3		✓	✓
	Chemical	Sulfate content	✓ NBN B11-254	✓ Acid-soluble	✓ BS 812-118	✓ UNE-EN 1744-1:99	✓ Water soluble		✓ EN 12620, Table 20, Acid-soluble	✓	✓	✓
		Chloride content	✓ NBN B11-202	✓ Acid-soluble	✓ BS 882	✓ (both) UNE-EN 1744-1:99 & UNE 80-127:91		✓	✓ EN 206-1, Table 10 Acid-soluble	✓		✓
		Leaching									✓	
	Weathering	ASR		✓								
		Freeze-thaw		✓					✓ EN 13242		✓	
	Content of material	Density (normal or light weight)	✓ 3 variations			✓ Lightweight particles			✓ EN 206-1 cl 3.1.26			
		Mixed Coarse RA?	✓ (stone, concrete, masonry, ceramic, excl. asphalt)	✓ (stone, concrete, masonry)			✓ (stone, concrete, masonry)		✓ (stone, concrete, masonry, asphalt)	✓	✓ (stone, concrete, masonry, asphalt)	✓ (stone, concrete, masonry, asphalt)
		Replacement ratio (%)	✓	✓	✓	✓	✓		✓ BS 8500-1 cl 6.2.2			✓
		Mix with asphalt		✓				✓	✓ BS 8500-2, Table 2		✓	
		Filler/Sand (%)	✓ <80μm, NBN B11-209	✓ <63μm, DIN4226-100	✓ <63μm, <4mm	✓ .UNE 7133:58	✓ <80μm, <4mm	✓ <75μm	✓ BS 8500-2, Table 2	✓	✓	
		Organic (%)	✓ NBN 589-207	✓		✓	✓					
		Foreign	✓	✓	✓	✓ (clay lumps)	✓	✓	✓ BS 8500-2, Table 2	✓	✓	✓
Properties of concrete with RA	Max Class strength		✓	✓	✓		✓		✓BS 8500-2, Table 3	✓		✓
	Tensile strength						✓					
	Flexural strength											✓
	Modulus of elasticity						✓					✓
	Creep coefficient						✓					✓
	Drying Shrinkage (%)						✓		✓ BS 8500-2 cl 4.3			✓
	Workability, Slump (mm)				✓							✓

Table 2.2: Properties used in international standards and proposals for classification of Recycled Aggregates

Reference		K. Bezzina (2003)	K. Bezzina (2003)	D. Mifsud (2003)	D. Muscat (2003)	R. Dalli (2009)	C. Farrugia (2009)	J. Cassar (2010)	B. Mizzi (2010)	S.Scicluna (2010)	M. Anastasi (2011)	S. Krauer (2011)	J. Magro (2011)	A. Muscat Xerri (2011)	M. Zahra (2011)	Ranges for Conventional Aggregates from different sources
Aggregate source and type (if specified)		Source 1	Source 2	Source 2	Source 2	Source 3	Source 4	Source 5	Source 6	Source 6	Source 6	Source 6	Source 5	Source 7	Source 8	
(upper/lower coralline limestone)		UCL	LCL			CL	LCL				Mixed UCL & LCL	Mixed UCL & LCL		Mixed UCL & LCL		
LA (%)		27.8	43.6				37.3				31.0	30.0		28.3	42.5	27.8 – 43.6
AIV (%)		21.1	33.8	34	33.8			27.5								21.1 - 34
TFV (kN)			103.45	100	96.2		34.3	96								96 – 103.45
Moisture content (%)	20mm	2.3	5.9	4.5	4.54		1.44	3.74						1.46	3.5	1.44 – 5.89
	10mm	2.3	5.9	5.9	5.88		1.48	2.97						0.69	2.65	0.69 – 5.9
	sand	8.2	8.2	8.3	8.35		1.63	5.4							1.55	1.55 – 8.35
apparent particle density (Mg/m^3)	20mm			2.67		2.62	2.38	2.60	2.63		2.63	2.61	2.53	2.55	2.65	2.55 – 2.67
	10mm	2.71	1.14		2.67	2.68	2.42	2.63	2.69	2.63	2.59	2.64	2.62	2.62	2.69	1.14 – 2.69
	sand			3.68	3.68	2.17	2.73	2.68	2.88	2.68	2.72	2.73	2.73		2.57	2.57 – 3.68
	filler								2.86							
ssd particle density (Mg/m^3)	20mm			2.39		2.54	2.29	2.45	2.45		2.48	2.43	2.36	2.44	2.47	2.29 – 2.54
	10mm	2.61	1.13		2.39	2.44	2.33	2.52	2.50	2.4	2.41	2.48	2.39	2.32	2.48	1.13 – 2.61
	sand			2.58	2.58	2.03	2.68	2.54	2.68	2.51	2.53	2.58	2.58		2.45	2.03 – 2.68
	filler								2.76							
Oven dry particle density (Mg/m^3)	20mm			2.23		2.48	2.22	2.35	2.34		2.40	2.32	2.25	2.37	2.35	2.22 – 2.48
	10mm	2.55	1.05		2.23	2.34	2.27	2.45	2.40	2.26	2.30	2.38	2.25	2.14	2.36	2.14 – 2.45
	sand			2.17	2.17	1.78	2.65	2.45	2.58	2.4	2.42	2.49	2.50		2.39	1.78 – 2.65
	filler								2.71							
24h Water absorption (%)	20mm	2.4	7.45	7.5		2.2	2.93	4.04	4.68		3.7	4.8	4.98	2.75	4.8	2.2 – 7.45
	10mm	2.4	7.45		7.45	4.26	1.48	2.85	4.59	6.16	4.8	4.1	6.25	6.87	5.02	1.48 – 7.45
	sand			18.9	18.93	6.05	1.14	3.49	4.11	4.33	4.6	3.6	3.47		2.31	1.14 – 6.05
	filler								1.99							

Table 2.3: Results of tests for mechanical and physical properties on NA from 8 local factories

2.5.2 Typical results for mechanical and physical properties of local NA

Quality of RCA is achieved by comparison to properties of NA. Table 2.3 is a compilation of results from tests performed by undergraduate on the physical and mechanical properties for NA from a total of eight different local quarries.

2.5.3 Geometrical properties

2.5.3.1 Particle size distribution

A grading zone (showing the particle size distribution of a sample) is more easily explained when set down on logarithmic graph paper. Usually an envelope is specified with the particle size distribution lying within this envelope (figure 2.6) in order to be considered appropriate for a particular application. If the "plot" leaves the grading zone, the aggregate sample is out of specification (C.J. Summers, 2010). The graphical representation enables one to conclude whether a material is well-graded or gap-graded, a fine or a coarse material.

Figure 2.6: Typical grading of material lying within envelope for a particular application
Source: Summers (2010)

A well-graded material is what enables the concrete product to be of good quality; this is achieved when there is a good distribution of all aggregate sizes (largest to smallest) where the particles position themselves in a way to produce a compact matrix. It will possess good stability, with good distribution loads and stresses spreading out through the material. Achieving the required strength, corresponding to a given w/c ratio, requires full compaction and sufficient workability to obtain optimum density with a reasonable amount of work. Handling and storage of material should be carried out properly to avoid segregation of material which produces variations of particle size distribution.

There is no ideal grading curve but a compromise is aimed at. Neville (1995) reports that the concept of the 'ideal' grading curve (Fuller's curves) still finds favour even though there exist different proposals by other researchers. The main factors which govern the desired grading are the surface area of the aggregate (determines the amount of water necessary to wet all sides of solid), the relative volume occupied by the aggregate, workability of the mix and also, the tendency to segregate (Neville, 1995).

Grading envelopes for use in general concrete applications

Locally grading of RCA is to be stipulated as for NA, according to EN 12620. Grading plays a significant role in influencing drying shrinkage, workability, and production cost. Both physical and economic requirements are important and so concrete has to be made with materials which can be produced cheaply so that no narrow limits can be imposed on the aggregate (Neville, 1995). It is to be noted that the grading limits proposed in BS 882: 1992, Tables 3/4/5 and EN 12620: 2002, Tables 2/3 undergo a somewhat different philosophy.

The 'old code' (BS 882) specifies limits according to particular sieve sizes and applications e.g. heavy duty floor finishes, all-in aggregate, coarse aggregate, sand with specific size designations e.g. 5/40, 5/20 and so on (table 2.4).

Table 3 — Coarse aggregate

Sieve size	Percentage by mass passing BS sieves for nominal sizes							
	Graded aggregates			Single-sized aggregate				
mm	40 mm to 5 mm	20 mm to 5 mm	14 mm to 5 mm	40 mm	20 mm	14 mm	10 mm	5 mm[a]
50.0	100	—	—	100	—	—	—	—
37.5	90 to 100	100	—	85 to 100	100	—	—	—
20.0	35 to 70	90 to 100	100	0 to 25	85 to 100	100	—	—
14.0	25 to 55	40 to 80	90 to 100	—	0 to 70	85 to 100	100	—
10.0	10 to 40	30 to 60	50 to 85	0 to 5	0 to 25	0 to 50	85 to 100	100
5.0	0 to 5	0 to 10	0 to 10	—	0 to 5	0 to 10	0 to 25	45 to 100
2.36	—	—	—	—	—	—	0 to 5	0 to 30

[a] Used mainly in precast concrete products.

Table 2.4: Grading limits for coarse aggregate as per BS 882.
Source: BSI (1992). BS 882, Table 3

EN 12620 is more general as it presents a table with limiting values in terms of d and D and other parameters based on multiples or fractions of these such as 2D, 1.4D, d/2 (table 2.5).

Table 2 — General grading requirements

Aggregate	Size	Percentage passing by mass					Category G [d]
		$2D$	$1,4D$ [a&b]	D [c]	d [b]	$d/2$ [a&b]	
Coarse	$D/d \leq 2$ or $D \leq 11,2$ mm	100 100	98 to 100 98 to 100	85 to 99 80 to 99	0 to 20 0 to 20	0 to 5 0 to 5	$G_C85/20$ $G_C80/20$
	$D/d > 2$ and $D > 11,2$ mm	100	98 to 100	90 to 99	0 to 15	0 to 5	$G_C90/15$
Fine	$D \leq 4$ mm and $d = 0$	100	95 to 100	85 to 99	–	–	G_F85
Natural graded 0/8	$D = 8$ mm and $d = 0$	100	98 to 100	90 to 99	–	–	$G_{NG}90$
All-in	$D \leq 45$ mm and $d = 0$	100 100	98 to 100 98 to 100	90 to 99 85 to 99	–	–	G_A90 G_A85

[a] Where the sieves calculated are not exact sieve numbers in the ISO 565:1990 R 20 series then the next nearest sieve size shall be adopted.
[b] For gap graded concrete or other special uses additional requirements may be specified.
[c] The percentage passing D may be greater than 99 % by mass but in such cases the producer shall document and declare the typical grading including the sieves D, d, $d/2$ and sieves in the basic set plus set 1 or basic set plus set 2 intermediate between d and D. Sieves with a ratio less than 1,4 times the next lower sieve may be excluded.
[d] Other aggregate product standards have different requirements for categories.

Table 2.5: General grading requirements as per EN 12620
Source: BSI (2002). EN 12620, Table 2

Grading envelopes for local road applications

Mr. Briffa (personal communication) at Transport Malta (TM)[1] states that at present, road works are still based on the 'old' UK Road Specifications, Series 800. TM (2003a), Series 800, is being phased out slowly to be replaced with EN 13242 (BSI, 2002d) used in conjunction with EN 13043 (BSI, 2002c) and EN 13285 (BSI, 2003). The disadvantage with Series 800 of TM (2003a) is that ASTM sieves are used for the grading envelopes and hence do not comply with the European Standards. A comparison of all the envelopes mentioned shall be done in Chapter 5 with particle size distributions from different sources of RCA fitted to them and also those provided in Der Österreichische Baustoff-Recycling Verband (2007a, b), Austrian guidelines for recycled building materials.

[1] TM was previously known as MTA or ADT.

Der Österreichische Baustoff-Recycling Verband (2007a) provides its own sets of envelopes (see Appendix G.1) for base and sub-base applications according to EN sieve sizes. It is important to note that this 'Green Guideline' (as it is referred to), is used for aggregates originating from hydraulically or bituminously bound and unbound mineral demolition waste whereas Der Österreichische Baustoff-Recycling Verband (2007b), (referred to as the 'Red Guidline') is used for aggregates originating from unbound or cement bound and sand from mineral waste.

The 'Green guideline' allows mixed ratios with asphalt, concrete and stone. It should be noted that the grading envelopes provided in the 'Green Guideline' are allowed for only coarse aggregates with grading sizes of 0/22 up to 0/90. For grading sizes less than 0/22, the 'Red Guideline' can be used. The 'Red guideline' allows mixed ratios with concrete, bricks and stone (excluding asphalt). Both guidelines provide envelopes for all-in aggregates only. This is to be a predetermined request for the aggregate manufacturer in control of crusher settings.

Crusher types and settings

Hansen (1992) cites a correlation between crusher setting and particle size distribution. It is generally assumed that when rock is fed to a crusher it will break according to a 'straight-line' distribution with 15% of the crusher product being of a size above crusher setting. It should also be noted that different crushers (figures 2.7 to 2.9) such as jaw crushers, impact crushers, hammer mills and cone crushers provide different grain-size distributions. The results of a Dutch investigation (as cited in Hansen, 1992, p17) suggest that jaw crushers provide the best grain-size distribution of RA for concrete production while that produced by impact crushers is best used for road construction purposes.

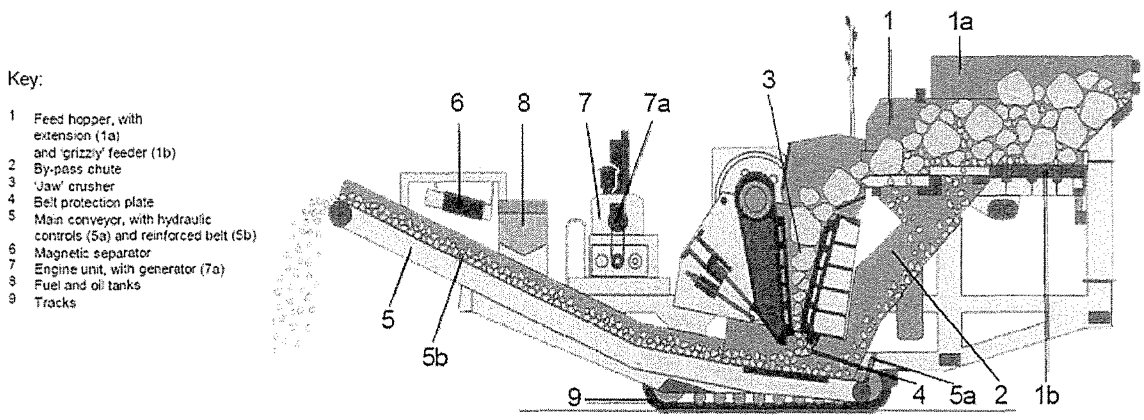
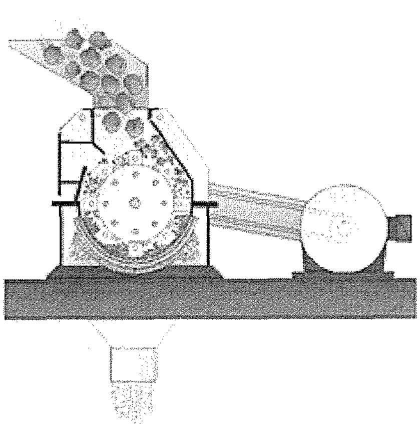


Figure 2.7: Cross section of a 'Jaw' crusher mounted on a mobile chassis with associated equipment. Source: Symonds (1999), Figure 4.6



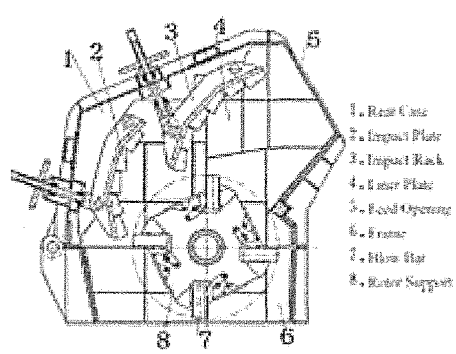


Figure 2.8: Hammer mill (left) and impact (right) crushers
Sources: www.hammer-mill.silverstarengineers.com
www.prlog.org/11198492-impact-crusher-partimpact-crusher-spare.html

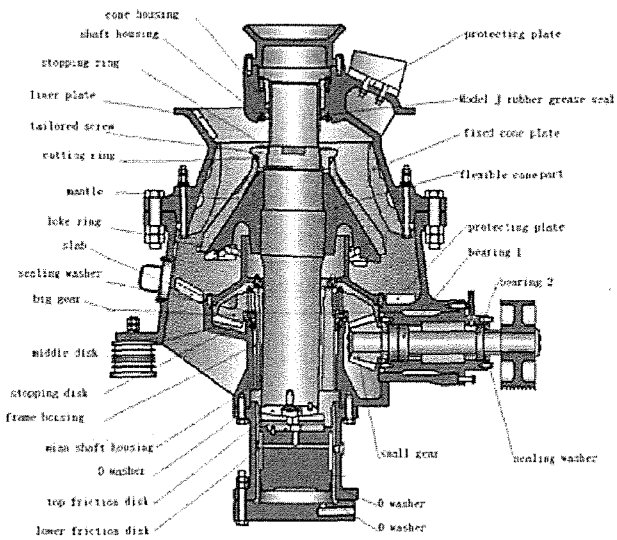


Figure 2.9: Cone crusher. Source: www.crushing-plant.org/stonecrusher/HCS90conecrusher.html

In the crushing process, economy of coarse aggregate production can be maximised by balancing types of crushers (Hansen, 1992, p 17). Caution should be taken with mobile crushers since, although often more economical in that they avoid transporting C&D/E waste away from site, they are rarely sophisticated enough to remove all impurities.

2.5.3.2 Flakiness index

Characteristics and variations in shape of aggregate particles affect water demand, workability, mobility, bleeding, finishability and strength of concrete (Newman, 2003). Newman (2003) reports that aggregate producers can exercise some control over particle shape through the processing of the aggregate. In general, equi-dimensional shapes are preferred over flaky or elongated particles (figure 2.11), so as to produce a dense concrete matrix. The main reason is that there is the tendency for bleeding water and air voids forming underneath flaky particles resulting from their orientation in one plane (Neville, 1995, p115).

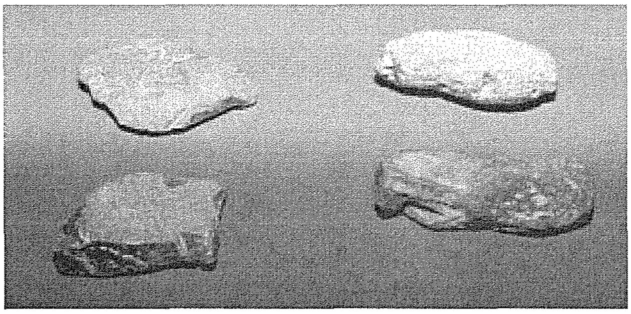


Figure 2.11: Flaky (left) and elongated (right) particles
Source: Newman, J.B. (2003) fig 8.5

Flakiness index is the most common shape test. Flaky is the term applied to aggregate that is flat and thin with respect to its length or width. The index is the mass of flaky particles expressed as a percentage of the mass of the sample. This is done by grading the size fractions, obtained from a normal grading aggregate, in special sieves for testing flakiness. These sieves have elongated rather than square apertures and allow aggregate particles, having a dimension less than the normal specified size, to pass.

A particle is classified as flaky if its least dimension is less than 50% of its upper sieve size according to the EN933 test. This limit is 60% for the British standards (Newman, 2003 & Neville, 1995). The difference is because the indices are based on different dimensional ratios. BSI (2009a) reports the British Standard requirements (BS 882 clause 4.2) of maximum flakiness index 40 for crushed rock equivalent to European Standard category of 35.

The relevance of the flakiness test can be comprehended with the case of a granular sub-base having a high proportion of flakey aggregate which would tend to segregate and be difficult to compact. This high proportion could not be recognized with a normal aggregate sieve analysis test alone since it would either wise falsely indicate conformity to specification (Summers, 2010).

2.5.4 Physical properties

2.5.4.1 Particle density

This is the ratio of the mass on a given volume of material to the mass of the same volume of water (Tam et al., 2008, p86). There are three particle densities which can be calculated from EN 1097-6. These are the apparent, dry or saturated surface dry state (ssd). The oven dry state is the particle density which results in the least numerical value from all states mentioned and is the one chosen for specification of limits in most classification schemes. Some however use limits for density in ssd state and it is often recommended to pre-soak the RCA before using in a mix, since it tends to absorb more water than NA. The particle density is an essential property for concrete mix design and for calculating volume of concrete produced.

Tam at al (2008) report a correlation between water absorption of 20mm RCA, as well as ssd particle density, with flakiness index with an R^2 value of 0.80.

2.5.4.2 Water absorption

Rates of water absorption and moisture content are used to assess levels of porosity and absorption. Crushed concrete can be highly porous and absorb water in the range between 5 to 10% by mass (Dhir et al, 2005c as cited in Dhir et al, 2007). Water absorption of RCA was found to be roughly 4.5 times higher than the NA from which they were produced (Dhir et al, 2007). On the other hand, water absorption of 10mm RCA roughly 11.5 times higher than that of typical NA can be concluded from the results of Tam et al (2008).

Tam et al's report that the water absorption of 20mm aggregate is less than that of 10mm aggregate inferring that larger size aggregate may have less cement mortar adhered to the surface leading to a lower absorption. Hence, using large aggregate would result in a better final quality concrete, in this aspect.

<u>Modification to EN 1096-7: Timely Assessed water absorption (TAWA)</u>

Tam et al. point out that the standard BS method needs to be modified as it was noticed that full saturation may be reached after even 48 or even about 127 hours. The reasons for this suggested modification are the following:

1. Full saturation of RCA generally requires more than the 24 hour requirement specified for NA.
2. Surface-drying with a cloth after removal from pyknometer may remove any cement paste sticking to surface of aggregate which may be loosened when soaked, varying mass readings taken prior to soaking.
3. The removal of embedded crystallised water in the RCA occurs at temperatures higher than 100°C. When recording the oven-dried mass of the aggregate sample at this temperature the absence of the water in the aggregate due to both absorption and crystallisation are mistakenly both assumed to be due to absorption alone. A temperature of 75 ±5 °C is recommended.

Tam et al. found a very good correlation (R^2 value of 0.92) between particle density and water absorption. One could save time to carry out the test for particle density if a simple water absorption test is only carried out.

Importance of knowing the right amount of water absorption

The absorption capacity is probably the most significant property that distinguishes RA from NA. It affects both fresh and hardened concrete properties. Variations in water absorption and hence free water available, influence rate of hydration of cement and the workability of the fresh mix after absorption. The free water content and water/cement ratio are the factors ultimately responsible for the final strength of the concrete.

Dhir et al (2007) also realise the importance of the water absorption variation. In fact, a water/cement ratio reduction factor is used in the classification scheme to achieve equal cube strength as NA. However, it is stated that from a practical point of view, it is likely to be unsustainable to permit large reductions in w/c ratio as this may lead to much higher cement content. Also, the need for large dosages of admixtures may arise to achieve the required consistence class.

Gutiérrez et al (2004) report that the Spanish standard for structural concrete restricts the maximum value of water absorption of NA to 5%. It is suggested to reduce this limit to 4.5% for NA when using a 20% replacement ratio[1] with RCA, so that the mix ('blend') [4] still complies with the requirement. This way, RA which usually exceeds this 5% limit, can be used more often with a limit of 7% and not discarded (first graph in figure 2.11). The higher the percentage of RA used, the stricter is the limit for conventional aggregate (second graph in figure 2.11). The 3% limit drawn for RA is the requirement for Type III according to RILEM (1994). In this case a very strict limit of 2%for NA would be required for allowing the 7% water absorption for RCA, being suggested.

[1] Definition in Appendix A.

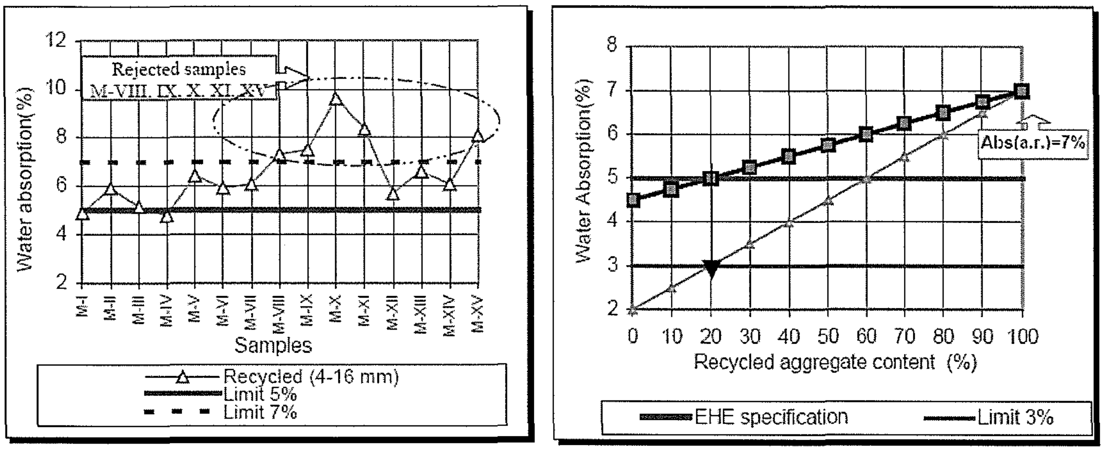


Figure 2.11: Water absorption of RA (left) and absorption of mixed aggregates (right)
Source: Gutiérrez et al (2004)

2.5.5 Mechanical properties

There are a number of test methods available for investigating the mechanical properties of RA and other aggregates. Prior to the publication of EN12620, the Ten percent fines value [TFV] and Aggregate Impact Value (AIV) tests were carried out. Dhir et al (2007) suggest that the TFV has potential as a means for expressing a measure of quality of RA without reference to its composition, however since it is no longer included in EN 12620, it is unlikely to ever be used for this purpose. Some authors have reported a good correlation between TFV, AIV and Los Angeles (LA) (Bjarnson et al, 2000 as cited in Dhir et al, 2007). Dhir et al, investigate RA quality with use of LA test, which seems to be the preferred test in all literature reviewed.

2.5.5.1 Resistance to fragmentation: Los Angeles test

The LA value reflects aggregate strength performance due to its good correlation with wear of aggregate and also with compressive and flexural strength of the concrete (Neville, 1995). The LA value is the percentage in loss of mass over the overall mass of aggregate sample, with a lower value signifying a better resistance to fragmentation.

2.5.5.2 Quantification of attached mortar content in RA

A new property CSCement index, is proposed by Tam et al (2008), whereby a more direct method of measuring the amount of cement paste is possible. The amount and porosity of the cement mortar remaining adhered to aggregate, directly influences properties such as low strength, high water absorption and low density of the aggregate as a whole. Since the cement is the main reason for the lower quality of the RA, having a direct means of measuring it, is recommended to be a good method of assessing the quality of the aggregate. The method involves undergoing sieve analysis before and after placing in a pan mixer. The value is derived from the difference in percentages of particle size distribution before and after stirring.

This value is expected to be zero for natural aggregate since no cement is attached and can loosen off. Typical values recorded for this test by Tam et al (2008) range from 3.81 to 5.13 for 10mm aggregate and from 10.28 to 16.90 for 20mm aggregate, for 10 samples originating from demolished buildings. This suggests that it is easier to remove the cement paste adhered to the RCA from the larger coarse aggregate.

It is interesting to note that the sample (sample number 11) originating from the centralised recycling plant, is recorded to have a very low CSCement index when compared to the crushed concrete from the demolished buildings (sample numbers 1 to 10), hence making it comparable to NA (sample number 12) used in Hong Kong. This suggests that the recycling plant produces better quality than the mobile crusher being suggested by Tam et al. This is a common remark among researchers. The mobile crusher would have the same type of equipment used in the lab (personal communication with Professor Tam).

Tam et al (2008) derive a strong correlation between CSCement index and water absorption (R^2 value of 0.82).

2.5.6 Chemical properties

2.5.6.1 Maximum availability leaching

Maximum availability leaching is defined as the maximum quantity of soluble fraction of a constituent that can be released into solution under aggressive leaching conditions. In theory it provides an estimate of the maximum mass of material that can be leached in a 100 to 1000 year time frame (Dhir et al, 2007). Leaching of materials is generally not expected to occur in significant amounts. Mueller (2007) reports that leachable heavy metals practically occur only in buildings with an "industrial history". Dhir et al (2007) suggests the Dutch availability leaching test NEN7341 while EN 1744-3:2002 is the method suggested by BSI.

Common elements which are tested for are Cd (Cadmium), Cr (Chromium), Pd (Lead), Cu (Copper) and SO_4 (Sulfate). Two sets of bar charts are provided in the report written by F.I.R.(2006) – one compares recycled materials with national limits while the other with primary materials. Der Österreichische Baustoff-Recycling Verband (2007a) sets the leaching parameters as part of the procedure for classification for recycled aggregates.

Table 2.6 on the next page shows a compilation of the leaching parameters from the F.I.R. (2006) document in one table. Each parameter is very specific to every country. The value which stands out the most is the maximum limit allowed for sulfate in Germany.

No such limits for local leaching parameters are known to exist as yet.

Parameter (mg/kg TS)	Austria [a, b]						Germany (Lower and upper limits)	South Tyrol (Italy) Limit values	Czech Rep Limit values	Netherlands [c]										Belgium				
	Limit values			Beton (0/05)	RB (0/32)	RA (0/32)				Limit value	Recycled materials				Primary materials					Limit value	Recycled materials			
	A+	A	B								AA [d]	CA [d]	MA [d]	BA [d]	Spl1	AS	FLS	STN	Spl2		AA [e]	CA [e]	MA [e]	SS [e]
Chromium total	0.3	0.5	0.5	0.02	0.22	0.03	0.5 - 2.2	0.5	0.1	2.1	0.04	0.6	0.11	0.12	0	0.01	0.05	0	0.03	0.5	0.05	0.06	0.15	0.08
Copper	0.5	1	2	0.08	0.14	0.03	0.9 - 10	0.5	0.5	1.1	0.045	0.15	0.23	0.08	0	0.015	0.0625	0	0.03	1.0	0.035	0.22	0.1375	0.12
Sulfate-SO_4	1500	2500	3500	100	325	100	2500 - 15000	2500	500	1200	775	100	575	450	75	75	150	225	525	?	425	50	1200	5475
Cadmium	0.04	0.04	0.04	0	0	0	0.05 - 0.5	0.05	0.005	0.04	0.006	0.006	0.005	0.005	0.006	0	0	0	0.005	0.03	0.014	0.011	0.011	0.015
Lead	0.5	0.5	0.5	0.09	0.03	0	0.05 - 1.8	0.5	0.1	2.7	0.078	0.1	0.092	0.07	0	0	0.98	0	0.06	1.3	0.09	0.068	0.1	0.052

[a] More parameters for leaching limits are available from Der Österreichische Baustoff-Recycling Verband (2007a) and (2007b). These are included in the Proposed guidelines for Malta in appendix G.1 as extracts from the reference, being compared to the proposed.

[b] Abbreviations for Austria
Beton Primary concrete
RB Recycled concrete aggregate
RA Recycled asphalt aggregate

[c] Dutch limit value category 1 materials at an application height of 0.4m

[d] Abbreviations for the Netherlands
AA Recycled asphalt aggregate
CA Recycled concrete aggregate
MA Recycled mixed aggregate
BA Recycled masonry aggregate
Spl1 Splitt-1: Primary stone material
AS Primary Asphaltbeton
FLS Flugsand: Primary sandy material
STN Primary stone
Spl2 Splitt-2: Primary stone material

[e] Abbreviations for Belgium
AA Recycled asphalt aggregate
CA Recycled concrete aggregate
MA Recycled mixed aggregate
BA Recycled sieve sand

Table 2.6: Comparison of leaching behaviour of recycled materials with national limit values and primary materials.

Source: F.I.R. (2006), Annex I and Annex II.

2.5.6.2 Chloride content

Source of chloride content

Chloride levels are considered to be significant, locally, due to the location and setting of the Maltese archipelago and the high humidity levels. Chlorides can be deposited on the surface of concrete in the form of air-borne very fine droplets of sea water or of air-borne dust which subsequently becomes wetted by dew (Neville, 1995). Nireki and Kabeya (1987) report that air-borne chlorides can travel substantial distances such as 2km, but travel over even greater distances is possible depending on wind and topography (as cited in Neville, 1995). Hence, it is important to consider the chloride content with local RCA crushed from demolished buildings or structures, especially in marine environments or similarly exposed elements.

It is important to note that chloride content in concrete can be increased also during mixing of the concrete, through the use of contaminated aggregate or of sea or brackish water, or by admixtures containing chlorides (Neville, 1995). In fact, Cutajar (2011) reports high chloride content in the water used locally (from boreholes, reservoirs or government mains) for production of concrete at factories. 45% of the 18 samples tested do not pass the limits for prestressed concrete while 34% do not pass the limits for reinforced concrete.

Implications of having high chloride levels

Chloride attack is distinct in that the primary action is the corrosion of steel reinforcement, in reinforced and prestressed concrete, and it is only as a consequence of this corrosion that the surrounding concrete is damaged (Neville, 1995). This results from the action of chloride ions destroying the passivity layer of oxide which protects the steel in the concrete's inner alkaline environment. In the presence of oxygen and water, optimum conditions are present for corrosion to occur. The products of corrosion occupy a volume several times larger than the original steel so that their formation results in cracking, spalling or delamination (figure 2.12).

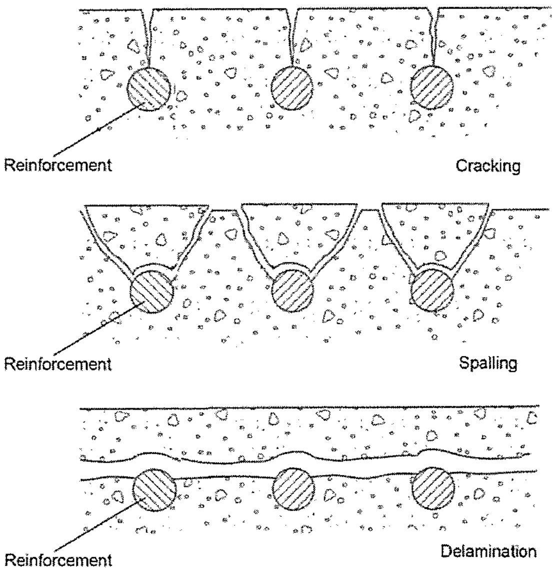


Figure 2.12: Damage induced by corrosion. Source: Neville (1995) p. 565

Types of chloride content

Chloride ions exist in concrete in three forms (NZRMCA, 2005)

- dissolved in the pore water ('free chlorides') and can penetrate sound concrete
- chemically bound to the hydrated cement paste ('bound chlorides')
- chemically bound within the minerals that make up the aggregate

Water-soluble or 'free' chlorides, are those that are dissolved by extraction in water. Acid-soluble chlorides are those that are dissolved by extraction in nitric acid. They include free and bound chlorides but do not include chlorides in the minerals that make up the rock. Water soluble chloride content is not a constant percentage of acid-soluble chloride but varies with the amount of chloride present, the mix constituents and the analytical test methods used.

Free chlorides initiate corrosion by depassivating the steel, and may also increase the subsequent corrosion rate. Bound chlorides do not directly take part in corrosion, but may eventually dissolve to become free chlorides. It is difficult to predict how much of the chloride in fresh concrete will remain free and how much will be bound once the concrete hardens, so it is prudent to test for both when controlling the amount of chloride present in fresh RAC. (NZRMCA, 2005)

Limits on chloride content

Some standards provide limits for water-soluble chlorides while others for acid-soluble chlorides. Chloride content by acid-soluble test provides a worst-case value and probably overestimates the availability of chlorides, thus providing a margin of safety (CEN/TC 154/SC 2 2005 as cited in Dhir et al, 2007). Limits in EN 206-1 are provided for maximum chloride content (acid-soluble) by mass of cement (table 2.7).

Application	Maximum chloride content by mass of cement	Designation
Not containing steel reinforcement/embedded metal	1%	Cl 1.0
Containing steel reinforcement/embedded metal	0.2% or 0.4%	Cl 0.2 or Cl 0.4
Containing prestressing steel	0.1% or 0.2%	Cl 0.1 or Cl 0.2

Table 2.7: Maximum chloride content by mass of cement. Source: EN 206-1:2000, Table 10

A different yet similar approach is used in EN 1744-5:2006 (specified in EN 12620 Table 20 and Amendments to EN 12620) where acid-soluble chloride content for recycled aggregate is found by mass of aggregate and not mass of cement. This is a better way of presenting the chloride content since original content of cement cannot be known for RCA. No limits are set for chloride content by mass of aggregate in the EN standards. The need arose for the author to derive equivalency to show the relationship of the limits provided in BS 882 and EN 206-1, as explained in Chapter 5, since BS 882 provides the limits by mass of combined aggregate (table 2.8). Similarities in the tests used by both standards were needed to be found to be sure that the BS 882 limits could be used for experiments specified by EN 12620.

Application	Max chloride content by mass of combined aggregate
Prestressed concrete	0.01%
Reinforced concrete with sulfate resisting cement	0.03%
Other reinforced concrete	0.05%

Table 2.8: Maximum chloride content by mass of combined aggregate
Source: BS 882:1992, Appendix C, Table 7

2.5.6.3 Sulfate content

Types of sulfate content

A proposed amendment to EN 12620 suggested by CEN/TC 154/SC 2 (2005), includes a possible limit of 0.2% for water-soluble sulfates (Dhir et al, 2007). The argument is that it is in fact the water-soluble sulfates that is reactive and causes expansive disruption of concrete and so the limit provided only for acid-soluble sulfates may restrict use of RA, as in the case for the bricks with 1.9% sulfate content reported by Dhir et al (2007). Locally, bricks are not used, so this is not an issue; however it is the author's opinion that both limits need to be considered for now in the classification of local RA, since the acid-soluble content limit still seems to be the only one specified in EN standards.

Source of sulfate content

Sulphur dioxide is a colourless gas which can be chemically transformed into acidic pollutants such as sulfuric acid and sulfates. Impurities in fuel may cause exhausts to contain sulfur dioxide, but only 3% of the total emissions of this substance come from transport, the rest mainly from industry and power generation (ABT, 2011). [1]

Another source of sulfates which might contaminant the RCA locally is sulfate-containing building materials such as plasterboard (gypsum board), anhydrite plaster floor, autoclaved aerated concrete or similar materials. Mueller (2008) reports that these materials should be dismantled before demolition of a building to reduce contamination of RCA. Consideration should be given to the use of sulfate resisting cement in RAC in a situation where plaster contamination is suspected (Hansen, 1992). The proposed amendment to EN12620, suggested by CEN/TC 154/SC 2 (2004) states that the sulfates in gypsum plasters are controlled through the categories given for class X (table 2.11), and additionally by the limit 1%, on acid-soluble sulfates.

[1] Similar information can be found at www.mepa.org.mt/air-sources

Also, contamination of aggregate in RAC is possible through the water used for the mix; however Cutajar (2011) reports very low values of sulfate content in the water used locally for production of concrete at factories.

Implications of having high sulfate levels

Sulfuric acid may cause surface weathering of exposed concrete (Neville, 1995, p 507) while sulphur compounds may oxidise in RAC to produce sulfates under appropriate exposure conditions, leading to harmful expansive reactions in concrete (EN 12620:2002 Annex G, cl G.2). Solid sulfate salts do not attack concrete but, when present in solution, they can react with hydrated cement paste. Sulfuric acid is particularly aggressive because, in addition to the sulfate attack of the aluminate phase in hydration of cement, acid attack on $Ca(OH)_2$ and C-S-H takes place (Neville, 1995, p 507). The products of sulfate attack cause the concrete to disintegrate and permit corrosion of steel to begin.

2.5.7 Weathering properties

2.5.7.1 Magnesium sulfate soundness

As a means of indicating resistance to freeze/thaw attack, the magnesium sulfate soundness of an aggregate is often calculated. However, it should be noted that this test is regarded as unreliable for RCA, (ECCO, 1999 as cited in Dhir et al, 2007 for WRAP). Locally, freeze/thaw attack is not considered relevant since such temperatures are not reached.

2.5.7.1 Bulk oxide analysis

The presence of alkalis (usually from cement) and reactive silica in aggregate may lead to expansive alkali-silica reaction. Consequently care is to be taken to limit the alkali content of the constituents of concrete. Research has shown that in most cases, total equivalent sodium oxide, Na_2O_{eq}, values for Portland cement concrete containing RCA are below the recommended limit (Dhir et al, 2007). As a result RCA could be regarded as a normal reactivity aggregate.

2.5.8 Content of material

2.5.8.1 Replacement ratio [4]

In general, replacement of NA with recycled sand is not recommended (table 2.9) and further research is to be carried out. The following reasons (RILEM, 1994) are given:

- Large amounts of contaminations are usually found in fine RA and operational testing procedures and acceptance criteria are not readily available.
- A relevant test method for determination of strength of fine RA is not available.
- Reliable test method for determination of residual alkali reactivity of fine RA is not available.
- Use of fine RA has been reported to lead to production problems e.g. in the control of free water and in the flow of materials during production.

Mifsud (2003) confirms the last point and improved workability with the use of admixtures. In fact, use of 100% replacement of natural with recycled sand provided no slump. However, in general this adds to the expense of the mix and is thus possibly not a feasible solution.

	Classification		Replacement	
	Density	Composition	Fine aggregates	Coarse aggregates
Belgium	+	+	allowed with restrictions	up to100 %
Denmark	+	+	limited (20%)	up to 100 %
Germany	+	+	not allowed	up to 45 %
The Netherlands	+	+	limited (20%)	up to 20 %
Switzerland	-	+	allowed	in dependence of application
United Kingdom	-	+	not allowed	up to 20 %

Table 2.9 Replacement ratios for coarse and fine aggregates. Source: Mueller (2007), slide 18

It has been observed that the replacement ratio of coarse NA with RCA, allowed for different applications, vary in different countries. Most countries limit this to 20%, as with UK practice and as specified in European standards (BSI, 2006a).

When more research is done, and applications are not generalised but assessed with particular attention, a wider variety of options become available. The common misperception that recycled concrete is not suitable for structural concrete can be proven wrong by practice carried out in the US, UK, Australia and Germany where guidelines permitting recycling of up to 10%, 20%, 30% and 45%, respectively are used (CSI,2009). The UK has developed its 20% limit further, through the WRAP initiative, with replacement ratios up to 40% for use in structural concrete with exposure conditions (X0, XF1 to XF4, XC1 to XC4, XD1 to XD2, XS1 to XS2, DC1, DC2,), if the RCA is of Class A (Dhir et al, 2007).

2.5.8.2 Mix ratio[1]

Chapter 3 discusses the mix ratios with concrete, stone, bricks and asphalt used abroad. BS 8500: Part 2 (BSI, 2006) states that composites of coarse RCA/RA and NA are to conform to the general requirements for aggregate specified in EN12620. A proposed amendment to EN 12620 to incorporate clauses for RA has created a number of potential categories (Table 12.10).

CONSTITUENT	CONTENT (% by mass)	CATEGORY
R_C	≥ 90	R_C90
	≥ 70	R_C70
	< 70	R_CDeclared
	No requirement	R_CNR
R_C+R_U	≥ 90	R_{CU}90
	≥ 70	R_{CU}70
	≥ 50	R_{CU}50
	< 50	R_{CU}Declared
	No requirement	RCUNR
R_B	≤ 10	R_B10
	≤ 30	R_B30
	≤ 50	R_B50
	> 50	R_BDeclared
	No requirement	RBNR
R_A	≤ 1	R_A1-
	≤ 5	R_A5-
	≤ 10	R_A10-
FL_S+FL_{NS}	≤ 1	FL_{total}1
	≤ 3	FL_{total}3
FL_{NS}	≤ 0.01	FL_{NS}0.01
	≤ 0.05	FL_{NS}0.05
	≤ 0.1	FL_{NS}0.1
$X+R_G$	≤ 0.2	XR_G0.2
	≤ 0.5	XR_G0.5
	≤ 1	XR_G1

Table 2.10: Proposed categories for constituents of coarse RA. Source: Dhir et al (2007), p 12

[1] Definition in Appendix A.

It is clear that mix and replacement ratios[1] for RA is being encouraged in the EN standards with the more detailed classification nomenclatures suggested for coarse RA in prEN 933: Part 11 (2005). Having a wider variety of materials (table 1.11) in a classification localises weak from strong materials and aids in using a larger proportion of the aggregate for recycling. This can be considered an improvement on the classes categorised in BS 8500-2 which were only RA and RCA. Further optional subclasses exist for masonry and other materials also exist (table 2.12).

Class	Type	Percentage by mass	Category
A	Bituminous materials	≤ 5 ≤ 10 > 10	M_A5 M_A10 M_ADeclared
		No requirement	M_ANR
B	Masonry units	≤ 5 > 5	M_B5 M_BDeclared
		No requirement	M_BNR
C	Concrete, concrete products, mortar Concrete masonry units		M_C
G	Glass		
L	Lightweight (<1.0Mg/m^3)	≤ 0.5 ≤ 1.0 > 1.0	$M_L0.5$ $M_L1.0$ M_LDeclared
		No requirement	M_LNR
U	Unbound aggregate, natural stone Hydraulically bound aggregate		M_U
X	Other foreign materials	≤ 1.0 > 1.0	$M_X1.0$ M_LDeclared
		No requirement	M_XNR
The proportions of concrete (class C) and unbound aggregates (Class U) shall be documented and declared on request.			

Table 2.11: Constituents of coarse recycled aggregates
Sources: BSI (2005) - prEN 933-11, table 2 and CEN/TC 154/SC 2 N 189 E (2004), Table 18

Subclass	Type	Symbol used for mass
	Class B, Masonry	
B_1	Baked clay units such as bricks, tiles etc	M_{B1}
B_2	Units with calcium silicate	M_{B2}
B_3	Concrete (lightweight or normalweight)	M_{B3}
B_4	Aerated non-floating concrete	M_{B4}
B_5	Blockwork	M_{B5}
	Class X, Other materials	
X_1	Cohesive materials: clay, soil	M_{X1}
X_2	Miscellaneous: wood, metal, rubber, plastic	M_{X2}
X_3	Gypsum, plaster	M_{X3}

Table 2.12: Sub-classes for masonry and other materials (optional)
Source: BSI (2005) prEN 933-11, table 3

[1] Definition in Appendix A.

2.5.8.3 Fines content

The maximum amount of fines is set to 5% for RCA in BS 8500: Part 2, due to the fact that some concrete elements may be coated with gypsum plaster, and on crushing most of this gypsum plaster finishes in the fine RCA or RA (BSI, 2006). Excess gypsum plaster can lead to delayed ettringite formation and it is the judgement of BSI that there is no practical sampling system that would detect localized high volumes of sulfate. For these reasons, the use of fine RCA is left to the project specification, which can take account of the particular source of RCA. Otherwise, clean fine RCA is suitable for use in concrete. Different applications require different specifications for fines content. Also, different crushers give different amount of fines. Mueller (2007) reports that jaw crushers lower portion of fines and increase shape index while impact crusher increase portion of fines and decrease shape index.

2.6 Properties of RAC (concrete with RCA)

Once the aggregate is classified as being appropriate for use in concrete for a particular application, it can be used as a fraction of the total aggregate added to the mix. Several researchers report a variation in results of how RCA affect the properties of RAC when

i) varying the mix ratio of RA
ii) using aggregates of different qualities to achieve same target values
iii) adopting certain techniques different than with NA, while preparing the RAC mix

Some researchers report an increase in quality with some properties, while others the opposite. Since the water demand is increased significantly with RCA, the desired amount to saturate the RCA to achieve good workability is to be done before or during mixing. Malešev et al (2010) report that the same workability for concrete with NA can be achieved with RAC, if the aggregate is used in a saturated surface dry condition. In fact where RA is processed as a product in foreign recycling plants (figure 2.4), washing is part of the cycle for refining the aggregate.

Mifsud (2003) reports that confidence levels of compression and flexural strength results are higher with pre-soaking.

A decrease in quality of RAC may arise if the quality of the RCA itself is not good enough. In fact, Malešev et al (2010) report the compressive strength of the RAC depends more on the quality of the RA rather than the quantity, with the same effective w/c ratio. This means that if good quality RA is used for the production of RAC, the RA has no influence on the compressive strength, regardless of the replacement ratio of natural coarse aggregate with RA.

It has been found that increasing the amount of coarse RCA might increase the compressive strength of the RAC in some cases (Hansen, 1992). There is a chance that unhydrated cement in the RCA becomes active during mixing of RAC and this might result in an increase of compressive strength. This has been proved to be true for Mifsud (2003) and also Malešev et al (2010) who raised the compressive strength up to 25%.

Malešev et al (2010) report that in general, the performance of RAC, was mainly satisfactory with at time better results than control, except for modulus of elasticity and shrinkage deformation. Hence, it is recommended that RAC not be used for structural elements where large deformations are expected or where structures are exposed to aggressive environment conditions. However, having such positive results with all the other properties is quite rare. Tam et al. (2008) summarise the results of several researchers who have investigated how the quality of RAC decreases. These are shown in table 2.13.

RAC properties	RA replacement ratio			
	25%	50%	75%	100%
Density*# (reduced %)	0% to 1.4%	0.12% to 2.4%	0.77% to 6%	1.11% to 10%
Compressive strength*# (reduced %)	0.3% to 31.8%	1.2% to 57.8%	1.22% to 54.5%	1.49% to 86.4%
Flexural strength*# (reduced %)	0% to 10.4%	0% to 8.1%	2.39% to 10.03%	8.1% to 20%
Tensile splitting strength~# (reduced %)	10.6% to 50.7%	12.84%	21.40%	6% to 29.95%
Modulus of elasticity~# (reduced %)	6.16% to 22.7%	2.8% to 30.5%	2.27% to 21.9%	1.1% to 50%
Shrinkage ^# (increased %)	0.4% to 30.9%	0.1% to 53.4%		5.9% to 88%
Creep ^# (increased %)	33.13% to 47.26%			166.47% to 215.75%
Air permeability ^# (reduced %)	0% to 26.47%			0% to 57.41%
Water permeability ^# (reduced %)	0% to 23.52%			0% to 28.84%
Chloride permeability ^# (reduced %)	0% to 23.7%			0-30.25%
Notes: # The data collected from the previous researchers and Tam et al's (2008) experimental results. ~Tests conducted at 28 days of curing, * 7 to 56 days of curing, ^ 14 to 182 days of curing				

Table 2.13: Variation of RAC properties with percentage replacement of RA.
Source: Tam et al (2008) [1]

[1] References used by Tam for this compilation of data:

Acker A. V. Recycling of concrete at a precast concrete plant. Sustainable construction: use of recycled concrete aggregate: proceedings of the International Symposium London, United Kingdom London: Thomas Telford, 1889, 321-332.

Ahmed A. and Struble L. Effects of microstructure of fracture behaviour of hardened cement paste. Microstructure of cement-based systems/Bonding and interfaces in cementitious materials: symposia Boston, Massachusetts, U.S.A., 1995, 99-108

Bretschneider A., http://www.b-i-m.de/public/tudmassiv/decon98ruehl.htm

Frondistou-Yannas S. Waste concrete as aggregate for new concrete. ACI Journal 177, 5, No 373-376

Ikeda T., Yamane S. and Sakamoto A. "Strength of concrete containing recycled concrete aggregate." Demolition and Reuse of Concrete and Masonry, London : Chapman and Hall, 1988 585-594

Grubl P., Ruhl M. and Buhrer M., http://www.b-i-m.de/public/tudmassiv/damcon99grueblruehl.htm

Kakizaki M., Harada M., Soshiroda T., Kubota S., Ikeda T. and Y.K. "Strength and elastic modulus of recycled aggregate concrete." Demolition and Reuse of Concrete and Masonry, London: Chapman and Hall, 1988, 565-574.

Khatib J. M. Properties of concrete incorporating fine recycled aggregate. Cement and Concrete Research, 2005, 35, No. 4, 763-769.

Masood A., Ahmad T., Arif M. and Mahdi F.,http://link.springer.de/link/service/journals/10022/contents/01/00034/papers.

Nishibayashi S. and Yamura K. "Mechanical properties and durability of concrete from recycled coarse aggregate prepared by crushing concrete." Demolition and Reuse of Concrete and Masonry, London: Chapman and Hall, 1988, 652-659.

Roos D. I. F., http://www.b-i-n,de/public/TUM/dundeeroos.htm

Sagoe-Crentsil K. K., Brown T. and Taylor A. H. Performance of concrete made with commercially produced coarse recycled concrete aggregate. Cement and Concrete Research, 2001, 31, No. 707-712

Teranishi K., Kikuchi M., Dosho Y. and Narikawa M. Application of recycled aggregate concrete for structural concrete: part 3 production of recycled aggregate by real-scale plant and quality of recycled aggregate concrete. Sustainable construction: use of recycled concrete aggregate: proceedings of the International Symposium London, UK London: Thomas Telford, 1988, 143-156.

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Xiao J., Li J. and Zhang C. Mechanical properties of recycled aggregate concrete under uni-axial loading. Cement and Concrete Research, 2005, 35, No. 6, 1187-1194.

Yanagi K., Hisaka M, and Kasai Y. Physical properties of recycled concrete using recycled coarse aggregate made of concrete with finishing materials. Demolition and Reuse of Concrete and Masonry: Guidelines for Demolition and Reuse of Concrete and Masonry: Proceeding of the Third International RILEM Symposium on Demolition and Reuse of Concrete Masonry: London: E and FN Spon, 1993, 379-390

Tam et al (2008) suggest RAC improvement with:

i) Pre-soaking treatment method (PSTM) in acidic conditions (explained in section 2.4.3.5)

ii) Variations of the Two-stage mixing approach (TSMA): Tam et al (2008) report that where usually the mixer is first charged with about one half of the coarse aggregate, followed by fine aggregate, then cement and then the remaining coarse aggregate, adding water immediately before rotation of the drum, TSMA divides the mixing process into two parts. The required water is split into two which are added at different times. Adding silica fume was a variation of the experiment. It was highlighted that the optimal performance for the TSMA occurred at 20% RA substitution.

The properties usually tested for, to assess the quality of the RAC are density, compressive and flexural strength, tensile splitting strength, modulus of elasticity, shrinkage, creep, air/water/chloride permeability, initial surface absorption and carbonation.

RILEM (1994) also suggests that the RA must not contain any material or any other substances which retard the setting of the concrete by more than 15% compared with the setting of the identical composition with NA. This can be tested according to EN1744-6:2006.

CHAPTER 3: INTERNATIONAL CLASSIFICATION SCHEMES for RCA

This chapter is an overview of how the limit values specified by foreign countries affect the choice of application for RCA or for a mix of this with other types of RA. Differences in criteria required for structural concrete are discussed. Interpretation of values is used to modify (where necessary) limits for local use to be included in the proposed local guidelines.

3.1 Typical applications from international standards and guidelines

The most common application for RCA is bulk filling or road sub-base, most commonly in unbound form[1] since its quality is taken for granted as being very poor, without further tests carried out. The quality of aggregate depends on the quality of the original material and the degree of processing and sorting. Refining aggregate[2] may produce aggregate of higher quality with, however, the consequence of negative impact on the environment (CSI, 2009). Foreign countries handle RA of varying qualities (depending on available resources) differently and hence limit values used for assessing quality vary in most cases.

The following pages show a compilation of the limits provided in international standards and guidelines, an elaboration of the properties listed in table 2.2. The first criteria which one notices in the classification scheme, is the varying number of grades. The highest grade of each set is highlighted for visual aid, since different numbers, codes and letters are used in each case. Each grade corresponds to a particular set of possible applications. Countries like Spain and UK provide only one set of limits by comparing it to a quality as good as NA (best quality) which restricts the possibility for variety in applications of RA. On the other hand, countries such as Austria and Germany provide limits for several different grades and hence can be successfully used for a variety of different applications every day.

The recommended limits and applications for Hong Kong, UK and Spain carried out by Tam et al, Dhir et al and Gutiérrez et al, respectively, have also been included. The recommendations were concluded after extensive research was carried out not only on the RCA but also on the final product, RAC.

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[1] An unbound mixture is a granular material, normally of a controlled grading with d=0, which is generally used in pavement bases and sub-bases. It does not contain an added binder. Source: EN 13285: 2003

[2] Removal of foreign materials, contaminations or cement.

Reference			Belgian (NBN) standard as cited in Tam et al. (2008, p 46-47)		German (DIN 4226-100: 2002) standard as cited in Mueller (2007), Tam et al (2008, p 51) and Marinkovic et al (2010)				Hong Kong Building Depart. (2003) APP-129		Spanish (EHE) standard as cited in Gutiérrez (2004)
Grades for classifying RA, Higher grade is highlighted			GBSB-I	GBSB-II	1 Concrete chippings + crusher sand	2 Construction chippings/crusher sand	3 masonry chippings + crusher sand[1]	4 mixed chippings + crusher sand	20P (prescribed mix)	25D - 35D (designed mix)	
Recycled Aggregate properties	Geometrical	Particle size distribution			Same as NA	Same as NA	Same as NA	Same as NA	Same as NA	Same as NA	
		Particle shape			Same as NA	Same as NA	Same as NA	Same as NA	FI_{40}[2]	FI_{40}[4]	
	Mechanical and physical	Dry Part. density Mgm^{-3}	≥ 1.6	≥ 2.1	≥ 2.0	≥ 2.0	≥ 1.8	≥ 1.5	> 2.0	> 2.0	≥ 2.0
		Water absorption (%)	< 18	< 9	< 10	< 15	< 20	No limit	< 10	< 10	≤5 (standard, for NA) ≤7 (recomm. Gutiérrez)
		TFV (kN)							100	100	
		AIV (%)									
		LA									≤40
	Chemical	Sulfate content (%)	< 1	< 1	< 1	< 1	< 1	< 1	≤ 1	≤ 1	≤ 1
		Chloride content (%)	< 0.06	< 0.06	< 0.04	< 0.04	< 0.04	< 0.04	≤ 0.05	≤ 0.05	≤ 0.05
		Leaching									
	Weathering	ASR			Same as NA	Same as NA	Same as NA	Same as NA			
		Freeze-thaw resistance			Same as NA	Same as NA	Same as NA	Same as NA			
	Content of material	Density (normal or light weight) $1Mgm^{-3} = 1000kgm^{-3}$	<10% is <1.6Mgm^{-3} <1% is <1.0Mgm^{-3}	<10% is <2.1Mgm^{-3} <1% is <1.6Mgm^{-3} <0.5% is <1.0Mgm^{-3}							≤ 1% is <1.0Mgm^{-3}
		Mixed Coarse RA (%)	> 95	> 95	≥ 90	≥ 70	≤ 20	≥ 80			
		Replacement ratio RA with NA (%)	≤100 coarse no recycled sand	≤100 coarse no recycled sand	≤45 coarse no recycled sand	≤35 coarse no recycled sand	no recycled sand	no recycled sand	≤ 100 coarse	≤ 20 coarse	≤ 20 coarse
		Mix with asphalt			≤ 1	≤ 1	≤ 1	≤ 20			
		Fines/Filler/Sand (%)	< 5 (sand <80μm)	< 3 (sand <80μm)	< 4 (fines i.e. <63μm)	< 4 (fines i.e. <63μm)	< 4 (fines i.e. <63μm)	< 4 (fines i.e. <63μm)	≤ 4 (filler) ≤ 5 (sand)	≤ 4 (filler) ≤ 5 (sand)	≤ 1 (fines)
		Organic (%)	< 0.5	< 0.5	Like NA	Like NA	Like NA	Like NA			
		Foreign (%)	< 1	< 1	≤ 0.2 ≤ 2 (other mineral material)	≤ 0.5 ≤ 3 (other mineral material)	≤ 0.5 ≤ 5 (other mineral material)	≤ 1 ≤20 other mineral material	≤ 1	≤ 1	≤ 0.25 clay lumps
Properties of concrete with RA		Max Class strength	C16/20	C30/37	C30/37	C30/37			20	25-35	
		Tensile strength									
		Flexural strength									
		Drying Shrinkage (%)									
		Workability							Slump of 75mm with wetted RCA		
Applications Explained in more detail in sections 31.1 to 3.1.10			Interior of buildings with dry environment. Components in non-aggressive soil & water Road base/sub-base; Realization of parking areas; filling materials for river embankment, Land-filling		Dry/low humidity environments, No lightweight concrete, No prestressed concrete Replacement of natural by recycled coarse aggregates is reduced when environmental effects or "attacks" on concrete. Road construction and as filling materials for earthwork				Minor and non-structural work[3]	No major structural concern[5]	Not specified (comparable to normal aggregate)
			For GBSB-I, water should not be exposed to frost.		RA > 2 mm can be used for structural concrete		Grades 3 & 4 not to be used for structural concrete		Not to be used in liquid-retaining or pre-stressed structures, transfer/hanger structures		

Table 3.1a: Properties used in international standards and proposals for classification of RA (to be read with table 2.2 in Chapter 2)

[1] Masonry consists of brick work which is not used locally. Hence they are still listed, but in grey, as they shall not be used for classification purposes of local aggregate.
[2] BS 882 clause 4.2 specifies a flakiness index limit of 40 for crushed rock/gravel. It is important to note that the equivalent limit using EN standards is 35.
[3] See definitions in Appendix A.

Reference			Japanese standard as cited in Mueller (2007), Tam et al (2008) and Dhir et al (2007)		RILEM (1994)			British Standards BSI (1987, 1992, 2002a,b,d, 2006a,b)	Dhir et al (2007) for WRAP		
Grades for classifying RA, Higher grade is highlighted			RA-H coarse	RA-H fine	Type I Masonry rubble[1]	Type II Concrete rubble	Type III Mix of NA and RA	RA / RCA	A	B	C
Recycled Aggregate properties	Geometrical	Particle size distribution						EN 12620			
		Particle shape	≮ 55[2]	≮ 53[7]	Same as NA	Same as NA	Same as NA	< 35			
	Mechanical and physical	Dry Particle density Mgm^{-3}	≮ 2.5	≮ 2.5	≥ 1.5	≥ 2.0	≥ 2.4	> 2.0 for normal-weight > 2.6 for heavy-weight concrete	> 2.55 (ssd)	> 2.45 (ssd)	> 2.15 (ssd)
		Water absorption (%)	≯ 3	≯ 3.5	< 20	< 10	< 3	< 3 (prestressed/water retaining)	≤ 2	≤ 6	no limit
		TFV (kN)						150 (heavy duty concr floor finishes) 100 (pavement wearing surfaces) 50 (others)			
		AIV (%)						25 (heavy duty conc floor finishes) 30 (pavement wearing surfaces) 45 (others)			
		LA	≯35 (abrasion)	-	Same as NA (abrasion)	Same as NA (abrasion)	Same as NA (abrasion)	< 40 for concrete	< 25	< 30	< 40
	Chemical	Sulfate content (%)			< 1	< 1	< 1	<1 (a-s) & <0.2 (w-s)	same as BS	same as BS	same as BS
		Chloride content (%)	≯ 0.04	≯ 0.04	Same as NA	Same as NA	Same as NA	<0.1 or <0.2 or <0.4 or <1.0[3]	same as BS	same as BS	same as BS
		Leaching									
	Weathering	ASR			Same as NA	Same as NA	Same as NA				
		Freeze-thaw resistance			Same as NA (durability factor >80x%)	Same as NA (durability factor >80x%)	Same as NA (durability factor >80x%)	Resistant if WA_{24} ≤ 2%			
	Content of material	Density (normal or light weight)			<10% is <1.8Mgm^{-3} (ssd) <1% is <1.0Mgm^{-3} (ssd)	<10% is <2.2Mgm^{-3} (ssd) <1% is <1.8Mgm^{-3} (ssd) <0.5% is <1.0Mgm^{-3} (ssd)	<10% is <2.2Mgm^{-3} (ssd) <1% is <1.8Mgm^{-3} (ssd) <0.5% is <1.0Mgm^{-3} (ssd)	Light weight bulk density < 1.0			
		Mixed Coarse RA (%)					< 10 from type 1		> 10	> 10	> 10
		Replacement ratio (%) RA with NA			≤100 coarse recycled sand not recommended	≤100 coarse recycled sand not recommended	≤20 coarse recycled sand not recommended	≤20 coarse no recycled sand	≤ 40 coarse	≤ 80 coarse	no limit
		Mix with asphalt	> 2	> 2				< 5			
		Fines/Filler/Sand (%)	≯ 1 (sand <75μm)	≯ 7 (sand <75μm)	< 3 (fines, <63μm) < 5 (sand)	< 2 (fines, <63μm) < 5 (sand)	< 2 (fines, <63μm) < 5 (sand)	<5 fines for RCA <3 fines for RA			
		Organic (%)			< 1	< 0.5	< 0.5				
		Foreign (%)	< 3	< 3	< 5	< 1	< 1	< 1	same as BS	same as BS	same as BS
Properties of concrete with RA		Max Class strength			C16/20 C30/37 if density ssd> 2Mgm^{-3}	C50/60	No limit	GEN0-3 (100% replacement ratio), RC20/25 to RC40/50	±7.5% of equiv for NA	±15% of equiv for NA	±30% of equiv for NA
		Tensile strength			1	1	1				
		Flexural strength			0.65	0.8	1				
		Modulus of elasticity			1	1	1				
		Creep coefficient			2	1.5	1				
		Drying Shrinkage (%)						≤ 0.075 (for aggregate)	≤ 0.075	≤ 0.075	≤ 0.075
		Workability						S3: 100 to 150mm			
Applications Explained in more detail in sections 31.1 to 3.1.10					Additional testing for concrete used under exposure conditions other than dry condition, non-aggressive soils and/or water or with no exposure to frost.			Exposure conditions: X0, XC1 to XC4, XF1, DC-1. Not to be used with FND , PAV or RC50XF designated concretes	XD1-2, XS1-2	Not applicable	
									Above and XC3-4, DC2, XF1-4		Not applicable
									Exposure classes above and X0, XC1-2, DC1[4]		

Table 3.1b: Properties used in international standards and proposals for classification of RA (to be read with table 2.2 in Chapter 2)

[1] Masonry consists of brick work which is not used locally. Hence they are still listed, but in grey, as they shall not be used for classification purposes of local aggregate.
[2] These limits are not specified for flakiness index, but listed under 'Percentage of solid volume for evaluation of particle shape'. Not comparable to other standards.
[3] Depends on application (whether it contains steel or not). Also, note that these limits specified by mass of cement and not by mass of aggregate.
[4] Maximum aggregate size is 20mm and not to be used with designated concretes PAV or FN. See together with table 3.7 for better explanation of applications.

Reference			Classification proposal by Tam et al (2008) for Hong Kong							Der Österreichische Baustoff-Recycling Verband (2007a) (Austrian Green guideline)[1]			
Grades for classifying RA, Higher grade is highlighted			A	B	C	D	E	F	G	I	II	III	IV
Recycled Aggregate properties	Geometrical	Particle size distribution	Like NA	Like NA	Like NA	Like NA	Like NA	Like NA	Like NA	Figures in guidelines for road applications (Appendix G.1), otherwise like NA			
		Particle shape	< 8.0	9 - 16	17 - 22	23 - 28	29 - 34	35 - 40	> 40				
	Mechanical and physical	Dry Particle density Mgm^{-3}	> 2.5	2.49 – 2.4	2.39 – 2.3	2.29 – 2.2	2.19 – 2.1	2.09 – 2.0	< 2.0				
		Water absorption (%)	<1%	1.1 – 3.0	3.0 – 5.0	5.1 - 7.1	7.1 – 9.0	9.1 – 10	> 10.0	≤4 RCA and/or asphalt aggregate ≤2 RCA and/or asphalt aggregate mix with NA		Depends on application	Depends on application
		TFV (kN)	> 150	149 - 120	119 - 110	109 - 100	99 - 80	79 - 50	< 50				
		AIV (%)	< 20	21 - 23	24 - 26	27 - 28	29 - 31	32 - 35	> 35				
		LA								40 for all RA but no requirement for recycled asphalt		Not required (NR)	Not required (NR)
	Chemical	Sulfate content (%)	< 0.015	0.016-0.03	0.031-0.05	0.051-0.1	0.101-0.5	0.501-1.0	> 1.0				
		Chloride content (%)	< 0.015	0.016-0.03	0.031-0.05	0.051-0.1	0.101-0.5	0.50-1.0	> 1.0				
		Leaching								Separate tables exist (Appendix G.1)			
	Weathering	ASR											
		Freeze-thaw resistance								$f_4, f_3, f_5, f_7, f_9, f_{12}$	$f_4, f_3, f_5, f_7, f_9, f_{12}$	f_{NR}, f_{NR}	f_{NR}, f_{NR}
	Content of material	Density (normal or light weight)											
		Mixed Coarse RA (%)										Depends on application	Depends on application
		Replacement ratio (%)	≤20	≤20	≤20	≤100	≤100	≤100		≤ 50	≤ 50	Depends on application	Depends on application
		Mix with asphalt								≤ 50	≤ 50	Depends on application	Depends on application
		Fines/Filler/Sand (%)											
		Organic (%)											
		Foreign (%)	< 1	< 1	< 1	< 1	< 1	< 1		≤5 [2] Impurities ≤1	≤12 [11] Impurities ≤1	Depends on application ≤5 , ≤10 , ≤12 [11] Impurities ≤1	Depends on application ≤25 RA/RB, ≤33 other Impurities ≤1
Properties of concrete with RA	Max Class strength												
	Tensile strength												
	Flexural strength												
	Modulus of elasticity												
	Creep coefficient												
	Drying Shrinkage (%)												
	Workability												
Applications Explained in more detail in sections 31.1 to 3.1.10			Non-structural elements for all grades						Not applicable. Discard material	Hydraulically bound road base courses applicable for all grades			
			minor structural elements, Road surfaces, base courses, Embankment & fill, Insulation barrier			Not applicable for grades D-F				frost-resistant materials, unbound road base/sub-base		noise protection embankments, infill/filling of trenches for roads, subsoil improvement	
			Structural/ pre-stressed concrete	Structural/ pre-stressed concrete is not applicable for grades B-F						bituminous bound road base courses		agricultural/forestry road construction, parking areas, noise protection embankments, infill/filling of trenches for roads, subsoil improvement	

Table 3.1c: Properties used in international standards and proposals for classification of RA (to be read with table 2.2 in Chapter 2)

[1] The limits and applications for Grades III and IV are shown for the Green guidelines only due to limited space in table on this page. (section 3.1.11)

[2] See definition of foreign materials for this guideline, in Appendix A.

3.1.1 Belgium

The classification seems to be based mostly on the density and water absorption of the RA in question. Belgium allows for the highest chloride content, with a maximum limit of 0.06%. It also allows for very high water absorption when compared to other countries, allowing more RA to fall under the lower-quality category, GBSB-I. This is possibly targeted more for RA with masonry as is a similar case with Germany and RILEM (1994).

The applications for both grades are restricted to dry interior of buildings and dry, non-aggressive environments (soil/water) for structural concrete. The difference between one and the other is the frost exposure where the lower grade is not to be used. Other applications include road base or sub-bases, realization of parking areas, filling materials for river embankment, land-filling.

Tam et al (2008) report that there are currently about ninety concrete recycling plants in Belgium which follow this classification scheme. They are either fixed or mobile plants with fixed or mobile installations with the most advanced installations usually comprising of:

- A weighting bridge and equipment for pre-processing
- A preliminary sieve to eliminate earth, sand and gypsum
- A primary crusher with electrical magnet systems
- A sieve installation to separate materials in accordance with the size of obtained materials
- An air sieve or a washing installation
- A secondary crusher and sieve installation.

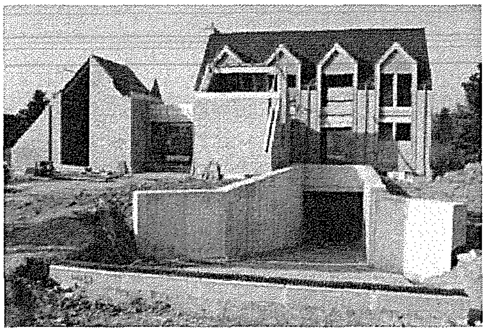
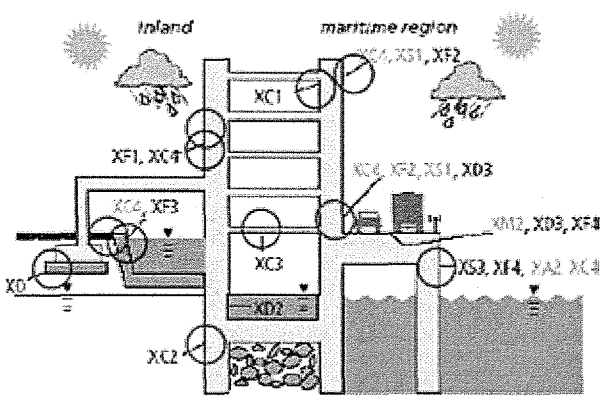


Figure 3.1: Recycled house in Belgium (1997-2000). Source: www.eco-serve.net/uploads/ETN_NL2.pdf

3.1.2 Germany

Classification allows for four grades of RA, two of higher quality than the other. Only chippings greater than 20mm, for types I or II, can be used for structural concrete in only dry or environments with low humidity (Mueller, 2007 and Tam et al, 2008) as illustrated in figure 3.2, with Type I being the higher quality aggregate. The greatest replacement ratio allowed is 45% which is reduced when environmental effects are more severe. This is probably the highest allowed ratio from all classification schemes for use in structural concrete (considering such high allowances for water absorption and dry density).



Field of application				Replacement by RCA [vol.-%]	
ASR-guideline	DIN EN 206-1 and DIN 1045-2			Type 1	Type 2
	Exposure class	Effect	Stress		
WO (dry)	XC 1	Carbonation	dry	≤ 45	≤ 35
WF (humid)	X 0	No concrete attack			
	XC 1 to XC 4	Carbonation	dry to wet		
	XF 1 and XF 3	Freeze-thaw without salt	moderate and high water saturation	≤ 35	≤ 25
	XA 1	Chemical attack	weakly corrosive	≤ 25	≤ 25

Figure 3.2: Allowed replacement of RA with exposure classes according to guideline of the German Committee for Reinforced Concrete (DAfStb, 1998) for use of RA in concrete. Source: Mueller (2007), slide 25

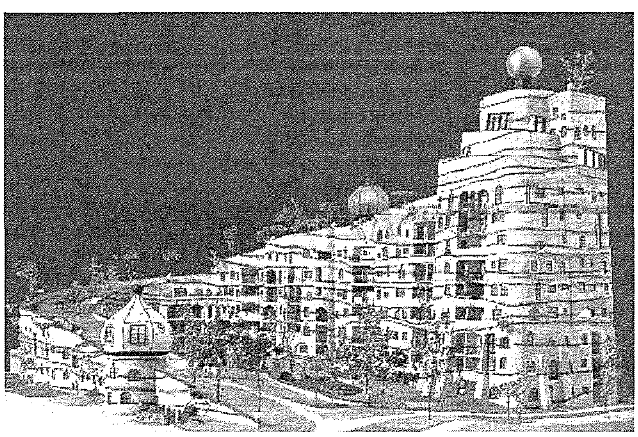
No RA is allowed to be used for lightweight or prestressed concrete or to produce a strength greater than C30/37. Type III is for masonry chippings and shall not be discussed since bricks are not used locally (this is why it is listed in grey). Type IV is used as poor quality aggregate in roads and as filling materials for earthwork.

As with Belgium, relatively high water absorption is allowed for (10% and 15%) for use with high grade applications. It should be noted that a possibility for allowing such limits is that the NA it is used with, is of exceptionally good quality. It should be noted that Germany is the only country with a water absorption experiment based only on 10 minutes and not 24 hours.

Figures 3.3 and 3.4 show case studies where RA has been used in quite a large volume for the construction of two buildings back in 1998 (thirteen years ago) which shows that recycling of aggregates in Germany has been going for quite a long period now and with experience, comes the wider variety of applications including use in structural ones.

Component	Type	Quantity (kg/m^3)
Recycled aggregate	0/2 mm	585
	2/8 mm	545
	8/16 mm	568
Portland cement	CEM I 42,5 R	310
Free water		170
Additives	pulverised fuel-ashe	40
Superplasticiser		5-18 ml/kg of cement
Workability (flow table value)	550 mm	
Compressive strength (28 days)	45 MPa on average	

Figure 3.3: 480m^3 RAC built in Vilbeler Weg office building, Darmstadt, Germany, (1997/1998)
Source: Marinković (2010) and www.b-i-m.de/projekte/projframe.htm



Component	Type	Quantity (kg/m^3)	
		C30/37	C25/30
Recycled aggregate	0/2 mm	616	615
	2/8 mm	530	290
	8/16 mm	569	334
	16/32 mm		554
Portland cement	CEM I 42,5 R	300	
Portland cement	CEM I 32,5 R		290
Additives	pulverised fuel-ashe	50	40
Superplasticiser		1.5 kg/m^3	
Workability		Normal (according to DIN 1045)	
Compressive strength (on average at 28 days)		42.9 MPa	36.4 MPa

Figure 3.4: 12000m^3 RAC built in Waldspirale residential building in Darmstadt, Germany, 1998
Source: Marinković (2010) and www.b-i-m.de/projekte/projframe.htm

3.1.3 Hong Kong

Throughout the trial period of the central recycling plant, the recycling of C&DW was used as follows: 1% for foundations, retaining walls, ground beams and pile caps; 15% for drainage surrounds and haunching; 50% for back fill and filter layers; 15% for sub-base in roads and 20% for paving blocks.

APP-129 is the document used where specifications for RA and RAC are provided. Two possible types of RAC are allowed, one of higher quality than the other. In no case, is the RA used for liquid-retaining/prestressed structures or transfer/hanger structures.

Below are the definitions for the applications specified in table 3.1a, as written in Hong Kong Building Department (2003).

a) Non-structural work include on-grade slabs, blinding layer, U-channels/stepped channels, bedding and haunching for pipe works, concrete footings for posts and fences, and mass concrete fill which does not sustain appreciable loading.

b) Applications with no major structural concern include

i) Reinforced/unreinforced concrete landscape features e.g. planters/planter walls, fence walls, mass concrete walls & footings for supporting landscape features

ii) Manholes & sand traps except manholes for foul water, grease traps & petrol interceptors where leakage of contaminated liquid to surrounding soil

iii) Carriageway pavements or overlays, reinforced concrete infill walls and mass concrete under footings or rafts

3.1.4 Spain

The Spanish standard seems to restrict use of RA, as the limits specified are the same as for NA; hence only RCA of very good quality may pass these limits. Since increased water absorption is one of the main problems with RA, the low 5% limit permissible, might lead to this physical property being the cause which does not pass the waste as being recyclable.

A modified limit of 7% is suggested by Gutiérrez et al (2004) for RCA. In reality, when used in mixed portions (20%) with natural aggregate, for say structural applications, most of the water absorption is by the natural aggregate (80%). With the modified limit, a blend ratio[1] of 5% still results if only 20% of total aggregate used is RCA with natural aggregate with limited water absorption of 4.5%, compensating for the increased risk of water absorption from the other aggregate. This is explained graphically by Gutiérrez et al (2004) in figure 3.5.

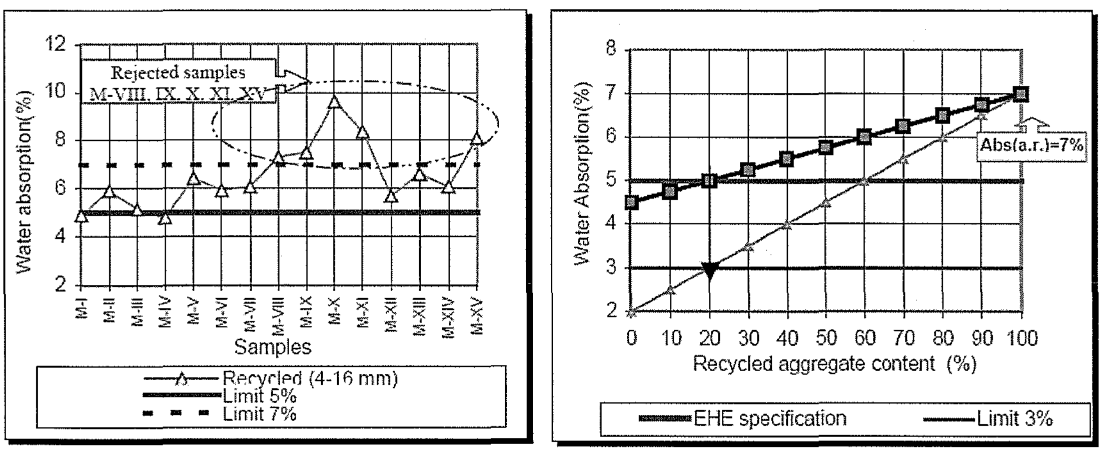


Figure 3.5: Graphs showing water absorption of RA (left) and absorption of blended aggregates (right). Source: Gutiérrez et al (2004)

Locally, water absorption of not only RCA but also conventional aggregate might be problematic. Using the limit from Spain blend ratios can be calculated with a similar approach as follows.

$$RA_{20\%} \text{ with } WA_{24}7 \quad + \quad NA_{80\%} \text{ with } WA_{24}4.5 \quad = A_{total=100\%} \text{ with blend of } WA_{24}5$$

$$(0.2*7\%) \quad + \quad (0.8*4.5\%) \quad = \quad 5\%$$

It should also be noted that it seems as though only Spain and RILEM (1994) use a property specifically for clay content (maximum of 0.25%) to classify the RA.

[1] Definition in Appendix A.

3.1.5 Japan

In the year 2000, 42% of total C&DW generated in Japan was concrete with 96% of it being recycled according to data collected by Tam et al (2008, p60). This was a result of the strict landfill fees policies. In fact, government and several organizations have drafted several guidelines and logistics for recycling of almost every kind of material. The recycling law has been enforced since 1991 (Tam et al, 2008) and hence, Japan is one of the leading countries that it is quite advanced in improving the techniques used for making good quality RCA (section 2.4.3). As a result, there are several different grades where RA may be used (tables 3.2 and 3. 3).

In fact, classification of the quality of aggregate (High, medium or Low) is primarily based on the method of processing used for the aggregate as highlighted in table 3.4 and figure 3.6.

Type	Recycled coarse aggregate				Recycled fine aggregate	
	Type C1	Type C2		Type C3	Type F1	Type F2
Absorption (%)	≤ 3	≤ 3	≤ 5	≤ 7	≤ 5	≤ 10
Sulfate soundness (%)	≤ 12	≤ 40	≤ 12	-	≤ 10	-
		≤ 40 [(1)]				
(1) Where freezing and thawing resistance is not required.						

Table 3.2: Quality standard of recycled aggregate concrete for public work in Japan
Source: Tam et al (2008), Table 2.10

	Type	Recycled Coarse aggregate	Fine aggregate	Suggested design strength (MPa)	Suggested use of recycled aggregate concrete
Civil work applications	CI	Type C1	Normal	18 to 24	Reinforced or plain concrete; lower structure of bridges, tunnel lining, retaining walls, etc
	CII	Type C2	Normal or recycled Type F1	16 to 18	Plain concrete; masonry units, bases for road attachment, gutters, gravity type retaining walls, etc
	CIII	Type C3	Recycled Type F2	< 16	Subslab concrete, back filling concrete, levelling concrete, etc
Building work applications	BI	Type C1	Normal	≥ 18	Ordinary reinforced concrete buildings
	BII	Type C2	Normal	≥ 18	Concrete attached to ground; foundation, cast-in-place concrete piles, concrete slabs on steel decks, etc
	BIII	Type C2	Recycled Type F1	≥ 18	Foundation slabs, earthen floor slabs, subslab concrete, back filling concrete, levelling concrete, etc
	BIV	Type C3	Recycled Type F2	≥ 18	Subslab concrete, back filling concrete, levelling concrete, etc

Table 3.3 Types of RCA and suggested uses in civil and building work in Japan
Source: Tam et al (2008), Table 2.11

RA Class	Requirements of recycled aggregate	Suggested concrete applications
Class H (High)	RA which performs advanced processing of a separation, grinding down by friction and classification from the concrete mass generated by demolition of the structures.	It can be used in the main structure part of a concrete structure object on a par with natural river gravel and sand, and the macadam[1] and crushed sand.
Class L (Low)	RA which crushed and manufactured concrete waste which arises when a concrete structure object is mainly demolished by the machines for beating and crushing and which has not performed advanced wastewater treatment	It can be used on concrete without applying energy and costs. 3 types of concrete are suggested: - a stock item - a salt regulation article, and - a technical-specification order article
Class M (Medium)	RA which is processed by demolition, grinding down by friction and classification	It can be used for components which cannot be easily influenced by drying shrinkage or freezing and thawing such as stake, withstanding-pressure version, a footing beam and steel-tubing in filled concrete.

Table 3.4: Requirements of RA and suggested concrete applications in Japan
Source: Tam et al (2008), Table 2.12

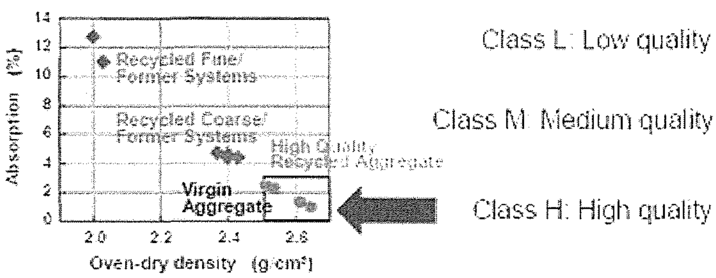


Figure 3.6: Quality of recycled aggregate in Japan
Source: Mueller (2007), slide 19

It should be noted that not only does Japan allow the use of recycled sand in the specifications (as is not common with other countries), but a grade of high quality is dedicated to it.

Also, very strict limit values (3%, 5% or 7%) are specified for water absorption coarse RA, when compared to other countries as mentioned previously.

[1] Macadam is a type of road construction where one paves by laying and compacting successive layers of broken stone, often with asphalt or hot tar. Source: http://dictionary.reference.com

3.1.6 RILEM

The classification proposed back in 1994 is allowed for three types of aggregates: masonry, concrete or a mix of natural aggregate (NA) with the other types. The higher grade is the mix with NA while the lower one is the one with only aggregate from masonry (bricks). There are to be additional testing requirements for applications other than those in non severe exposure conditions as listed.

Similarities can be noticed with limits proposed in other standards. However, limits are provided for properties of concrete specifically with RA, which do not seem to be available in BS 8500-1, BS 8500-2 or EN 206-1 or any of the other standards as yet, except for those proposed by Dhir et al (2007). The classification scheme is based primarily on the density of RA and on its composition, an approach which Dhir et al have also used (section 3.3).

It is the only standard which specifies that the sulfate content to be tested for is the water soluble sulfate. Also, like Spain, clay swelling content is to be tested.

3.1.7 United Kingdom

In the UK, it is often commented that the current limits provided in the codes, restrict use of recycled aggregate, mainly due to the fact that content of masonry in RA is limited at 5%, which is quite a rare scenario since brick masonry is one of the main construction material used.

Type of aggregate	Requirement A)					
	Maximum masonry content	Maximum fines	Maximum lightweight material B)	Maximum asphalt	Maximum other foreign material e.g. glass, plastics, metals	Maximum acid-soluble sulfate (SO_3)
RCA A), C)	5	5	0.5	5.0	1.0	1.0
RA	100	3	1.0	10.0	1.0	— D)

A) Where the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing, the only requirements are those for grading and maximum fines.
B) Material with a density less than 1 000 kg/m³.
C) The provisions for coarse RCA may be applied to mixtures of natural coarse aggregates blended with the listed constituents.
D) The appropriate limit and test method needs to be determined on a case-by-case basis (see Note 6 to 4.3).

Table 3.5: Requirements for coarse RCA and RA given as mass fraction (%) in BS 8500-2
Source: BS 8500-2:2006, Table 2

The specific requirements for RA are not found listed on their own as is done in Hong Kong, but rather as an amendment to the limits specified for NA. In fact, standards could be referred to since we base our local standards on these. Other requirements exist for applications in roads as per EN 13285, EN 13242 and EN 13043 together with the Highway road Specifications.

It is worth noting that the geometrical, physical, mechanical and weathering limits for NA are used also for RA while those for chemical properties, content of RA and applications are specific to RA. It is important to note that for chemical properties (chloride content), caution is to be taken with using limits being provided for results of experiments with different units as indicated in the footnote of table 3.1b. (section 2.5.6.2 explains this further)

Even though the standards are still in the process of being modified further to allow a better variety for use of RA, there are other initiatives which promote their use also. For example, BRE certification rewards sustainable points for use of recycled materials. Over 1500 m^3 of RAC was supplied for the BRE office building itself (Figure 3.7) for foundations, floor slabs, structural columns and waffle floors. For the foundations, a C25 mix (75 mm slump) was used with a minimum OPC based cement content of 350 kg/m3 and maximum free water/cement ratio of 0.5. For floor slabs, a C35 mix, also with 75 mm slump was specified. (Marinković et al, 2010)

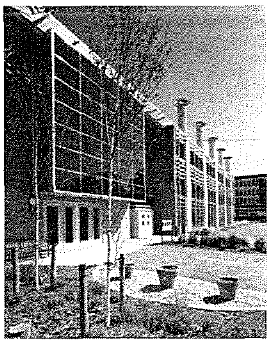


Figure 3.7: BRE office building itself in Watford (1995-1996). Source: www.lensebuildings.com/downloads/projects/05%20UK_BRE_Watford_LEnSE_Building_Report.pdf

3.1.8 Proposal by Dhir et al for WRAP, UK

The classification scheme proposed by Dhir et al (2007) is similar to the approach used by RILEM as stated previously. Table 3.6 shows how the classification is based on two approaches, a performance related approach and a compositional approach for use of combined RA in RAC. The methodology behind the following proposed classification scheme for UK is explained further in section 3.3.

PROPERTIES	CLASS A	CLASS B	CLASS C
Minimum LA Class	LA_{25}	LA_{30}	LA_{40}
Minimum density, SSD, kg/m^3	2550	2450	2150
Maximum water absorption, %	2	6	No limit
Drying shrinkage value, %	0.075	0.075	0.075
Maximum RA content, %	40	80	No limit
Maximum R_B content, % total aggregate	5	10	20
Drying shrinkage value, %	0.075	0.075	0.075

These classes only to be used for aggregates containing a minimum of 10% RA

Table 3.6: Performance related and compositional requirements for proposed classes of combined RA
Source: Dhir et al (2007), Tables 27, 28

It can instantly be observed in table 3.7, that due to the increase in number of grades (three from one) from the current UK standard, more applications with different exposure conditions are allowed for since previously only exposure classes X0, XC1-4, XF1, DC-1 where accepted.

	ALLOWABLE ENVIRONMENTS	R_C50 R_C+U50 R_B50	R_C70 $R_{C+U}70$ R_B30	R_C90 $R_{C+U}90$ R_B10
CLASS A	XO, XC-4, XD-2, XS-2, XF-2, DC-2	10%	16%	50%
CLASS B	XO, XC-4, XF-2, DC-2	20%	33%	80%
CLASS C	XO, XC-2, DC-1	40%	66%	100%

Table 3.7: Maximum permissible RA content for the 3 categories of RA and allowable environments
Source: Dhir et al (2007), Table 31

Class A (Best quality):
X0, XC1-4, XD1-2, XS1-2, XF1-4, DC1-2
Concrete exposed to carbonation, marine environments, sulphate conditions & other aggressive agents.

Class A
- W/c reduction factor ≥ 0.95
- Engineering properties within ±7.5% of that of equivalent NA concrete
- Initial surface absorption ≤ 0.6 ml/m²/s
- Drying shrinkage ≤ 0.075%
- ISA-10 < 0.5 ml/m²/s
- Rapid chloride permeability within ± 10% of that of equivalent NA concrete

Class B: X0, XC1-4, XF1-4 and DC1-2
Concrete exposed to carbonation, moderate sulphate conditions & other aggressive agents (provided appropriate cements are used), and moderate freeze/thaw conditions. Not to be used in chloride environments

Class B
- W/c reduction factor ≥ 0.90
- Engineering properties within ±15% of that of equivalent NA concrete
- Initial surface absorption ≤ 0.8 ml/m²/s
- Drying shrinkage ≤ 0.075%
- ISA-10 < 0.8 ml/m²/s

Class C: X0, XC1-2 and DC1
Concrete exposed to moderate levels of carbonation or where there is no risk of corrosion or attack

Class C
- W/c reduction factor ≥ 0.80
- Engineering properties within ± 30% of that of equivalent NA concrete
- Drying shrinkage ≤ 0.075%

No risk of corrosion	XO			
Corrosion induced by carbonation	XC-1	XC-2	XC-3	XC-4
Corrosion induced by chlorides	XD-1	XD-2		
Corrosion induced by chlorides (seawater)	XS-1	XS-2		
Freeze/thaw attack	XF-1	XF-2	XF-3	XF-4
Sulfate attack	DC-1	DC-2		

Figure 3.8: Requirements for grades proposed by Dhir et al.
Source: Dhir et al (2007)

It can be noted that Class B being proposed, is very similar to High quality recycled coarse aggregate in JIS 5021: 2005 (Japanese standard) (section 3.1.5).

Details of exposure classes are given in table 3.8 as found in BS 8500-1 and EN 1992-1-1:2004. The exposure classes in the two codes are essentially the same however, the one given in BS 8500-1 is more detailed than that in EN 1992.

Exposure classes		Informative examples applicable in the UK	
Class designation	Class Description	As listed in BS8500-1 Table A.1	As listed in EN 1992-1-1:2004 Table 4.1
1 No risk of corrosion or attack			
X0 ii) C12/15	For concrete without reinforcement/embedded metal: all exposures except where there is freeze/thaw, abrasion/chemical attack For concrete with reinforcement or embedded metal: very dry	Unreinforced concrete surfaces inside structures Unreinforced concrete completely buried in soil classed as AC-1 and with a hydraulic gradient not greater than 5 Unreinforced concrete permanently submerged in non-aggressive water Unreinforced concrete surfaces in cyclic wet and dry conditions not subject to abrasion, freezing/chemical attack Reinforced concrete surfaces exposed to very dry conditions	Concrete inside buildings with very low air humidity.
2 Corrosion induced by carbonation A) (where concrete containing reinforcement or other embedded metal is exposed to air and moisture)			
XC1 i) 0.65 ii) C20/25 iii) 260	Dry or permanently wet	Reinforced and prestressed concrete surfaces inside enclosed structures except areas of structures with high humidity. Reinforced and prestressed concrete surfaces permanently submerged in non-aggressive water.	Concrete inside buildings with low air humidity. Concrete permanently submerged in water.
XC2 i) 0.6 ii) C25/30 iii) 280	Wet, rarely dry	Reinforced and prestressed concrete completely buried in soil classed as AC-1 and with a hydraulic gradient not greater than 5 B)	Concrete surfaces subject to long-term water contact. Many foundations.
XC3 i) 0.55 ii) C30/37 iii) 280	Moderate humidity	External reinforced and prestressed concrete surfaces sheltered from, or exposed to, direct rain Reinforced and prestressed concrete surfaces subject to high humidity (e.g. poorly ventilated bathrooms, kitchens) Reinforced and prestressed concrete surfaces exposed to alternate wetting and drying Interior concrete surfaces of pedestrian subways not subject to de-icing salts, voided superstructures or cellular abutments Reinforced or prestressed concrete beneath waterproofing	Concrete inside buildings with moderate or high air humidity. External concrete sheltered from rain.
XC4 i) 0.5 ii) C30/37 iii) 300	Cyclic wet and dry		Concrete surfaces subject to water contact, not within exposure Class XC2.
3 Corrosion induced by chlorides other than from sea water A) (Where concrete containing reinforcement or other embedded metal is subject to contact with water containing chlorides, incl de-icing salts, from sources other than from sea water) NOTE Concerning moisture conditions, see also sec2 of this table.			
XD1 i) 0.55 ii) C30/37 iii) 300	Moderate humidity	Concrete surfaces exposed to airborne chlorides Reinforced and prestressed concrete wall and structure supports more than 10 m horizontally from a carriageway Bridge deck soffits more than 5 m vertically above the carriageway Parts of structures exposed to occasional/slight chloride conditions	Concrete surfaces exposed to airborne chlorides.
XD2 i) 0.55 ii) C30/37 iii) 300	Wet, rarely dry	Reinforced and prestressed concrete surfaces totally immersed in water containing chlorides C) Buried highway structures more than 1 m below adjacent carriageway	Swimming pools. Concrete exposed to industrial waters containing chlorides.
4 Corrosion induced by chlorides from sea water (XS classes) A), D) where concrete containing reinforcement or other embedded metal is subject to contact with chlorides from sea water or air carrying salt originating from sea water			
XS1 i) 0.5 ii) C30/37 iii) 300	Exposed to airborne salt but not in direct contact with sea water	External reinforced and prestressed concrete surfaces in coastal areas	Structures near to or on the coast
XS2 i) 0.45 ii) C35/45 iii) 320	Permanently submerged	Reinforced and prestressed concrete surfaces completely submerged and remaining saturated, e.g. concrete below mid-tide level C)	Permanently submerged Parts of marine structures

5 Freeze/thaw attack with or without de-icing agents Where concrete is exposed to significant attack by freeze/thaw cycles whilst wet, the exposure shall be classified as follows:			
XF1 i) 0.55 ii) C30/37 iii) 300	Moderate water saturation, without de-icing agent	Vertical concrete surfaces such as façades and columns exposed to rain and freezing Non-vertical concrete surfaces not highly saturated, but exposed to freezing and to rain or water	Vertical concrete surfaces exposed to rain and freezing.
XF2 i) 0.55 ii) C25/30 iii) 300	Moderate water saturation, with de-icing agent	Concrete surfaces such as parts of bridges, which would otherwise be classified as XF1, but which are exposed to de-icing salts either directly or as spray or run-off	Vertical concrete surfaces of road structures exposed to freezing and airborne de-icing agents
XF3 i) 0.50 ii) C30/37 iii) 320	High water saturation, without de-icing agent	Horizontal concrete surfaces, such as parts of buildings, where water accumulates and which are exposed to freezing Concrete surfaces subjected to frequent splashing with water and exposed to freezing	Horizontal concrete surfaces exposed to rain and freezing.
XF4 i) 0.45 ii) C30/37 iii) 340	High water saturation, with de-icing agent or sea water F)	Horizontal concrete surfaces, such as roads and pavements, exposed to freezing and to de-icing salts either directly or as spray or run-off Concrete surfaces subjected to frequent splashing with water containing de-icing agents and exposed to freezing	Road and bridge decks exposed to de-icing agents. Concrete surfaces exposed to direct spray containing de-icing agents and freezing. Splash zones of marine structures exposed to freezing.
EN206-1:2000 Table F.1 provides i) Maximum w/c ii) minimum strength class iii) minimum cement content A) The moisture condition relates to that in the concrete cover to reinforcement or other embedded metal, but in many cases, conditions in the concrete cover can be taken as reflecting that in the surrounding environment. In these cases classification of the surrounding environment may be adequate. This may not be the case if there is a barrier between the concrete and its environment. (See A.3) B) For concrete in soil classed as AC-2 or above or an element with a hydraulic gradient greater than 5, the ACEC class is used to determine the concrete quality and minimum cover to reinforcement (see A.4.4). C) Reinforced and prestressed concrete elements where one surface is immersed in water containing chlorides and another is exposed to air are potentially a more severe condition, especially where the dry side is at a high ambient temperature. Specialist advice should be sought where appropriate, to develop a specification that is appropriate to the actual conditions likely to be encountered. (All side notes and footnotes are from BS8500-1:2006 unless stated otherwise) F) It is not normally necessary to classify in the XF4 exposure class those parts of structures located in the United Kingdom which are in frequent contact with the sea.			
Note that exposure classes in Malta do not include XF1-4.			

Table 3.8: Exposure classes for applications of RA proposed by Dhir et al (2007)
Source: BS 8500-1, Table A.1 and EN 1992-1-1:2004, Table 4.1

3.1.9 AggRegain[1]

It is the author's opinion that WRAP has managed to provide an effective service through the AggRegain website by helping the public or any one involved in the construction industry, to go through all the potential applications for use of secondary and recycled aggregates as per existing UK standards and guidelines, in a very efficient manner, without the need of having to go through all the references provided. Applications are thoroughly explained both in writing and visually. The website is designed such that an end user selects (by clicking on images) a type of construction application from the following list and continues choosing particular criteria.

1 Concrete roads
2 Bituminous roads
3 Hydraulically bound roads
4 Ground improvements
5 Earthwork embankments
6 Earthwork cuttings
7 Shallow foundations
8 Deep foundations
9 Utilities – new trenches
10 Utilities – reinstatement in roads
11 Concrete substructures
12 Concrete structures
13 Industrial buildings
14 Residential buildings

The author has compiled eight pages with all these applications in Appendix K. The 14 applications mentioned above are divided further into more specific applications as can be seen in the appendix. It is important to read the notes at the beginning of the appendix to understand the table, since there are ***two modifications*** made to the way the data available in the British website is presented.

Firstly, ***few applications are in grey***, signifying that they are not applicable to local construction methods. Since locally, we base most of our practice on that used in the UK, and also, since roads are designed as per most of the Specifications to road work in the UK, most of these applications are considered suitable for application in Malta.

Secondly, a list of grades is provided, such as R-A, R-B and so on. These ***are not specified in the website*** by AggRegain but are ***additions made by the author***. These are the grades proposed for the local guidelines, as explained in Chapter 7. They are included since reference is made to these applications in the proposed guidelines.

[1] AggRegain is a free Sustainable Aggregates information service provided by the WRAP Aggregates Programme. Source: http://aggregain.wrap.org.uk/opportunities/applications/index.html

3.1.10 Proposal by Tam et al for Hong Kong

In response to the low-grade applications specified for RA in Hong Kong (section 3.1.3), an improvement on the classification has been made by Tam et al. Three main grades are being specified (table 3.9) with further minor specifications, which distinguish between say Class B and C in the same grade, resulting in a total of eight applications with different specifications. This is one of the few classification schemes where very high grade applications such as prestressed concrete elements are listed. RA used for these are comparable to NA of excellent quality, used in Hong Kong. This naturally depends on the amount of processing performed on the RA. Also, a minimum number of tests are being recommended for efficient classification. The methodology is explained further in section 3.2.

Class A (Best quality)	Structural / minor structural / non-structural / pre-stressed elements Road surfaces, Base courses, Embankment & fill, Insulation barrier.
Class B, C	Minor structural and non-structural elements Road surfaces, Base courses, Embankment & fill, Insulation barrier.
Class D, E, F	Non-structural elements
Class G	No applications. Discard samples.
It can be noted that the properties which limit classes to a higher grade are Chemical property: Maximum chloride content for minor structural elements, road surfaces, base courses, embankment & fill, insulation barrier (Class D) and Mechanical property: Minimum TFV for all applications except structural & prestressed concrete (Class B)	

Table 3.9: Quality Classes for RCA proposed by Tam et al (2008). Source: Tam et al (2008)

3.1.11 Austria

The classification scheme of the Austrian guidelines is focussed mainly on the compositional properties of the RA, since mix portions are specified. It is to be noted that from the data collected, this is the only guideline which specifies binder content.

The Austrian guidelines have been replicated in the right columns in Appendix G, as explained in the Instructions of how to read the guidelines at the beginning of the appendix. The importance of the Austrian guidelines for this dissertation is highlighted in Chapter 7, which is a chapter dedicated entirely to the discussion of the Proposed Guidelines for Recycled Aggregate in Malta, which are structured on these Austrian guidelines. Tables G.2 and G.3 in Appendix G shows all the applications permitted by the Austrian guidelines.

3.2 Methodology for carrying out classification scheme of RCA by Tam et al

Tam et al (2008) show a manual method of classification of RCA (total of six steps) which could be concluded after a number of tests were carried out on samples from a number of different sources. This is an improvement to the one provided already by the Hong Kong Government (section 3.1.3) where only low-grade utilisations are allowed for RA use.

In order to write up a classification scheme, a range of specimens from demolished buildings was required. All the buildings were originally constructed from in situ concrete and the RAC produced was with blue limestone from Hong Kong itself (personal communication with Professor V. Tam). Selective demolition was only carried out for each building for the different types of materials (concrete, steel and so on) and not for different concrete strengths, hence RCA of good and poor quality from the same building were mixed, as it was not feasible to do otherwise.

	Government practice note	Recommended guidelines
Tests required for classification system	• Particle density • Water absorption • Content of wood and other materials • Content of other foreign materials • Fines particles • Content of sand • Content of sulphate • Flakiness index • TFV • Grading • Chloride content	• Grading • Water absorption • TFV • Chloride content • Sulphate content
Slump requirement	Min. 75 mm	Min. 75 mm but higher slump recommended for RAC made from water-sprayed RA in contrast to fully soaked RA
Slump loss	—	To consider the effects of slump loss for RAC (both for fully soaked or water-sprayed RA)
Mix proportioning	Designated mix only	Allow for designed mix
Quality of RAC	—	Highlight changes in quality of RAC in different proportions of RA
Percentage of RA to replace natural aggregate	20% for structural and 100% for non-structural elements	From 0–100%
Types of RAC application	Structural and non-structural	Structural, minor-structural, non-structural, pre-stressed concrete, road surface, insulation barrier, base course, and embankment and fill

Table 3.10: Requirements for RCA and RAC by Hong Kong Government and Tam et al
Source: Tam et al (2007), Table 6

Table 3.11 shows the steps carried out by Tam et al to arrive at the classification being proposed (section 3.1.10). It should be noted that limits from ASTM, BS and Hong Kong existing standards were used for the classification. EN standards were not used. It can be observed that the main properties which distinguish one class for use of an application from another are geometrical, physical and chemical. All tables were extracted from Tam et al (2008).

Step 1: Collection of limits and their requirements for various construction applications

Properties	Structural element	Minor structural element	Non-structural element	Pre-stressed concrete element	Road surface	Base course	Embankment and fill	Insulation barrier
Grain-size qualification	BS 882	BS 882	BS 882	BS 882	ASTM D448-03	ASTM D2940-03	ASTM D2940-03	BS 882
Minimum particle density (kgm^{-3})	2000	2000	2000	2000	2000	2000	2000	2000
Maximum water absorption (%)	10	10	10	10	10	10	10	10
Maximum flakiness index (%)	40	40	40	40	40	40	40	40
Minimum Ten Percent Fine Value (kN)	150	100	50	100	100	50	50	100
Maximum Aggregate Impact value (%)	25	30	35	25	30	35	35	30
Maximum chloride content (%)	0.05	0.05	1	0.015	0.05	0.05	0.05	0.05
Maximum sulfate content (%)	1	1	1	1	1	1	1	1

Step 2: Results of tests of several samples, to have a range of results for each property

Sample	Particle Size Distribution		Particle Density		Porosity and Absorption		Particle Shape		Strength and Toughness		Chemical Composition		
	Sieve Analysis		Particle Density on an Oven-Dried Basis (Mg/m3)		Water Absorption		Flakiness Index (%)		TFV (kN)	AIV (%)	Chloride Content (%)		Sulphate Content (%)
	10mm	20mm	10mm	20mm	10mm	20mm	10mm	20mm			10mm	20mm	
1	Pass	Pass	2.16	2.20	5.83	6.89	11.13	9.68	93.89	33	0.0078	0.0089	0.031
2	Pass	Pass	2.22	2.14	6.36	6.40	10.44	10.08	61.36	36	0.0108	0.0091	0.017
3	Pass	Pass	2.20	2.18	7.50	7.35	15.17	8.61	107.42	31	0.0013	0.0019	0.005
4	Pass	Pass	2.20	2.20	6.93	7.25	15.42	7.91	112.82	23	0.0019	0.0019	0.005
5	Pass	Pass	2.15	2.19	7.31	6.82	17.82	12.96	92.09	32	0.0054	0.0061	0.006
6	Pass	Pass	2.25	2.27	5.20	5.77	11.96	9.93	155.53	25	0.0008	0.0025	0.006
7	Pass	Pass	2.11	2.13	8.74	7.30	12.86	5.70	110.18	30	0.0976	0.0902	0.013
8	Pass	Pass	2.10	2.12	8.58	7.99	15.12	9.78	83.48	34	0.0013	0.0014	0.005
9	Pass	Pass	2.21	2.24	6.94	6.11	13.78	12.17	92.87	36	0.0459	0.0352	0.024
10	Pass	Pass	2.20	2.23	6.85	5.95	16.47	9.92	89.91	28	0.0494	0.0430	0.018
11	Pass	Pass	2.46	2.53	2.63	1.65	25.97	29.52	102.97	33	0.0021	0.0070	0.008
12	Pass	Pass	2.59	2.62	0.77	0.57	28.27	22.52	189.38	21	0.0012	0.0016	0.003

Note: Samples 1 to 10 are from demolished crushed concrete, sample 11 is RCA from the only centralised recycling plant at the time and sample 12 is natural aggregate

Step 3: Dividing range of results into six grades with equally divided smaller ranges

Properties	Classification						
	A	B	C	D	E	F	G
Particle Density	> 2.5	2.49 – 2.4	2.39 – 2.3	2.29 – 2.2	2.19 – 2.1	2.09 – 2.00	< 2.00
Water absorption	< 1.0	1.1 – 3.0	3.0 – 5.0	5.1 – 7.0	7.1 – 9.0	9.1 – 10.0	> 10.0
Flakiness index	< 8	9 – 16	17 – 22	23 – 28	29 – 34	35 – 40	> 40
TFV	> 150	149 – 120	119 – 110	109 – 100	99 – 80	79 – 50	< 50
AIV	< 20	21 – 23	24 – 26	27 – 28	29 – 31	32 – 35	> 35
Chloride content	< 0.015	0.016 – 0.03	0.031 – 0.05	0.051 – 0.1	0 .101 – 0 .500	0 .501 – 1.000	> 1.0
Sulfate content	< 0.015	0.016 – 0.03	0.031 – 0.05	0.051 – 0.1	0 .101 – 0 .500	0 .501 – 1.000	> 1.0

Step 4: Specifying each application with a minimum grade particular to each property using limits from data collected in step 1

Sample number	Structural element	Minor structural element	Non-structural element	Pre-stressed concrete element	Road surface	Base course	Embankment and fill	Insulation barrier
Dry Particle Density	F	F	F	F	F	F	F	F
Water absorption	F	F	F	F	F	F	F	F
Flakiness index	F	F	F	F	F	F	F	F
TFV	A	D	F	D	D	F	F	D
AIV	C	E	F	C	E	F	F	E
Chloride content	C	C	F	A	C	C	C	C
Sulfate content	F	F	F	F	F	F	F	F

Step 5: Classifying each sample with a grade particular to each property

Sample number	Size	1	2	3	4	5	6	7	8	9	10	11	12
Dry Particle Density	10mm	E	D	D	D	E	D	E	E	D	D	B	A
	20mm	D	E	E	D	E	D	E	E	D	D	A	A
Water absorption	10mm	D	D	E	D	E	D	E	E	D	D	B	A
	20mm	D	D	E	E	D	D	E	E	D	D	B	A
Flakiness index	10mm	B	B	B	B	C	B	B	B	B	C	D	E
	20mm	B	B	B	A	B	B	A	B	B	B	E	D
TFV	-	E	F	D	C	E	A	C	E	E	E	D	A
AIV	-	F	G	E	B	F	C	E	F	G	D	F	B
Chloride content	10mm	A	A	A	A	A	A	D	A	C	C	A	A
	20mm	A	A	A	A	A	A	D	A	C	C	A	A
Sulfate content	-	C	B	A	A	A	A	A	A	B	B	A	A

Step 6: Combining tables in steps 4 and 5 for classifying each sample with an application

Samples	Structural element	Minor structural element	Non-structural element	Pre-stressed concrete element	Road surface	Base course	Embankment and fill	Insulation barrier
1			✓			✓	✓	
2								
3		✓	✓		✓	✓	✓	✓
4		✓	✓	✓	✓	✓	✓	✓
5			✓			✓	✓	
6	✓	✓	✓	✓	✓	✓	✓	✓
7			✓					
8			✓			✓	✓	
9								
10			✓			✓	✓	
11			✓			✓	✓	
12	✓	✓	✓	✓	✓	✓	✓	✓

Table 3.11 Steps used by Tam et al to conclude a classification scheme and grade RCA

In addition to this, it is suggested that wherever strong correlations are found, the number of tests to be performed are reduced to save on time. After, the experiments were concluded and correlations found, the table used in step 1 could be reduced to the following.

Properties	Structural element	Minor structural element	Non-structural element	Pre-stressed concrete element	Road surface	Base course	Embankment and fill	Insulation barrier
Grain-size qualification	BS 882	BS 882	BS 882	BS 882	ASTM D448-03	ASTM D2940-03	ASTM D2940-03	BS 882
Maximum TAWA (%)	5	10	10	10	10	10	10	10
Minimum Ten Percent Fine Value (kN)	150	100	50	100	100	50	50	100
Maximum chloride content (%)	0.05	0.05	1	0.015	0.05	0.05	0.05	0.05
Maximum sulfate content (%)	1	1	1	1	1	1	1	1

Table 3.12 Minimum amount of experiments to be carried out on RCA for classification according to Tam et al

Tam et al suggest the property called TAWA, which is an improved version of water absorption to the method provided in the standard. Water absorption is measured after constant mass is reached and not after 24 hours. This is completely in contrast to the German water absorption test of 10 minutes. This way, TAWA can be used instead of all other physical properties and TFV instead of the mechanical properties. However, one should note that TFV is not a method used another more in EN standards and it is unlikely to ever be used again (BSI, 2009a).

3.3 Methodology for carrying out classification scheme of RA by Dhir et al for WRAP

WRAP is an organisation in the UK which creates markets for recycled resources. Dhir et al are a group of researchers who have written several papers for WRAP throughout the years, trying to improve the limits provided in current UK standards and create more efficient methodologies for classification and processing to persuade more people to take initiative.

The first step towards creating a classification scheme is to understand the aggregate properties of several samples from different sources and then making concrete mixes. Between 2005 and 2007, a very detailed report (Dhir et al, 2007) was written and a classification scheme proposed for all possible types of RA for use in RAC.

A total of 125 concrete mixes were cast and tested with

- Natural aggregate
- 3 types of crushed concrete (RCA-10, RCA-35, RCA-60 from lab mixes)
- 7 types of crushed bricks
- 8 combinations of concrete and brick (termed artificial RA)
- Combinations of natural aggregate and concrete and brick (termed genuine RA) with a small percentage of foreign materials (glass, other)

Correlations between different properties are discussed in the research paper. Different types of RAC (grade 20 with w/c of 0.84 and grade 35 with w/c of 0.61) are analyzed from both a performance based approach (to conclude a grading scheme) and composition based approach (to conclude a limit on the amount of RA to be used). The applications are given as exposure conditions (section 3.1.8), a similar approach as that used in the German standard.

Performance based approach

A maximum w/c ratio correction factor of 0.9 is suggested by Dhir et al (2007) to compensate for the increased water absorption from the recycled aggregates tested. This way a range of strengths for grade C20 (w/c ratio of 0.84) and grade C35 (w/c ratio of 0.61) could be derived. The grey shaded areas (figure 3.9) show these ranges for C20 where the ranges of w/c ratio between 0.84 and (0.9*0.84) result in 16 to 20 Nmm^{-2} and ranges for C35 where the ranges of w/c ratio between 0.61 and (0.9*0.61) result in 34.5 to 40 Nmm^{-2}.

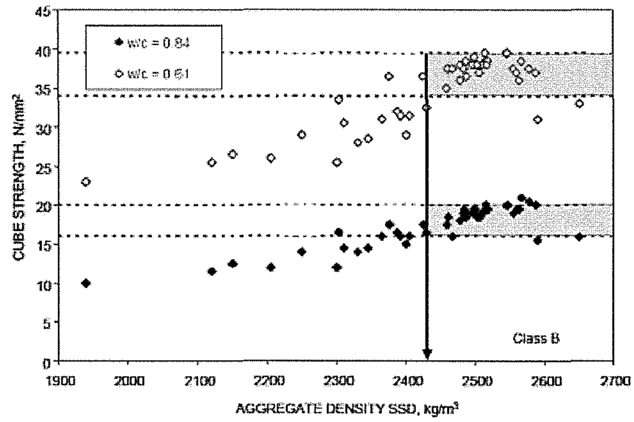


Figure 3.9: Limit on aggregate density required to achieve cube strength within 15% of natural gravel concrete. Source: Dhir et al (2007), Figure 37

Figure 3.9 uses density as the factor to assess the effect of RCA on cube strength. This is recommended by Xiao et al (2006) (as cited in Dhir et al, 2007). However, Dhir et al point out that not as many samples fall within the range (grey shaded area) as with the same graph plotted against LA (figure 3.10) and not density.

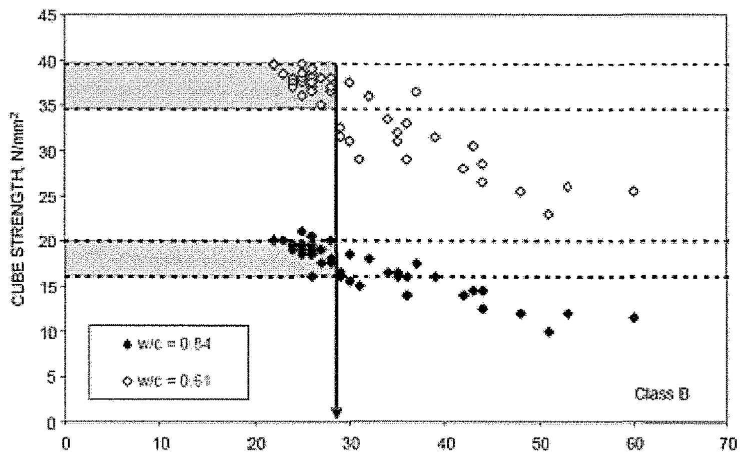


Figure 3.10: Limit on LA coefficient required to achieve cube strength within 15% of natural gravel concrete. Source: Dhir et al (2007), Figure 36

The conclusions in table 3.6 are based on the results from graphs plotted similar to those for grades A, B and C in table 3.13. These are for cube strengths with strong correlations with LA. The other properties listed are categorised similarly with other correlations.

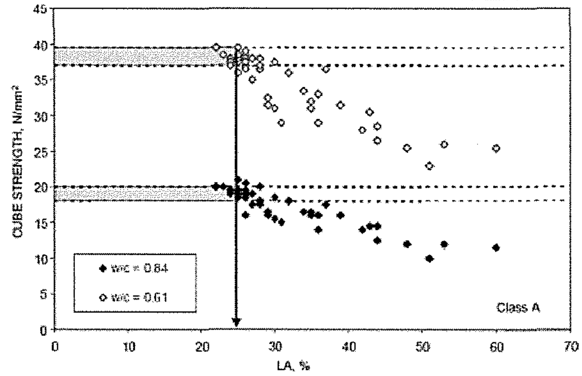
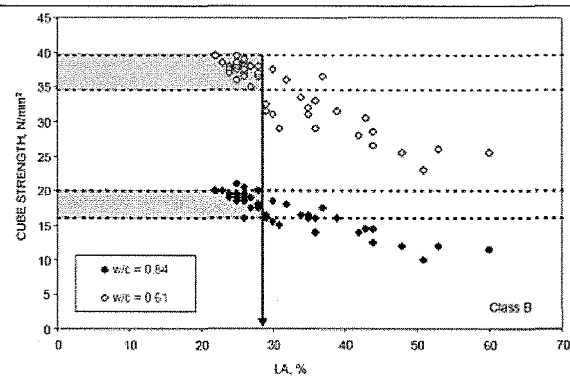
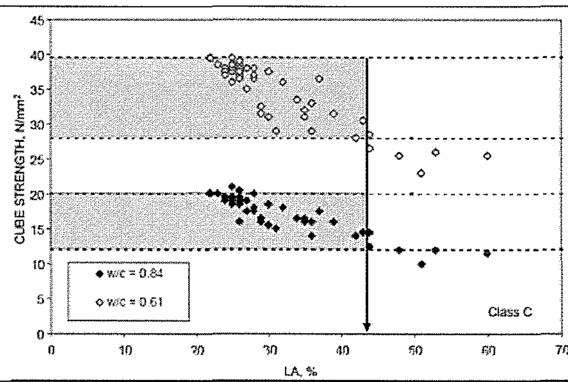
		cube strength within X % of natural aggregate concrete	LA coefficient	
GRADE	**A**	**X = 7.5%**	**≤25%**	
	B	**X =15.0%**	**≤30%**	
	C	**X = 30.0%**	**≤45%**	

Table 3.13: Limits on Los Angeles value for Grades A, B and C. Source: Dhir et al (2007)

Composition based approach

A similar approach is used for concluding limits for brick content. Results of the graphs plotted are also in table 3.6. As can be noticed, several concrete mixes are required to achieve such results. It is recommended that this approach be tried locally for an improvement on the classification schemes being proposed in the local guidelines.

CHAPTER 4: WASTE GENERATION INVENTORY: Local Case studies

This chapter gives an overview of types and amounts of building-related waste generated from typical common local (public and residential) buildings. The processing of the RCA tested in this dissertation was carried out with machinery at a typical Concrete Factory, usually used for NA, since no recycling plant exists as yet. Reasons as to why this material was chosen to be tested on are explained in Chapter 5. To broaden the spectrum of RCA used to derive conclusions for the Proposed Guidelines, results from tests carried out on RCA from a bridge are also used. An account of the processing of the material from the beginning of its life to testing for grading purposes is given. Conclusions derived and observations from processing of material are used for the drafting of the Proposed Guidelines as discussed in Chapter 7. Use of returned fresh concrete as a waste material is also mentioned. Finally, results of experiments carried out on local NA (original aggregate in any RCA) is compared to NA and RCA in Hong Kong and its quality assessed with the methodology used by Tam et al in section 3.2.

4.1 Cradle to cradle versus cradle-to-grave: Closing the loop

With the cradle-to-cradle approach, materials are reused until their properties are fully exhausted in a theoretical closed loop (figure 4.1). The reuse or recycle options in the waste management Hierarchy mentioned in Chapter 1 are cradle-to-cradle lifecycle techniques. Ideally deconstruction for recycling of building materials is designed for at the initial stages of the project, as this is a dismantling process which aids in the reuse or recycling of materials. Wood and steel with bolted connections seem to have better potential for this. Locally, construction is with stone masonry and concrete which raises difficulty for deconstruction especially with load-bearing walls.

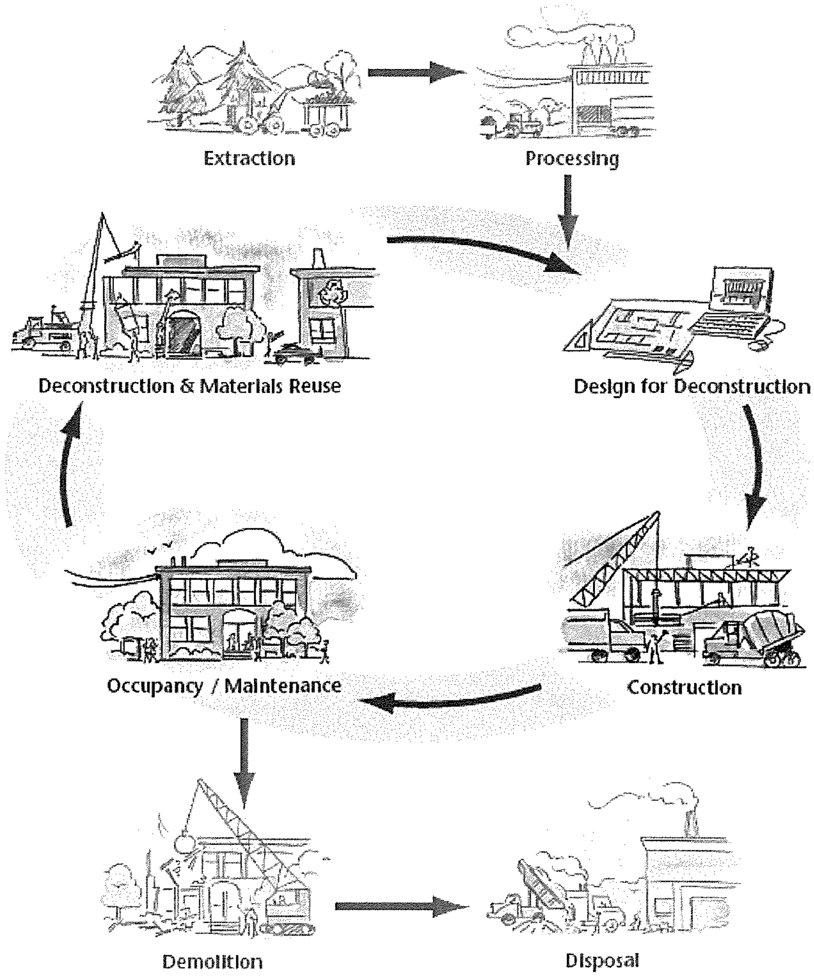


Figure 4.1: Closing the loop in the material lifecycle. Source: Environmental Protection agency, US (2008)

According to CSI (2009), concrete is the second most consumed material in the world, after water and is the basis for the urban environment. It is also, however, the most challenging material to design for future reuse, especially when cast insitu. The structure is formed of one contiguous whole with no convenient joints where it can be separated to be salvaged, being heavy and difficult to move as a whole (Webster et al 2005).Precast concrete offers greater reuse potential than cast-in-place concrete since it often comes in standard sizes and with standard amounts of reinforcement, and members are often joined together using mechanical fasteners. One problem is that precast floors are often covered with cast-in-place topping slabs for lateral stability of the structure.

4.2 Generation of local Construction, Reconstruction and Demolition waste

4.2.1 Waste inventories for theoretical demolition of typical local buildings

Due to the space confinement we are burdened with locally, 'Demolish, clear and build' sites are the most common type of waste-generating building sites. However, since no statistics of mixed C&DW collected at landfill sites exists (personal communication with Ms Mallia at Wasteserv), a different method needs to be adopted to comprehend the types and amounts of waste generated from buildings. Usually a proper C&DW management plan (FCC, 2011; Building and Safety Division, 2008; IWMD, 2011 & PW, 2011) for recycling/reuse of building materials includes a waste inventory. Appendix F shows waste inventories from typical types of local projects compiled by the author, where all types of waste mentioned are included with their European waste catalogue (EWC) reference (Appendix H).

The building waste material being focussed on in this dissertation is concrete and a mix of concrete and stone. The reason is that concrete is becoming more popular for building whole projects, mainly residential and offices, (figure 4.2) rather than with stone block work only. This is because concrete masonry is lighter to carry than stone, during placing of block work. Also, we are exhausting our quarries from good quality stone and hence concrete is being used instead.

Figure 4.2: Typical local buildings with construction mainly of concrete and stone masonry
Photos taken by author (2011)

4.2.2 Discussion of waste inventories for three typical local demolition scenarios

When carrying out a classification scheme for RA, it is often the case, as discussed in Chapter 2, to use mix ratios[1] for different types of RA. This section explores the most common mix ratios of stone and concrete, for typical local buildings if they were to be demolished.

Two typical local buildings have been assessed and the waste generation from a theoretical demolition calculated in Appendix F. These are the Faculty for the Built Environment (table 4.1) (a public building) and a typical block of apartments (4.2a) (a residential building). Another scenario, using the same block of apartments (table 4.2b) is considered also. Locally, construction of this type of building is at times built completely from concrete masonry in lieu of stone masonry. Hence, the values for the stone walls were adapted as though built only of concrete masonry.

The method adopted is using a waste inventory to estimate the quantity of waste products (stone, concrete, tiles, metal, glass and wood) by percentage of mass and volume. Once the volume is calculated, the densities are chosen from Annex A of EN 1991 (BSI, 2002e) and the corresponding masses of each material found (mass is volume multiplied by density). This is the method used mostly for calculating masses; however in some cases (such as space frame) typical rule-of-thumb mass per cubic metre was used as explained later.

The exact materials used in the Block of Apartments are known, since the author witnessed its construction from beginning to end. It should be noted that very few concrete blocks were used in random parts of the building, and hence are not considered in the calculations. In both case studies, certain materials and elements mainly foundations, steel reinforcement, finishes, insulation, water proof membranes and electrical/water/drainage services have not been considered in the calculations, since amounts are difficult to compute.

[1] Definition in Appendix A.

Some assumptions have been made for the Faculty, especially for internal walls. It is difficult to say where limestone or concrete block work was used since the interior walls are painted over. Hence it has been assumed that all the walls are from masonry block work on the interior also, except for the toilets, where a missing tile from the soffit revealed the concrete block work in the walls. Quantities or concrete block work has been calculated on the basis a typical load bearing block of 0.0196m^3 and 35.5kg (Catalogue from Ballut concrete factory).

Also, in the Faculty, there exist different types of tiles which include gres (porcelain), terrazzo (cement based) and travertine; however they have been quantified in unison.[2] Mr. Martin Pillow was contacted to answer queries about the space frame and data was kindly shared.

The percentages of materials have been provided both by mass and by volume as can been seen in Appendix F. The method adopted in the report for estimating Construction and Demolition waste in the US (Franklin Ass., 1998) expresses the percentages as totals of the masses. Providing the percentage by volume helps one understand what volumes would either wise be disposed at landfills. Also, the number of trucks to be summoned or number of voyages of same truck, for delivery to either landfill or recycling plant, can be known beforehand. No extra effort was required since volumes were calculated to find the masses by multiplying with the densities. Experienced contractors might estimate correct amounts to save time.

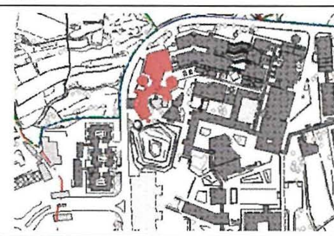
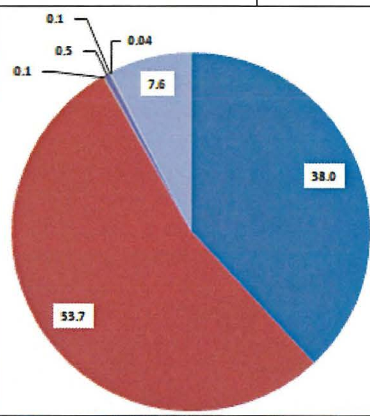
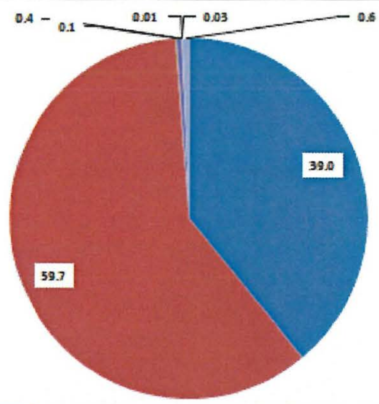
Tables 4.1 and 4.2 show pie charts with the results from the inventories generated. It can be seen that these case studies show two main types of mix ratios of NA and RCA. The percentage of concrete by mass of the total waste as less than 50% for the Faculty (39%) and as greater than 50% for the block of apartments (57.1%)[3]. These ratios are referred to in Chapter 6, for verification of the replacement and mix ratios[4] being specified in the proposed local guidelines.

[2] It is interesting to note that the next significant C&DW in line after concrete and stone is tiles with an approximate amount of 5.2% from total C&DW (excluding excavation waste) according to Camilleri C. (2011).

[3] Note that a 50% ratio is used in the Austrian guidelines also for NA mixed with RCA and asphalt.

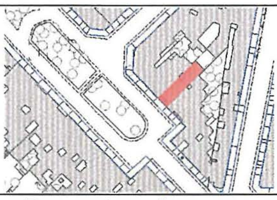
[4] Definitions in Appendix A.

Table 4.1: Breakdown of demolition waste of Faculty for the built Environment

Type of building **Faculty for the Built Environment**	Tal-Qroqq, University premises. Built in the 1980s with several extensions and alterations throughout the years.	
Material	**Percentage by volume**	**Percentage by mass**
concrete	38.0	39.0
stone	53.7	59.7
other	8.3	1.3
Pie charts showing Breakdown of theoretical Demolition waste ■ Concrete (insitu, block work, screed) ■ Tiles (floor) ■ Metals (wrought iron, steel, aluminum) ■ Stone (block work, torba) ■ Wood (windows, doors) ■ Glass (windows, doors, curtain walls) ■ Gypsum (soffit)		

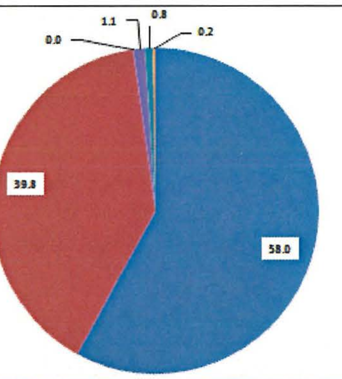
All photos as taken by the author in 2011, except the aerial view of the Faculty which was obtained from www.pillowspaceframe.com/html/portfolio/portfolio.cfm?ID=17&SubID=39

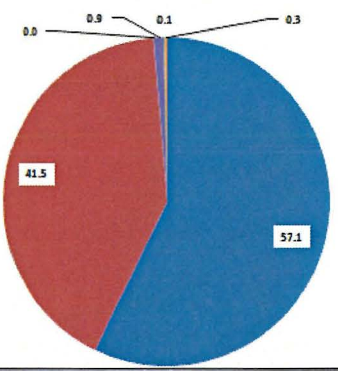
Table 4.2a: Breakdown of demolition waste of typical block of apartments

Type of building **Block of apartments**	Site: Qormi Construction between 2009 and 2010. Interior decoration is currently underway.	
Material	**Percentage by volume**	**Percentage by mass**
concrete	58.0	57.1
stone	39.8	41.5
other	2.2	1.4

Pie charts showing Breakdown of theoretical Demolition waste

- Concrete (insitu, precast, screed)
- Tiles (floor, walls)
- Stone (block work, torba)
- Wood (windows, doors)
- Glass (windows, doors)
- Metals (wrought iron, aluminum)





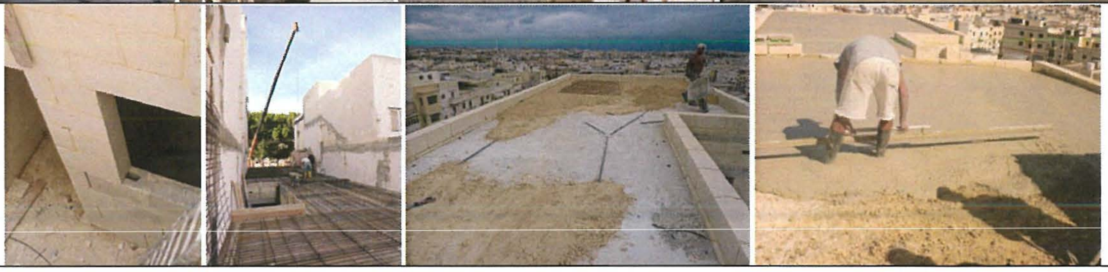
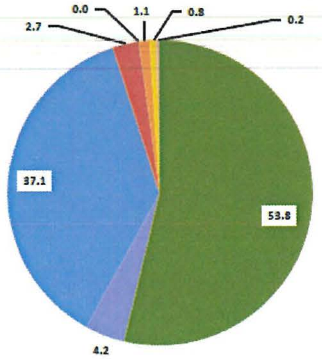
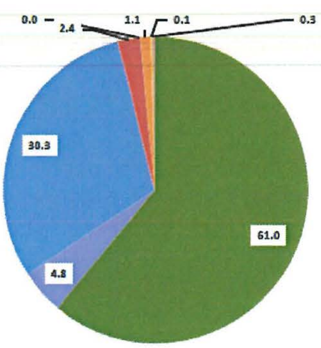


Table 4.2b: Considering same building but assuming concrete block work instead of stone block work.

- In situ concrete
- Precast concrete
- Concrete blockwork
- Stone (torba)
- Glass (windows, doors)
- Tiles (floor, walls)
- Wood (windows, doors)
- Metals (wrought iron, aluminum)





In table 4.2b, a breakdown of the different types of concrete for the block of apartments has been made. The results show that roughly 61% is insitu concrete, 30% is block work and 5% is precast slabs. This is another type of mix ratio that is considered in Chapter 6 for verification of classification scheme being proposed.

Other construction methods with say, stone slabs ('xorok'), use of wooden/steel beams, cast insitu walls, external cladding, are not considered here. Hence, there are several other types of mixing ratios from different types of buildings with other types of construction materials which should be investigated in future research. The focus in this dissertation is on concrete and stone since these are the most common types of construction materials found in local buildings. Chapter 3 shows that other countries consider other types of mixing ratios, such as bricks in the UK and several other countries. Also, countries such as Finland make extensive use of wood.

4.2.3 Construction waste from typical local sites

Construction waste is another type of building waste material. However it is not as large in amount as demolition waste. Figures 4.3 and 4.4 below show that typical construction waste mainly includes meshes, cut block work, form work, bags and crushed concrete or stone. Reuse of materials such as wooden formwork is practiced as much as possible since builders are sensitive to the concept of producing minimal waste due to the increased price in disposal at landfill. All materials mentioned justify the designation of materials discussed in Chapter 7.

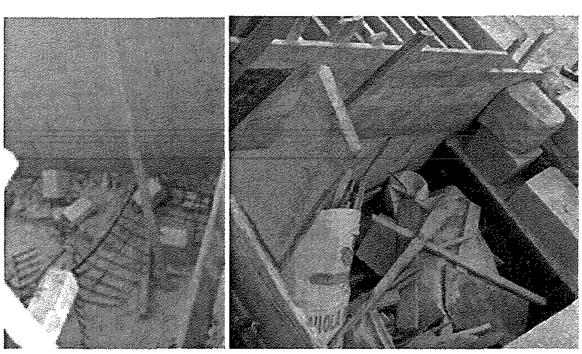


Figure 4.3: Construction waste for the block of apartments being analysed in table 4.2a
Photo by author (2009)

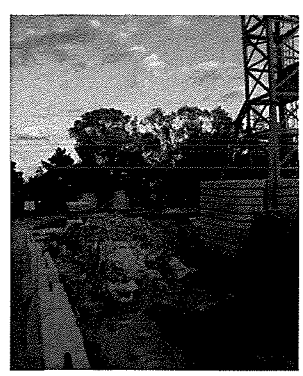


Figure 4.4: Construction waste for the new IT faculty being built at University
Photo by author (2011)

4.2.4 Reconstruction waste from Manuel Dimech Bridge

Another type of local waste is generated from civil engineering projects. Material from the Manuel Dimech bridge reconstruction/rehabilitation project between 2005 and 2008, in San Gwann (figure 4.5) was available for testing for this dissertation. Various waste materials were considered for recycling in 2008, including in particular the steel reinforcement and the concrete. The concrete waste was collected and stored for future research purposes, one of which is this dissertation. The compressive strength values in the bridge construction drawings were reported to be 35 Nmm^{-2} and those resulting from core tests in 2008, were 47Nmm^{-2} for the superstructure (Borg, 2008) from which the tested RCA originated.

Figure 4.5: Reinforced Concrete elements before and after demolition of the bridge in 2006
Source: MEPA website (plan) and Borg (2008) (photos)

The bridge, originally built between 1967 and 1971, has been exposed to certain atmospheric conditions. A relatively high chloride and sulfate content were expected to result due to exposure to pollution and acid rain during the circa forty years of its life. These are discussed in Chapter 6 together with results of experiments already carried out in 2009 by the author's supervisor.

Figure 4.6: Sample preparation of bridge material for flakiness index and chemical tests
A distinct visual difference can be made between natural (white) and recycled (grey) aggregate.
Photos by author (2011)

4.3 Factory production waste at a local precast/ready-mix concrete facility

4.3.1 Factory waste at Blokrete

The amount of concrete factory waste generated daily is not to be underestimated. This is usually stockpiled as one batch of mixed waste to be sent to a landfill (figure 4.7). Hence, certain changes in the processing routine in table 4.3, which are described in the Proposed Guidelines in Appendix G, would be necessary for high quality recycling of the material, as is done abroad.

Figure 4.7: Normal storage of waste materials at Blokrete
Photo taken by author (2011)

Chapter 6 discusses the experiments carried out on waste material collected from Blokrete: cut-offs from precast elements (planks, beams) or precast elements which sometimes fail in say, shear, test cubes and defective block work, as shown in Figure 4.8.

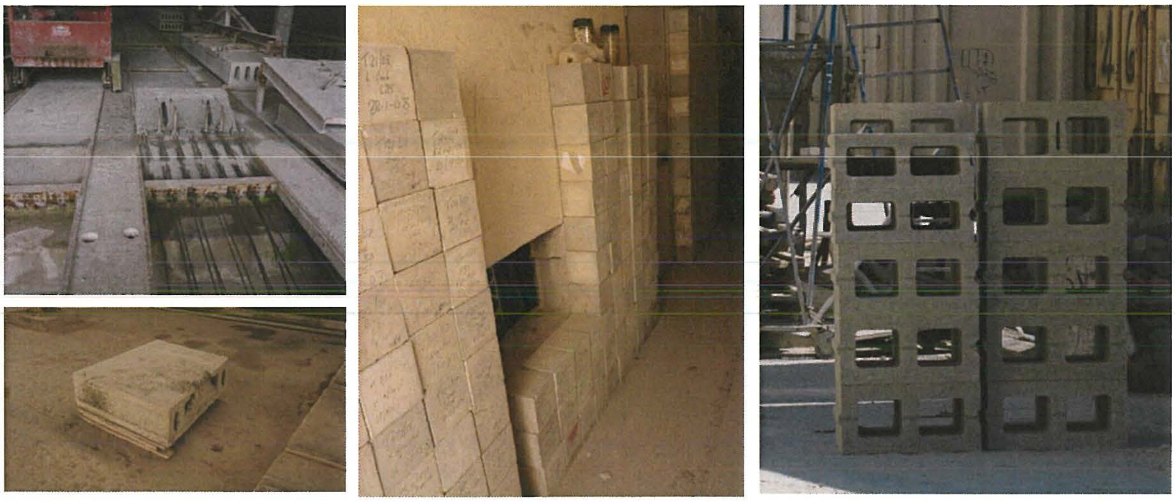


Figure 4.8: Cut-offs from precast elements, test cubes and block work
Photo taken by author (2011)

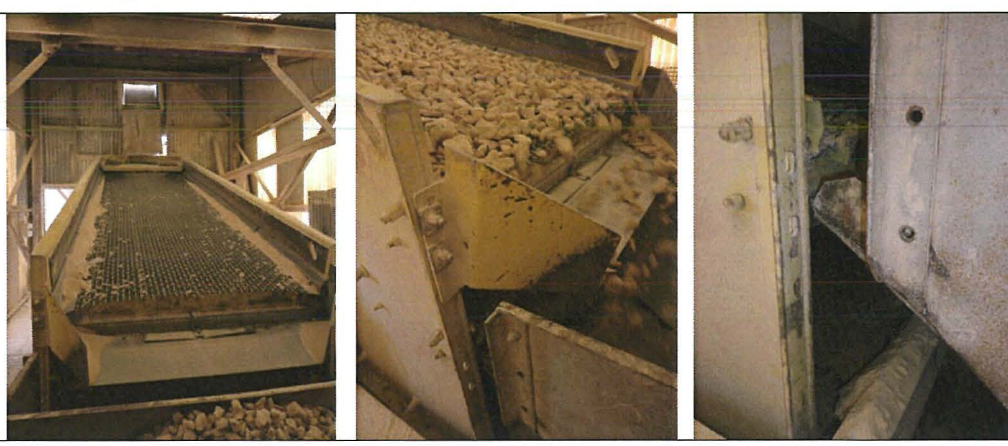
4.3.2 Processing of aggregate at Blokrete

The material gathered for testing, was processed using the existing technologies used for conventional aggregate, in a typical local concrete factory, Blokrete, as a local C&DW recycling plant does not exist as yet. Table 4.3 shows a photographic account of storage and processing of the aggregate, up to the production of the material as RA.

Step 1: Loading material into truck.

Step 2: Crushing process of the material with jaw then cone then granulator crusher.

Step 3: Sieving the material into different grades (0 to 6mm, 6 to 9mm, 9 to18mm)



Step 4: Transfer of sieved material on conveyor belt.

Step 5: Collection and loading of crushed and sieved material into truck.

Step 6A: Conventional aggregates in every day routine are separated with retaining blocks into specific stockpiles

Step 6B: Recycled aggregates are labelled and stored in plastic bags tied with a string then placed in trays to avoid contamination (such as dust) from surroundings

Table 4.3: Photographic account of processing of RCA factory waste. Photos taken by author (2011)

It should be noted, that locally in some factories, the material is not covered/protected from contamination of surroundings or precipitation. Also, the material is not washed as is done abroad. When preparing concrete mixes, water from boreholes, government mains or reservoirs is used, which have be found to contain high chloride levels from local research carried out by Cutajar (2011). Ideally, pure distilled water is used during concrete mixing; however, it does not seem feasible or economic to do so in most instances locally.

Tests have been already carried out by Borg (2008) on the material from the Manuel Dimech Bridge project. Further tests were carried out by the author on this material after it was stored for three years on wooden pallets in a dry storage room at Carmel Asphalt Ltd. It should be noted however, that the plastic bags were not sealed and surface material was exposed leading to possible contaminations during storage, even though they were isolated (figure 4.9). Also, plastic bags were deteriorating and hence all material was transferred to new clean ones as soon as they were collected.

Figure 4.9: Storage of material from Manuel Dimech Bridge when collected.
Photo taken by author (2011)

4.3.3 Visual comparison between RCA from different waste types at Blokrete

EN 933-11 specifies that a visual sorting test for RA is to be used for sorting and labelling as mentioned in Proposed Guidelines in Appendix G. In this case all material is classified under R_C.

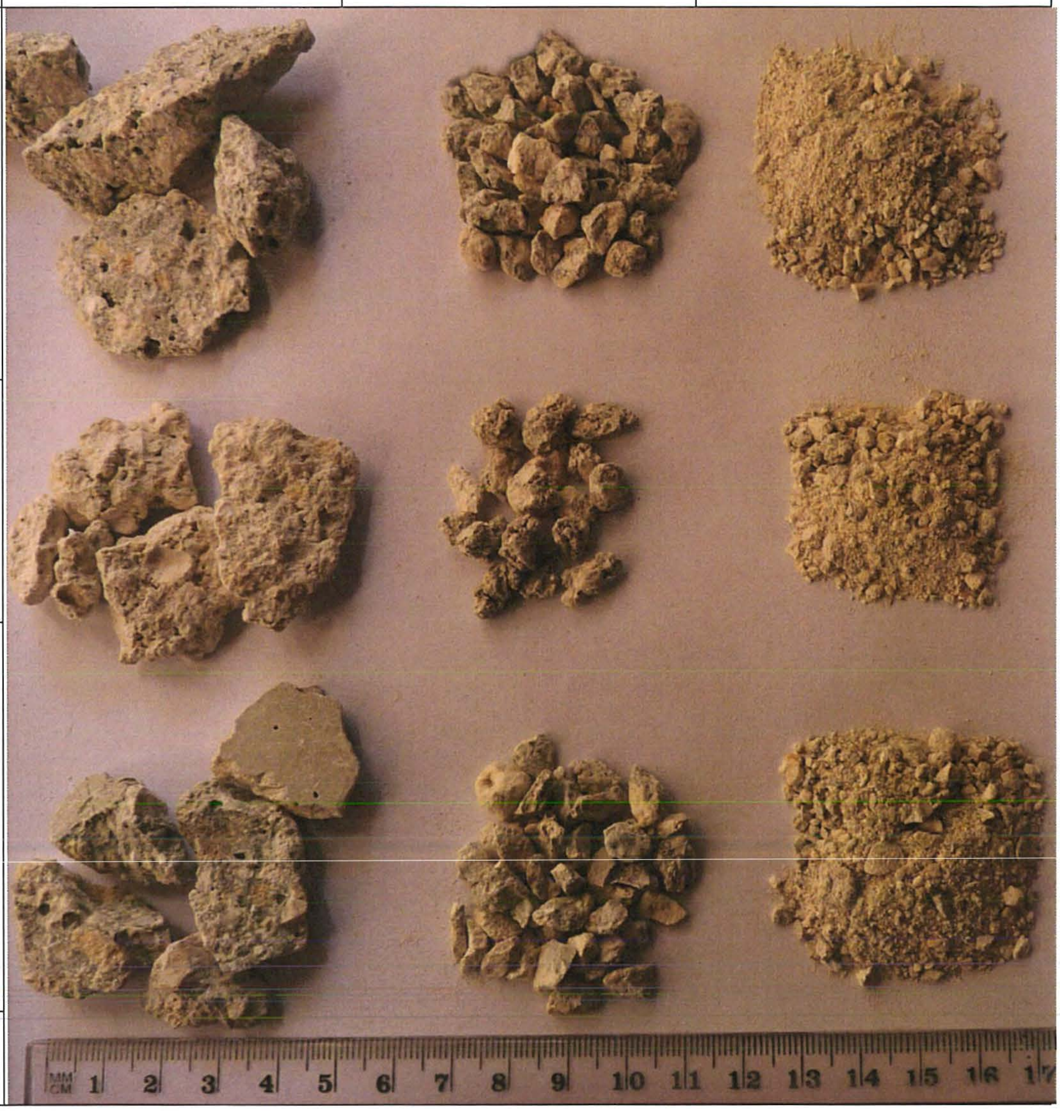
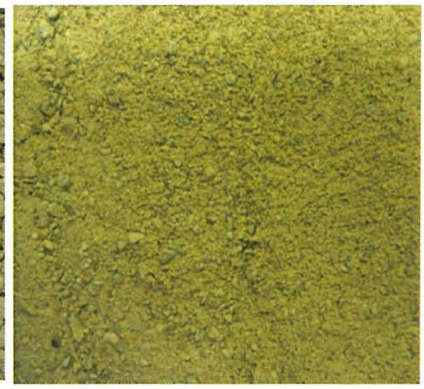
Waste from	**Different grading sizes of Recycled Concrete Aggregates (RCA)**		
	9 to 18mm	**6 to 9mm**	**0 to 6mm**
Planks (C37/40)			
Block work (C15/20)			
Test cubes of mixed strengths			
Ruler			

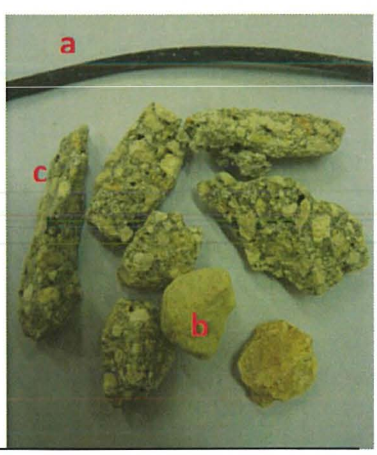
Table 4.4: Visual comparison of different factory waste RCA. Photo taken by author (2011)

4.3.4 Waste from planks

Table 4.5 Visual comparison of different grading sizes of RCA from planks. Photos taken by author (2011)

9 to 18mm	6 to 9mm	0 to 6mm
		

Initial visual observations



a) 9 to 18 mm graded material was mixed with few pieces of reinforcement steel bars (average of 17mm in length) which were manually removed while preparing samples for testing material

b) Very few unbounded normal aggregates could be observed in the 9 to 18 mm batch. [5]

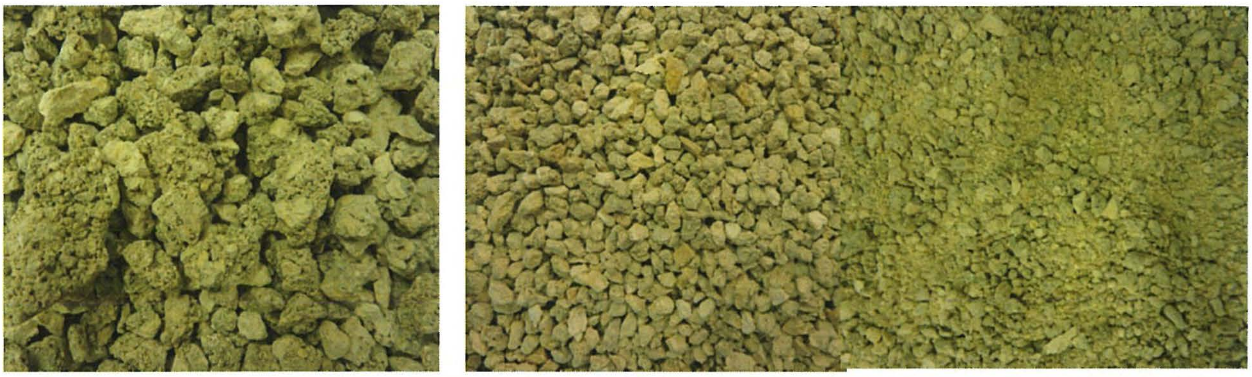
c) Darker, more elongated, flaky and dense particles in the 9 to 18mm batch and finer particles in the 0 to 6mm batch were observed, at first glance, when compared to the other types of waste material.

[5] The author was informed beforehand by the foreman about this. Even though the foreman clearly instructed that there should be removal of NA from the crushers before processing of RCA (not to have a mix of the two), not all could be removed at that time. During the experiments, the few NA could be easily removed manually during sample preparation.

4.3.5 Waste from concrete block work

Table 4.6 Visual comparison of grading sizes of RCA from block work. Photos taken by author (2011)

9 to 18mm	6 to 9mm	0 to 6mm



Initial visual observations

a) Less compact particles, with air voids, in the coarse aggregates were immediately observed, at first glance, when compared to the other types of waste material

b) Aggregates were observed to be rounder and lighter than other types of waste material

c) Slight variations in colour (due to mixed block work)

d) Very few unbounded conventional aggregates could be observed in the 9 to 18 mm and 6 to 9 mm batch.[6]

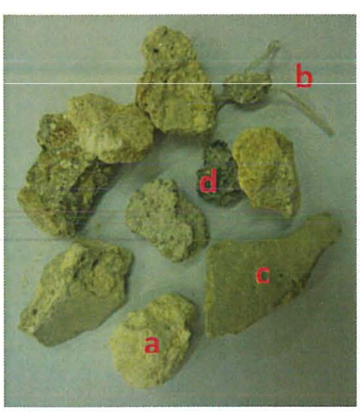
[6] During the experiments, the few NA could be easily removed manually during sample preparation.

4.3.6 Waste from mixed test cubes

Table 4.7 Visual comparison of different grading sizes of RCA from test cubes. Photos by author (2011)

9 to 18mm	6 to 9mm	0 to 6mm

4.3.6.2 Initial visual observations



a) Very few unbounded conventional aggregates could be observed in the 9 to 18 mm and 6 to 9 mm batch.[7]

b) Very few aggregates had pieces of fibres attached to them. The foreman explained that some concrete mixes were designed with these fibres hence their presence in the cubes.

c) Several particles had flat edges since they originated from test cubes, hence the need for checking flakiness index.

d) Variations in colour and textures (due to mixed types of test cubes)

[7] During the experiments, the few NA could be easily removed manually during sample preparation.

4.4 Returned fresh concrete from ready-mix trucks

Returned concrete is the unused ready-mixed concrete that is returned to the plant in the concrete truck as excess material (CSI, 2009). It is reported by CSI, that typically the amount of waste left over at the bottom of the drum in the truck can be as low as 0.4% to 0.5% of the total production. However this can increase up to 5% to 9% during peak seasons when supply is greatest.

If the concrete has hardened already, it can be treated as waste mentioned in section 4.3. Otherwise it can be recovered by washing and reused in concrete production. Figure 4.10 below shows the process involved with wet washing (CSI, 2009). Sometimes 'dry washing' is used before this procedure. This involves first mixing the material with conventional aggregates and then it is returned to the aggregates pile for use in new concrete, after wet washing.

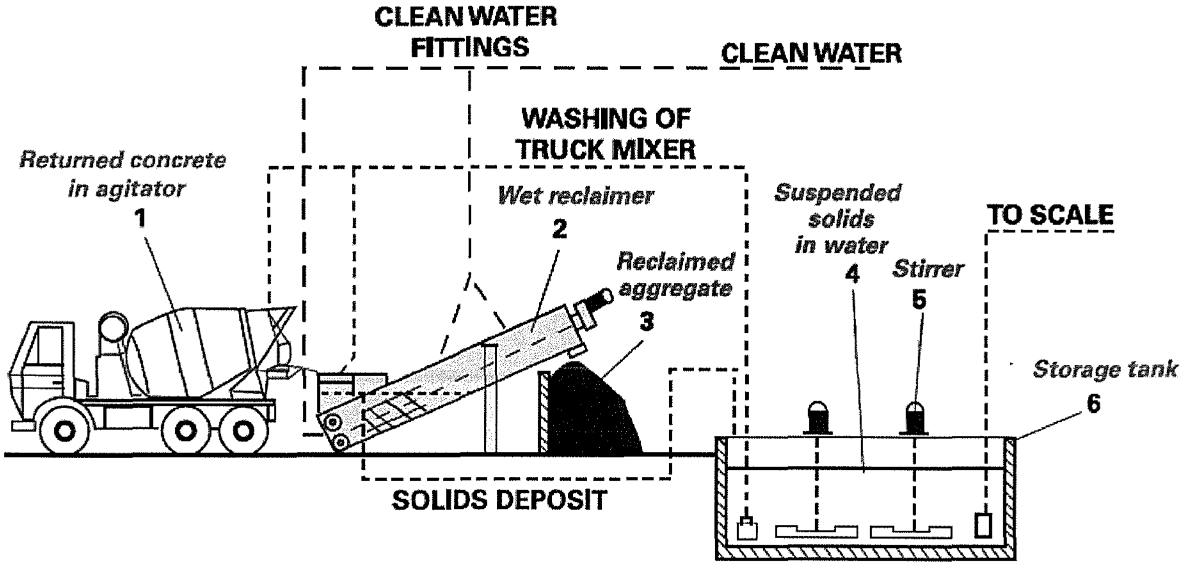


Figure 4.10: Typical system for reclaiming wet concrete
Source: Boral Concrete, Australia as cited in CSI (2009) p24

4.5 Using Tam et al's classification scheme for assessing quality of local NA

Once international classification schemes for RCA have been reviewed in Chapter 3, local NA and RCA should be compared with each other and also with foreign values to understand how the limits should be adapted for local use.

This section deals with the assessment of quality of local aggregate with foreign aggregate. The other comparisons are dealt with in later chapters. Here, local NA is being compared to NA from Hong Kong as an example. Other countries may be chosen, however the scope of this exercise is not to derive any numerical results but rather to prove that local NA is of poorer quality than that used in places such as Hong Kong. Hence it would not make sense to provide limits which not even local NA might pass, let alone RCA which is of poorer quality.

The following is an exercise where the compilation of results on local NA in table 2.3 is being set under the classification parameters set by Tam et al for Hong Kong RCA. The aim is to see how the properties of NA and RCA in Hong Kong vary from the properties of NA in Malta. NA in Hong Kong passes all of the limits being provided in the classification scheme for RCA. The methodology by Tam et al (2008) explained in section 3.2, is being adopted here.

Step 1: Using same limits as Tam et al (section 3.2)

Step 2: Using range of results of local NA (table 2.3)

Step 3: Using same ranges of grades as Tam et al (section 3.2)

Step 4: Using same table of minimum grades for different applications as Tam et al (section 3.2)

Step 5: next page

Step 5: Classifying each sample with a grade particular to each property

Sample number	Size	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Dry Particle Density	10mm	A	-	-	D	C	D	B	B	D	C	C	D	E	C
	20mm	-	-	D	-	B	D	C	C	-	B	C	D	C	C
Water absorption	10mm	B	E	-	E	C	B	B	C	D	C	C	D	D	D
	20mm	B	E	E	-	B	B	C	C	-	C	C	C	B	D
TFV	-	-	D	D	E	-	-	E	-	-	-	-	-	-	-
AIV	-	B	F	F	F	-	-	D	-	-	-	-	-	-	-
Chloride content	4mm	-	-	-	-	-	-	-	-	-	B/D	-	-	-	-
		-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sulfate content (SO_3)	-	-	-	-	-	-	-	-	-	-	A	-	-	-	-

Note that not all tests have been carried out on all samples in results collected from past dissertations. Also, chemical tests carried out on sample number 10 were done by the author. The other results are those from Anastasi's (2011) research. Two letters are provided for chloride tests since one is the water-soluble results and the other, acid-soluble result.

Step 6: Combining tables in steps 4 and 5 for classifying each sample with an application

Sample no	Structural element	Minor structural element	Non-structural element	Pre-stressed concrete element	Road surface	Base course	Embank-ment and fill	Insulation barrier
1	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
2	× TFV, WA, AIV	× AIV	✓ ALL	× AIV	× AIV	✓ ALL	✓ ALL	× AIV
3	× TFV, WA	✓ ALL	✓ ALL	× AIV	× AIV	✓ ALL	✓ ALL	× AIV
4	× TFV, WA, AIV	× AIV, TFV	✓ ALL	× AIV, TFV	× AIV, TFV	✓ ALL	✓ ALL	× AIV, TFV
5	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
6	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
7	× TFV, AIV	× TFV	✓ ALL	× TFV, AIV	× TFV	✓ ALL	✓ ALL	× TFV
8	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
9	× WA	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
10	✓ ALL	✓ ALL	✓ ALL	× Cl	✓ ALL	✓ ALL	✓ ALL	✓ ALL
11	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
12	× WA	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
13	× WA	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL
14	× WA	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL	✓ ALL

Note that highlighted cells indicate which properties of local NA do not pass the limits specified for RCA in Hong Kong.

It is evident that local aggregate in general, does not pass the limits provided for RCA by Tam et al (2008). This proves that the limits cannot be used and need to be adapted to local aggregate.

It is interesting to note that the natural aggregate used by Tam et al during their research was also a limestone, called bluestone (personal communication with Prof. Tam). However, it is fairly clear that it is an aggregate of excellent quality, from results of experiments provided by Tam et al (2008), when the properties of the blue limestone aggregate are compared to local coralline limestone aggregate.

If one compares the values of local NA of best quality (highlighted values below) with those of RCA from the recycling plant in Hong Kong, one realises that most properties show that the quality of the RCA in Hong Kong is even better than that of local NA.

Aggregate Property	Aggregate size	Range of local results NA from table 2.3			NA Tam et al (2008)	RCA from recycling plant Tam et al (2008)	RCA from demolished buildings Tam et al (2008)
Oven dry particle density (Mg/m^3)	10mm	2.14	–	2.45	2.59	2.46	2.1 - 2.25
	20mm	2.22	–	2.48	2.62	2.53	2.12 - 2.27
24h Water absorption (%)	10mm	1.48	–	7.45	0.77	2.63	5.2 - 8.58
	20mm	2.2	–	7.45	0.57	1.65	5.77 - 7.99
AIV (%)		21.1	–	34	21	33	23 - 36
TFV (kN)		96	–	103.45	189.38	102.97	61.36 - 155.53
Acid-soluble chloride content		0.0911			0.0012	0.0021	0.0013 - 0.0976
Acid-soluble sulfate content		0.0113			0.003	0.008	0.005 – 0.031

Table 4.8 Comparison between local NA and NA and RCA from Hong Kong

CHAPTER 5: EXPERIMENTAL METHODOLOGY

This chapter outlines the methodology and approach used for derivation of limits to be used in the proposed local guidelines discussed in Chapter 7. The steps shown in the schematic diagram below are discussed in more detail in the following pages.

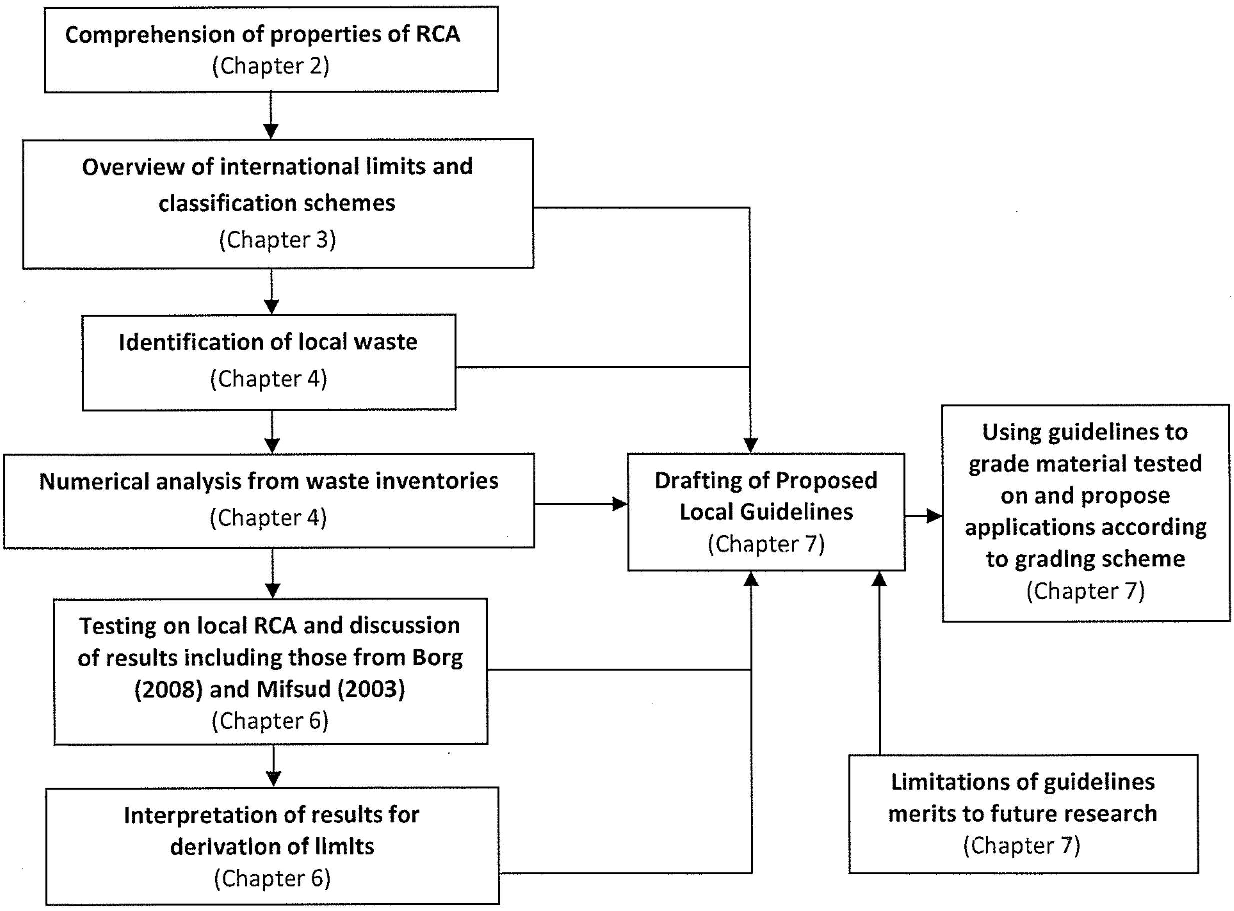


Figure 5.1 Schematic diagram of methodology used to draft Local Proposed guidelines

Processing and use of RA is at different stages in different countries. Some countries are quite advanced and are refining the techniques to improve quality of RA, others have just begun while other countries, such as Malta, are still in the process of drafting guidelines and introducing laws.

Once literature was reviewed and the main properties and criteria to research further highlighted, typical local waste was identified and investigated through waste inventories and experimental testing. Since local RCA can originate from demolished buildings or structures, construction waste, civil engineering projects or concrete factory waste, materials from all these sources should be considered for the drafting of the proposed local guidelines. However, due to the limited time available to carry out this dissertation, it was impossible to carry tests out from all these sources so a strategy was developed to try and involve each type of waste.

Firstly, two buildings were chosen as case studies for a waste inventory to understand amounts and types of wastes from construction and demolition projects, with three possible scenarios and therefore three different sets of results were derived, as discussed in Chapter 4. The case studies were a public building and a domestic building, the two most common types of buildings found locally with the most common method of construction, that is, stone and concrete masonry. The mix ratios which were concluded were used for verification and derivation of limits as discussed in the results in Chapter 6 and used in the proposed guidelines.

Existing limits were checked to be adequate for local aggregate and those which needed adaption to the local RCA were identified and calculated accordingly. Methodologies from different countries reviewed in Chapter 2 were compared and used for derivation of limits which is shown in the discussion of results in Chapter 6.

Next, material testing was first carried out on three types of concrete, which are representative samples from the main concrete materials derived from the breakdown of the waste inventories. These are planks, block work and test cubes representing precast high grade elements, masonry concrete and cast-in situ concrete for a typical building.

Also, results from tests carried out on a civil engineering project (Manuel Dimech bridge) were available from Borg (2008) and when they were not, they were carried out by the author (flakiness index, loose bulk density, chloride and sulfate tests). Results of experiments carried out on RCA by Mifsud (2003) were retrieved and eventually analysed also, in light of some of the different standards used a few years back.

The results of the RCA were compared to available results of tests carried out on NA from eight different concrete factories to understand the difference in quality and why certain limits provided by foreign countries do not even satisfy local NA. The exercise carried out in section 4.5 justifies this. Where results from tests for NA were not available (specifically the chemical tests), these were carried out by the author on the same type of NA used by Anastasi (2011).

Now, since a C&DW recycling plant does not exist locally, the same machinery used for processing of NA was used for the material after cleaning it as much as possible from any left over NA from previous processing. (Machinery at Blokrete was used for the factory waste and that at Carmel Vella for bridge material). In reality, separate machinery would be needed at a recycling plant but would be identical to that used for NA, with additions depending on the refinement and advanced quality of RCA being produced, such as washing and material separation equipment (such as magnets, containers for material separation by density and so on).

The Drafted Proposed Guidelines discussed in Chapter 7 collect best practices from literature reviewed in Chapters 2 and 3, and also specifies limits derived from the discussion of results in Chapter 6. Once the testing was carried out on the materials and the interpretation of the international classification schemes (Chapter 3) completed, the limits of the properties being proposed for testing could be identified as being limits which can be identical to those used in reviewed literature or limits which needed to be derived to suit local aggregate.

Once limits were interpreted and adapted to the local scenario. They were included in the Proposed Guidelines. The next step was to generate a classification scheme with a number of grades based on research finalised in this dissertation, which is included in the guidelines also. As future research is carried out and more materials investigated, this classification scheme is be prone to change and possibly expand.

Finally, all the available results from test experiments carried out on local RCA, that is, from this dissertation, Borg (2008) and Mifsud (2003), were interpreted and the guidelines being proposed used to propose possible applications based on the research carried out by the author.

CHAPTER 6: DISCUSSION OF RESULTS

This chapter discusses results derived from experiments and desk-work exercises performed in previous chapters. Each section discusses a different property which was tested and how, if necessary, the limit being proposed was modified to suit local needs.

6.1 Geometrical properties

6.1.1 Particle Size Distribution (Sieve analysis)

Results from the sieve analyses (Appendix B.1) are summarised in table 6.1. Highlighted boxes are considered to be fit for use according to application.

Source	Type of crusher	Type of crushed Waste concrete to be used as RCA	Aggregate size or grading as delivered	EN standards		Series 800 / 900			Der Österreichische Baustoff-Recycling Verband (2007) Austrian guidelines						
				concrete	roads	Base courses	Sub base courses	Asphalt concr for combined base & wearing course	Hydraulically bound and unbound construction methods (Red guideline)				Base courses		Sub base courses
				EN 12620	EN 13242	Type 1 0/37.5	Type 2 0/37.5	0/37.5	Grade 3 0/4	RS 0/4	Grade 3 0/8	Grade 3 0/16	Grade 1 0/22	Grade 2 0/22	Grade 3 0/22
Blokrete	Jaw crusher Cone crusher Granulator At Blokrete	Mixed Test cubes (author)	0-6	✓	✓				✓	✓					
			6-9	✓	✓							×			
			9-18	✓	✓	×	×	×					×	×	×
		Block work (author)	0-6	×	×				×	×					
			6-9	✓	✓							×			
			9-18	≈	✓	×	×	×					×	×	×
		Planks (author)	0-6	✓	✓				✓	✓					
			6-9	✓	✓							×			
			9-18	≈	✓	×	×	×					×	×	×
Manuel Dimech Bridge	Granulator At Carmel Vellla Ltd	bridge (civil engineering) (Borg)	sand	✓	✓				✓	✓					
			10mm	✓	✓							×			
			20mm	×	≈	×	×	×					×	×	×
Polidano	Jaw crusher At university laboratory	C20 test cubes (Mifsud)	sand	✓	✓				✓	✓					
			10mm	✓	✓							×			
			20mm	×	×	×	×	×					×	×	×
		C30 test cubes (Mifsud)	sand	✓	✓				✓	✓					
			10mm	✓	✓							×			
			20mm	✓	✓	×	×	×					×	×	×
		C45 test cubes (Mifsud)	sand	✓	✓				✓	✓					
			10mm	≈	≈							×			
			20mm	✓	✓	×	×	×					×	×	×

✓ Means that the cumulative curve passes the envelope for a particular application.
≈ Means that the cumulative curve almost passes the envelope for a particular application.
× Means that the cumulative curve does not pass the envelope for a particular application.

Table 6.1: Results from sieve analysis

Sieve analysis of sand

All cumulative curves of the 0/6 samples except those from waste of crushed block work, pass the Austrian and EN 12620 envelopes. The cumulative curves for the block work are in fact very different from the other results as all the others lie roughly at the centre of the envelope while for the block work, more aggregate is retained on the upper sieves (4mm and 2mm). The probable reason for this is that block work is less dense in its nature and has more voids, while say, planks are very dense and small particles fill in the voids that would otherwise exist in the block work. Hence, when the material is crushed, a representative sample of the sand of dense materials would contain finer particles of smaller sizes for the same sample masses.

The sieve analysis carried out by the author for sand, show results for both washed (figure 6.1) and unwashed samples. This is because, in reality, the aggregate is usually not washed locally as is done abroad. Results suggest that washing the aggregate does not make a significant difference on the pass/fail result when it comes to fitting the particle-size distribution in the envelopes. However, washing the RCA from test cubes gives the curve a better fit.

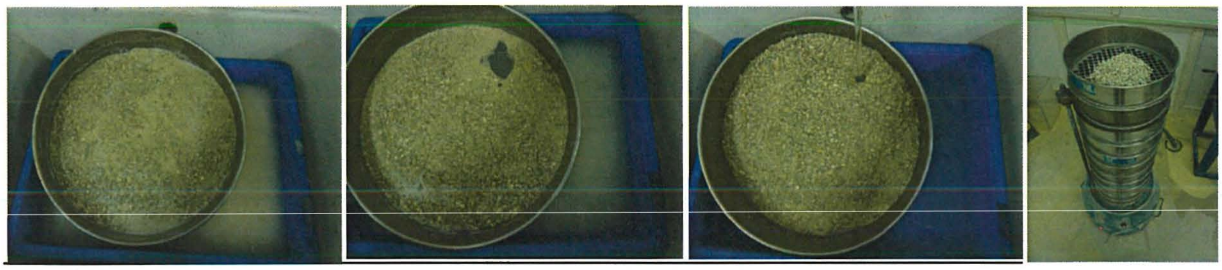


Figure 6.1: Washing of oven dry sand until clear water passes the 63μm sieve and sieve analysis after drying. Photo taken by author (2011)

It can also be noticed that a larger percentage of fines was produced by waste from Blokrete when compared to that of the bridge. It is possible that this is caused by the secondary and tertiary crushing which might increase the fines content as opposed to crushing only once as was done with the bridge material.

In the initial inspection of material, discussed in Chapter 4, there is written that on delivery, the waste from planks 0/6 batch appeared to have finer material than the other types of waste, which was quite visible. This can in fact be confirmed from the higher fines content and also the higher amount of material passing the higher sieve sizes. In general, fines can be reduced significantly by wet sieving, if the limit specified in the particular project is exceeded.

Sieve analysis of medium size aggregate (< 10mm)

The particle size distributions of all samples pass the EN 12620 and EN 13242 envelopes. Cumulative curves from bridge seem to have the worse fit in the envelopes from all samples.

Sieve analysis of large size aggregate (< 20mm)

The crushers used at Blokrete were a jaw crusher followed by a cone crusher followed by a granulator crusher. The bridge material was crushed using only a granulator (type of jaw crusher) while Mifsud's was crushed with the jaw crusher in the University laboratory. Hansen (1992) suggests that in the crushing process, economy of coarse aggregate production can be maximised by balancing types of crushers. However it seems that using only one jaw crusher (Mifsud), gives a good enough distribution.

All samples do not pass the envelopes for road applications in Series 800/900 or Austrian guidelines. This is because these standards only give grading for all-in aggregate and not graded aggregate. Hence, there is a possibility that they would otherwise pass. This is where the flexibility of the envelopes provided in EN 13242 and its advantages can be observed. Grading of material depends greatly on the crusher setting used. It should also be noted that the Specifications for road works series 800 and 900, which are those used locally, are given only for 0/37.5 aggregate with ASTM sieves. EN 13242 is at present still being introduced at Transport Malta (personal communication with Mr. Briffa).

6.1.2 Flakiness index for coarse aggregate

On delivery of the crushed concrete waste from Blokrete it was noticed that most of the RCA from the test cubes and planks had flat edges (figure 6.2) due to the fact that the original elements have flat edges in their geometrical nature. As a result from crushing, most particles appeared to be elongated and flaky, hence a shape index test was considered. Another factor which could possibly contribute to this is also the use of the jaw crusher as opposed to other types of crushers which might increase the flakiness index.

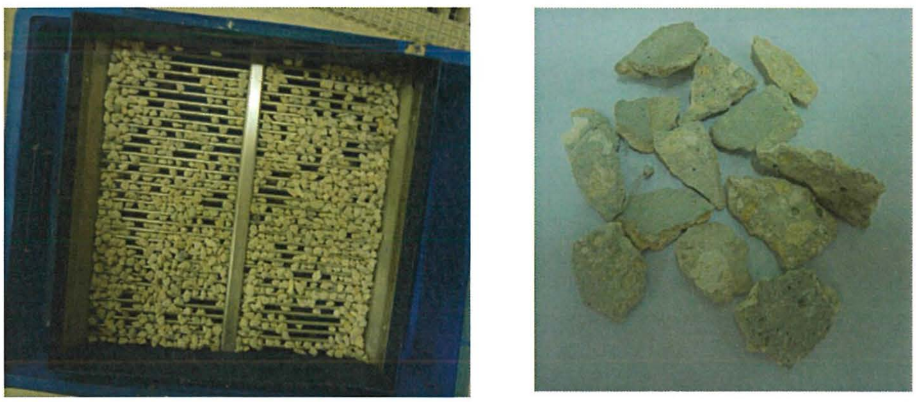


Figure 6.2: Sieving material for Flakiness Index as per EN 933-3 (left) and flaky RCA from crushed test cubes (right). Photo by author (2011)

The flakiness index limit for use in concrete is 35 (EN value) while 25 is used in all local road applications (personal communication with Mr. Briffa at TM). The values of Flakiness index obtained for all samples were well below these limits with a maximum value of 12.7 for RCA from the crushed mixed test cubes of grading 6/9mm. Therefore limits need not be modified for local scenario. The graph in figure 6.3 suggests that flakiness index increases with high quality aggregate (the more resistant the aggregate the flakier it is). Another possible factor could be the crusher used. In fact it is interesting to note that10mm NA (bluestone) from Hong Kong cannot be used for local road applications as it exceeds the limit. Therefore this test need be checked only when the RCA might contain foreign aggregate.

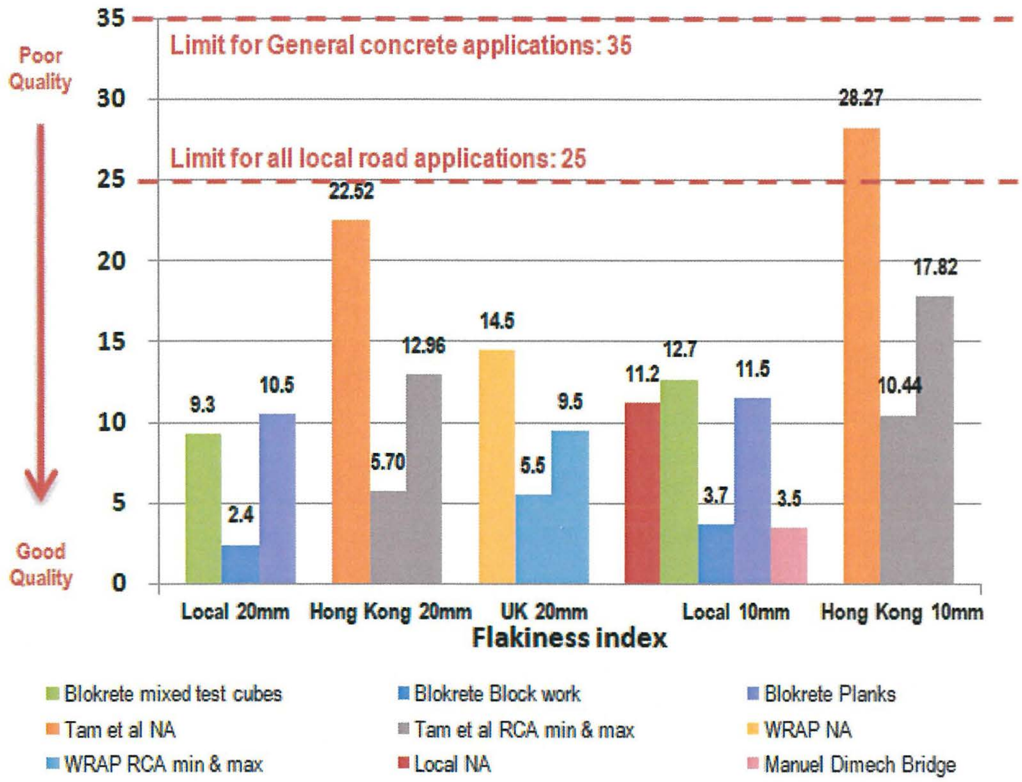


Figure 6.3: Results of flakiness index experiments on local and foreign RCA and NA

6.1.3 CSCement index

The experiment suggested by Tam et al (2008) to quantify the amount of cement mortar attached to the aggregate was given a try. Whereas a zero CSCement index resulted for NA with the pan mixer in Hong Kong (signifying no cement attached to RCA), the local NA tested did not have enough resistance to fragmentation and the CSCement index resulted as 4.1. Although a significant difference in CSCement index could be noticed between the NA and RCA (range between 17.7 and 23.4), and a considerable amount of mortar was removed, there was also a considerable amount of original aggregate in the remains (figure 6.4). Hence it would be incorrect to say that the CSCement index can be used to quantify the amount of cement only, with local RCA.

Figure 6.4: Mixing sample (greater than 4mm) in pan mixer (left) and washed material passing 4mm sieve after mixing in pan mixer (right). Photos by author (2011)

Quantifying the amount of cement does in fact assess the quality of RCA since it the cement itself which reduces aggregate quality. More techniques which are used abroad, such as thermal treatment at 500°C, are mentioned in section 2.4.3, should be tried out locally.

6.2 Mechanical properties: Los Angeles values

In this experiment a clear distinction can be made in results since RCA from block work shows a large discrepancy in value from the other types of RCA. The resistance to fragmentation of the RCA from planks and bridge are fairly similar while the RCA from test cubes show a very good resistance to fragmentation and are almost comparable to local NA of good quality. Results are also comparable to those obtained by Dhir et al (2007). It is important to note that Transport Malta set limits for the wearing course at LA_{25} which is not even achieved with the best quality NA recorded from local results in table 2.3. In fact, aggregate needs to be imported for use in local wearing courses in arterial and distributor roads with a high AADT, since imported basalt has better consistency in grading and quality (personal communication with Mr. Briffa from TM).

Figure 6.5: Process of LA experiment carried out on graded material of 10/14 up to wet sieving of material retained on 1.6mm sieve. Photo by author (2011)

It can therefore be concluded that existing local limits should not be modified for local RCA and also that block work does not pass this limit by a considerable and significant amount.

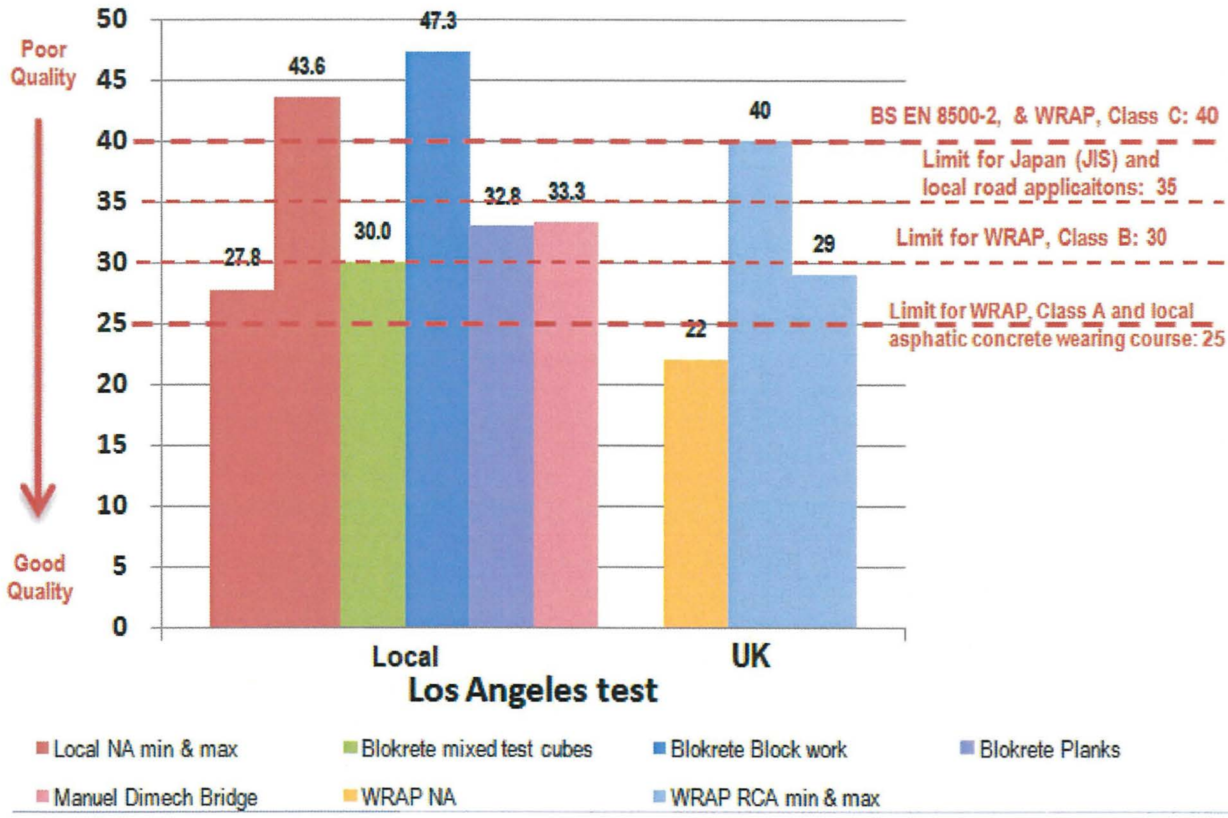


Figure 6.6: Results of Los Angeles experiments on local and foreign RCA and NA

6.3 Physical properties

6.3.1 Water absorption

This section first describes the experiments carried out. It is then followed by calculations showing a particular method used by Gutiérrez et al (2004) for calculation of water absorption limits with replacement ratios[1] of NA with RCA for

- RCA from separated factory waste
- RA from demolished case studies with mix ratios[1] of RCA and NA
- RCA from demolished case study with mix ratios of different types of concrete

Reference to the case studies in Chapter 4 is made.

[1] Definition in Appendix A.

6.3.1.1 Experiments carried out

Figure 6.9 shows the results of all water absorption experiments as per EN 1097-6, carried out on local RCA together with limits for water absorption for the different countries compiled in tables 3.1 a, b and c. It is clear that this property is the one which varies most since there are quite of number of different limits used. It is definitely one of the more important parameters for classification of RCA and since we already deal with problems of water absorption for NA locally, much research is required in this field.

Figure 6.7: Water absorption using wire basket for all samples graded 9/18
Photo by author (2011)

The wire basket method was used for coarse aggregate, 9/18 (figure 6.7) while the pyknometer method was used for grades 6/9 and 0/6. It should be noted that the pyknometer apparatus specified in the standard could not be used as the only pyknometer available in the lab had broken at the beginning of the academic year. Instead, measuring cylinders (figure 6.8) were bought to replace the pyknometer. Although having a narrow tube when topping up with water would result in more accurate results, the different samples were tested under the same conditions and also at one go, which could otherwise not be done with the single pyknometer had it been available.

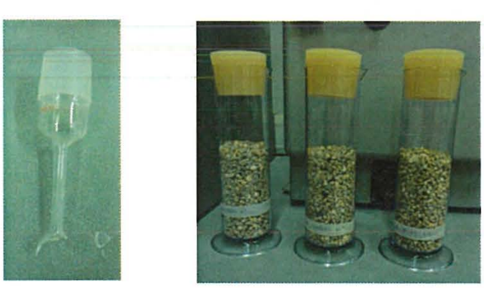


Figure 6.8: Broken pyknometer (left) and use of measuring cylinders for carrying out water absorption experiment as per EN 1097-6 (right). Photo by author (2011)

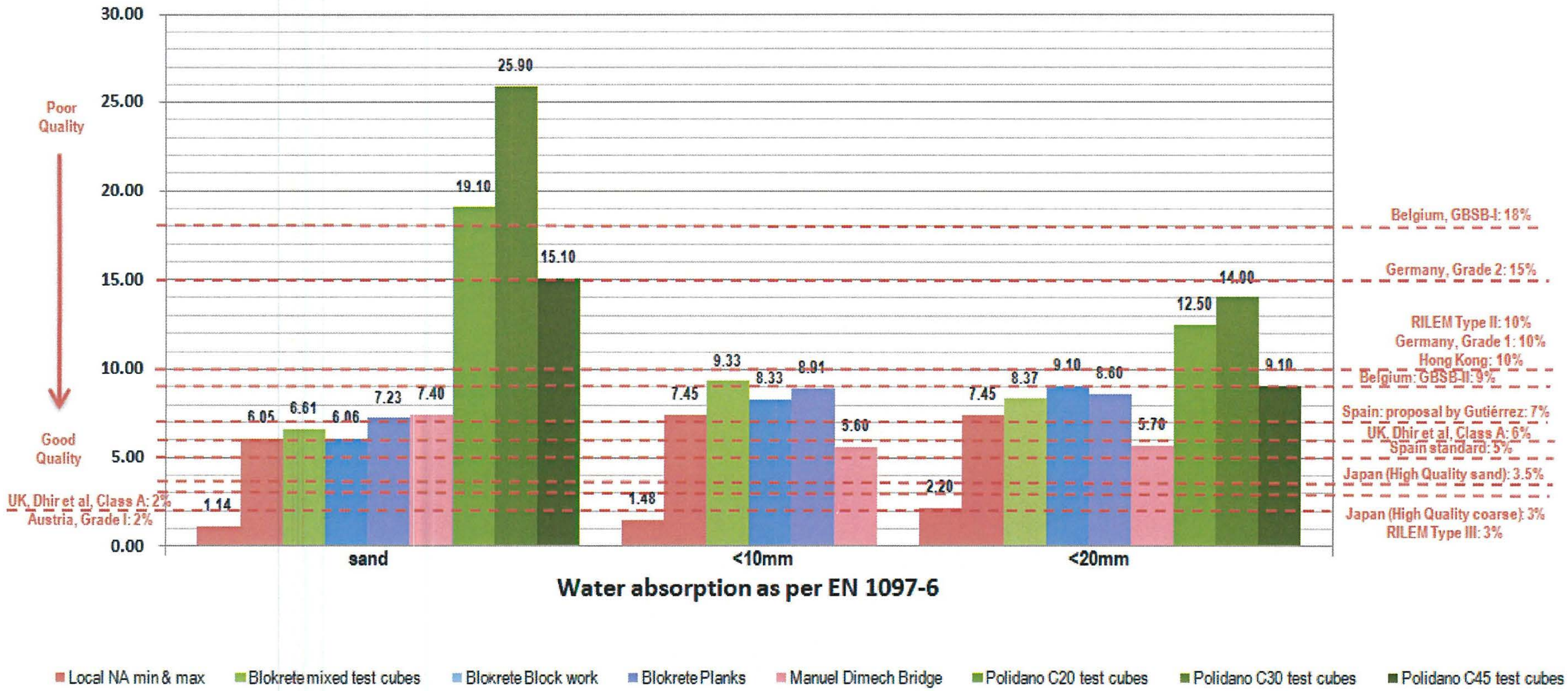


Figure 6.9: Results of water absorption experiments as per EN 1097-6, on local RCA

Note that RCA from all test cubes (author's and Mifsud's) are in different shades of green for visual aid in comparison of the two.

Results of 10mm aggregate by Mifsud are not included since they were not carried out.

It is clear that there is a large discrepancy between water absorption by the fine RCA used by Mifsud (2003) from crushed test cubes of different original strengths and the fine RCA (figure 6.10) from mixed test cubes from Blokrete.[1] It should be noted that the source of the original test cubes are different and this suggests the discrepancy. In fact, water absorption of NA from Mifsud's source is recorded to have very high water absorption values (table 6.2). This clearly shows that the quality of the RCA depends on the quality of the original aggregate used when it comes to water absorption. It is also possible that samples used by Mifsud (2003) contained high levels of unhydrated cement.

Aggregate size	Water absorption of NA from Source 2 in 2003	Highest values of water absorption from Source 2 RCA in 2003	Water absorption increase, X times higher
< 20mm	7.5%	14.0 (C30)	X = 1.9
< sand	18.9%	25.90 (C30)	X = 1.4

Table 6.2 Comparison of water absorption for NA and RCA from Source 2 (Mifsud, 2003)

Figure 6.10: Process of reaching saturated surface dry state after two and a half hours of drying material with a current of warm air to evaporate surface moisture. Photo by author (2011)

Results of water absorption of 10mm aggregate were not recorded by Mifsud and hence these cannot be compared. The 20mm RCA results suggest that the mixed test cubes used by the author were of relatively high original concrete grade since these are comparable to the C45 test cubes used by Mifsud, which portray best results for quality in Mifsud's results.

[1] RCA from all test cubes (author's and Mifsud's) are in different shades of green for visual aid.

The aggregate used in the RCA from factory waste used by the author is from Source 5 in the list of properties in table 2.3. If one uses the sets of results on local NA from Source 5 (Blokrete) the water absorption increase caused by the mortar in RCA can be calculated.

Type of aggregate	< 20mm	Water absorption increase, X times higher	< 10mm	Water absorption increase, X times higher	sand	Water absorption increase, X times higher
NA	4.98		6.25		3.47	
RCA (test cubes)	8.37	8.37 / 4.98 = X = 1.7	9.33	X = 1.5	6.61	X = 1.9
RCA (block work)	9.1	X = 1.8	8.33	X = 1.3	6.06	X = 1.7
RCA (planks)	8.6	X = 1.7	8.91	X = 1.4	7.23	X = 2.1

Table 6.3 Water absorption of NA and RCA from Source 5 (Blokrete) in 2011

Dhir et al (2007) report water absorption values for RCA roughly 4.5 times higher than the NA from which they were produced. With local results the worst case is water absorption being 2.1 times more than the NA. It is interesting to note that the lowest result for water absorption of RCA recorded locally is from the Manuel Dimech Bridge.

6.3.1.2 Proposal of water absorption limits for local RCA from separated factory waste

No standard limit of WA_{24} seems to exist locally for concrete applications. If one adopts the 5% limit used in Spain, it can be noticed that two out of the eight factories whose water absorption properties were recorded in table 3.2 (extract is in table 6.4) would have their NA exceeding the limit as highlighted in table 6.4. These values are relatively high and it is not recommended that a more lenient limit should be provided for good quality production of concrete.

Source no.	1	2	3	4	5	6	7	8	
Sample nos.	1	2-4	5	6	7, 12	8-11	13	14	Range
Avg WA_{24} for 20mm	2.4	7.45	2.2	2.93	4.51	4.39	2.75	4.8	2.2 – 7.45
Avg WA_{24} for 10mm	2.4	7.45	4.26	1.48	4.55	4.91	6.87	5.0	1.48 – 7.45

Table 6.4 Local NA exceeding 5% limit for water absorption

Therefore, in order to classify RCA for water absorption, a maximum of 5% for the 100% use of RCA is being suggested to be comparable to NA for concrete production. However, from results gathered, all of the RCA exceed this limit and hence a mix of NA and RCA will be required for most applications. A replacement ratio of NA with RCA needs to be calculated to fit the properties of the RCA.

It is usually recommended by most standards (tables 3.1 a, b, c) that not more than 20% of RCA is used for RAC in structural elements of certain non-severe exposure conditions. After considering all the limits of the properties used in the classification scheme and performing iterative calculations, it was decided to set a maximum water absorption limit of 9% for use in structural concrete, as an optimized limit. If one considers the results recorded from all local RCA (table 6.5), the materials which exceed this 9% limit fail to be used for structural elements not because of water absorption but due to the limits of other properties, hence they should not affect the decision of a pass/fail when choosing the limit for water absorption. A maximum 9% limit has been found to be the ideal one for these test samples to allow for best use for applications. Research on more samples may prove this limit may need to increase or decrease.

Water absorption values for different types of RCA								
	Source 5				Source 2			
Sample	Test cubes	Block work	Planks	Bridge	Mifsud-C20	Mifsud-C30	Mifsud-C45	Range
WA_{24} for 20mm	8.37	9.1	8.6	5.7	12.5	14	9.1	5.7 - 14
WA_{24} for 10mm	9.33	8.33	8.91	5.6	-	-	-	5.6 - 9.33

Table 6.5 Local RCA results for water absorption

Table 6.6 summarizes the conclusions derived from calculations involving different replacement ratios with NA to satisfy limits for applications. For example,

For concrete applications with an allowed percentage of $WA_{24}5$ for 100% NA [1],

35% RA with $WA_{24}6$ + 65% NA with $WA_{24}4.5 \leq$ 100% of total aggregate with blend of $WA_{24}5$

$(0.35*6\%) + (0.65*4.5\%) = 5.0\% \Rightarrow$ OK

15% RA with $WA_{24}7.5$ + 85% NA with $WA_{24}4.5 \leq$ 100% of total aggregate with blend of $WA_{24}5$

$(0.15*7.5\%) + (0.85*4.5\%) = 4.95\%$ which is less than 5.0% $\Rightarrow$ OK

10% RA with $WA_{24}9$ + 90% NA with $WA_{24}4.5 \leq$ 100% of total aggregate with blend of $WA_{24}5$

$(0.1*9\%) + (0.9*4.5\%) = 4.95\%$ which is less than 5.0% $\Rightarrow$ OK

[1] Limit 24-hour water absorption for conventional aggregate in general concrete applications could not be found in any standards. Sometimes it is specified as 2.5% in local tenders, but can be taken as 5% here (personal communication with Perit Borg). It can be taken as 5% in this case since this way more concrete factories can use their aggregate which does not increase this 5% limit, and hence a greater opportunity for introduction of RA in Malta is created.

Similarly, for prestressed elements with an allowed percentage of $WA_{24}3$ for 100% NA[1],

15% RA with $WA_{24}5.5$ + 85% NA with $WA_{24}2.5 \leq$ 100% of total aggregate with blend of $WA_{24}3$

(0.15*5.5%) + (0.85*2.5%) = 2.95% which is less than 3.0% ⇒ OK

In reality a replacement ratio (RR) of 17% may be used (not just 15%) however showing an absolute number with a tolerance is more practical. Hence it is represented by 15% ± 2%.

For road applications with an allowed percentage of $WA_{24}4$ for 100% NA [2],

35% RA with $WA_{24}6$ + 65% NA with $WA_{24}3 \leq$ 100% of total aggregate with blend of $WA_{24}4$

(0.35*6%) + (0.65*3%) = 4.0% ⇒ OK

15% RA with $WA_{24}9.5$ + 85% NA with $WA_{24}3 \leq$ 100% of total aggregate with blend of $WA_{24}4$

(0.15*9.5%) + (0.85*3%) = 3.975% which is less than 4.0% ⇒ OK

Several other combinations may exist; however, these are the optimal ones in the author's view, when it comes to balancing the existing quality of NA available locally and the quality of RCA being tested, under the processing machinery available to the author.

Proposed grade[3]	G-A	R-A, R-B	G-A, G-B	R-C, G-C, F
Application	Prestressed concrete	Road applications	Structural concrete	Bulk and fill or where there is NR in other applications
WA_{24} for 100% NA (to use as resultant blend ratio)	3%	4%	5%	No requirement (NR)
Max replacement ratio (RR) of NA with RCA of High quality	15% ± 2%	35%	35%	100%
Max replacement ratio (RR) of NA with RCA of Medium quality	Not recommended	15% ± 1%	15% ± 2%	100%
Max replacement ratio (RR) of NA with RCA of Low quality	Not recommended	Not recommended	10% ± 2%	100%
Max WA_{24} for RR % of RCA allowed in mix	5.5%	6% for RR of 35% 9.5% for RR of 15%	6% for RR of 35% 7.5% for RR of 15% 9% for RR of 10%	NR / 14%
Max WA_{24} for (100% - RR%) of NA allowed in mix	2.5%	3%	4.5%	NR
No. of factories from table 5.4 which can provide NA with WA_{24} requirement	3 from 8	4 from 8	6 from 8	8 from 8

Table 6.6: Replacement ratios[4] being proposed for applications

[1] Limit 24-hour water absorption for NA in prestressed concrete applications is found in BS 8007 clause 4.2.2.
[2] Limit 24-hour water absorption for NA in bituminous road applications is found in TM (2003b) Series 900 clause 901.
[3] These grades are being proposed by the author as specified in the designation of materials in the Proposed Guidelines, discussed in Chapter 7.
[4] Definition in Appendix A.

6.3.1.3 Analysis of water absorption limits for local RA from demolished case studies with mix ratios of RCA and NA

The values being proposed in table 6.6 are based on results from RA tested in this research which are entirely concrete, since they are from concrete factory waste. It should be noted that in reality, when buildings are demolished, the RA can be found in mix ratios of less than 50% or more than 50% RCA with NA as discussed in Chapter 4.

So, in reality, the 6%, 7.5% and 9% water absorption ratios of RCA, can be increased to

- 7.5%, 11.3% and 15% respectively, for the case of the Faculty of the Built Environment
- 6.7%, 9.3% and 12% respectively, for the case of the Block of apartments

The calculations for these values are below. Naturally these are only theoretical percentages derived from approximations carried out in the waste inventories in Chapter 4. However this proves that it is safe to say, that there is a <u>margin of safety with the limits being proposed when it comes to RA from demolished buildings with a mix of RCA and NA</u>, since there would exist an intrinsic aid in the RA from the NA mixed with it.

Mix ratio[1] for Faculty of Built environment: <50% RCA and ≥50% NA

(0.39*X%) + (0.61*5%) = 6.0% ⇒ X% = 2.56 (6.0% - 3.1%) = 7.5%

(0.39*X%) + (0.61*5%) = 7.5% ⇒ X% = 2.56(7.5% - 3.1%) = 11.3%

(0.39*X%) + (0.61*5%) = 9.0% ⇒ X% = 2.56 (9.0% - 3.1%) = 15%

Mix ratio for Block of apartments: ≥50% RCA and <50% NA

(0.57*X%) + (0.43*5%) = 6.0% ⇒ X% = 1.75 (6.0% - 2.2%) = 6.7%

(0.57*X%) + (0.43*5%) = 7.5% ⇒ X% = 1.75 (7.5% - 2.2%) = 9.3%

(0.57*X%) + (0.43*5%) = 9.0% ⇒ X% = 1.75 (9.0% - 2.2%) = 12%

On another note, the lowest replacement ratio in the literature reviewed is 10% in the US. This could be because having an even lower replacement ratio would not render the processing of the RA feasible. Replacement ratios in table 6.6 which result less than 10% are therefore not recommended.

[1] Definition in Appendix A.

6.3.1.4 Analysis of water absorption limits for local RCA from demolished case study with mix ratios of different types of concrete

The next step is to assess RCA from mixed concrete types as shown in table 6.7. The mix ratio resulting from the waste inventory carried out in section 4.3 for a block of apartment made fully out of concrete is being assessed.

Factory waste	Factory waste as representation of	Percentage of total building (from 96.6%)	Effective percentage of total RCA (100%)	Max WA_{24} from 10mm and 20mm of Source 2 only	
Test cubes	Cast-in situ	61	63.1	0.632*9.33	5.89
Block work	Block work	30.8	31.9	0.319*9.1	2.90
Planks	Precast	4.8	5.0	0.05*8.91	0.45
TOTAL		96.6%	100%	Total effective WA	9.24

Table 6.7: 9.5% limit for WA_{24} is enough if Source 5 only is considered

	Percentage of total building (from 96.6%)	Effective percentage of total RCA (100%)	Worst WA_{24} from 20mm of both Source 2 and 5	
Test cubes	61	63.1	0.632*14	8.85
Block work	30.8	31.9	0.319*9.1	2.90
Planks	4.8	5.0	0.05*8.6	0.43
TOTAL	96.6%	100%	Total effective WA	12.18

Table 6.8: 9.5% limit for WA_{24} is not enough if mixed concrete from mixed Sources are considered

Table 6.8 shows that there should be a third grade of even lower quality when concrete from different factory sources are mixed together, as would happen at a centralised recycling plant[1]. This grade should be used for very low grade applications. It is being taken as 14% to allow all RCA to be classified (including that of Mifsud (2003)). It should be noted however that for mixed waste from one factory (Source 2), the 9.5% limit is sufficient in this particular case.

[1] It is important to remember that all test results are based on RA which has not been processed at a centralised recycling plant which would otherwise possibly be of better quality, if aggregate is refined.

6.3.2 Particle density

In general, if the oven-dry particle density is set at a minimum of 2.0Mgm^{-3} as per EN 206-1, all coarse RCA would pass (figure 6.12). So no modification is necessary. It should be noted that the bridge material has the highest particle density. In the case of RCA having an oven-dry particle density less than 2.0Mgm^{-3}, they should be used for low-grade applications (less than C16/20) as stated in the Belgian standard in exposure condition X0 and XC1 only.

Whereas, density and Los Angeles are some times used for classifying RA (Dhir et al, 2007), on a compositional based approach, water absorption is used here. The reason is that not enough samples were tested for Los Angeles value to have sufficient amount to find a correlation. Since there is a high correlation between particle density and water absorption (-0.944) (figure 6.11) and since several limits for water absorption were found in international standards, water absorption was chosen to understand better the implication of these different limits.

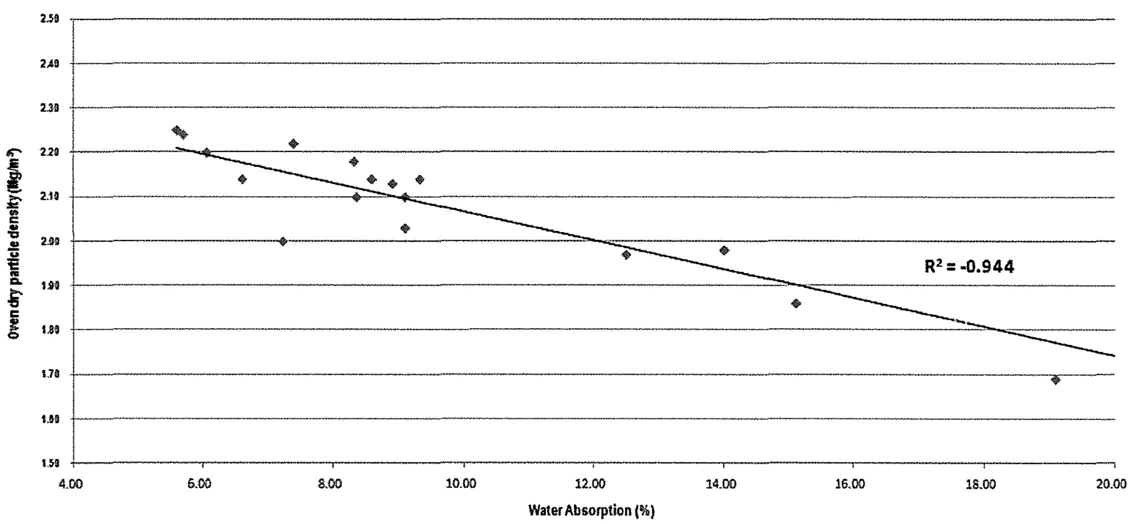


Figure 6.11: Correlation between oven dry particle density and water absorption

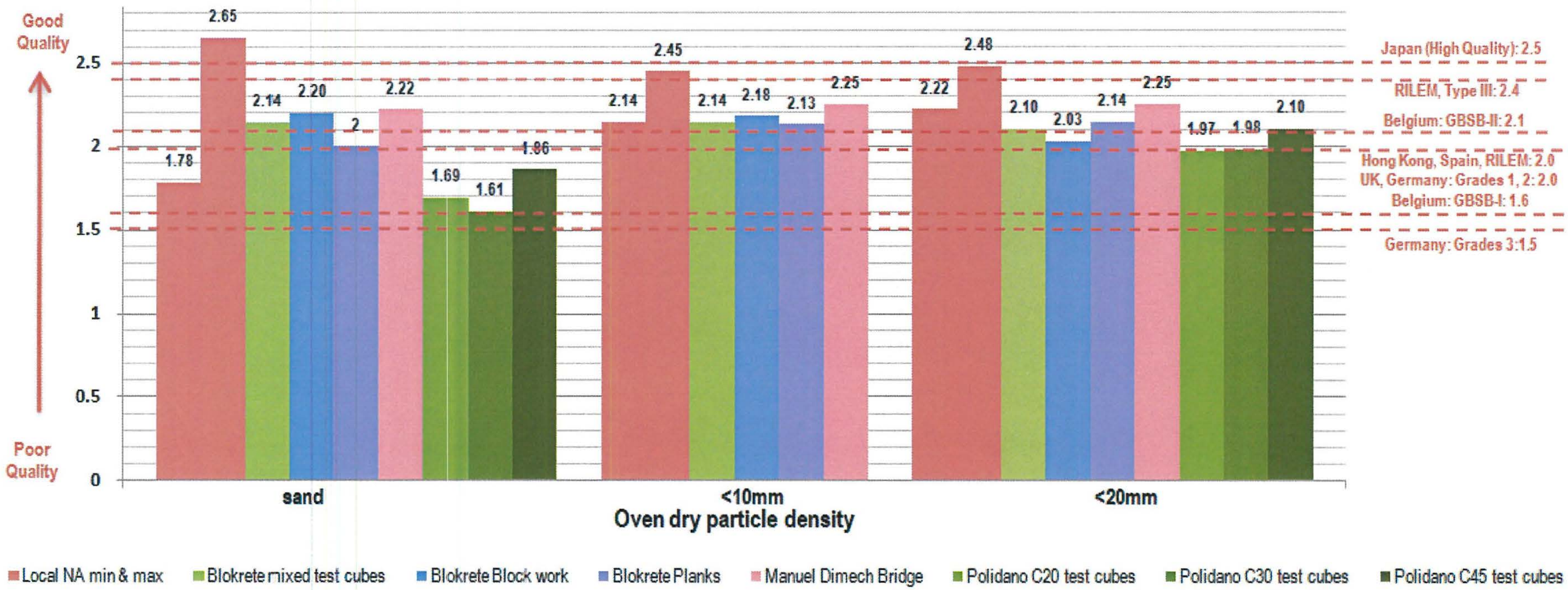


Figure 6.12: Results of oven-dry particle density on local RCA

6.3.3 Loose bulk density

EN 933-11 specifies that lightweight (below 1.0Mgm^{-3}) RCA be classified under concrete sub-class B_3. It is curious to note that light weight aggregate in EN 206-1 is classified so if below 1.2Mgm^{-3}. However this is written for aggregates in general. Since EN 933-11 is written specifically for RA, this limit shall be used and only 20mm RCA from block work is below this (figure 6.13). Block work in its nature is lighter since it is built with voids to be carried by builders. It should be noted however, that the result depends greatly on the diameter of the container being used. The measuring cylinder used for water absorption experiment was used here also.

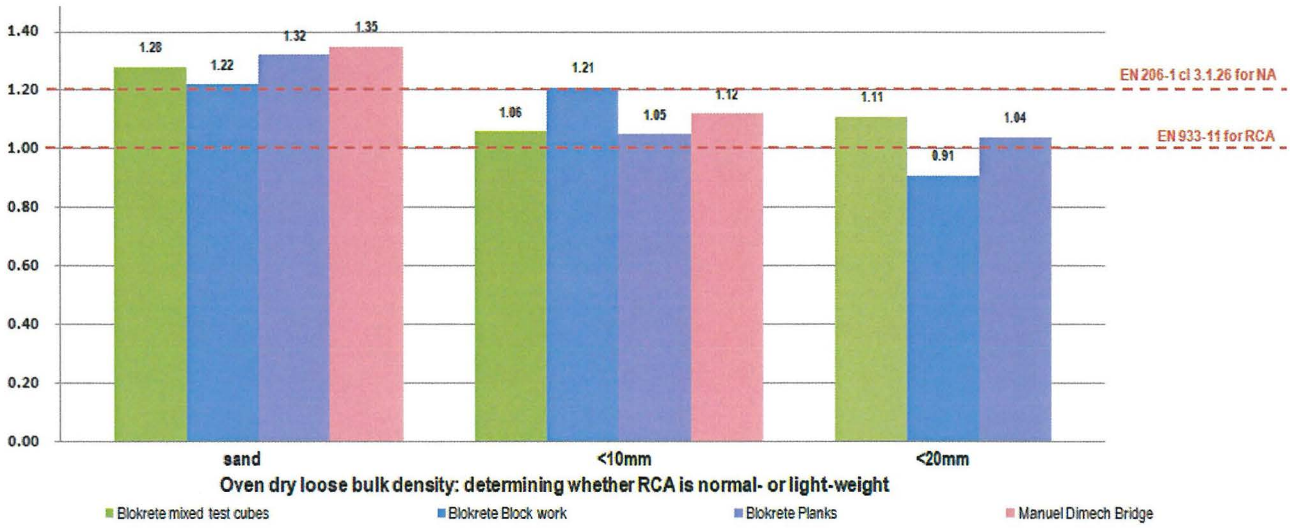


Figure 6.13: Results of oven-dry loose bulk density on local RCA

6.4 Chemical properties

6.4.1 Units of different limits provided in BS 882 and not EN 206-1

So that results from this dissertation comply with the most updated standards EN 1744-5 and EN 1744-1, it has been decided to check these results with the limits specified in BS 882 and not EN 206-1:2000, since the latter gives limits by mass of cement, and cement content of RCA is not known. This is explained in more detail in section 2.5.6.2.

It has been concluded that the limits in both standards are equivalent, only representing different fractions of concrete. No literature on the derivation of the limits in both standards could be found however the author has proven their equivalence. (Appendix D.1) The need of this exercise arose since not all limits for applications provided in EN 206-1 are in BS 882; hence use of the derived multiplication factor solved this problem.

6.4.2 Water-soluble chloride content

It is very visible that chloride content levels are high in general (figure 6.16).Limits are generally provided for acid-soluble content chloride since water-soluble chloride content is only a fraction of it and it is difficult to say when chlorides change from one to the other would hydraulically bound.

Although the water-soluble chloride content for all samples fall below the limits provided for reinforced concrete, none of the RCA may be used for prestressed concrete. As is discussed in section 2.5.6.2, Cutajar (2011) shows that chloride levels in water used as typical concrete factories are already high already since some exceed limits for reinforced concrete while all samples gathered exceed limits for prestressed concrete. The main reason is that distilled or deionised water is not used. Hence the results come as no surprise. It may be required to lower the limits provided even further if very the water to be used in the mix is found to already exceed the chloride limits.

NA also shows that it should not be used with prestressed concrete as it just exceeds the 0.01% limit[1]. A possible reason is that this particular aggregate might have been exposed to rain water and hence chloride contamination. It should be noted, that although the limits provided by other countries are higher than those provided in the EN and BS standards, the final applications cannot be used in severe exposure conditions or prestressed concrete, in general.

Figure 6.14 below shows the process involved in finding the water-soluble chloride content. Clear supernatant water is extracted from the sample soaked in water and a yellow indicator solution is used to witness a colour change. As soon as there is a first hint of colour change (figure 6.15), the result is recorded and used in the equation provided in EN 1744-1 to find the chloride content.

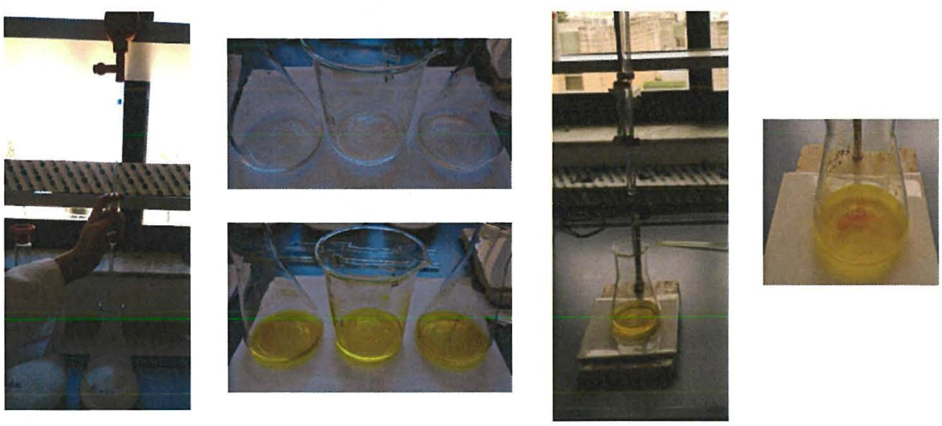


Figure 6.14 Process for carrying out water-soluble chloride test

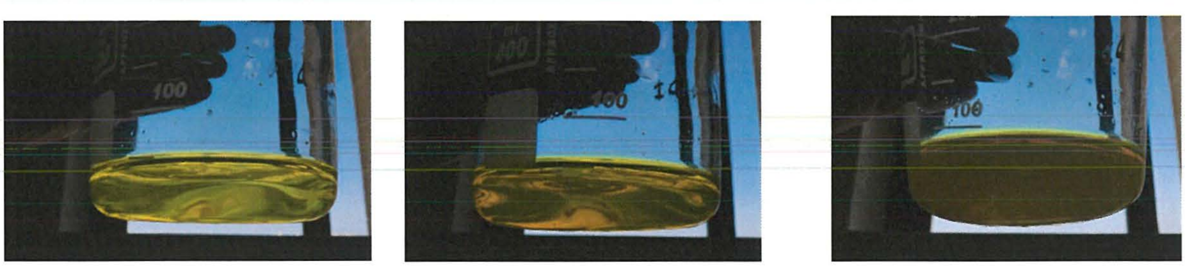


Figure 6.15 Colour change from yellow to first hint of colour change to overshot titration

[1] A limit of 0.03% (0.1% by mass of cement) is specified in EN 206-1 as an alternative limit to prestressed concrete. However, it is not certain under what conditions this is different from the other limit provided. Hence the worse case is being used. With 0.03% the NA does not exceed the limit for use in prestressed concrete.

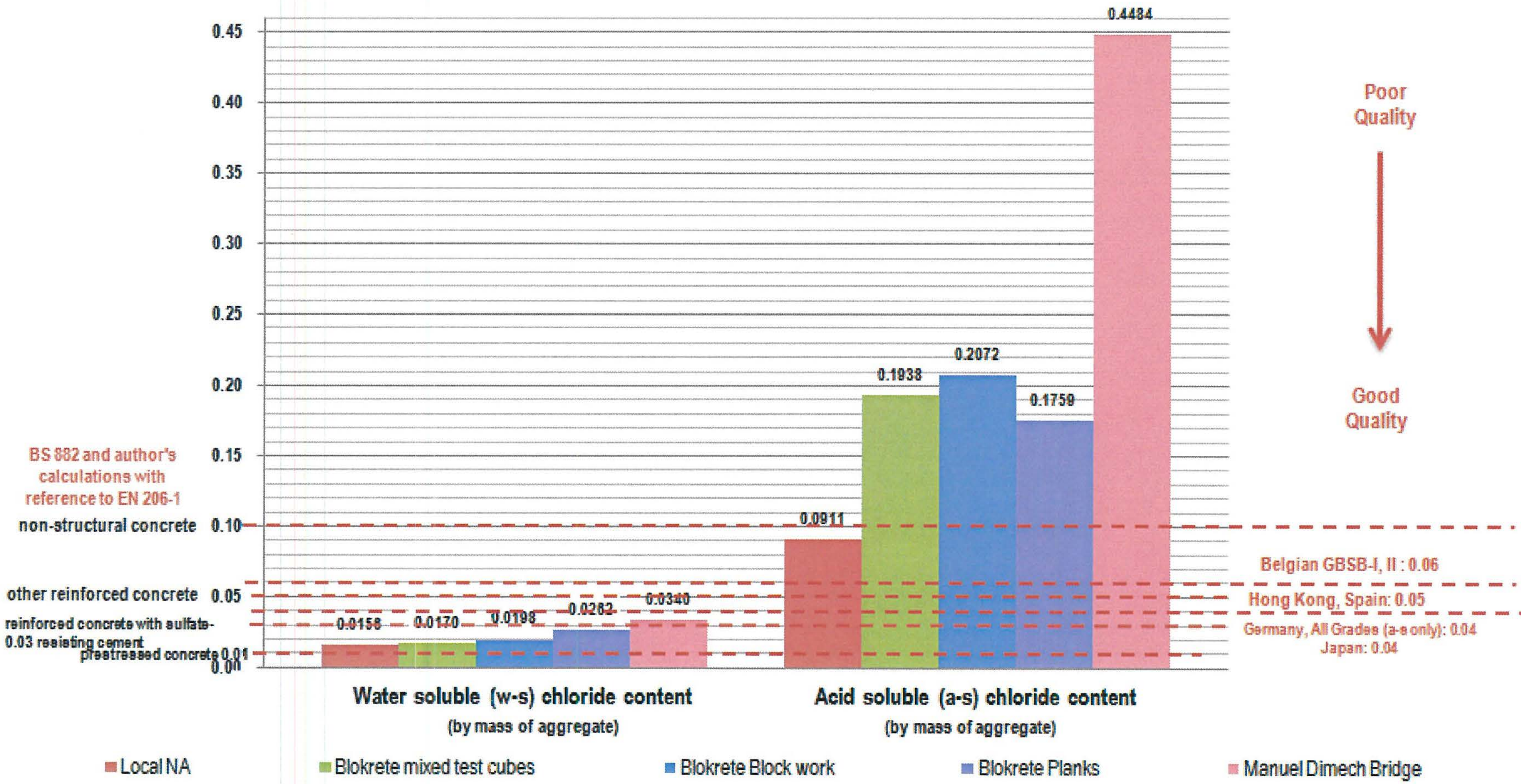


Figure 6.16: Results of water- and acid-soluble chloride content on local NA and RCA

6.4.3 Acid soluble chloride content

All samples exceed limits provided for acid-soluble chloride content (figure 6.16). Figure 6.17 shows the process involved in find the value. It should be noted that the higher value of chloride content of the bridge material could be detected instantly during the titration as the brown circle at the surface of the solution that results from the back-titration, disappeared at a much faster rate that with NA or the other RCA, on first addition of thiocyanate solution.

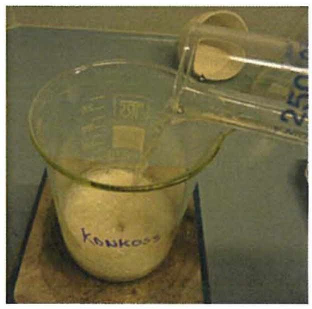


Figure 6.17a Stirring with dilute nitric acid (HNO3), Adding silver nitrate (AgNO3) and boiling, then filtering. Filtrate is then back-titrated with thiocyanate solution with the Volhard method.

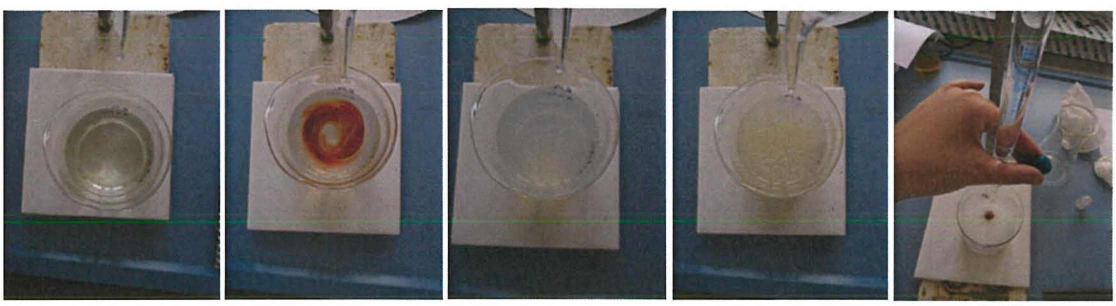


Figure 6.17b: Photos showing gradual change in colour from clear filtrate to opaqueness up to finally the overshoot of the limit with a permanent brown trace. The limit (recorded result) is easily detected since the brown trace on the white colour is very distinct (fourth to fifth photo below).

6.4.4 Difficulties encountered with sulfate tests as per EN1744-1

Appendices D.4 and D.6 explain the difficulties encountered and how they were solved.

6.4.5 Water soluble sulfate content

It can be observed that water-soluble sulfates are well below the limits specified (figure 6.20). [1]

Figure 6.18 shows some of the steps involved in the experiment.

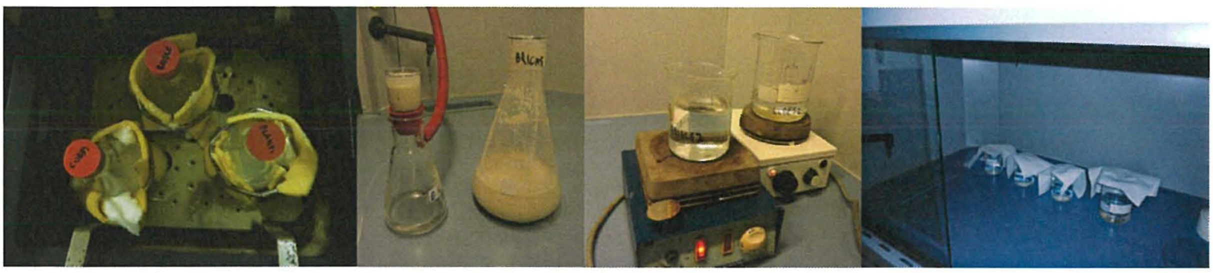


Figure 6.18: Process for carrying out water-soluble sulfate test (as per clause 10.1 in EN 1744-1)

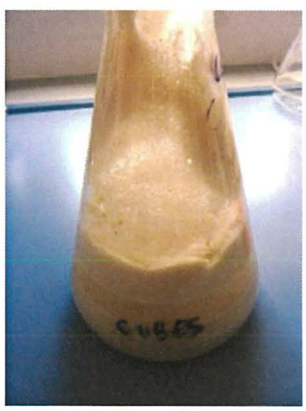
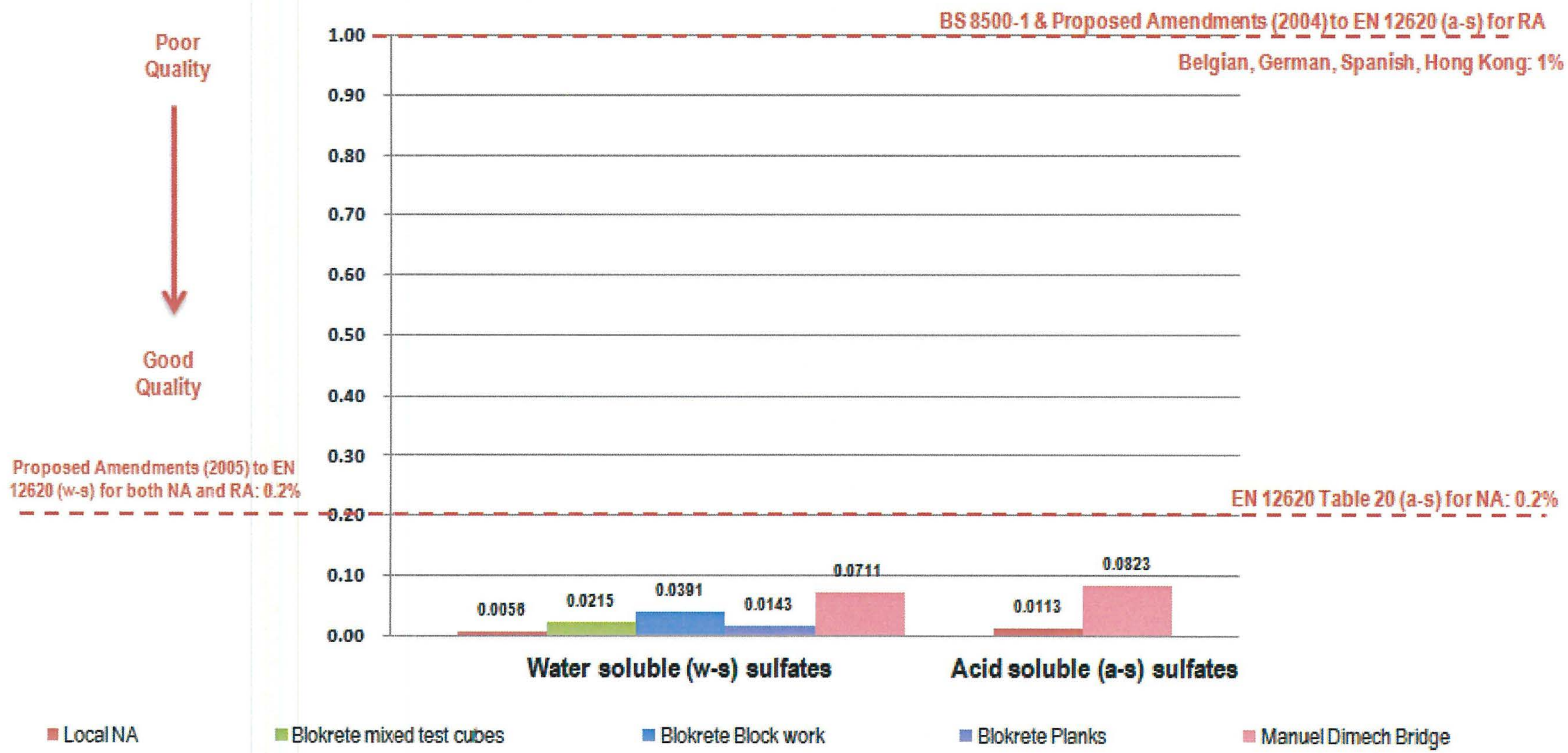


Figure 6.19: Froth produced by mixed test cubes after shaking for 24.5 hours in water

An observation that was made is the production of a massive amount of froth, believed to be carbon dioxide, after shaking the sample from test cubes for 24.5 hours. This was not observed with the other specimens. However, the froth did not interfere with the experiment in any way.

[1] Experiments for Blokrete waste is not carried out since acid-soluble sulfates for material obtained by crushing hardened concrete (of known composition) that has not been in use e.g. surplus precast units or returned fresh concrete, need not be checked according to BS 8500-2, Table 2.



Note: difference in value for acid-soluble sulfates for RA and NA in UK is due to possible sulfate content in brick and presence of sulfates combined as cement hydrates but which are unlikely to play any further part in the cement hydration reactions in new concrete.

Figure 6.20: Results of water- and acid-soluble sulfate content on local NA and RCA

6.4.6 Acid soluble sulfate content

It can be observed that acid-soluble sulfates are also well below the limits specified. Figure 6.21 shows some of the steps involved in the experiment.

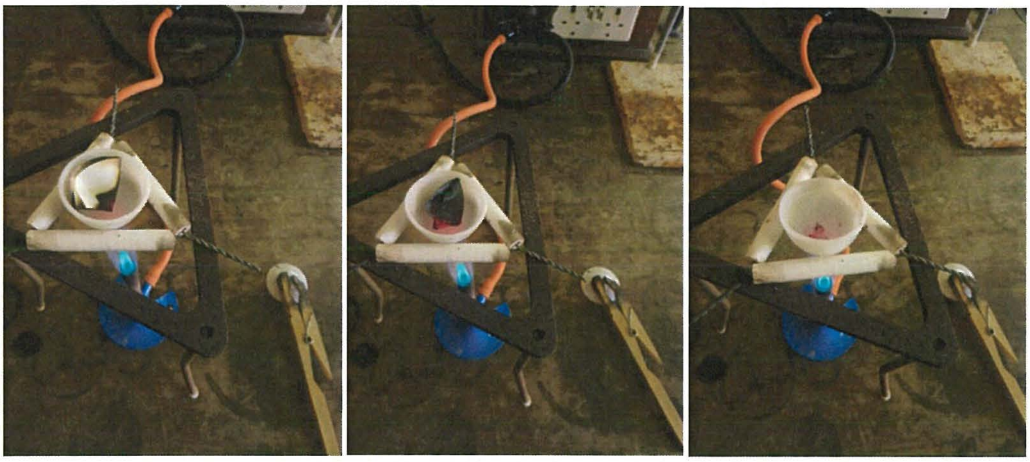


Figure 6.21: Burning of filter paper with precipitate in acid-soluble sulfate test

The result obtained with BS 1881-124 is intended to be per mass of cement, however this is not known, as explained with the chlorides experiments. For the same reason, the results using the BS experiment are can be converted to the equivalent EN results, this time by dividing by the conversion factor.

Sulfate content = $\frac{L}{M_d} * 34.30 * \frac{100}{C_1}$ using BS 1881-124...(1)

Sulfate content = $\frac{m_7}{m_6} * 34.30$ using EN 1744-1....(2)

For one to convert from (1) to (2), one needs to divide (1) by the conversion factor $\frac{100}{C_1}$. Hence, cement content need not be known and equation provided by EN 1744-1 used directly.

CHAPTER 7: PROPOSED LOCAL GUIDELINES FOR RA IN MALTA

This chapter discusses the structure and content of the guidelines proposed in Appendix G, as a result of the research carried out in this dissertation. The limitations of the guidelines being proposed and the use of the guideline to determine applications for the material tested and discussed in Chapter 6, follows.

7.1 Relevance of Austrian guidelines to Malta: Twinning project

As mentioned in Chapter 1, a recommendation suggested in 2008, as part of a Twinning Project (Car et al, 2008) between Malta and the Austrian Federal Environment Agency was of writing guidelines for recycled building materials. The project is currently on hold (personal communication with Perit R.P. Borg, involved in project). The research and testing carried out in this dissertation have allowed the author to make an attempt to produce such a guideline (Appendix G). The main recycling building material being tackled is recycled concrete aggregate.

Best practices from international literature have been included with any local requirements. Notes about the guidelines themselves and a comparison to the Der Österreichische Baustoff-Recycling Verband, Austrian guidelines are also included in the appendix. The Austrian guidelines are the only detailed texted document which the author has come across which gives a full account of the processing up to certification of RA as a product. The next section describes the structure of the proposed guidelines and how they are based on the Austrian guidelines, with any limitations of the guidelines per section.

7.2 Structure and limitations of proposed local Guidelines in Appendix G

Following the instructions of how to read the guidelines is a short description of the field of application. As this dissertation focuses mainly on RCA, due to the limited time to complete the research, all limits are based on the interpretation of results from concrete testing.

The main division of sections in the proposed guidelines and also in the Austrian guidelines is suggested in the F.I.R. (2004) document 'Recommendation Guidelines for Quality Assessment of Recycled Building Materials'. The main sections are described in table 7.1 below.

Section in guidelines	**Description with limitations**
Recovery	Recovery of typical RA is discussed together with control over contaminations and over the RA itself with legal responsibility towards the environment with reference to local directives and British practices.
	Limitations - Guidelines of how to handle the pure selection of materials does not exist locally like in Austria.
Storage	Delivery procedures with reference to the compilation of waste inventories as discussed in Chapter 4 for aiding in pre-sorting and storage of material with instructions for correct labeling as per EN933-11 and protection of material are highlighted.

Processing	Processing of material, whether on-site or off-site, is to be decided according to the project specifications and restrictions (Appendix I). The decisions made to achieve the level of quality required from the RA and for example, the types and amounts of crushers used, are dependent also on the final end applications. The applications and uses of local RCA are presented in Table G.1. Tables G.2 and G.3 are those used in the Austrian guidelines. It is important to note that the three-column layout used in the appendix as described in the instructions, cannot be used for tables and graphs due to lack of space in the columns, and hence a separate page is dedicated to each one. Limitations - No recycling plant for proper processing of material exists locally. - Table G.1 is to be expanded further when more research on mixing ratios of RCA with NA, asphalt and possibly tiles (or other RA) is carried out.
Quality category	Quality category: The designations being proposed for particular grading of aggregate depending on its quality are the following: - For general concrete applications, G-A, G-B, G-C - For road applications, R-A, R-B, R-C - For low grade applications (bulk filling, embankment): F Grading of materials can be carried out once preliminary testing of representative samples is done and comparison to different limits particular to each application is carried out. G-A is of better quality than G-B, G-C and F in that order, with G-B better than G-C and so on. This applies also grade R-A compared with R-B, R-C and F.
Constructional engineering assays	Table G.4a is what the guidelines are focused on, since the limits being proposed are the results of research carried out in this dissertation. This table is reproduced in table 7.2 of this chapter. The tests to be carried out on the representative samples are specified in this table with limits being provided. Table G.7 shows the grading envelopes to be used for the applications. Limitations - Limits are based on experiments carried out on concrete factory waste material and material from Manuel Dimech Bridge only.

Composition of the material	The examples of mix ratios of materials of local case studies calculated in Chapter 4 are provided with the designations being proposed. These are mainly based on nomenclatures proposed in Published documents of EN 12620 and also, partly on the Austrian nomenclature.
	Limitations - No data available from tests performed on ▪ RA from demolished buildings ▪ other types of aggregates from buildings or civil engineering projects
Environment compatibility	Limitations - No data on hydro-ecologically delicate areas exist locally and so this section which is part of the classification scheme in the Austrian guidelines could not be completed.
Inspection (Internal and external)	As noted on page 31 of the guidelines, the reminder of the guidelines from this section onwards are only extracts from the Austrian guidelines. All the three columns are now used to list the text for this section, as a continuation of the Proposed Maltese guidelines, with terms such as 'Austrian' changed to 'Maltese'. The same logistics behind the inspections and legalities for certification of RA as a product can be adapted to the Maltese scenario once an official local organization is set up. Until then, the same procedures used in the Austrian guidelines are replicated in the Proposed local Guidelines.
	Limitations - An official Maltese agency dedicated for recycling of building materials which can be responsible for organizing these inspections does not exist.

Table 7.1 Structure description and limitations of proposed local guidelines

It should be noted that once the aggregate is graded, applications are illustrated in Appendix K, as extracted from the AggRegain website mentioned in section 3.1.9. The text at the beginning of the appendix elaborates more on this.

It has been concluded that in the proposed Local guidelines, limits of

- Geometrical properties are standard since they are dependant solely on the application being used and hence existing local limits need not be altered
- Physical properties, specifically water absorption need to be adapted to local aggregate
- Mixing ratios and replacement ratios need to be adapted to local aggregate
- Chemical properties are still being amended by BSI for use of RA. Existing limits in EN standards can be used however further research is required specifically on utilization of water-soluble versus acid-soluble limits. The latest amendments found are used and where there are missing limits in the EN 206, limits in BS 882 have been proved to be of equivalence, as discussed in Appendix E.1.
- Weathering properties are not important for the local scenario since according to literature discussed in Chapter 2, the main test being for frost resistance
- Fines content are usually provided in project specifications

Table 7.1 summarizes the limits discussed in Chapter 6 and their adaptation for local aggregate. This is reproduced in the proposed guidelines found in Appendix G with additional notes.

Table 7.2 Proposed grades with limits, according to application for local RCA

Use of RCA				In concrete elements (hydraulically bound)					In road construction/renovation (hydraulically/bituminously bound/unbound)					For other (unbound)
Application description				Prestressed or water-retaining (highest quality)	Structural (>C20/25) and minor-structural (C20/25) Containing reinforcement or embedded metal			Non-structural (lean concrete) Not containing reinforcement or embedded metal	Wearing course (40mm road surfacing) MSA is 12.5mm		Intermediate binding course and Base course MSA is 20mm		Sub-base (foundation) course (usually unbound) MSA is 31.5mm	Fill and embankment (unbound) (lowest quality)
Grade				G-A	G-B1	G-B2	G-B3	G-C	R-A1	R-A2	R-B1	R-B2	R-C	F
Exposure class				X0, XC1-4, XD1-2, XS1	X0, XC1, XC2			X0	X0, XC1, XC2					n/a
Strength classes				≤ C30/37, C32/40, C35/45, C40/50	≤ C20/25, C25/30, C28/35 [C20/25 not to be used in XC2]			C12/15, C16/20	C16/20 to C25/30					n/a
Replacement ratio (RCA instead of NA)				≤ 15% ± 2%	≤ 35%	≤ 15% ± 2%	≤ 10% ± 2%	≤ 100%	≤35%	≤15% ± 1%	≤35%	≤15% ± 1%	≤ 100%	≤ 100%
Final blend ratio due to different water absorptions of NA and RA according to replacement ratio				3% with NA of WA_{24}2.5	5% with NA of WA_{24}4.5			NR	4% with NA of WA_{24}3				NR	n/a
Test		Property	units											
MSA EN 933-1	Geometrical	Particle-size Distribution	Not applicable	EN 12620	EN 12620			EN 12620	Series 800, EN 13242		Series 800, EN 13242		Series 800, EN 13242	NR
MSA EN 933-3	Geometrical	Maximum flakiness index	%	FI_{35}	FI_{35}			FI_{35}	FI_{25}		FI_{25}		NR	NR
MSA EN 197-6	Physical	Minimum oven dry particle density, ρ_{rd}	Mgm^{-3}	2.0	2.0			NR	2.0		2.0		NR	NR
MSA EN 1097-3	Physical	Minimum loose bulk density	Mgm^{-3}	1.0	1.0			<1% = 1.0	1.0		1.0		NR	NR
Tam et al (2008)	Physical	Maximum water absorption	% by mass of dry aggregate	WA_{24} 5.5	WA_{24} 6	WA_{24} 7.5	WA_{24} 9	WA_{24} 14	WA_{24} 6	WA_{24} 9.5	WA_{24} 6	WA_{24} 9.5	NR	NR
MSA EN 1097-2	Mechanical	Maximum Los Angeles value	%	LA_{40}	LA_{40}			LA_{40}	LA_{20}		LA_{35}		LA_{35}	NR
MSA EN 1744-5	Chemical	Maximum water-soluble chloride content	% by mass of aggregate	$Cl_{0.01}$	$Cl_{0.03}$ (sulfate resisting cement) $Cl_{0.05}$ (all other)			$Cl_{0.1}$	$Cl_{0.1}$		$Cl_{0.1}$		$Cl_{0.1}$	NR
MSA EN 1744-1	Chemical	Maximum acid-soluble chloride content	% by mass of aggregate	$Cl_{0.01}$	$Cl_{0.03}$ (sulfate resisting cement) $Cl_{0.05}$ (all other)			$Cl_{0.1}$	$Cl_{0.1}$		$Cl_{0.1}$		$Cl_{0.1}$	NR
MSA EN 1744-1	Chemical	Max water-soluble sulfate content	% by mass of aggregate	$WS_{0.2}$										WS_1
MSA EN 1744-1	Chemical	Max acid-soluble sulfate content	% by mass of aggregate	AS_1										AS_1
Visual Test/EN 1744-1	Content	Max foreign materials content	%	1 or 0.5 for organic										
MSA EN 933-9	Content	Fines content	%	$f_{Declared}$										NR

7.3 Analysis of critical properties to be tested in RCA in general

A study of the properties which are likely to limit use to a higher grade is made in Appendix J. Relative values of all properties in the classification scheme are plotted on a single graph, for each application. This way the most critical parameter is easily spotted graphically. Values above the limit boundary line set at zero, are how the good qualities vary and those below are which make the RCA of poor quality. A summary of conclusions from this study is in table 7.3. Flakiness index never causes problems and it is not expected to ever do unless RCA contains foreign aggregate. Also, if there is clear evidence that no gypsum board or any building material which might contribute to increase in sulfate content is present, it too may not be tested.

Grade	Most critical →					Least critical
G-A	Acid-soluble chloride	water-soluble chloride	Water absorption	Los Angeles	Loose-bulk density	Oven-dry particle density
G-B1 to G-B3	Acid-soluble chloride	Water absorption	Los Angeles	Loose-bulk density	Oven-dry particle density	
G-C	Acid-soluble chloride	Water absorption	Los Angeles			
R-A1, R-A2	Acid-soluble chloride	Los Angeles	Water absorption	Loose-bulk density	Oven-dry particle density	
R-B1, R-B2	Acid-soluble chloride	Water absorption	Los Angeles	Loose-bulk density	Oven-dry particle density	
R-C	Acid-soluble chloride	Los Angeles	Loose-bulk density			
F	Acid-soluble chloride					

Table 7.3: Summary of study of critical RCA properties in Appendix J

7.4 Use of Proposed local guidelines to grade RCA tested

Table 7.4 is completed when a comparison of test results and limits in the proposed guidelines is made. The criteria which limit the material from being classified under a higher grade are indicated adjacent to the ticks. Conclusions are made in the next page, Chapter 8.

		In concrete elements					In road construction/renovation					Bulk	Critical parameter
type	size	G-A	G-B1	G-B2	G-B3	G-C	R-A1	R-A2	R-B1	R-B2	R-C	F	
Test cubes	9/18	×	×	×	✓	✓	×	×	× WA	✓	✓	✓	WA
	6/9												
	0/6	×	×	✓	✓	✓	×	×	× WA	✓	✓	✓	WA
Block work	9/18	×	×	×	×	× LA	×	×	×	×	× LA	✓	Loose bulk density & LA
	6/9	×	×	×	×	× LA	×	×	×	×	× LA	✓	LA
	0/6	×	×	×	×	×	×	×	×	×	×	✓	PSD
Planks	9/18	×	×	×	✓	✓	×	×	× WA	✓	✓	✓	WA
	6/9												
	0/6	×	×	✓	✓	✓	×	×	× WA	✓	✓	✓	WA
Bridge	20mm	×	×	×	×	× PSD	×	× LA	✓	✓	✓	✓	PSD conc
	10mm	× WA, Cl	✓	✓	✓	✓	×	× LA	✓	✓	✓	✓	WA, Cl
	sand	×	× WA	✓	✓	✓	×	×	× WA	✓	✓	✓	WA

Table 7.4: Quality grading of RCA tested on for this dissertation

CHAPTER 8: CONCLUSIONS and FUTURE RESEARCH

The applications for RCA tested in this dissertation are derived using the Proposed Local Guidelines, with additional reference to more specific applications in Appendix K. Conclusions from desk-work exercises are also discussed followed by proposals for future research for completion of any sections missing in the proposed guidelines due to lack of information.

8.1 Applications for RCA tested on, using limits in Proposed local Guidelines

The following table shows all the information which can be concluded from the classification scheme being proposed and applied to the material tested from Blokrete and the Manuel Dimech Bridge.

	RCA from crushed waste of:							
	Mixed test cubes and Planks			**Block work**	**Manuel Dimech Bridge**			
of grading...	6/9 , 9/18, 0,6	6/9 , 9/18	0/6	0/6 , 6/9 , 9/18	20mm, 10mm	10mm	sand	
can be used with a replacement ratio of...	≤15% ±1%	≤10% ±2%	≤15% ±1%	100%	≤35%	≤35%	≤15% ±1%	
For...	Intermediate binding course and base course	Structural Minor-structural or unreinforced concrete		Bulk filling	Intermediate binding course and base course	Structural Minor-structural or unreinforced concrete	Structural Minor-structural or unreinforced concrete	Intermediate binding course and base course
With max RAC strength of...	C25/30	C28/35		NR	C25/30	C28/35	C28/35	C25/30
In exposure classes...	X0, XC1, XC2	X0, XC1, XC2		NR	X0, XC1, XC2	X0, XC1, XC2	X0, XC1, XC2	X0, XC1, XC2
With NA of WA_{24} of	≯ 3.0%	≯ 4.5%		NR	≯ 3.0%	≯ 4.5%	≯ 4.5%	≯ 3.0%
For final blend ratio of WA_{24} for NA + RCA of...	4.0%	5.0%		NR	4.0%	5.0%	5.0%	4.0%
MAX GRADE	R-B2	G-B3	G-B2	F	R-B1	G-B1	G-B2	R-B2
Critical parameters hindering achievement of a higher grade	Water absorption	Water absorption		Loose bulk density Los Angeles and Particle size distribution	Los Angeles	Water absorption and Chloride content	Water absorption	Water absorption

Note that all samples may be used for bulk filling and embankment as unbound granular material.

In general, fine aggregate is not recommended to be used in any applications according to foreign standards. However, this should be tried out locally with RCA sand which is graded as high quality sand according to the proposal being made.

Table 8.1 Summary of applications for RCA tested in this dissertation

It can be concluded that the best quality aggregate from those tested is the 10mm bridge material which can be used with a replacement ratio of up to 35% for structural, minor-structural or unreinforced concrete. Had it not been for particle size distribution not fitting the grading envelope, the 20mm aggregate could be used in a similar manner. It is possible that the crushing technique used was not adequate. Further processing might solve this. If we take as the 10mm RCA an example, the applications being proposed can be defined as the following:

Recycled concrete aggregate (RCA) from crushed waste of **Manuel Dimech Bridge** of grading **≤10mm** can be used

- with a replacement ratio of **≤35%** for **structural, minor-structural or unreinforced concrete** with maximum recycled aggregate concrete (RAC) strength of **C28/35** in exposure classes **X0, XC1 and XC2** with conventional aggregate (NA) of 24-hour water absorption (WA_{24}) of not more that **4.5%** for a final blend ratio of water absorption for NA and RCA of **5.0%**. Quality of this material is set at a grade not more than **G-B1**. The critical parameters hindering achievement of a higher grade are **water absorption and chloride content**.

and also

- with a replacement ratio of **≤35%** for **intermediate binding course and base course** with maximum recycled aggregate concrete (RAC) strength of **C25/30** in exposure classes **X0, XC1 and XC2** with conventional aggregate (NA) of 24-hour water absorption (WA_{24}) of not more that **3.0%** for a final blend ratio of water absorption for NA and RCA of **4.0%**. Quality of this material is set at a grade not more than **R-B1**. The critical parameter hindering achievement of a higher grade is **Los Angeles value**.

Appendix K can then be used for more specific applications according to the Grades indicated. Since grades G-B1 and R-B1 are specified for the 10mm bridge material the applications listed under GB, GC, RB, RC and F in Appendix K are all possible options. It is important to note that applications with grades of lower quality can automatically be used for material being graded as explained in the text at the beginning of the Appendix.

It is also important to note that the results from acid-soluble chlorides are not being considered here, since otherwise only low-grade applications would result for all the samples. Further investigation with this property is definitely required and techniques to possibly reduce the chloride content researched. It should be noted that the water-soluble chloride content is the actual fraction which affects the concrete durability, and this has been assessed in the grading procedure and results in table 8.1. It is difficult to predict how much of the chloride in fresh concrete will remain free and how much will be bound once the concrete hardens, according to literature reviewed in Chapter 2 (NZRMCA, 2005), hence the current discussions for amendments carried out by BSI standards authorities.

Also, the material tested on by Mifsud could not be fully graded due to missing test results; however, with those available, the maximum grade given to the aggregate is F (the lowest grade) mainly due to high water absorption values.

8.2 Other conclusions

1. Concrete forms a significant percentage (86%) of total C&DW in local construction and recycling it solves environmental, social and possible economical problems. Marketing, legislation and refinement of the material for better quality play a major role to make recycling a sustainable option.

2. A preliminary classification scheme can be drafted using only properties of the RCA. A further improvement and essential requirement, would be designing concrete mixes to justify and possible deem necessary certain modifications in replacement ratios being proposed in the Guidelines of this dissertation.

3. In order to classify RCA for water absorption, a maximum limit of 5% for the 100% replacement of NA with RCA is being suggested (as per international standards) to be comparable to NA for concrete production. However, from results gathered, all RCA exceed this limit and hence a mix of NA and RCA will be required for high-grade applications. Locally the main mixing ratios one deals with are with concrete and stone. Different mixing ratios of RA and NA would result in crushed RA from different demolished buildings or structures. Results from waste inventories of some local case studies show typical mixing ratios to be (1) 39% concrete with 60% stone; (2) 57% concrete with 42% stone and (3) 96% concrete alone, as percentages by mass of the total waste from demolition. These ratios are used in calculations to find an optimal balance between the proposed replacement ratios and water absorption limits of RCA mixed with NA (section 6.3.1).

4. Selective demolition of different types of waste material and also, if possible, of different types of concrete is preferred for better assessment of RA quality, when it is feasible to do so. The 96% amount of concrete waste mentioned in point 8.2 (2) can be broken down further to roughly 61% insitu concrete, 30% block work and 5% precast slabs for the case study. From tests carried out on samples representing these types of concrete, it is very evident that the 30% amount of block work would lower the overall quality of the RA drastically (specifically mechanical properties), if these different concrete types were mixed together. Further reduction in quality has been observed if RCA of different factories are mixed, representing the scenario resulting from a centralised recycling plant (section 6.3.1).

5. Visual inspection as per EN933-11 helps in identifying block work from different types of concrete as its nature is quite distinct. Higher grade concrete types do show more particular characteristics however a distinction between them is fairly difficult. Separation of different types of concrete, especially where block work is present, should ideally be done on site, when feasible to do so.

6. When specifying limits for different aggregate properties, some limits depend on the application (such as geometrical properties) and need not be modified while others (such as water absorption) depend on the intrinsic properties of NA and RCA and need modifications to suit local aggregate (section 7.2).

7. It is very evident that the quality of RCA depends almost entirely on the original quality of NA used, its exposure conditions and the amount of cement mortar attached to it after processing. Very significant comparisons made to NA from Hong Kong and UK show that even the overall quality of local aggregate is relatively poor, even with processed RCA in Hong Kong. 100% use of mixed RCA for good quality, high-grade applications is not envisaged to be possible at this stage, with use of local aggregate alone. Replacement of NA with only a certain percentage of RCA is possible for optimum quality of product from research carried out in this dissertation (as mentioned in point 8.2 (4)), the main issue being water absorption and some times chloride content. This is why the classification scheme proposed in the guidelines is present with the choice of different replacement ratios. Pre-soaking the material in water before mixing might help solve this problem. However the water must be distilled or deionised as chloride limits are a major problem with water already used in factories. This unfortunately, increases costs for processing significantly. Further research on cost analysis and environmental impact is deemed essential.

8.3 Future research possibilities

1. It should be understood that it is only a theoretical grading classification which is being proposed. The aggregate quality of RCA of the different samples have been assessed however, the actual testing and monitoring of RCA in concrete mixes with the proposed replacement ratios allowed are next to follow this research to understand the affect of local RCA on the durability of concrete for in both general concrete structural applications and roads. Once enough concrete mixes have been tested on, the classification scheme with adjustments due to results derived from concrete mixes, would be enough to grade the quality of any RA. The guidelines provided in Appendix G together with different sections of this dissertation describe several best practices for achieving good quality aggregate before mix design. The innovative techniques mentioned in Chapter 2, for removing the mortar from the RCA should be attempted and implications discussed.

2. Investigations on concrete mixes where the properties of recycled concrete aggregates, are beneficial should be investigated locally. These properties include production of very fine particles useful in self-compacting concretes (Coppola, 2004).

3. Although leaching of RA is not considered to be that critical according to literature reviewed, unless originating from an industrial area, the Austrian guidelines still give great importance to it. Further research on this and evaluation of leaching limits for local use would complete a missing section in the proposed guidelines.

4. Since no recycling plant exists locally, existing machinery for NA was used, hence the question arises how much processing is actually needed if applications can already be theoretically deciphered. Product analysis of the costs involved for recycling the aggregates and any possible profit margins that may arise (as discussed in section 1.7) could be researched.

It could be assumed that a concrete factory is converted to a dedicated aggregate recycling plant (since most of the equipment required is similar to that needed for processing of NA). It could also be assumed that both natural aggregates and dumping sites are scarce, with high tipping fees for landfill use, hence creating a high demand future scenario for RCA, and also include projected inflation rates when projecting graphs.

5. It would also be interesting if more types of RCA are tested, especially from demolished buildings and also using crushers from different factories, since it has been reviewed that crusher types and settings affect certain geometrical properties.

6. Also, when many more tests on RCA are carried out, correlations between different properties should be attempted. When strong correlations are found (such as that between water absorption and particle density as derived in this dissertation), they can justify a reduction in the number of experiments required for high quality grading of RA. This would save both time and money and serve as a motivation for stake holders to use RCA.

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Appendix A

Definitions

Appendix A Definitions

Note that there exists a definition in this appendix (A.1 or A.2) for any dotted underlined words used in the definitions themselves.

A.1 Definitions as encountered in literature reviewed

'Demolish, clear and build' sites: These are sites where the structures or infrastructures are demolished prior to the erection of new ones. (Symonds et al, 1999, p10)

Foreign materials according to different guidelines (sections 2.5.1 and 3.2):

BS 8500-2, table 2	glass, plastics, metal
Belgium	metals, glass, bitumen, soft material
Germany	glass, non-ferrous metal slag, lump gypsum, plastic, metal, wood, plant residue, paper, others Other mineral materials include porous brick, lightweight concrete, no-fines concrete, plaster, mortar, porous slag, pumice stone
RILEM	metals, glass, soft materials, bitumen
Hong Kong	metals, plastics, clay lumps, asphalt and tar, glass etc
Japan	Termed as deleterious substances which include (A) tile, brick, ceramics, asphalt concrete, (B) glass, (C) inorganic substances other than plaster, (D) plastics and (E) wood, paper, asphalt
Tam et al.	asphalt, plaster, metal, glass, bitumen, clay lumps, tar, stony material, soft material, degradable organic materials
Austria	Bitumen and any constituents of mineral origin which are not included in the definition of the recycled building material in question. Asbestos cement is not permitted in principle. With regards to RA - any constituents that cannot be regarded as bituminously bound materials and additives thereto (e.g. tiles, unbound material) RB - constituents that cannot be regarded as concrete and additives thereto RAB - constituents that cannot be regarded as bituminously bound material and concrete or additives thereto RM - all other constituents of mineral building demolition waste, such as tiles, building ceramic RG – all other constituents of mineral building demolition waste, such as tiles, building ceramic RMH, RS, RZ, RHZ, RH – all other constituents of mineral building demolition waste not as per definition and also asphalt and gaseous concrete Impurities may include dirt, humus (ground surface), gypsum, wood, plastics, paper, metals

EN 13242	Impurities are foreign matters such as wood, glass and plastic that will cause damage to end use product.

Natural aggregate: Aggregate from mineral sources which has been subjected to nothing more than mechanical processing (BSI, 2002a)

Original / conventional / old / demolished concrete: Concrete from reinforced structures, plain concrete structures or precast concrete units which can be used as raw material for production of recycled aggregates (or for other useful purposes). Original concrete is occasionally referred to as old concrete, demolished concrete or conventional concrete (Hansen, 1992, p7).

Original Aggregates: These are conventional aggregates from which original concrete is produced. Original aggregates are natural or manufactured, coarse or fine aggregates commonly used for production of conventional concrete. When no misunderstanding is possible, original aggregates may also be referred to as virgin or conventional aggregates (Hansen, 1992, p7).

Recycled aggregate (RA): BS 8500-1 refers to these as aggregates resulting from the reprocessing of inorganic material previously used in construction (BSI, 2006a).

It is very important to realize differences used for abbreviations in different countries and understand what type of aggregate is being referred to. For example:

In Austria, recycled concrete aggregate is RB (B is an abbreviation for the translated word 'concrete' which is 'beton'), RA is recycled asphalt aggregate and RZ is recycled brick aggregate.

In UK, R_C is recycled concrete aggregate, R_A is recycled asphalt aggregate and R_B is recycled brick aggregate. RA (without subscript) is recycled aggregate which includes all: R_A, R_B, R_C.

Recycled aggregate concrete (RAC): Concrete produced using recycled aggregates or combinations of recycled aggregates and other aggregates. It is sometimes referred to as new concrete (Hansen, 1992, p7).

Recycled concrete Aggregate (RCA):

- Aggregate produced by crushing of original concrete; such aggregates can be fine or coarse recycled aggregate (Hansen, 1992, p7).
- Unless otherwise specified, means aggregate made from construction and demolition waste concrete or waste concrete (and includes coarse and fine aggregate unless specified) (CSI, 2009, p38).

Recycled coarse aggregate for concrete (RCAC): Term used in RILEM (1994). Refers to recycled aggregate concrete using only coarse recycled aggregate.

A.2 Definitions as used in this dissertation (not necessarily quoted from literature reviewed) (in alphabetical order)

Blend ratio for water absorption The final effective percentage of water absorption of a sample of RA consisting of two or more materials with a particular mix ratio or replacement ratio of conventional aggregate. The final blend ratio for water absorption should be equal to the maximum limit of water absorption for NA specified in local standards (if they exist).

Fine aggregate: designation given to the smaller aggregate sizes with D ≤4 mm (BSI, 2002a)

Coarse aggregate: designation given to the larger aggregate sizes with D greater than or equal to 4 mm and d greater than or equal to 2 mm (BSI, 2002a)

Construction and Demolition waste (C&DW) Hazardous or non-hazardous mineral waste (as per EWC) and other materials such as glass, wood, metals, plastics and so on which may be reused raw or processed. In foreign countries, bricks fall also under this category.

Contaminations / Impurities may include dirt, clay lumps, gypsum (plaster), plastics, glass, non-ferrous metal slag, metals and organic materials which can reduce quality or cause damage to end use (application) of product (RA)

Conventional aggregate (NA): Locally this refers to natural, virgin aggregate quarried from upper or lower coralline, sedimentary limestone, for production of normal concrete (for different applications, structural or not) in the building construction industry or for use in road construction or renovation. It may be found as coarse or fine aggregate. Natural aggregate is not to be understood as aggregate which can be physically picked from rivers or lakes, as referred to abroad, since such aggregates do not exist in Malta.

Filler aggregate: aggregate, most of which passes a 0.063mm sieve, which can be added to construction materials to provide certain properties (BSI, 2002a)

Fine aggregate: designation given to the smaller aggregate sizes with D ≤4 mm (BSI, 2002a)

Fines. particle size fraction of an aggregate which passes the 0.063mm sieve (BSI, 2002a)

Foreign materials: building material waste which have potential to be recycled aggregate but are collected in the wrong stockpile that is recycled aggregate of another material, intended possibly for a different application. For example, asphalt in a batch dedicated to storage of concrete only.

Impurities See definition for contaminations.

Mix ratio The maximum permissible percentage of recycled aggregate of a particular material to be used together with that of another material, to form a single recycled aggregate product of mixed materials.

Non-hazardous mineral waste Locally this is referred to a composition of rocks, stone aggregates, sand, concrete, ceramics and tiles, gypsum among other materials, generated by construction, demolition and excavation works (NSO, 2009) which are not hazardous as per European Waste Catalogue (EWC). Concrete waste may also originate from concrete factory waste or returned fresh concrete.

Organic materials: matter that has come from a once-living organism; is capable of decay, or the product of decay such as plant residue, wood, paper, humus (ground surface), textile fabrics.

Recycled aggregate (RA): Aggregate resulting from the reprocessing of inert material to be as a replacement of conventional aggregate in concrete or road applications. It may be found as coarse or fine aggregate and is usually specified for use in concrete as a proportion of total aggregate (replacement ratio), depending on the application. RA may include crushed concrete, asphalt, stone, rubber, polystyrene beads, ceramic tiles, glass.

Recycled aggregate concrete (RAC): Concrete produced using recycled aggregate or a mix of recycled and conventional aggregate.

Recycled concrete aggregate (RCA): A type of recycled aggregate originating from crushed concrete from either construction and demolition waste, waste from concrete factories or returned fresh concrete. It may be found as coarse or fine aggregate.

Replacement ratio: The maximum permissible percentage of recycled aggregate to replace conventional aggregate in a recycled aggregate batch consisting of a mix of the two. The mix may consist of more than one material of recycled aggregate.

Returned fresh concrete: The unused ready-mixed concrete that is returned to the plant in the concrete truck as excess material (CSI, 2009). The aggregate can be reused or recycled.

Unbound mixture: A granular material, normally of controlled grading with d=0, which is generally used in pavement bases/ sub-bases. It does not contain an added binder. (BSI, 2003)

Appendix B

Experimental results: Geometrical properties

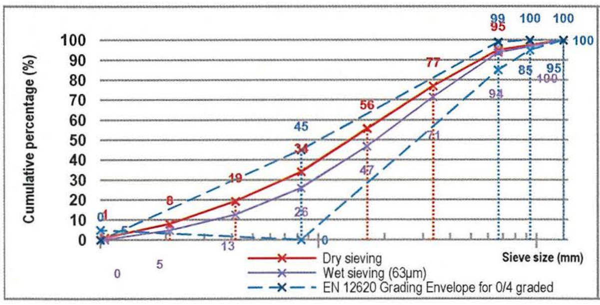
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

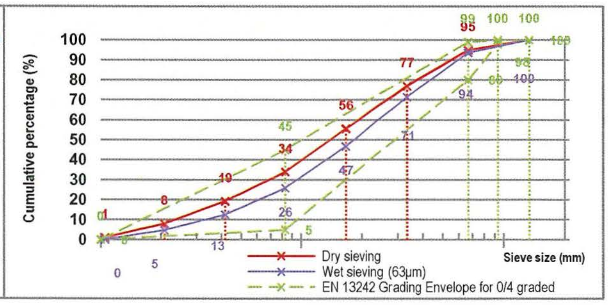
B.1.1 Crushed waste concrete from mixed test cubes — Dates: 24/03/2011 & 05-07/04/2011

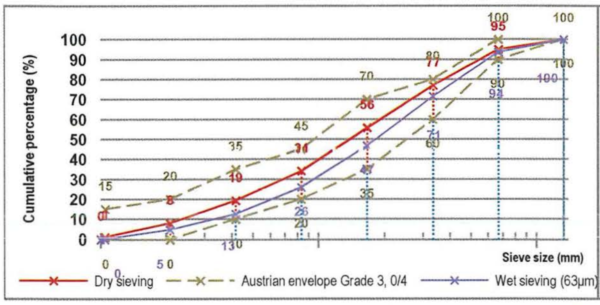
B.1.1.1 Grading: sand — **Source:** Blokrete

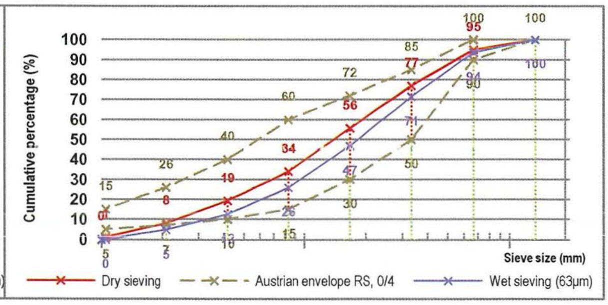
Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Dry sieving: Sample B mass retained on sieve (g)	Dry sieving: Avg % retained $R_{i,avg}/M_{avg}$*100	Dry sieving: Cum. % passing sieve	Wet sieving (63µm): mass retained on sieve (g)	Wet sieving (63µm): % retained R_i/M*100	Wet sieving (63µm): Cum. % passing sieve	Sample mass (g) 1200.15
R_1	8	0.0	0.0	0.0	100	0.0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	4	55.3	65.6	5.0	95	63.5	6.3	94	
R_3	2	211.4	219.7	18.0	77	223.9	22.2	71	1127.44
R_4	1	256.3	255.0	21.3	56	248.9	24.7	47	Dry mass after washing, M_2 (g)
R_5	0.5	264.2	255.6	21.7	34	210.8	20.9	26	
R_6	0.25	177.9	176.3	14.8	19	133.4	13.2	13	1008.23
R_7	0.125	156.3	115.2	11.3	8	79.3	7.9	5	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_8	0.063	70.2	94.8	6.9	1	47.3	4.7	0	
P	0	8.5	18.0	1.1	0	1.1	0.1	0	
$\Sigma R_i + P =$		1200.1	1200.2	100		1008.2	100.0		119.21

Wet sieving : Percentage fines passing the 63µm sieve, f (%) **10.7** Check <1% **0.003**









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/4	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/4 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	8	100	100	8	100	100	Cumulative curves for both wet and dry sieving pass all envelopes.
1.4D	5.6	100	95	5.6	100	98	
D	4	99	85	4	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	Jaw then cone then granulator crushers were used at Blokrete.
d	0	0	0	0	-	-	
D/d	-	G_F85		-	G_F80		

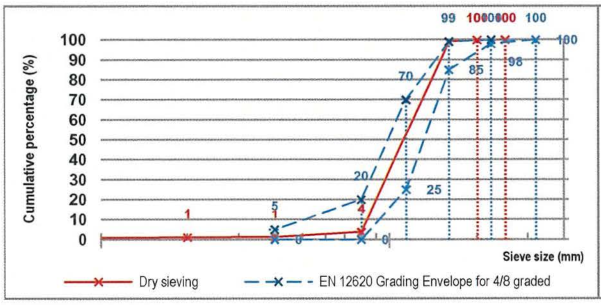
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

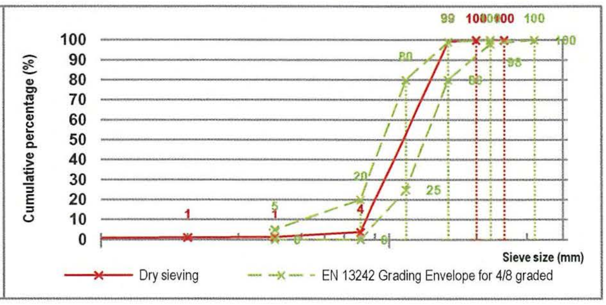
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

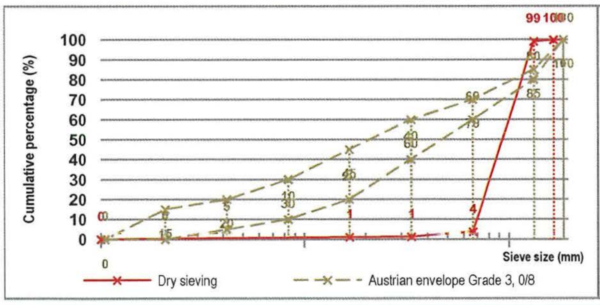
B.1.1 Crushed waste concrete from mixed test cubes — Date: 25/03/2011

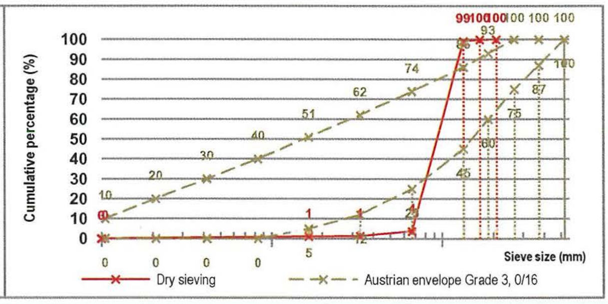
B.1.1.2 Grading: 6 to 9mm — Source: Blokrete

Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	12.5	0	0	0.0	0.0	100
R_2	10	1.7	0.0	0.9	0.1	100
R_3	8	12.2	10.7	11.4	0.8	99
R_4	4	1340.0	1363.1	1351.6	95.4	4
R_5	2	41.0	28.7	34.9	2.5	1
R_6	1	3.5	2.9	3.2	0.2	1
R_7	0.063	11.7	12.3	12.0	0.8	0
P	0	3.6	1.7	2.7	0.2	0
$\Sigma R_i + P =$		1413.7	1419.5	1416.6	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 4/8 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 4/8 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	16	100	100	16	100	100	
1.4D	11.2	100	98	11.2	100	98	Cumulative curve passes EN 12620 and EN 13242 envelopes.
D	8	99	85	8	99	80	
D/1.4	5.7	70	25	5.7	80	25	
d	4	20	0	4	20	0	Jaw then cone then granulator crushers were used at Blokrete.
d/2	2	5	0	2	5	0	
D/d	2.0	$G_C85/20$		2.0	$G_C80/20$		

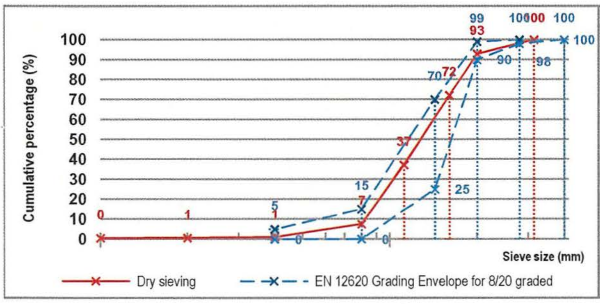
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

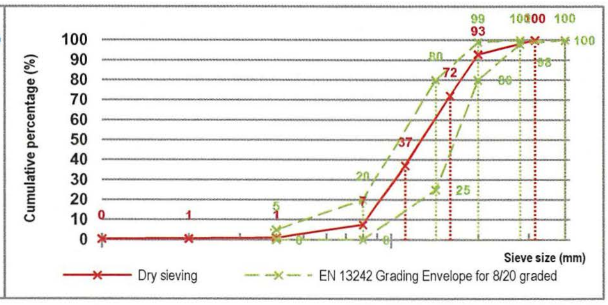
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

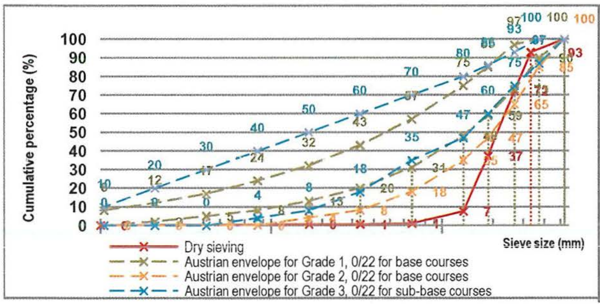
B.1.1 Crushed waste concrete from mixed test cubes — Date: 25/03/2011

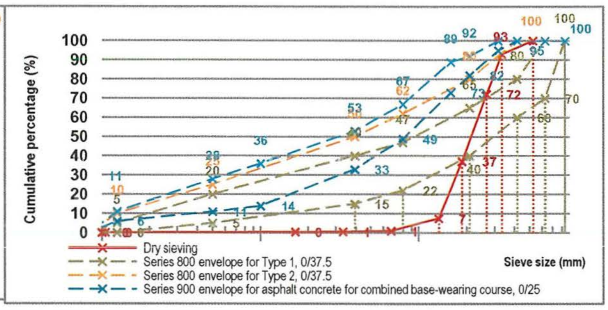
B.1.1.3 Grading: 9 to 18mm — **Source:** Blokrete

Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	31.5	0.0	0.0	0.0	0.0	100
R_2	20	365.9	257.1	311.5	7.1	93
R_3	16	1015.7	811.6	913.7	20.7	72
R_4	11.2	1472.5	1611.7	1542.1	35.0	37
R_5	8	1240.3	1376.5	1308.4	29.7	7
R_6	4	272.6	302.0	287.3	6.5	1
R_7	2	22.6	15.4	19.0	0.4	1
R_8	1	3.7	5.1	4.4	0.1	0
R_9	0.063	11.1	16.7	13.9	0.3	0
P	0	7.6	2.3	5.0	0.1	0
$\Sigma R_i + P =$		4412.1	4398.4	4405.2	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 8/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 8/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	8	15	0	8	20	0	Jaw then cone then granulator crushers were used at Blokrete.
d/2	4	5	0	4	5	0	
D/d	2.5	G_C90/15		2.5	G_C80/20		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

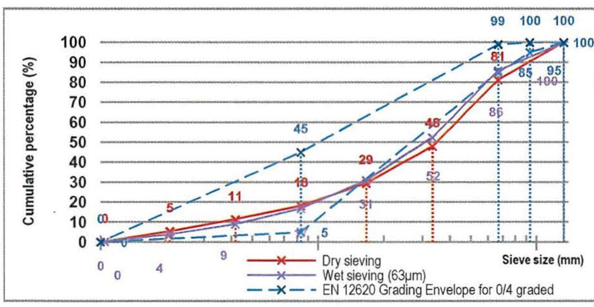
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

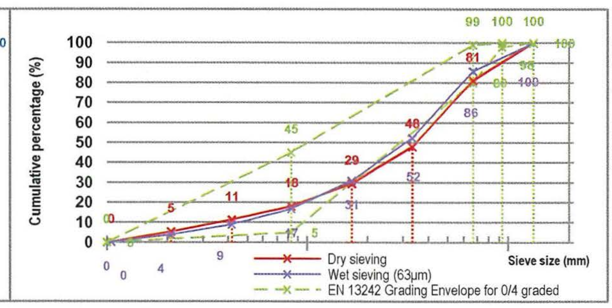
B.1.2 Crushed waste concrete from block work — Dates: 24/03/2011 & 25-27/04/2011

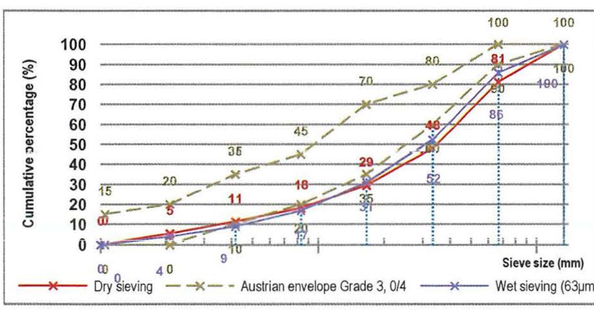
B.1.2.1 **Grading:** sand — **Source:** Blokrete

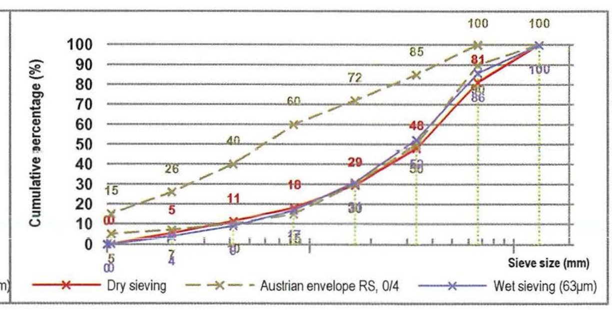
		Dry sieving				Wet sieving (63μm)			
Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cum. % passing sieve	mass retained on sieve (g)	% retained R_i/M*100	Cum. % passing sieve	Sample mass (g) 1200.07
R_1	8	0.0	0.0	0.0	100	0.6	0.1	100	Total dry mass before washing, M_1 (g) 1155.85
R_2	4	250.3	203.5	18.9	81	144.8	14.1	86	
R_3	2	398.0	397.9	33.2	48	343.5	33.5	52	
R_4	1	218.5	225.9	18.5	29	219.4	21.4	31	Dry mass after washing, M_2 (g) 1026.53
R_5	0.5	127.5	145.2	11.4	18	145.1	14.2	17	
R_6	0.25	76.2	86.8	6.8	11	80.8	7.9	9	
R_7	0.125	71.3	71.6	6.0	5	52.9	5.2	4	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_8	0.063	56.1	66.8	5.1	0	35.8	3.5	0	
P	0	2.3	2.4	0.2	0	2.2	0.2	0	
$\Sigma R_i + P =$		1200.2	1200.1	100		1024.9	100.0		129.32

Wet sieving : Percentage fines passing the 63μm sieve, f (%) **11.4** Check <1% **0.16**









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/4	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/4 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	8	100	100	8	100	100	Cumulative curves do not pass any of the envelopes.
1.4D	5.6	100	95	5.6	100	98	
D	4	99	85	4	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	Jaw then cone then granulator crushers were used at Blokrete.
d	0	0	0	0	-	-	
D/d	-	G_F85		-	G_F80		

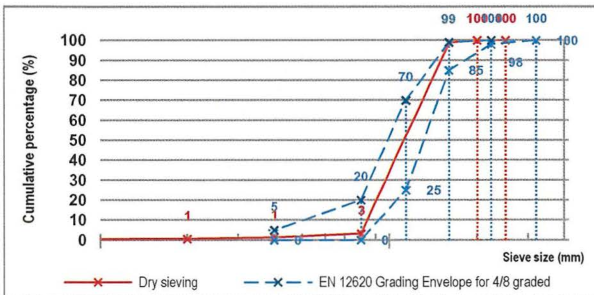
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

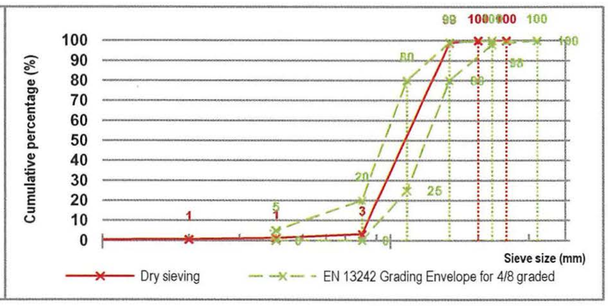
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION Operator: Author

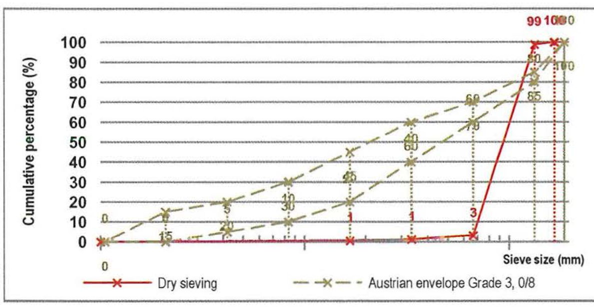
B.1.2 Crushed waste concrete from block work Date: 25/03/2011

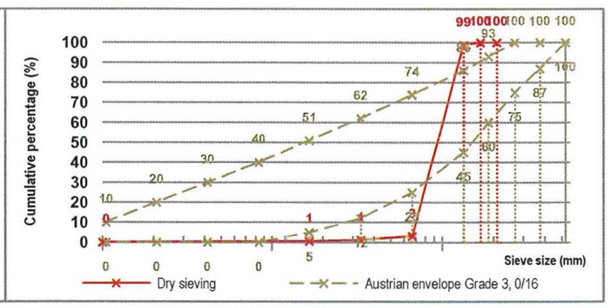
B.1.2.2 Grading: 6 to 9mm Source: Blokrete

		Dry sieving				
Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	12.5	0	0	0.0	0.0	100
R_2	10	0.0	0.0	0.0	0.0	100
R_3	8	12.2	22.9	17.5	1.2	99
R_4	4	1403.8	1400.7	1402.2	95.7	3
R_5	2	30.5	23.1	26.8	1.8	1
R_6	1	20.1	1.4	10.7	0.7	1
R_7	0.063	7.6	5.9	6.7	0.5	0
P	0	1.3	0.7	1.0	0.1	0
$\Sigma R_i + P =$		1475.3	1454.6	1465.0	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 4/8 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 4/8 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	16	100	100	16	100	100	
1.4D	11.2	100	98	11.2	100	98	
D	8	99	85	8	99	80	Cumulative curve passes EN 12620 and EN 13242 envelopes.
D/1.4	5.7	70	25	5.7	80	25	
d	4	20	0	4	20	0	
d/2	2	5	0	2	5	0	Jaw then cone then granulator crushers were used at Blokrete.
D/d	2.0	$G_C85/20$		2.0	$G_C80/20$		

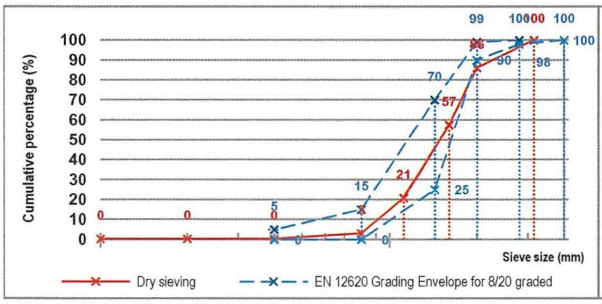
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

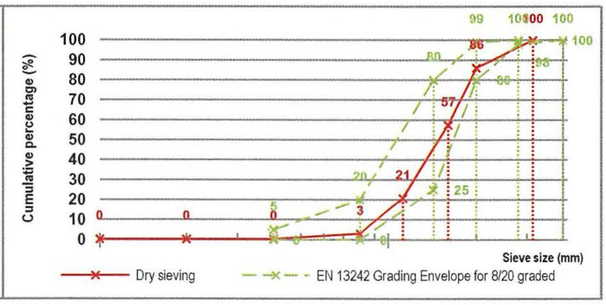
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

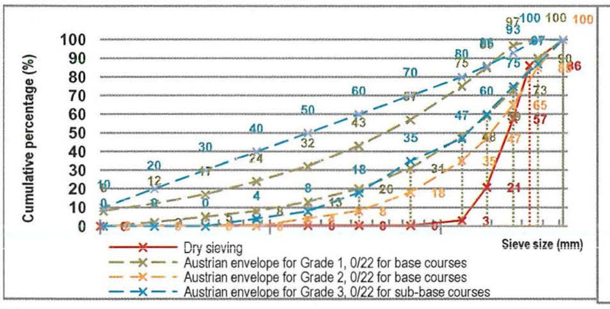
B.1.2 Crushed waste concrete from blockwork — Date: 25/03/2011

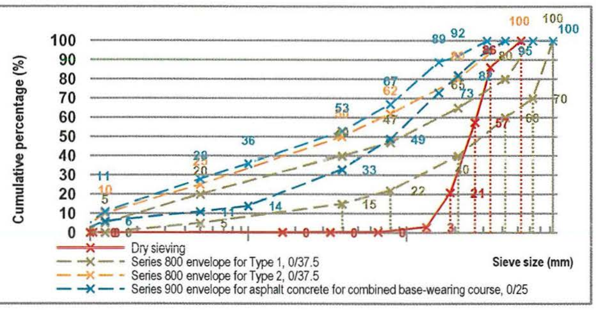
B.1.2.3 Grading: 9 to 18mm — Source: Blokrete

Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Dry sieving: Sample B mass retained on sieve (g)	Dry sieving: Avg mass retained on sieve (g)	Dry sieving: Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	31.5	0.0	0.0	0.0	0.0	100
R_2	20	524.1	684.4	604.2	13.9	86
R_3	16	1103.4	1388.6	1246.0	28.6	57
R_4	11.2	1702.2	1487.1	1594.7	36.6	21
R_5	8	848.0	707.7	777.8	17.9	3
R_6	4	142.7	87.2	115.0	2.6	0
R_7	2	1.6	1.2	1.4	0.0	0
R_8	1	1.7	0.5	1.1	0.0	0
R_9	0.063	9.4	5.8	7.6	0.2	0
P	0	5.4	2.8	4.1	0.1	0
$\Sigma R_i + P =$		4338.5	4365.4	4351.9	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 8/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 8/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve almost passes EN 12620 and passes EN 13242 envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	8	15	0	8	20	0	Jaw then cone then granulator crushers were used at Blokrete.
d/2	4	5	0	4	5	0	
D/d	2.5	$G_C90/15$		2.5	$G_C80/20$		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

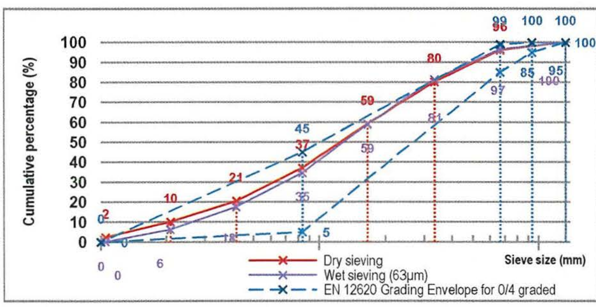
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

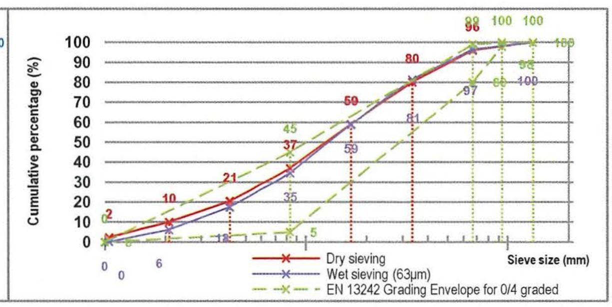
B.1.3 Crushed waste concrete from planks — Dates: 24/03/2011 & 25-27/04/2011

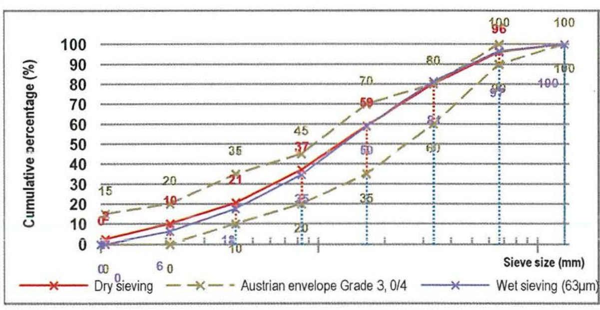
B.1.3.1 Grading: sand — Source: Blokrete

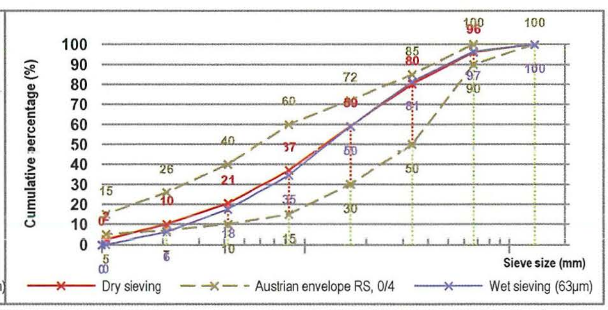
Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Dry sieving: Sample B mass retained on sieve (g)	Dry sieving: Avg % retained $R_{i,avg}/M_{avg}*100$	Dry sieving: Cum. % passing sieve	Wet sieving (63µm): mass retained on sieve (g)	Wet sieving (63µm): % retained $R_i/M*100$	Wet sieving (63µm): Cum. % passing sieve	Sample mass (g) 1200.11
R_1	8	0.0	0.0	0.0	100	0.0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	4	47.7	46.7	3.9	96	32.6	3.4	97	
R_3	2	207.3	174.7	15.9	80	145.4	15.2	81	1103.97
R_4	1	252.8	252.6	21.1	59	215.5	22.5	59	Dry mass after washing, M_2 (g)
R_5	0.5	254.4	275.2	22.1	37	233.3	24.4	35	
R_6	0.25	184.4	210.8	16.5	21	163.1	17.0	18	958.93
R_7	0.125	124.3	127.8	10.5	10	108.4	11.3	6	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_8	0.063	90.8	94.9	7.7	2	58.1	6.1	0	
P	0	38.4	17.4	2.3	0	1.6	0.2	0	
$\Sigma R_i + P =$		1200.1	1200.1	100		958.0	100.0		145.04

Wet sieving : Percentage fines passing the 63µm sieve, f (%) **13.3** Check <1% **0.09**









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/4	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/4 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	8	100	100	8	100	100	
1.4D	5.6	100	95	5.6	100	98	Cumulative curves for both wet and dry sieving pass all envelopes.
D	4	99	85	4	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	
d	0	0	0	0	-	-	Jaw then cone then granulator crushers were used at Blokrete.
D/d	-	G_F85		-	G_F80		

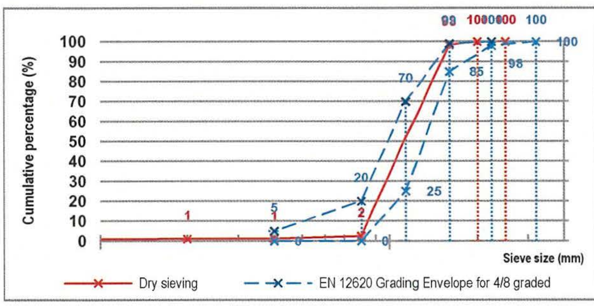
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

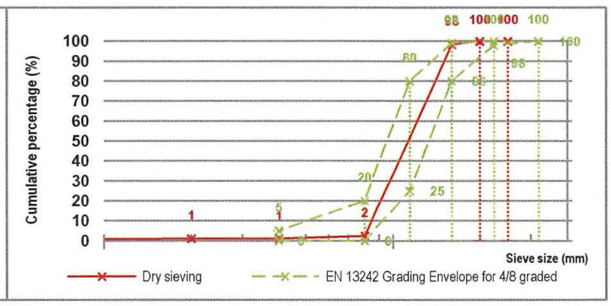
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: Author

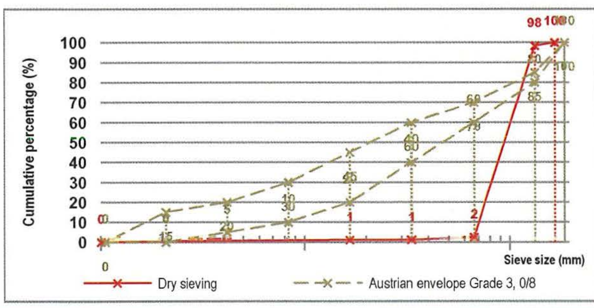
B.1.3 Crushed waste concrete from planks — Date: 25/03/2011

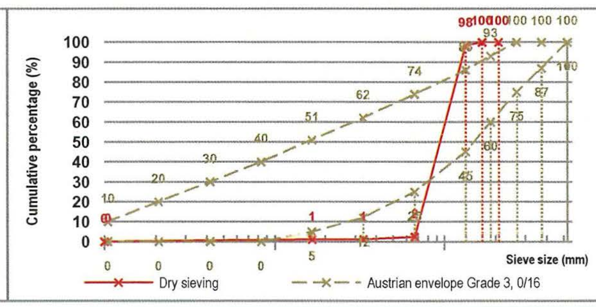
B.1.3.2 Grading: 6 to 9mm — **Source:** Blokrete

Sieve aperture size (mm)		Dry sieving: Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	12.5	0	0	0.0	0.0	100
R_2	10	0.0	0.0	0.0	0.0	100
R_3	8	12.2	33.7	22.9	1.6	98
R_4	4	1366.6	1361.1	1363.8	96.0	2
R_5	2	21.7	14.8	18.2	1.3	1
R_6	1	1.9	0.8	1.4	0.1	1
R_7	0.063	13.6	10.4	12.0	0.8	0
P	0	1.3	4.0	2.6	0.2	0
$\Sigma R_i + P =$		1417.2	1424.8	1421.0	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 4/8 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 4/8 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	16	100	100	16	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	11.2	100	98	11.2	100	98	
D	8	99	85	8	99	80	
D/1.4	5.7	70	25	5.7	80	25	
d	4	20	0	4	20	0	Jaw then cone then granulator crushers were used at Blokrete.
d/2	2	5	0	2	5	0	
D/d	2.0	G_C85/20		2.0	G_C80/20		

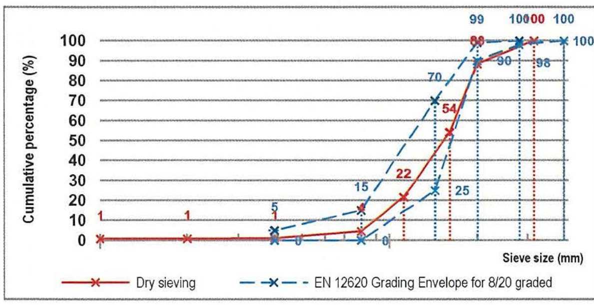
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

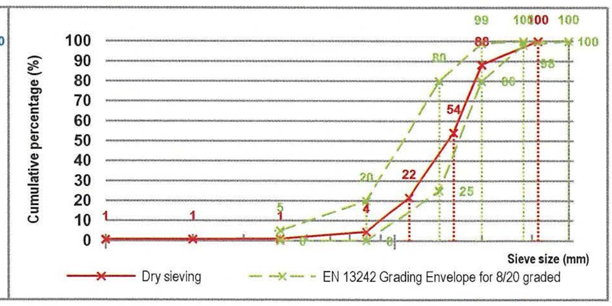
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION Operator: Author

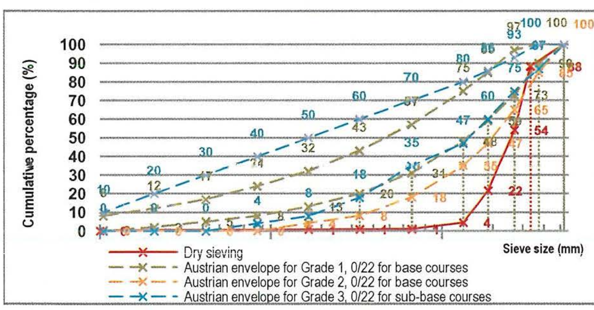
B.1.3 Crushed waste concrete from planks Date: 25/03/2011

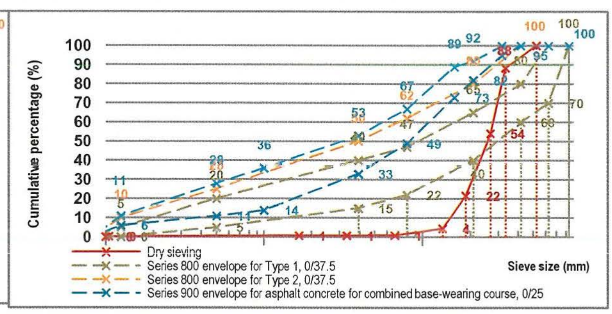
B.1.3.3 **Grading:** 9 to 18mm **Source:** Blokrete

		Dry sieving				
Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	31.5	0.0	0.0	0.0	0.0	100
R_2	20	488.0	500.7	494.3	11.7	88
R_3	16	1483.8	1399.9	1441.8	34.2	54
R_4	11.2	1345.0	1401.4	1373.2	32.5	22
R_5	8	762.2	687.2	724.7	17.2	4
R_6	4	139.4	158.0	148.7	3.5	1
R_7	2	1.6	9.9	5.8	0.1	1
R_8	1	0.8	5.9	3.4	0.1	1
R_9	0.063	11.5	25.7	18.6	0.4	0
P	0	9.3	12.0	10.6	0.3	0
$\Sigma R_i + P =$		4241.5	4200.7	4221.1	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 8/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 8/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve almost passes EN 12620 and passes EN 13242 envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	8	15	0	8	20	0	Jaw then cone then granulator crushers were used at Blokrete.
d/2	4	5	0	4	5	0	
D/d	2.5	G_C90/15		2.5	G_C80/20		

BSI, Testing for geometrical properties of aggregates, EN 933-1 : 1997 : Determination of particle size distribution: Sieve Analysis
BSI, Aggregates for concrete, EN 12620 : 2002, Tables 2,3 with PD 6682-1:2009
BSI, Aggregates for hydraulically bound materials for use in civil engineering work and road construction, EN13242 : 2002, Tables 2, 3
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials.

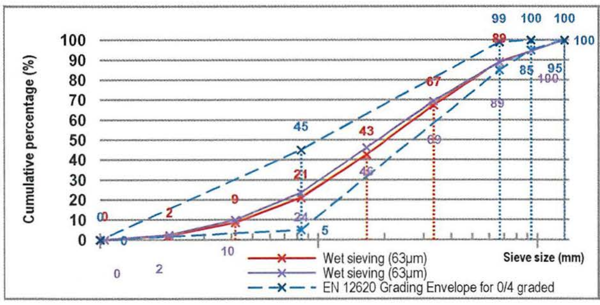
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION   Operator: R. P. Borg

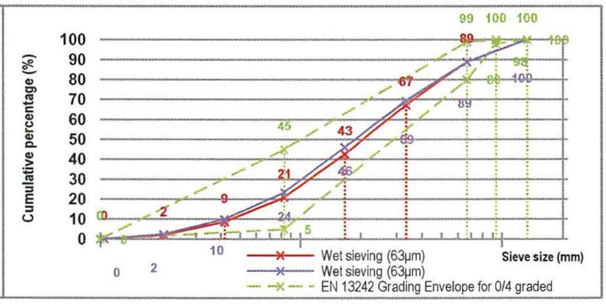
B.1.4 Crushed waste concrete from Manuel Dimech bridge   Date: Sept 2009

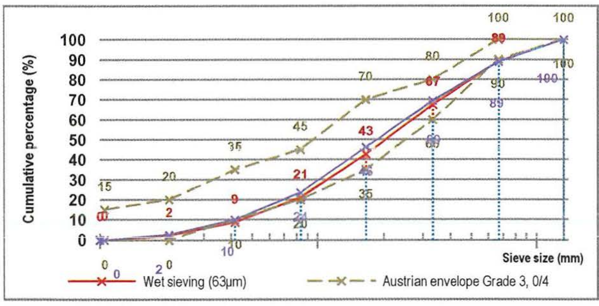
B.1.4.1 Grading: sand

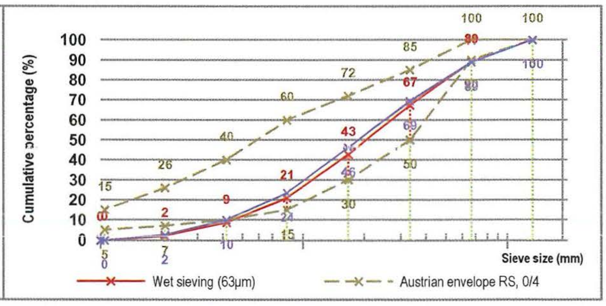
		Wet sieving (63µm)				Wet sieving (63µm)			
Sieve aperture size (mm)		Sample mass (g) 1505	mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Sample mass (g) 1505
R_1	8	Total dry mass before washing, M_1 (g)	0.0	0.0	100	0.0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	4		155.5	11.0	89	158.0	11.2	89	
R_3	2	1460	306.3	21.7	67	273.9	19.4	69	1459.8
R_4	1	Dry mass after washing, M_2 (g)	349.2	24.7	43	328.3	23.3	46	Dry mass after washing, M_2 (g)
R_5	0.5		306.8	21.7	21	319.0	22.6	24	
R_6	0.25	1414.6	174.6	12.3	9	190.6	13.5	10	1410.9
R_7	0.125	Dry mass of fines removed by washing, $M_1 - M_2$ (g)	93.6	6.6	2	106.3	7.5	2	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_8	0.063		27.9	2.0	0	33.5	2.4	0	
P	0		0.7	0.0	0	1.3	0.1	0	
$\Sigma R_i + P =$		45.4	1414.6	100.0		1410.9	100.0		48.9

Percentage fines passing the 63µm sieve, f (%)   3.2   3.4   Check <1%   0.00   0.00









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/4	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/4 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	8	100	100	8	100	100	
1.4D	5.6	100	95	5.6	100	98	Cumulative curves pass all envelopes.
D	4	99	85	4	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	
d	0	0	0	0	-	-	Granulator (type of jaw crusher) was used at Carmel Vella Ltd.
D/d	-	G_F85		-	G_F80		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Borg (1998).

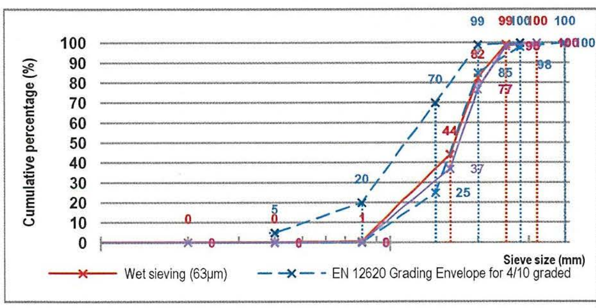
B.1.4 Crushed waste concrete from Manuel Dimech bridge

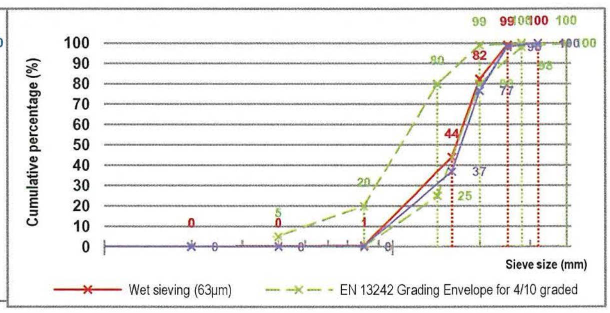
Date: Sept 2009

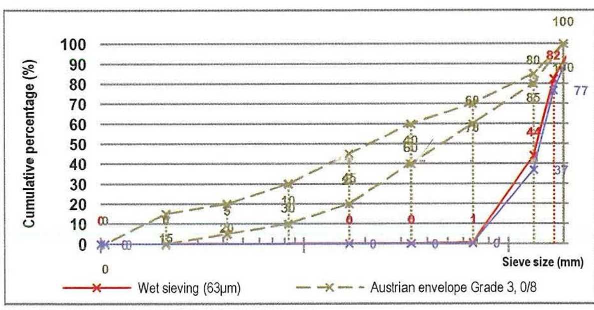
B.1.4.2 Grading: 10mm

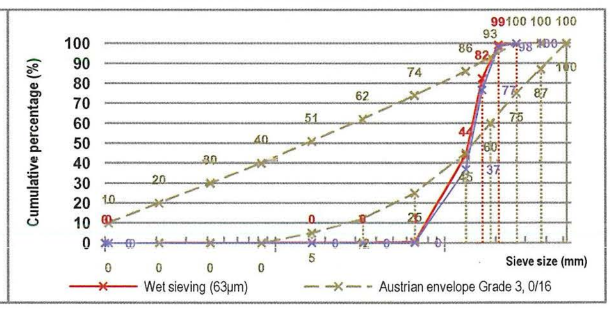
		Wet sieving (63µm)				Wet sieving (63µm)			
Sieve aperture size (mm)		Sample mass (g) 1505.5	mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Sample mass (g) 1505.5
R_1	16	Total dry mass before washing, M_1 (g)	0.0	0.0	100	0.0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	12.5		12.1	0.8	99	25.9	1.8	98	
R_3	10	1480.6	247.0	16.8	82	317.7	21.5	77	1479.2
R_4	8	Dry mass after washing, M_2 (g)	565.8	38.4	44	586.7	39.8	37	Dry mass after washing, M_2 (g)
R_5	4		640.6	43.5	1	541.1	36.7	0	
R_6	2	1473.7	4.4	0.3	0	2.2	0.1	0	1475.3
R_7	1	Dry mass of fines removed by washing, $M_1 - M_2$ (g)	0.8	0.1	0	0.2	0.0	0	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_8	0.063		2.8	0.2	0	1.2	0.1	0	
P	0		0.2	0.0	0	0.3	0.0	0	
$\Sigma R_i + P =$		6.9	1473.7	100.0		1475.3	100.0		3.9

Percentage fines passing the 63µm sieve, f (%) 0.5 0.3 Check <1% 0.00 0.00









Aggr size in terms of d/D	EN 12620 Grading Envelope for 4/10 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 4/10 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	20	100	100	20	100	100	
1.4D	14	100	98	14.0	100	98	Cumulative curves pass EN 12620 and EN 13242 envelopes.
D	10	99	85	10	99	80	
D/1.4	7.1	70	25	7.1	80	25	
d	4	20	0	4	20	0	
d/2	2	5	0	2	5	0	Granulator (type of jaw crusher) was used at Carmel Vella Ltd.
D/d	2.5	G_C85/20		2.5	G_C80/20		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Borg (1998).

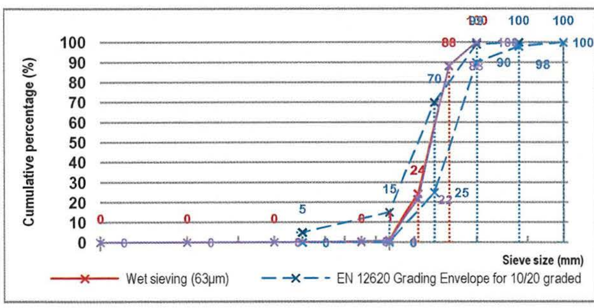
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION   Operator: R.P. Borg

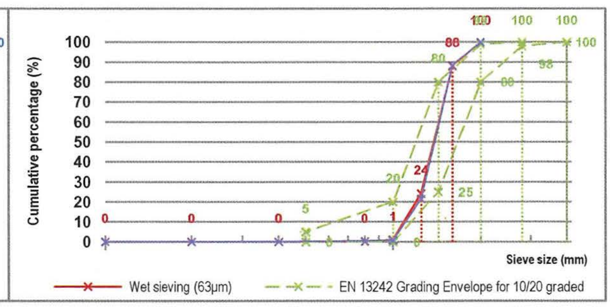
B.1.4 Crushed waste concrete from Manuel Dimech bridge   Date: Sept 2009

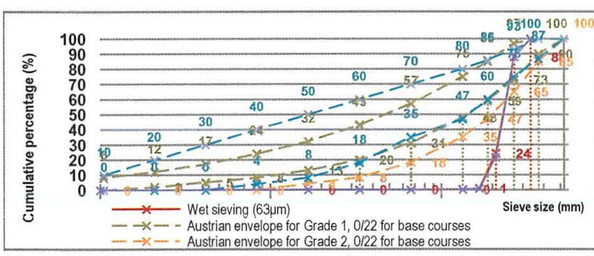
B.1.4.3a Grading: 20mm

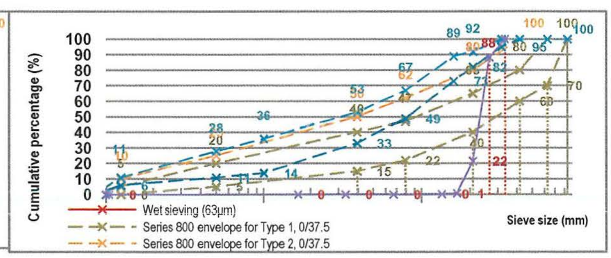
Sieve aperture size (mm)		Sample mass (g) 4143.9	Wet sieving (63µm): mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Wet sieving (63µm): mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Sample mass (g) 4143.9
R_1	20	Total dry mass before washing, M_1 (g)	0	0.0	100	0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	16		239.4	12.0	88	238.4	11.7	88	
R_3	12.5		1278.0	63.8	24	1359.8	66.8	22	
R_4	10	2007.5	462.6	23.1	1	421.3	20.7	1	2045.2
R_5	8	Dry mass after washing, M_2 (g)	18.7	0.9	0	9.6	0.5	0	Dry mass after washing, M_2 (g)
R_6	4		1.1	0.1	0	4.5	0.2	0	
R_7	2	2002	0.2	0.0	0	0.7	0.0	0	2036.7
R_8	1	Dry mass of fines removed by washing, $M_1 - M_2$ (g)	0.4	0.0	0	0.5	0.0	0	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_9	0.063		1.4	0.1	0	1.7	0.1	0	
P	0		0.2	0.0	0	0.2	0.0	0	
$\Sigma R_i + P =$		5.5	2002.0	100.0		2036.7	100.0		8.5

Percentage fines passing the 63µm sieve, f (%)   0.3   0.4   Check <1%   0.00   0.00









Aggr size in terms of d/D	EN 12620 Grading Envelope for 10/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 10/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve passes EN 13242 envelope.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	10	15	0	10	20	0	
d/2	5	5	0	5	5	0	Granulator (type of jaw crusher) was used at Carmel Vella Ltd.
D/d	2.0	$G_C90/15$		2.0	$G_C80/20$		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Borg (1998).

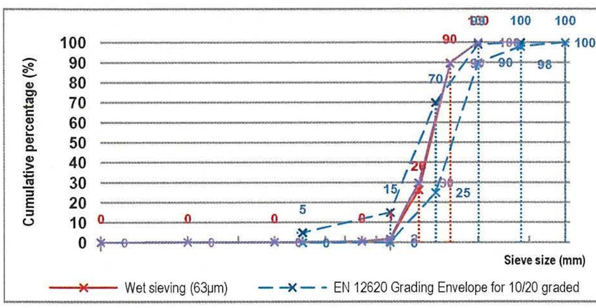
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION   Operator: R.P. Borg

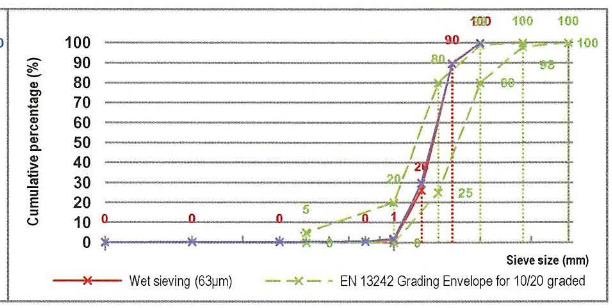
B.1.4 Crushed waste concrete from Manuel Dimech bridge   Date: Sept 2009

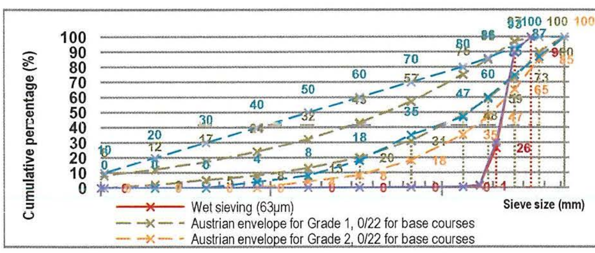
B.1.4.3b Grading: 20mm

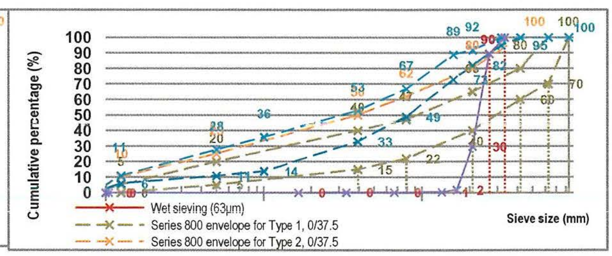
Sieve aperture size (mm)		Wet sieving (63µm) Sample mass (g) 4153.3	mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Wet sieving (63µm) mass retained on sieve (g)	% retained $R_i/M*100$	Cum. % passing sieve	Sample mass (g) 4153.3
R_1	20	Total dry mass before washing, M_1 (g)	0	0.0	100	0	0.0	100	Total dry mass before washing, M_1 (g)
R_2	16		210.6	10.2	90	207.4	10.4	90	
R_3	12.5		1306.2	63.5	26	1185.4	59.7	30	
R_4	10	2066.4	513.3	24.9	1	555.7	28.0	2	1999.7
R_5	8	Dry mass after washing, M_2 (g)	17.4	0.8	0	26.8	1.3	1	Dry mass after washing, M_2 (g)
R_6	4		3.3	0.2	0	3.7	0.2	0	
R_7	2	2057.5	1.8	0.1	0	1.9	0.1	0	1985.9
R_8	1	Dry mass of fines removed by washing, $M_1 - M_2$ (g)	1.3	0.1	0	1.4	0.1	0	Dry mass of fines removed by washing, $M_1 - M_2$ (g)
R_9	0.063		3.3	0.2	0	3.1	0.2	0	
P	0		0.3	0.0	0	0.5	0.0	0	
$\Sigma R_i + P =$		8.9	2057.5	100.0		1985.9	100.0		13.8

Percentage fines passing the 63µm sieve, f (%)   0.4   0.7   Check <1%   0.00   0.00









Aggr size in terms of d/D	EN 12620 Grading Envelope for 10/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 10/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve passes EN 13242 envelope.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	10	15	0	10	20	0	
d/2	5	5	0	5	5	0	Granulator (type of jaw crusher) was used at Carmel Vella Ltd.
D/d	2.0	$G_C 90/15$		2.0	$G_C 80/20$		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Borg (1998).

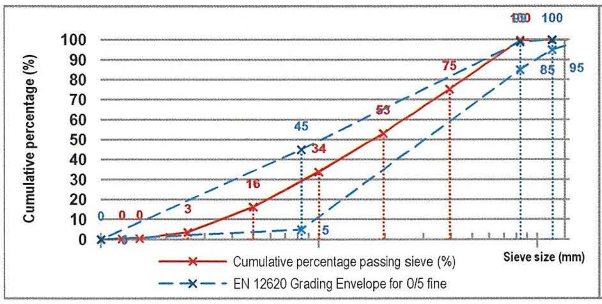
B.1.5 Crushed waste concrete from C20 test cubes

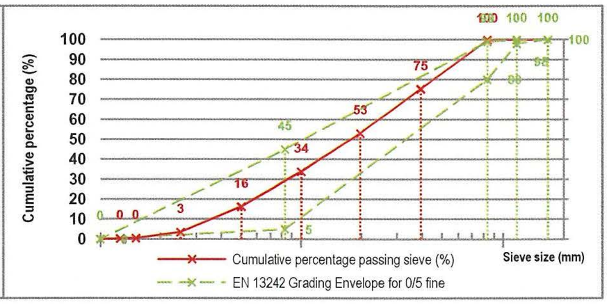
Date: 2003

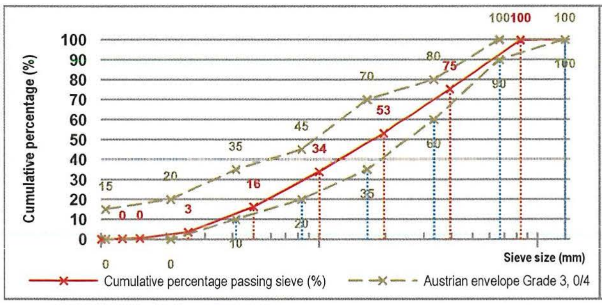
B.1.5.1 Grading: < 5mm

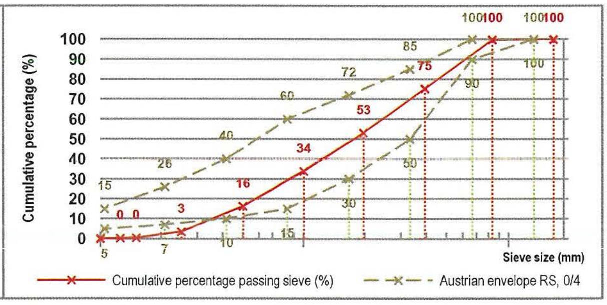
Source: Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	10	0	0	0.0	0.0	100
R_2	5	0.8	1.1	1.0	0.2	100
R_3	2.36	124.7	124.2	124.5	24.6	75
R_4	1.18	113.2	111.2	112.2	22.1	53
R_5	0.6	95.6	99.7	97.7	19.3	34
R_6	0.3	86.9	91.6	89.3	17.6	16
R_7	0.15	67.7	61.7	64.7	12.8	3
R_8	0.09	15.8	14.4	15.1	3.0	0
R_9	0.075	1.2	0.9	1.1	0.2	0
P	0	1.0	1.5	1.3	0.2	0
$\Sigma R_i + P =$		506.9	506.3	506.6	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/5	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/5 fine	EN 13242 max limit	EN 13242 min limit	Comments
2D	10	100	100	10	100	100	Cumulative curve passes all envelopes.
1.4D	7.0	100	95	7.0	100	98	
D	5	99	85	5	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	Jaw crusher was used at University concrete laboratory.
d	0	0	0	0	-	-	
D/d	-	G_F85		-	G_F80		

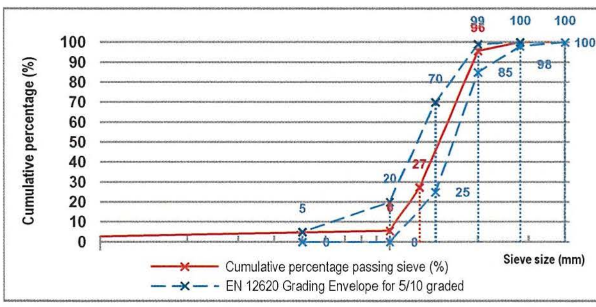
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

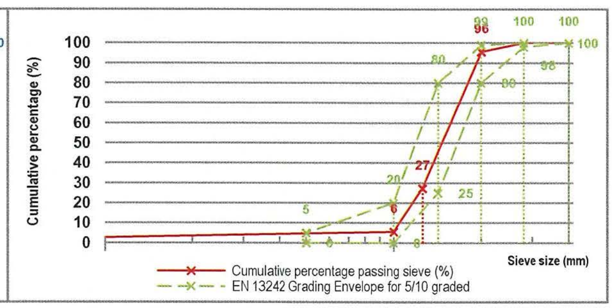
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

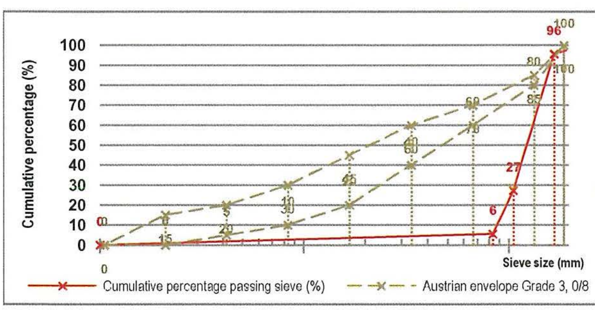
B.1.5 Crushed waste concrete from C20 test cubes — Date: 2003

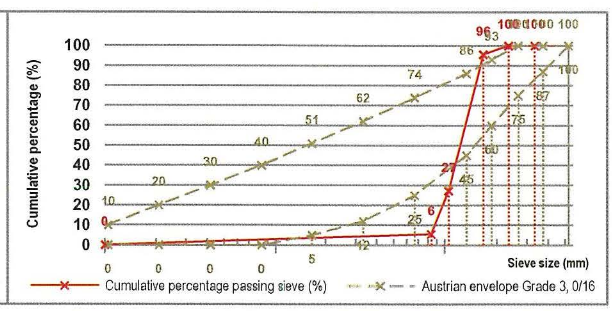
B.1.5.2 Grading: 10mm — **Source:** Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	100
R_2	20	0.0	0.0	0.0	0.0	100
R_3	14	0.0	0.0	0.0	0.0	100
R_4	10	44.7	17.9	31.3	4.3	96
R_5	6.3	451.5	532.6	492.1	68.4	27
R_6	5	182.0	131.0	156.5	21.7	6
P	0	44.3	35.6	40.0	5.6	0
$\Sigma R_i + P =$		722.5	717.1	719.8	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 5/10 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 5/10 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	20	100	100	20	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	14	100	98	14.0	100	98	
D	10	99	85	10	99	80	
D/1.4	7.1	70	25	7.1	80	25	
d	5	20	0	5	20	0	Jaw crusher was used at University concrete laboratory.
d/2	2.5	5	0	3	5	0	
D/d	2.0	G_C85/20		2.0	G_C80/20		

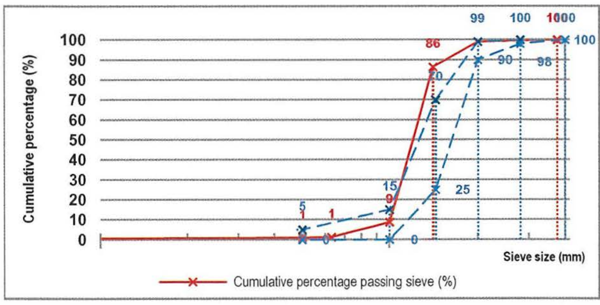
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

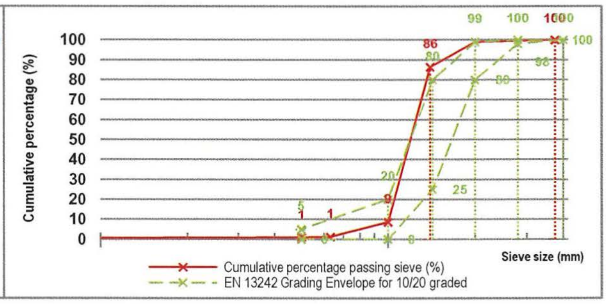
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

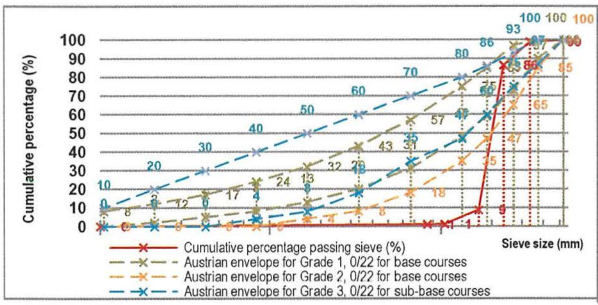
B.1.5 Crushed waste concrete from C20 test cubes — Date: 2003

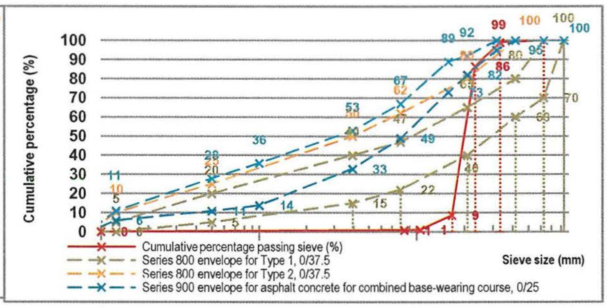
B.1.5.3 Grading: 20mm — **Source:** Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	100
R_2	20	17.4	6.5	12.0	1.1	99
R_3	14	177.2	94.6	135.9	12.5	86
R_4	10	891.0	801.3	846.2	77.7	9
R_5	6.3	84.9	78.6	81.8	7.5	1
R_6	5	2.4	2.3	2.4	0.2	1
P	0	15.7	5.4	10.6	1.0	0
$\Sigma R_i + P =$		1188.6	988.7	1088.7	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 10/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 10/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve does not pass any of the envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	10	15	0	10	20	0	Jaw crusher was used at University concrete laboratory.
d/2	5	5	0	5	5	0	
D/d	2.0	G_C90/15		2.0	G_C80/20		

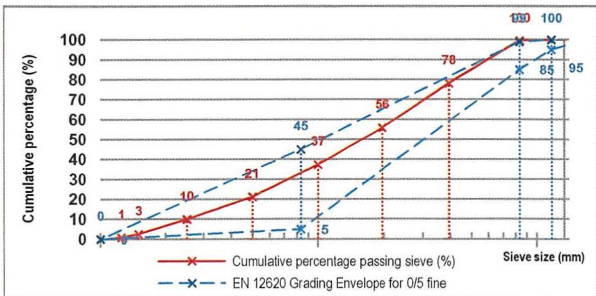
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

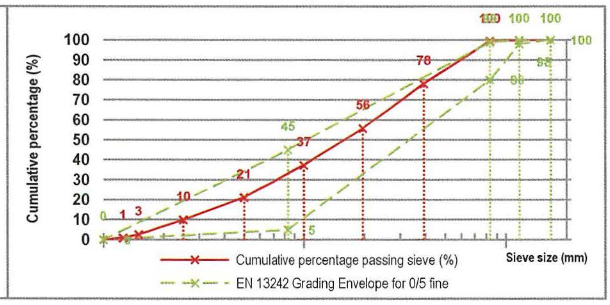
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

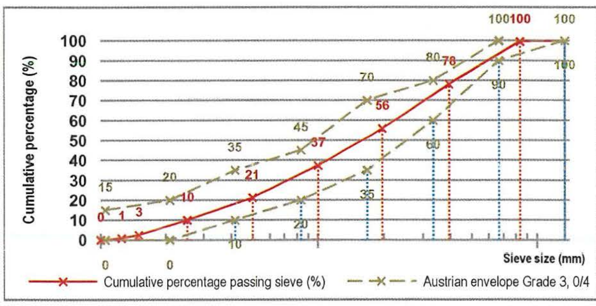
B.1.6 Crushed waste concrete from C30 test cubes — Date: 2003

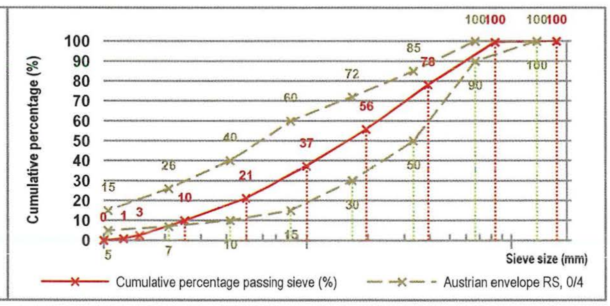
B.1.6.1 Grading: < 5mm — **Source:** Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	10	0	0	0.0	0.0	100
R_2	5	3.1	4.4	3.8	0.5	100
R_3	2.36	173.9	171.2	172.6	21.4	78
R_4	1.18	180.3	179.6	180.0	22.3	56
R_5	0.6	147.5	149.7	148.6	18.5	37
R_6	0.3	127.2	132.8	130.0	16.1	21
R_7	0.15	94.5	85.9	90.2	11.2	10
R_8	0.09	49.5	70.2	59.9	7.4	3
R_9	0.075	16.3	11.1	13.7	1.7	1
P	0	12.9	0.7	6.8	0.8	0
$\Sigma R_i + P =$		805.2	805.6	805.4	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 0/5	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 0/5 fine	EN 13242 max limit	EN 13242 min limit	Comments
2D	10	100	100	10	100	100	Cumulative curve passes all envelopes.
1.4D	7.0	100	95	7.0	100	98	
D	5	99	85	5	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	Jaw crusher was used at University concrete laboratory.
d	0	0	0	0	-	-	
D/d	-	G_F85		-	G_F80		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

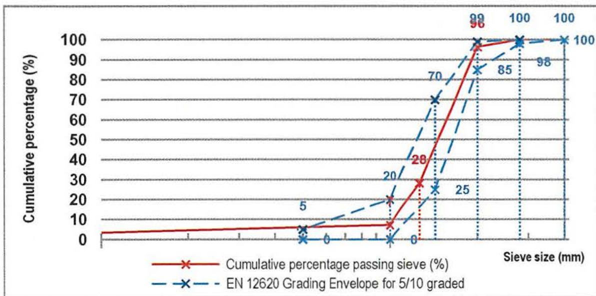
B.1.6 Crushed waste concrete from C30 test cubes

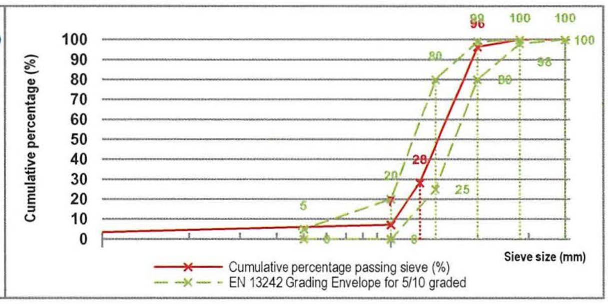
Date: 2003

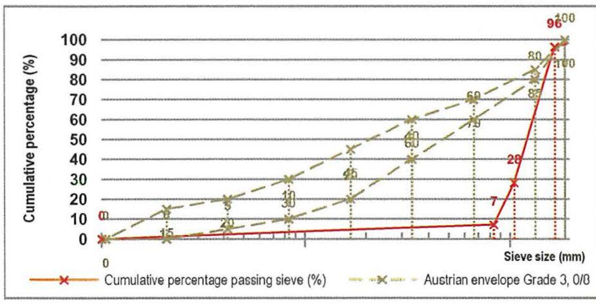
B.1.6.2 Grading: 10mm

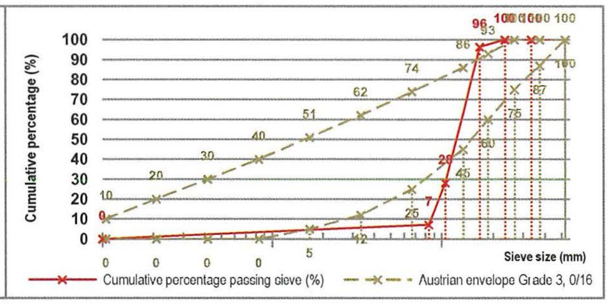
Source: Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	**100**
R_2	20	0.0	0.0	0.0	0.0	**100**
R_3	14	0.0	0.0	0.0	0.0	**100**
R_4	10	37.6	50.7	44.2	3.6	**96**
R_5	6.3	846.9	832.7	839.8	68.2	**28**
R_6	5	262.7	257.3	260.0	21.1	**7**
P	0	84.4	91.0	87.7	7.1	**0**
$\Sigma R_i + P =$		1231.6	1231.7	1231.7	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 5/10 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 5/10 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	20	100	100	20	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	14	100	98	14.0	100	98	
D	10	99	85	10	99	80	
D/1.4	7.1	70	25	7.1	80	25	
d	5	20	0	5	20	0	Jaw crusher was used at University concrete laboratory.
d/2	2.5	5	0	3	5	0	
D/d	2.0	$G_C85/20$		2.0	$G_C80/20$		

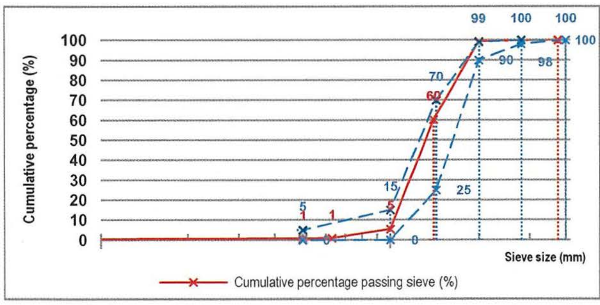
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

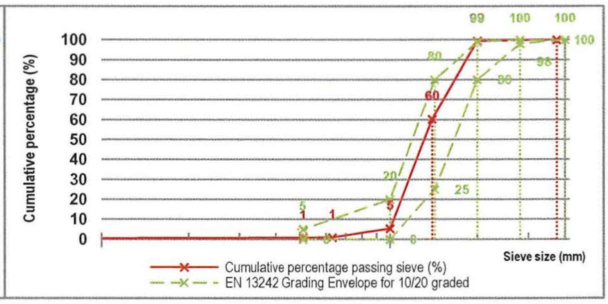
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

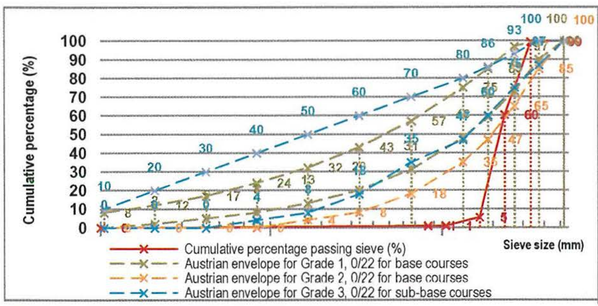
B.1.6 Crushed waste concrete from C30 test cubes — Date: 2003

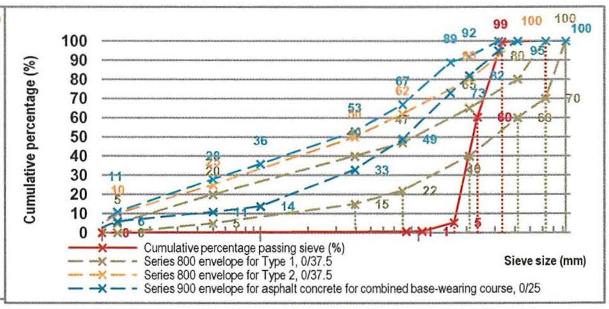
B.1.6.3 **Grading:** 20mm — **Source:** Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	100
R_2	20	14.8	15.6	15.2	0.6	99
R_3	14	1047.9	1020.9	1034.4	39.1	60
R_4	10	1452.0	1452.3	1452.2	54.9	5
R_5	6.3	110.8	128.1	119.5	4.5	1
R_6	5	2.4	4.7	3.6	0.1	1
P	0	16.6	23.8	20.2	0.8	0
$\Sigma R_i + P =$		2644.5	2645.4	2645.0	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 10/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 10/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	10	15	0	10	20	0	Jaw crusher was used at University concrete laboratory.
d/2	5	5	0	5	5	0	
D/d	2.0	G_C90/15		2.0	G_C80/20		

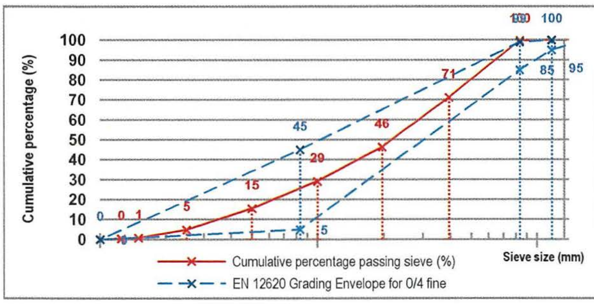
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

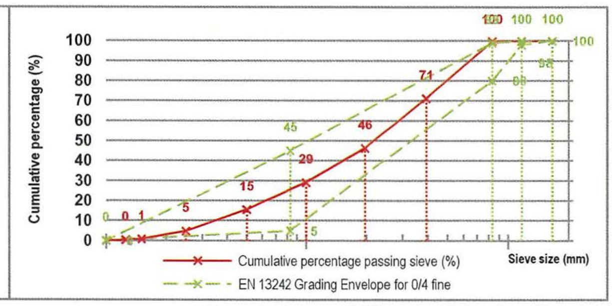
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

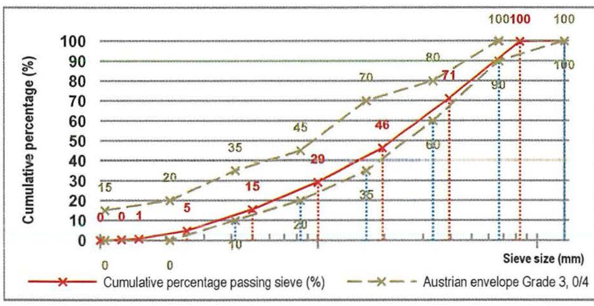
B.1.7 Crushed waste concrete from C45 test cubes — Date: 2003

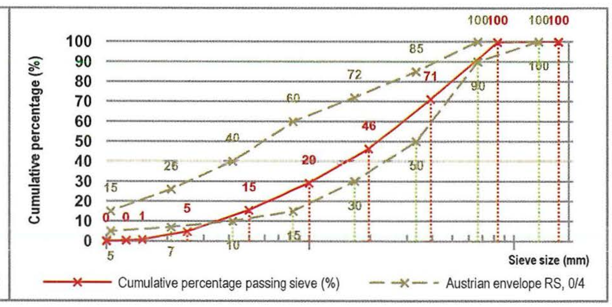
B.1.7.1 Grading: < 5mm — **Source:** Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}*100$	Cumulative percentage passing sieve (%)
R_1	10	0	0	0.0	0.0	100
R_2	5	3.0	2.3	2.7	0.2	100
R_3	2.36	331.8	335.2	333.5	28.5	71
R_4	1.18	295.0	286.3	290.7	24.9	46
R_5	0.6	201.2	201.9	201.6	17.3	29
R_6	0.3	155.9	162.3	159.1	13.6	15
R_7	0.15	128.8	120.6	124.7	10.7	5
R_8	0.09	44.8	50.5	47.7	4.1	1
R_9	0.075	4.5	4.6	4.6	0.4	0
P	0	3.6	4.2	3.9	0.3	0
$\Sigma R_i + P =$		1168.6	1167.9	1168.3	100.0	









	EN 12620 Grading Envelope for 0/4	EN 12620 max grading limit	En 12620 min grading limit	EN 13242 Grading Envelope for 0/4 fine	EN 13242 max limit	EN 13242 min limit	Comments
2D	10	100	100	10	100	100	Cumulative curve passes all envelopes.
1.4D	7.0	100	95	7.0	100	98	
D	5	99	85	5	99	80	
D/1.4	-	-	-	-	-	-	
0.5	0.5	45	5	0.5	45	5	Jaw crusher was used at University concrete laboratory.
d	0	0	0	0	-	-	
D/d	-	G_F85		-	G_F80		

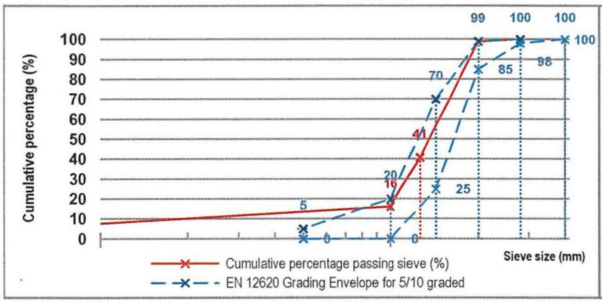
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Table 2 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Table 2 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

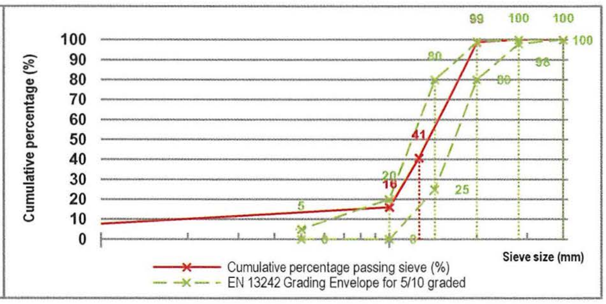
B.1 Geometrical properties - PARTICLE SIZE DISTRIBUTION — Operator: D. Mifsud

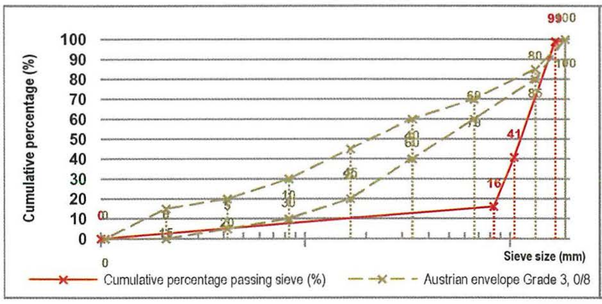
B.1.7 Crushed waste concrete from C45 test cubes — Date: 2003

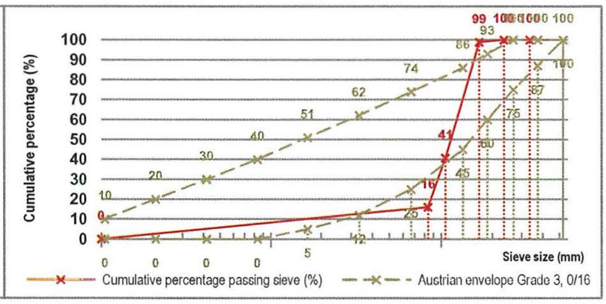
B.1.7.2 Grading: 10mm — Source: Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	**100**
R_2	20	0.0	0.0	0.0	0.0	**100**
R_3	14	0.0	0.0	0.0	0.0	**100**
R_4	10	13.8	12.6	13.2	1.1	**99**
R_5	6.3	700.2	643.8	672.0	58.1	**41**
R_6	5	263.8	307.9	285.9	24.7	**16**
P	0	178.4	192.6	185.5	16.0	**0**
ΣR_i + P =		1156.2	1156.9	1156.6	100.0	









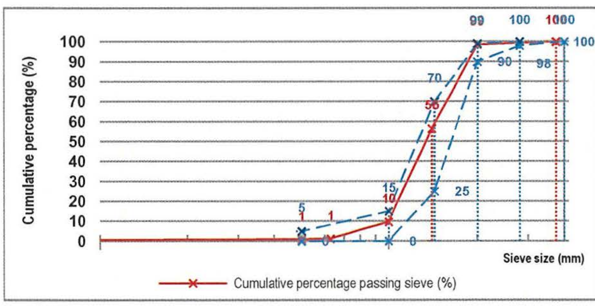
Aggr size in terms of d/D	EN 12620 Grading Envelope for 5/10 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 5/10 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	20	**100**	**100**	20	**100**	**100**	
1.4D	14	**100**	**98**	14.0	**100**	**98**	**Cumulative curve almost passes EN 12620 and EN 13242.**
D	10	**99**	**85**	10	**99**	**80**	
D/1.4	7.1	**70**	**25**	7.1	**80**	**25**	
d	5	**20**	**0**	5	**20**	**0**	
d/2	2.5	**5**	**0**	3	**5**	**0**	**Jaw crusher was used at University concrete laboratory.**
D/d	2.0	G_C85/20		2.0	G_C80/20		

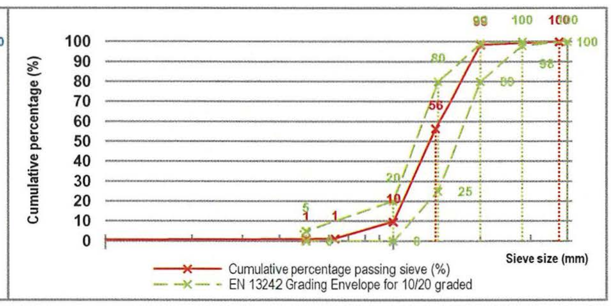
EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

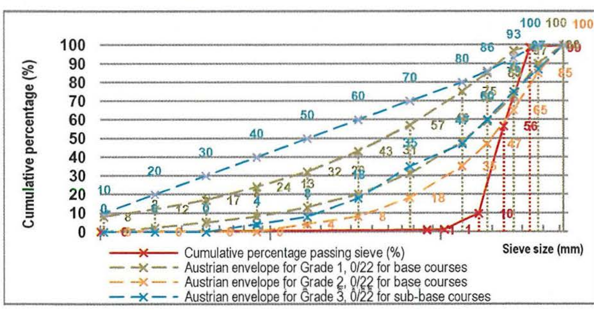
B.1.7.3 Grading: 20mm

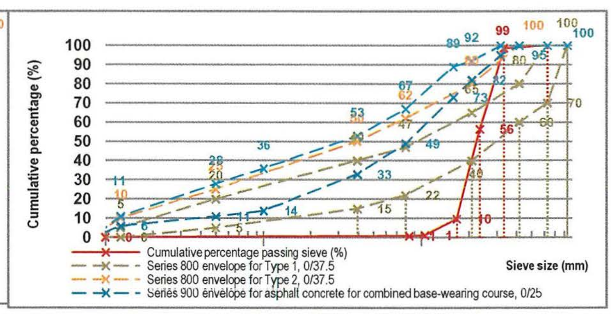
Source: Polidano

Sieve aperture size (mm)		Sample A mass retained on sieve (g)	Sample B mass retained on sieve (g)	Avg mass retained on sieve (g)	Avg % retained $R_{i,avg}/M_{avg}$*100	Cumulative percentage passing sieve (%)
R_1	37.5	0.0	0.0	0.0	0.0	100
R_2	20	47.4	38.4	42.9	1.5	99
R_3	14	1267.2	1197.2	1232.2	42.1	56
R_4	10	1344.5	1391.7	1368.1	46.8	10
R_5	6.3	236.9	260.1	248.5	8.5	1
R_6	5	9.0	8.1	8.6	0.3	1
P	0	21.5	30.0	25.8	0.9	0
$\Sigma R_i + P =$		2926.5	2925.5	2926.0	100.0	









Aggr size in terms of d/D	EN 12620 Grading Envelope for 10/20 graded	EN 12620 max grading limit	EN 12620 min grading limit	EN 13242 Grading Envelope for 10/20 graded	EN 13242 max limit	EN 13242 min limit	Comments
2D	40	100	100	40	100	100	Cumulative curve passes EN 12620 and EN 13242 envelopes.
1.4D	28	100	98	28.0	100	98	
D	20	99	90	20	99	80	
D/1.4	14.3	70	25	14.3	80	25	
d	10	15	0	10	20	0	Jaw crusher was used at University concrete laboratory.
d/2	5	5	0	5	5	0	
D/d	2.0	G_C90/15		2.0	G_C80/20		

EN 933-1 : 1997: Testing for geometrical properties of aggregates : Determination of particle size distribution: Sieve Analysis (BSI)
EN 12620 : 2002: Aggregates for concrete, Tables 2,3 with PD 6682-1:2009 (BSI)
EN13242 : 2002: Aggregates for hydraulically bound materials for use in civil engineering work and road construction, Tables 2,3 (BSI)
Der Österreichische Baustoff-Recycling Verband (2007) Guideline for recycled building materials. And Mifsud (2003).

B.2.1 Crushed waste concrete from mixed test cubes

Date: 30/03/2011

B.2.1.1 Grading: 6 to 9mm

Test portion mass M_0 (g) 1130.11

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	57.82
Sum of discarded masses (g)	57.82

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	170.90	2.5	12.98	7.6
5/6.3	472.30	3.15	54.98	11.6
6.3/8	419.96	4	68.18	16.2
8/10	9.02	5	0.49	5.4
$M_1 = \Sigma R_i =$	1072.18	$M_2 = \Sigma m_i =$	136.63	

$FI = (M_2/M_1) \times 100 =$ 12.7

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{(discarded masses)}]}{M_0} = 0.01 \quad < 1\%$$

B.2.1 Crushed waste concrete from mixed test cubes

Date: 01/04/2011

B.2.1.2 Grading: 9 to 18mm

Test portion mass M_0 (g) 3061.7

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	107.47
Sum of discarded masses (g)	107.47

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	17.68	2.5	2.35	0.13
5/6.3	22.21	3.15	3.1	0.14
6.3/8	202.78	4	22.02	0.11
8/10	511.92	5	38.08	0.07
10/12.5	817.26	6.3	91.49	0.11
12.5/16	660.92	8	63.34	0.10
16/20	586.34	10	52.89	0.09
20/25	135.26	12.5	0	0.00
$M_1 = \Sigma R_i =$	2954.37	$M_2 = \Sigma m_i =$	274.02	

$FI = (M_2/M_1) \times 100 =$ 9.3

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{(discarded masses)}]}{M_0} = 0.00 \quad < 1\%$$

B.2.2 Crushed waste concrete from block work

Date: 30/03/2011

B.2.2.1 Grading: 6 to 9mm

Test portion mass M_0 (g) 1162.54

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	33.17
Sum of discarded masses (g)	33.17

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	128.72	2.5	3.79	2.9
5/6.3	610.40	3.15	20.90	3.4
6.3/8	383.96	4	16.60	4.3
8/10	5.98	5	0.58	9.7
$M_1 = \Sigma R_i =$	1129.06	$M_2 = \Sigma m_i =$	41.87	

$FI = (M_2/M_1) \times 100 =$ 3.7

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{ (discarded masses)}]}{M_0} = 0.03 \quad < 1\%$$

B.2.2 Crushed waste concrete from block work

Date: 01/04/2011

B.2.2.2 Grading: 9 to 18mm

Test portion mass M_0 (g) 4346.78

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	31.78
Sum of discarded masses (g)	31.78

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	2.76	2.5	0	0.0
5/6.3	8.43	3.15	0.33	0.0
6.3/8	179.05	4	2.07	0.0
8/10	527.75	5	9.53	0.0
10/12.5	922.24	6.3	29.13	0.0
12.5/16	1276.56	8	21.1	0.0
16/20	1047.3	10	26.25	0.0
20/25	347.34	12.5	15.31	0.0
$M_1 = \Sigma R_i =$	4311.43	$M_2 = \Sigma m_i =$	103.91	

$FI = (M_2/M_1) \times 100 =$ 2.4

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{ (discarded masses)}]}{M_0} = 0.08 \quad < 1\%$$

B.2.3 Crushed waste concrete from planks — Date: 30/03/2011

B.2.3.1 Grading: 6 to 9mm — Test portion mass M_0 (g) 1130.11

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	30.59
Sum of discarded masses (g)	30.59

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	142.70	2.5	9.66	6.8
5/6.3	557.94	3.15	52.69	9.4
6.3/8	392.48	4	64.05	16.3
8/10	5.53	5	0.00	0.0
$M_1 = \Sigma R_i =$	1098.65	$M_2 = \Sigma m_i =$	126.40	

$FI = (M_2/M_1) \times 100 =$ 11.5

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{ (discarded masses)}]}{M_0} = 0.08 \quad < 1\%$$

B.2.3 Crushed waste concrete from planks — Date: 01/04/2011

B.2.3.2 Grading: 9 to 18mm — Test portion mass M_0 (g) 3588

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	23.75
Sum of discarded masses (g)	23.75

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	2.25	2.5	5.17	2.3
5/6.3	8.85	3.15	0.51	0.1
6.3/8	192.27	4	19.85	0.1
8/10	504.35	5	40.43	0.1
10/12.5	802.21	6.3	85.98	0.1
12.5/16	938.31	8	108.27	0.1
16/20	841.96	10	68.49	0.1
20/25	274.03	12.5	41.19	0.2
$M_1 = \Sigma R_i =$	3564.23	$M_2 = \Sigma m_i =$	372.88	

$FI = (M_2/M_1) \times 100 =$ 10.5

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{ (discarded masses)}]}{M_0} = 0.00 \quad < 1\%$$

B.2.4 Crushed waste concrete from Manuel Dimech bridge   Date: 30/03/2011

B.2.4.1   Grading: 6 to 9mm

Test portion mass M_0 (g) 1123.51

Mass retained on 80mm sieve (g)	0
Mass passing 4mm sieve (g)	1.04
Sum of discarded masses (g)	1.04

Sieving on test sieves		Sieving on bar sieves		
Particle size fraction d_i/D_i (g)	Mass (R_i) of particle size fraction d_i/D_i (g)	Nominal width of slot in bar sieve (mm)	Mass passing bar sieve	$FI_i = (m_i/R_i) \times 100$
4/5	3.02	2.5	0.00	0.0
5/6.3	95.67	3.15	3.74	3.9
6.3/8	410.12	4	14.06	3.4
8/10	329.93	5	13.08	4.0
10/12.5	260.57	6.3	6.38	2.4
12.5/16	20.32	8	1.90	9.4
$M_1 = \Sigma R_i =$	1119.63	$M_2 = \Sigma m_i =$	39.16	

$FI = (M_2/M_1) \times 100 =$ 3.5

$$100 \times \frac{M_0 - [\Sigma R_i + \Sigma \text{ (discarded masses)}]}{M_0} = 0.25 \quad < 1\%$$

Appendix C

Experimental results: Mechanical properties

C Mechanial properties - RESISTANCE TO FRAGMENTATION (Los Angeles test)

Operator: Author | Grading: 10 to 14mm | Revs: 500 | No. of balls: 11

C.1 Crushed waste concrete from mixed test cubes — Date: 23-25/03/2011

mass passing 12.5mm sieve (g)	3250.21	=	65.0	% from	5000.64
mass retained on 12.5mm sieve (g)	1750.43	=	35.0		
SAMPLE A: mass retained on 1.6mm sieve (g)	3493.25			Los Angeles value	30.1
oven dry mass retained on 1.6mm sieve (g)	3486.20			Los Angeles value	30.3
mass passing 12.5mm sieve (g)	3250.61	=	65.0	% from	5000.81
mass retained on 12.5mm sieve (g)	1750.20	=	35.0		
SAMPLE B: mass retained on 1.6mm sieve (g)	3522.62			Los Angeles value	29.5
oven dry mass retained on 1.6mm sieve (g)	3511.20			Los Angeles value	29.8
				Average LA value from samples A and B:	30.0

C.2 Crushed waste concrete from block work — Date: 28-30/03/2011

mass passing 12.5mm sieve (g)	3250.36	=	65.0	% from	5000.61
mass retained on 12.5mm sieve (g)	1750.25	=	35.0		
SAMPLE A: mass retained on 1.6mm sieve (g)	2605.70			Los Angeles value	47.9
oven dry mass retained on 1.6mm sieve (g)	2586.32			Los Angeles value	48.3
mass passing 12.5mm sieve (g)	3250.16	=	65.0	% from	5000.18
mass retained on 12.5mm sieve (g)	1750.02	=	35.0		
SAMPLE B: mass retained on 1.6mm sieve (g)	2704.64			Los Angeles value	45.9
oven dry mass retained on 1.6mm sieve (g)	2684.40			Los Angeles value	46.3
				Average LA value from samples A and B:	47.3

C.3 Crushed waste concrete from planks — Date: 25-29/03/2011

mass passing 12.5mm sieve (g)	3250.14	=	65.0	% from	5000.22
mass retained on 12.5mm sieve (g)	1750.08	=	35.0		
SAMPLE A. mass retained on 1.6mm sieve (g)	3378.90			Los Angeles value	32.4
oven dry mass retained on 1.6mm sieve (g)	3365.53			Los Angeles value	32.7
mass passing 12.5mm sieve (g)	3250.23	=	65.0	% from	5000.36
mass retained on 12.5mm sieve (g)	1750.13	=	35.0		
SAMPLE B: mass retained on 1.6mm sieve (g)	3364.85			Los Angeles value	32.7
oven dry mass retained on 1.6mm sieve (g)	3351.33			Los Angeles value	33.0
				Average LA value from samples A and B:	32.8

C.4 Crushed waste concrete from Manuel Dimech Bridge — Date: Sept 2009

Operator: R.P. Borg | Grading: 10 to 14mm | Revs: 500 | No. of balls: 11

mass passing 12.5mm sieve (g)	3250.80	=	65.0	% from	5001.50
mass retained on 12.5mm sieve (g)	1750.70	=	35.0		
mass retained on 1.6mm sieve (g)	3351.90			Los Angeles value	33.0
oven dry mass retained on 1.6mm sieve (g)	3333.00			Los Angeles value	33.3

EN 1097-2 : 1998 : Testing for mechanical and physical properties of aggregates: Methods for determination of resistance to fragmentation (BSI)

Appendix D

Experimental results: Physical properties

D.1.1 Crushed waste concrete from mixed test cubes

D.1.1.1 Grading: 0 to 6mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)			1200.12
Temperature of water (°C) 20.6	Density of water, ρ_w (Mgm^{-3})		0.9980
Mass of pyknometer, aggregate & added water after 24h (g)	M_2		868.79
Mass of pyknometer filled with water only (g)	M_3		600.65
Mass of saturated surface dried aggregate in air (g)	M_1		476.16
Mass of oven-dried aggregate (g)	M_4		446.65
Apparent particle density (Mgm^{-3})	ρ_a		2.50
Oven-dried particle density (Mgm^{-3})	ρ_{rd}		2.14
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}		2.28
Water absorption (% of dry mass)	WA_{24}		6.6
check	ρ_{ssd}		2.28

D.1.1.2 Grading: 6 to 9mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)			1200.15
Temperature of water (°C) 20.2	Density of water, ρ_w (Mgm^{-3})		0.9982
Mass of pyknometer, aggregate & added water after 24h (g)	M_2		1624.15
Mass of pyknometer filled with water only (g)	M_3		1183.57
Mass of saturated surface dried aggregate in air (g)	M_1		768.66
Mass of oven-dried aggregate (g)	M_4		703.09
Apparent particle density (Mgm^{-3})	ρ_a		2.67
Oven-dried particle density (Mgm^{-3})	ρ_{rd}		2.14
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}		2.34
Water absorption (% of dry mass)	WA_{24}		9.3
check	ρ_{ssd}		2.34

D.1.1.3 Grading: 9 to 18mm

Date: 05-07/04/2011

Test portion mass M_0 (before wet sieving) (g)			4500.69
Temperature of water (°C) 18.3	Density of water, ρ_w (Mgm^{-3})		0.9986
Apparent mass in water of wire basket with saturated aggregate (g)	M_2		3101.03
Apparent mass in water of empty wire basket (g)	M_3		549.70
Mass of saturated surface dried aggregate in air (g)	M_1		4554.12
Mass of oven-dried aggregate (g)	M_4		4202.37
Apparent particle density (Mgm^{-3})	ρ_a		2.54
Oven-dried particle density (Mgm^{-3})	ρ_{rd}		2.10
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}		2.27
Water absorption (% of dry mass)	WA_{24}		8.4
check	ρ_{ssd}		2.27

EN 1097-6 : 2000 : Testing for mechanical and physical properties of aggregates: Determination of particle density and water absorption (BSI)

D.1.2 Crushed waste concrete from block work

D.1.2.1 Grading: 0 to 6mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)		1200.04
Temperature of water (°C) 20.6 — Density of water, ρ_w (Mgm^{-3})		0.998
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	811.00
Mass of pyknometer filled with water only (g)	M_3	607.38
Mass of saturated surface dried aggregate in air (g)	M_1	356.32
Mass of oven-dried aggregate (g)	M_4	335.96
Apparent particle density (Mgm^{-3})	ρ_a	2.53
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.20
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.33
Water absorption (% of dry mass)	WA_{24}	6.1
check	ρ_{ssd}	2.33

D.1.2.2 Grading: 6 to 9mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)		1200.12
Temperature of water (°C) 20.2 — Density of water, ρ_w (Mgm^{-3})		0.9982
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	1649.25
Mass of pyknometer filled with water only (g)	M_3	1184.08
Mass of saturated surface dried aggregate in air (g)	M_1	805.21
Mass of oven-dried aggregate (g)	M_4	743.28
Apparent particle density (Mgm^{-3})	ρ_a	2.67
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.18
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.36
Water absorption (% of dry mass)	WA_{24}	8.3
check	ρ_{ssd}	2.36

D.1.2.3 Grading: 9 to 18mm

Date: 05-07/04/2011

Test portion mass M_0 (before wet sieving) (g)		4500.60
Temperature of water (°C) 18.3 — Density of water, ρ_w (Mgm^{-3})		0.9986
Apparent mass in water of wire basket with saturated aggregate (g)	M_2	3163.08
Apparent mass in water of empty wire basket (g)	M_3	575.98
Mass of saturated surface dried aggregate in air (g)	M_1	4713.92
Mass of oven-dried aggregate (g)	M_4	4321.12
Apparent particle density (Mgm^{-3})	ρ_a	2.49
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.03
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.21
Water absorption (% of dry mass)	WA_{24}	9.1
check	ρ_{ssd}	2.21

EN 1097-6 : 2000 : Testing for mechanical and physical properties of aggregates: Determination of particle density and water absorption (BSI)

D.1.3 Crushed waste concrete from planks

D.1.3.1 Grading: 0 to 6mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)			1200.02
Temperature of water (°C)	20.6	Density of water, ρ_w (Mgm^{-3})	0.998
Mass of pyknometer, aggregate & added water after 24h (g)		M_2	954.71
Mass of pyknometer filled with water only (g)		M_3	702.59
Mass of saturated surface dried aggregate in air (g)		M_1	470.91
Mass of oven-dried aggregate (g)		M_4	439.14
Apparent particle density (Mgm^{-3})		ρ_a	2.34
Oven-dried particle density (Mgm^{-3})		ρ_{rd}	2.00
Saturated surface dry particle density (Mgm^{-3})		ρ_{ssd}	2.15
Water absorption (% of dry mass)		WA_{24}	7.2
check		ρ_{ssd}	2.15

D.1.3.2 Grading: 6 to 9mm

Date: 25-27/04/2011

Test portion mass M_0 (before wet sieving) (g)			1200.09
Temperature of water (°C)	20.2	Density of water, ρ_w (Mgm^{-3})	0.9982
Mass of pyknometer, aggregate & added water after 24h (g)		M_2	1642.57
Mass of pyknometer filled with water only (g)		M_3	1181.38
Mass of saturated surface dried aggregate in air (g)		M_1	808.36
Mass of oven-dried aggregate (g)		M_4	742.24
Apparent particle density (Mgm^{-3})		ρ_a	2.64
Oven-dried particle density (Mgm^{-3})		ρ_{rd}	2.13
Saturated surface dry particle density (Mgm^{-3})		ρ_{ssd}	2.32
Water absorption (% of dry mass)		WA_{24}	8.9
check		ρ_{ssd}	2.32

D.1.3.3 Grading: 9 to 18mm

Date: 05-07/04/2011

Test portion mass M_0 (before wet sieving) (g)			4500.58
Temperature of water (°C)	18.3	Density of water, ρ_w (Mgm^{-3})	0.9986
Apparent mass in water of wire basket with saturated aggregate (g)		M_2	3125.89
Apparent mass in water of empty wire basket (g)		M_3	535.11
Mass of saturated surface dried aggregate in air (g)		M_1	4535.75
Mass of oven-dried aggregate (g)		M_4	4176.20
Apparent particle density (Mgm^{-3})		ρ_a	2.63
Oven-dried particle density (Mgm^{-3})		ρ_{rd}	2.14
Saturated surface dry particle density (Mgm^{-3})		ρ_{ssd}	2.33
Water absorption (% of dry mass)		WA_{24}	8.6
check		ρ_{ssd}	2.33

EN 1097-6 : 2000 : Testing for mechanical and physical properties of aggregates: Determination of particle density and water absorption (BSI)

D.1.4a Crushed waste concrete from Manuel Dimech Bridge — Date: Sept 2009

D.1.4a.1 Grading: < 4mm

Test portion mass M_0 (g)		1500.00
Density of water, ρ_w (Mgm^{-3})		1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	3763.4
Mass of pyknometer filled with water only (g)	M_3	2867.3
Mass of saturated surface dried aggregate in air (g)	M_1	1550.8
Mass of oven-dried aggregate (g)	M_4	1443.00
Apparent particle density (Mgm^{-3})	ρ_a	2.64
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.20
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.37
Water absorption (% of dry mass)	WA_{24}	7.5
check	ρ_{ssd}	2.37

D.1.4a.2 Grading: < 10mm

Test portion mass M_0 (g)		1501.00
Density of water, ρ_w (Mgm^{-3})		1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	3766.8
Mass of pyknometer filled with water only (g)	M_3	2867.3
Mass of saturated surface dried aggregate in air (g)	M_1	1552.3
Mass of oven-dried aggregate (g)	M_4	1470.3
Apparent particle density (Mgm^{-3})	ρ_a	2.58
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.25
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.38
Water absorption (% of dry mass)	WA_{24}	5.6
check	ρ_{ssd}	2.38

D.1.4a.3 Grading: < 20mm

Test portion mass M_0 (g)			4205.0
Density of water, ρ_w (Mgm^{-3})			1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	4166.90	4078.9
Mass of pyknometer filled with water only (g)	M_3	2867.30	2867.3
Mass of saturated surface dried aggregate in air (g)	M_1	2250.60	2102.6
Mass of oven-dried aggregate (g)	M_4	2134.00	1988.40
Apparent particle density (Mgm^{-3})	ρ_a	2.56	2.56
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.24	2.23
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.37	2.36
Water absorption (% of dry mass)	WA_{24}	5.5	5.7
check	ρ_{ssd}	2.37	2.36

EN 1097-6 : 2000 : Testing for mechanical and physical properties of aggregates: Determination of particle density and water absorption (BSI) and Borg (1998)

D.1.4b Crushed waste concrete from Manuel Dimech Bridge

Date: Sept 2009

D.1.4b.1 Grading: < 4mm

Test portion mass M_0 (g)		1505.00
Density of water, ρ_w (Mgm^{-3})		1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	1773.9
Mass of pyknometer filled with water only (g)	M_3	1364.3
Mass of saturated surface dried aggregate in air (g)	M_1	710.6
Mass of oven-dried aggregate (g)	M_4	662.40
Apparent particle density (Mgm^{-3})	ρ_a	2.62
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.20
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.36
Water absorption (% of dry mass)	WA_{24}	7.3
check	ρ_{ssd}	2.36

D.1.4b.2 Grading: < 10mm

Test portion mass M_0 (g)		1502.00
Density of water, ρ_w (Mgm^{-3})		1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	3812.5
Mass of pyknometer filled with water only (g)	M_3	2910.2
Mass of saturated surface dried aggregate in air (g)	M_1	1555.9
Mass of oven-dried aggregate (g)	M_4	1473.4
Apparent particle density (Mgm^{-3})	ρ_a	2.58
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.25
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	2.38
Water absorption (% of dry mass)	WA_{24}	5.6
check	ρ_{ssd}	2.38

D.1.4b.3 Grading: < 20mm

Test portion mass M_0 (g)			4205.7
Density of water, ρ_w (Mgm^{-3})			1
Mass of pyknometer, aggregate & added water after 24h (g)	M_2	4166.90	n/a
Mass of pyknometer filled with water only (g)	M_3	2910.20	n/a
Mass of saturated surface dried aggregate in air (g)	M_1	1851.20	n/a
Mass of oven-dried aggregate (g)	M_4	1749.80	n/a
Apparent particle density (Mgm^{-3})	ρ_a	3.55	2.56
Oven-dried particle density (Mgm^{-3})	ρ_{rd}	2.94	2.24
Saturated surface dry particle density (Mgm^{-3})	ρ_{ssd}	3.11	2.36
Water absorption (% of dry mass)	WA_{24}	5.8	5.7
check	ρ_{ssd}	3.11	2.36

EN 1097-6 : 2000 : Testing for mechanical and physical properties of aggregates: Determination of particle density and water absorption (BSI) and Borg (1998)

D.2 Physical properties - OVEN-DRY LOOSE BULK DENSITY   Operator: Author

D.2.1 Crushed waste concrete from mixed test cubes   Date: 08-09/04/2011

D.2.1.1 Grading: 0 to 6mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.3	0.1867	0.56827	0.38157	1.27
2	0.3	0.18669	0.57519	0.38850	1.30
3	0.3	0.18669	0.56925	0.38256	1.28
			average loose bulk density, ρ_b (Mgm^{-3})		**1.28**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.14	percentage of voids, v (%)	**40.15**

D.2.1.2 Grading: 6 to 9mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.4	0.1087	0.51653	0.408	1.02
2	0.5	0.18667	0.72789	0.541	1.08
3	0.5	0.18667	0.72058	0.534	1.07
			average loose bulk density, ρ_b (Mgm^{-3})		**1.06**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.14	percentage of voids, v (%)	**50.63**

D.2.1.3 Grading: 9 to 18mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.6	0.18665	0.896	0.709	1.18
2	0.8	0.18637	1.0265	0.840	1.05
3	0.8	0.18637	1.035	0.849	1.06
			average loose bulk density, ρ_b (Mgm^{-3})		**1.10**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.1	percentage of voids, v (%)	**47.72**

D.2 Physical properties - OVEN-DRY LOOSE BULK DENSITY

Operator: Author

D.2.2 Crushed waste concrete from block work

Date: 08-09/04/2011

D.2.2.1 Grading: 0 to 6mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.2	0.18667	0.44100	0.25433	1.27
2	0.2	0.18667	0.42296	0.23629	1.18
3	0.2	0.18667	0.42514	0.23847	1.19
			average loose bulk density, ρ_b (Mgm^{-3})		**1.22**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.2	percentage of voids, v (%)	**44.77**

D.2.2.2 Grading: 6 to 9mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.4	0.10876	0.54813	0.439	1.10
2	0.5	0.18667	0.74238	0.556	1.11
3	0.5	0.18667	0.75638	0.570	1.14
			average loose bulk density, ρ_b (Mgm^{-3})		**1.12**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.18	percentage of voids, v (%)	**48.79**

D.2.2.2 Grading: 9 to 18mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.6	0.18666	0.7609	0.5742	0.96
2	0.8	0.18678	0.8960	0.709	0.89
3	0.8	0.18679	0.8991	0.712	0.89
			average loose bulk density, ρ_b (Mgm^{-3})		**0.91**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.03	percentage of voids, v (%)	**55.11**

EN 1097-3: 1998: Testing for mechanical and physical properties of aggregates: Det. of loose bulk density and voids (BSI)

D.2.3 Crushed waste concrete from planks

Date: 08-09/04/2011

D.2.3.1 Grading: 0 to 6mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.3	0.1867	0.58982	0.40312	1.34
2	0.3	0.1867	0.57704	0.39034	1.30
3	0.3	0.18669	0.57925	0.39256	1.31
			average loose bulk density, ρ_b (Mgm^{-3})		**1.32**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2	percentage of voids, v (%)	**34.11**

D.2.3.2 Grading: 6 to 9mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.4	0.18706	0.62437	0.437	1.09
2	0.5	0.1867	0.70736	0.521	1.04
3	0.5	0.1867	0.69869	0.512	1.02
			average loose bulk density, ρ_b (Mgm^{-3})		**1.05**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.13	percentage of voids, v (%)	**50.57**

D.2.3.3 Grading: 9 to 18mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.6	0.18667	0.798	0.611	1.02
2	0.8	0.1871	1.0185	0.831	1.04
3	0.8	0.1871	1.025	0.838	1.05
			average loose bulk density, ρ_b (Mgm^{-3})		**1.04**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.14	percentage of voids, v (%)	**51.63**

D.2.4 Crushed waste concrete from Manuel Dimech bridge

Date: 08-09/04/2011

D.2.4.1 Grading: < 4mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.6	0.18668	1.0224	0.836	1.39
2	0.6	0.18659	0.9873	0.801	1.33
3	0.6	0.18659	0.9876	0.801	1.34
			average loose bulk density, ρ_b (Mgm^{-3})		**1.35**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.22	percentage of voids, v (%)	**39.00**

D.2.4.2 Grading: < 10mm

	capacity of container, V (l)	mass of empty container, m_1 (kg)	mass of container and specimen, m_2 (kg)	mass of dry specimen (kg)	loose bulk density, ρ_b (Mgm^{-3})
1	0.6	0.18662	0.86286	0.676	1.13
2	0.6	0.18664	0.85638	0.670	1.12
3	0.6	0.18665	0.86333	0.677	1.13
			average loose bulk density, ρ_b (Mgm^{-3})		**1.12**
	oven-dried particle density, ρ_{rd} (Mgm^{-3})		2.25	percentage of voids, v (%)	**50.06**

D.2.4.3 Grading: < 20mm

Note: this grading size was not available for testing in 2011 (time of dissertation)

Appendix E

Experimental results: Chemical properties

Appendix E.1 Proof of equivalence of limits provided in BS and EN

Proof why limits in BS 882 can be used for results of experiment in EN 1744-5 and EN 1744-1

Step 1: Comparison of different equations used in BS 1881-124 and EN 1744-5.

BS 1881-124:1986 is an old version of the experiments used in EN 1744-5, with same chemical being used. If the concentrations of solutions used are the same, it can be proven that the equations in one equal the equations in the other. The method in EN 1744-1 uses different reagents for finding water-soluble content. However, since water-soluble content is a fraction of acid-soluble content, same limits apply.

In BS 1881-124, Acid-soluble chloride content (% by mass of cement) = $\{V_5 - \frac{V_6 m}{0.1}\} \frac{0.3545}{M_c} * \frac{100}{C_1}$ where

V_5 is volume of silver nitrate solution added. Let V_5= 5ml (same as EN 1744-1)
V_6 is volume of thiocyanate solution added. Found during experiment.
m is molarity (mol/L) of thiocyanate solution = 0.1 (according to both BS 1881-124 and EN 1744-1)
c_1 is cement content of sample used (%). This is unknown with RCA.
M_c is mass of sample used. Let M_c = 2g (same as EN 1744-1)

Substituting in equation, Chloride content = $\{5 - \frac{V_6(0.1)}{0.1}\} * \frac{0.3545}{2} * \frac{100}{C_1} = \{5 - V_6\} * \frac{0.3545}{2} * \frac{100}{C_1}$

⇒ Chloride content = $\{5 - V_6\} * \frac{0.3545}{2} * \frac{100}{C_1}$ ..... (1)

In EN 1774-5, Acid-soluble chloride content (% by mass of aggregate) = $\frac{0.3545(5 - 10C_T V_1)}{m}$

where
C_T is molarity (mol/L) of thiocyanate solution = 0.1 (according to method in EN 1744-5)
V_1 is volume of thiocyanate solution added. Found during experiment.
m is mass of sample used = 2g (according to method EN 1744-5)
5ml silver nitrate solution added (according to EN 1744-5)

⇒ Chloride content = $\frac{0.3545(5 - 10(0.1)V_1)}{2} = (5 - V_1) * \frac{0.3545}{2}$ .....(2)

It can be noticed that the only difference between equations (1) and (2) is the factor $\frac{100}{C_1}$.

By mass of cement (1)........ $\{5 - V\} * \frac{0.3545}{2} * \frac{100}{c}$

By mass of RCA (2)............ $\{5 - V\} * \frac{0.3515}{2} * X \Rightarrow X = \frac{100}{c}$ ....(3)

∴ Conversion from chloride content by mass of cement (%) to chloride content by mass of RCA (%)

⇒ chloride content by mass of cement (%) is multiplied by $\frac{c}{100}$ (referred to as X)

Step 2: Deriving conversion factor X for typical local scenario

Now, c = maximum cement content of total concrete = $\frac{\text{density of cement}*100\%}{\text{density of concrete}}$ ....(4)

Where density of concrete in our case is density of RCA.

In order to test the theory (3): Limit value for (2) multiplied by a conversion factor, X, gives limit value for (1), the densities of cement and concrete shall be chosen in order to get the highest possible cement content. This way the lowest possible value is obtained as a result and used as a limit where experimental results are not to exceed this limit to be used for particular applications.

Now, to obtain the highest possible cement content, the lowest possible density of cement and the highest possible density of concrete are to be used.

Considering different types of concrete applications and their requirements,

Finding minimum local cement density

Reinforced concrete: maximum cement content for Portland cement is 400kgm^{-3} (BS 8007:1987 cl 6.3)
Prestressed concrete: max cement content for Portland cement is 500kgm^{-3} (BS 8007: 1987 cl 6.3)
Reinforced and prestressed concrete: least minimum cement content from all exposure classes is 260kgm^{-3} for XC1 (EN 206-1: Table F.1)

∴ Consider cement density of 260kgm^{-3}, which is the least possible density which is allowed.

Finding maximum local concrete density

Highest density for concrete used in design calculations: 2400kgm^{-3} (EN 1991-1-1, Table A.1)

Typical densities of blocks from Ballut: 1811 - 1852kgm^{-3}
Typical densities of prestressed slabs from Ballut (per m): 2228 - 2344kgm^{-3}
(smallest and largest depths of elements)

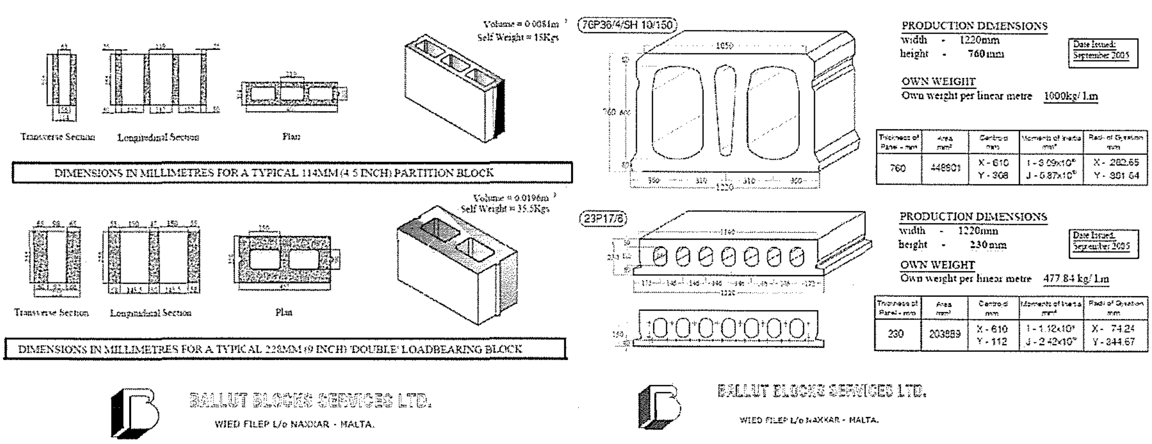


Figure D.1.1: Typical local concrete construction elements of minimum and maximum concrete densities. Source: http://www.ballutblocks.com/index.html

∴ Consider concrete density of 2400kgm^{-3}, which is the highest possible density which is used locally. This is to represent the RCA density used in the experiments.

(4) C = Maximum cement content of total concrete = $\frac{\text{MIN density of cement}*100\%}{\text{MAX density of concrete}} = \frac{260*100\%}{2400}$ = 11% = X

Step 3: Using derived conversion factor to confirm equivalence of limits and to find values for missing limits

Hence, if one uses the limits to be used for (1) and multiplies them by factor X, the limits to be used for (2) are to result. This is in fact the case for all concrete applications provided with limits. Calculations are in the middle column of Table 5.12.

Type of concrete	**Limit in EN 206-1 (by mass of cement)**	**Calculations**	**Limit in BS 882 (by mass of combined aggregate)**
Not containing reinforcement and embedded metal	1%	$\frac{1}{100} * \frac{260*100}{2400}$ = 0.11% ≈ 0.1%	No limit provided
Containing reinforcement and embedded metal (With sulfate resisting cement)	0.2%	$\frac{0.2}{100} * \frac{260*100}{2400}$ = 0.022% ≈ 0.03%	0.03%
Concrete containing reinforcement and embedded metal (Other reinforced concrete)	0.4%	$\frac{0.4}{100} * \frac{260*100}{2400}$ = 0.043% ≈ 0.05%	0.05%
Containing prestressing steel	0.1%	$\frac{0.1}{100} * \frac{260*100}{2400}$ = 0.011% ≈ 0.01%	0.01% (only one is mentioned)
	0.2%	$\frac{0.2}{100} * \frac{260*100}{2400}$ = 0.022% ≈ 0.03%	

Table D.1.2: Showing conversion of limits provided in EN 206-1 to those in BS 822

Hence, it has been concluded that although not specified by EN standards, the limits provided in BS 882 can be used locally for results of tests carried out by EN 1744-1 and EN 1744-5.

E.2 Chemical properties - WATER-SOLUBLE CHLORIDES (Mohr method) Operator: Author

E.2.1 Crushed waste concrete from mixed test cubes (Blokrete)	Date:07/04/2011
Mass of test specimen, m (g)	250.09
Volume of the silver nitrate solution, $V_{8,A}$ (ml)	0.6
Volume of the silver nitrate solution, $V_{8,B}$ (ml)	0.6
Average volume of the silver nitrate solution, $V_{8,AVG}$ (ml)	0.6
W = 1000/m	4.00
C = [0.01*(0,0354)*5*V_8*W*4] (%)	0.0170

E.2.2 Crushed waste concrete from block work (Blokrete)	Date:07/04/2011
Mass of test specimen, m (g)	250.12
Volume of the silver nitrate solution, $V_{8,A}$ (ml)	0.7
Volume of the silver nitrate solution, $V_{8,B}$ (ml)	0.7
Average volume of the silver nitrate solution, $V_{8,AVG}$ (ml)	0.7
W = 1000/m	4.00
C = [0.01*(0,0354)*5*V_8*W*4] (%)	0.0198

E.2.3 Crushed waste concrete from planks (Blokrete)	Date:07/04/2011
Mass of test specimen, m (g)	250.04
Volume of the silver nitrate solution, $V_{8,A}$ (ml)	0.9
Volume of the silver nitrate solution, $V_{8,B}$ (ml)	0.95
Average volume of the silver nitrate solution, $V_{8,AVG}$ (ml)	0.925
W = 1000/m	4.00
C = [0.01*(0,0354)*5*V_8*W*4] (%)	0.0262

E.2.4 Crushed waste concrete from Manuel Dimech bridge	Date:10/03/2011
Mass of test specimen, m (g)	250.17
Volume of the silver nitrate solution, $V_{8,A}$ (ml)	1.3
Volume of the silver nitrate solution, $V_{8,B}$ (ml)	1.1
Average volume of the silver nitrate solution, $V_{8,AVG}$ (ml)	1.2
W = 1000/m	4.00
C = [0.01*(0,0354)*5*V_8*W*4] (%)	0.0340

E.2.5 Crushed waste concrete from conventional aggregate (Ballut)	Date:10/03/2011
Mass of test specimen, m (g)	250.14
Volume of the silver nitrate solution, $V_{8,A}$ (ml)	0.6
Volume of the silver nitrate solution, $V_{8,B}$ (ml)	0.5
Average volume of the silver nitrate solution, $V_{8,AVG}$ (ml)	0.55
W = 1000/m	4.00
C = [0.01*(0,0354)*5*V_8*W*4] (%)	0.0156

EN 1744-1 : 2009 : Tests for chemical properties of aggregates: Chemical analysis; clause 9 (BSI)

E.3 Chemical properties - ACID-SOLUBLE CHLORIDES (Volhard Method) — Operator: Author

Volume of thiocyanate solution added, V_0 (ml)	24.8
Concentration of thiocyanate solution, $c_T = 2.5/V_0$ (moles/litre)	0.10081

E.3.1 Crushed waste concrete from mixed test cubes (Blokrete) — Date:08/04/2011

Mass of test specimen A, m_A (g)	2.0007	Mass of test specimen B, m_B (g)	2.0003
Volume of thiocyanate solution added $V_{1,A}$ (ml)	3.85	Volume of thiocyanate solution added $V_{1,B}$ (ml)	3.9
		Soluble chloride content, $C_{a,A} = 0.3545*(5-(10*c_T*V_{1,A}))/m_A$, (%)	0.1983
		Soluble chloride content, $C_{a,B} = 0.3545*(5-(10*c_T*V_{1,B}))/m_B$, (%)	0.1894
		Average soluble chloride content, $C_{a,AVG}$ (%)	0.1938

E.3.2 Crushed waste concrete from block work (Blokrete) — Date:08/04/2011

Mass of test specimen A, m_A (g)	2.0008	Mass of test specimen B, m_B (g)	2.0007
Volume of thiocyanate solution added $V_{1,A}$ (ml)	3.8	Volume of thiocyanate solution added $V_{1,B}$ (ml)	3.8
		Soluble chloride content, $C_{a,A} = 0.3545*(5-(10*c_T*V_{1,A}))/m_A$, (%)	0.2072
		Soluble chloride content, $C_{a,B} = 0.3545*(5-(10*c_T*V_{1,B}))/m_B$, (%)	0.2072
		Average soluble chloride content, $C_{a,AVG}$ (%)	0.2072

E.3.3 Crushed waste concrete from planks (Blokrete) — Date:08/04/2011

Mass of test specimen A, m_A (g)	2.0009	Mass of test specimen B, m_B (g)	2.0010
Volume of thiocyanate solution added $V_{1,A}$ (ml)	3.95	Volume of thiocyanate solution added $V_{1,B}$ (ml)	4
		Soluble chloride content, $C_{a,A} = 0.3545*(5-(10*c_T*V_{1,A}))/m_A$, (%)	0.1804
		Soluble chloride content, $C_{a,B} = 0.3545*(5-(10*c_T*V_{1,B}))/m_B$, (%)	0.1714
		Average soluble chloride content, $C_{a,AVG}$ (%)	0.1759

E.3.4 Crushed waste concrete from Manuel Dimech bridge — Date:14/03/2011

Mass of test specimen A, m_A (g)	2.0000	Mass of test specimen B, m_B (g)	2.0004
Volume of thiocyanate solution added $V_{1,A}$ (ml)	2.4	Volume of thiocyanate solution added $V_{1,B}$ (ml)	2.5
		Soluble chloride content, $C_{a,A} = 0.3545*(5-(10*c_T*V_{1,A}))/m_A$, (%)	0.4574
		Soluble chloride content, $C_{a,B} = 0.3545*(5-(10*c_T*V_{1,B}))/m_B$, (%)	0.4395
		Average soluble chloride content, $C_{a,AVG}$ (%)	0.4484

E.3.5 Crushed waste concrete from conventional aggregate (Ballut) — Date:14/03/2011

Mass of test specimen A, m_A (g)	2.0003	Mass of test specimen B, m_B (g)	2.0010
Volume of thiocyanate solution added $V_{1,A}$ (ml)	4.4	Volume of thiocyanate solution added $V_{1,B}$ (ml)	4.5
		Soluble chloride content, $C_{a,A} = 0.3545*(5-(10*c_T*V_{1,A}))/m_A$, (%)	0.1000
		Soluble chloride content, $C_{a,B} = 0.3545*(5-(10*c_T*V_{1,B}))/m_B$, (%)	0.0822
		Average soluble chloride content, $C_{a,AVG}$ (%)	0.0911

EN 1744-5 : 2006 : Tests for chemical properties of aggregates: Determination of acid soluble chloride salts (BSI)

Appendix E.4 Difficulties encountered with water-soluble sulfate test for RCA

Method specified for water-soluble sulfate content of RCA in EN 1744-1

In EN 1744-1, there are two methods proposed for water-soluble sulfates: one for natural aggregates (clause 10.1) and the other from recycled aggregates (clause 10.2). It should be noted however that the one for recycled aggregates uses a different method (spectrophotometry) than that for natural aggregates (precipitation).

It was decided to use clause 10.1 only, for all the water-sulfate experiments of NA and RCA for the following reasons:

1. The readings from the spectrophotometer (clause 10.2) are in 'abs' which is a measure of absorption of light set at a particular wavelength, while the readings from precipitation (clause 10.1) are in grams (mass of sulfate precipitate formed). Interpretation of the spectrophotometer results to be comparable to mass of precipitate is not possible since different parameters are being tested. Also, different concentrations are being handled in both experiments rendering them unfit to be compared. (Ratio of sample to water in experiment for natural aggregates is 1:2 while that for recycled aggregates is 1:40).

2. The method by spectrophotometry does not specify amount of barium chloride to be added but instead says that it is to be specified by manufacturer, nor does it specify the resting time required before inserting sample into spectrophotometer or the wavelength required to input in the apparatus before starting the experiment.

It is the author's view that this method should be revised with clearer and more detailed instructions by BSI.

The experiment was still carried out with the bridge material using the same amount of barium chloride as that for the NA experiment (clause 10.1), leaving it rest for 15 minutes and at a wavelength of 420nm. The spectrophotometer reads the absorption of light passing through the solution with the precipitate hindering its passage, so as long as there is excess of barium chloride for all the precipitate to form, the actual amount added is irrelevant. Since the precipitate was not even visible, 5ml was definitely an excess and sufficient. The wavelength was researched and found to be 420nm for sulfates. Results from this experiment (clause 10.2) were however inconclusive since sulfate content percentage could not be interpreted from the result attained (0.0027 abs).

E.5 Chemical properties - WATER-SOLUBLE SULFATES

Operator: Author

Hours of shaking (hrs) 24.5 | Shaker settings 200 rpm at room temp

E.5.1 Crushed waste concrete from mixed test cubes (Blokrete) — 18-20/04/2011

Mass of test specimen A, m_A (g)	250.1	Mass of test specimen B, m_B (g)	250.0
Mass of precipitate A, $m_{3,A}$ (g)	0.0196	Mass of precipitate B, $m_{3,B}$ (g)	0.0117
W = 500/$m_{3,A}$ (g)	2.00	W = 500/$m_{3,B}$ (g)	2.00
Soluble sulfate content SO_3=2*W*0.343*$m_{3,A}$ (%)	0.0269	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0323
Soluble sulfate content SO_3=2*W*0.343*$m_{3,B}$ (%)	0.0161	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0193
AVG Soluble sulfate content SO_3 (%)	0.0215	AVG Soluble sulfate content SO_4 (%)	0.0258

E.5.2 Crushed waste concrete from block work (Blokrete) — 19-21/04/2011

Mass of test specimen A, m_A (g)	250.0	Mass of test specimen B, m_B (g)	250.0
Mass of precipitate A, $m_{3,A}$ (g)	0.0438	Mass of precipitate B, $m_{3,B}$ (g)	0.0132
W = 500/$m_{3,A}$ (g)	2.00	W = 500/$m_{3,B}$ (g)	2.00
Soluble sulfate content SO_3=2*W*0.343*$m_{3,A}$ (%)	0.0601	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0721
Soluble sulfate content SO_3=2*W*0.343*$m_{3,B}$ (%)	0.0181	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0217
AVG Soluble sulfate content SO_3 (%)	0.0391	AVG Soluble sulfate content SO_4 (%)	0.0469

E.5.3 Crushed waste concrete from planks (Blokrete) — 18-20/04/2011

Mass of test specimen A, m_A (g)	250.0	Mass of test specimen B, m_B (g)	250.2
Mass of precipitate A, $m_{3,A}$ (g)	0.0111	Mass of precipitate B, $m_{3,B}$ (g)	0.0098
W = 500/$m_{3,A}$ (g)	2.00	W = 500/$m_{3,B}$ (g)	2.00
Soluble sulfate content SO_3=2*W*0.343*$m_{3,A}$ (%)	0.0152	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0183
Soluble sulfate content SO_3=2*W*0.343*$m_{3,B}$ (%)	0.0134	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0161
AVG Soluble sulfate content SO_3 (%)	0.0143	AVG Soluble sulfate content SO_4 (%)	0.0172

E.5.4 Crushed waste concrete from Manuel Dimech bridge — 18-20/04/2011

Mass of test specimen A, m_A (g)	250.0	Mass of test specimen B, m_B (g)	250.0
Mass of precipitate A, $m_{3,A}$ (g)	0.0634	Mass of precipitate B, $m_{3,B}$ (g)	0.0403
W = 500/$m_{3,A}$ (g)	2.00	W = 500/$m_{3,B}$ (g)	2.00
sulfate content SO_3=2*W*0.343*$m_{3,A}$ (%)	0.0870	sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.1044
sulfate content SO_3=2*W*0.343*$m_{3,B}$ (%)	0.0553	sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0663
AVG Soluble sulfate content SO_3 (%)	0.0711	AVG Soluble sulfate content SO_4 (%)	0.0854

E.5.5 Crushed waste concrete from conventional aggregate (Ballut) — 19-21/04/2011

Mass of test specimen A, m_A (g)	250.0	Mass of test specimen B, m_B (g)	250.1
Mass of precipitate A, $m_{3,A}$ (g)	0.0039	Mass of precipitate B, $m_{3,B}$ (g)	0.0042
W = 500/$m_{3,A}$ (g)	2.00	W = 500/$m_{3,B}$ (g)	2.00
Soluble sulfate content SO_3=2*W*0.343*$m_{3,A}$ (%)	0.0054	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0064
Soluble sulfate content SO_3=2*W*0.343*$m_{3,B}$ (%)	0.0058	Soluble sulfate content SO_4=2*W*0.4116*$m_{3,A}$ (%)	0.0069
AVG Soluble sulfate content SO_3 (%)	0.0056	AVG Soluble sulfate content SO_4 (%)	0.0067

EN 1744-1 : 2009 : Tests for chemical properties of aggregates: Chemical analysis; clause 10.1 (BSI)

Appendix E.6 Difficulties encountered with acid-soluble sulfate test for RCA

Explanation for use of BS 1881-124 instead of EN 1744-1

Some problems were encountered with apparatus used at the Chemistry department as specified EN 1744-1.

1. The sintered silica filter crucible of porosity grade 4 melted (figure D.6.1) at the temperature specified in the code (900°C), possibly because the filter crucibles available were not made from pure silica. The experiment was repeated at a temperature of 300°C which did not result in melting hence this solved the first problem.

Figure D.6.1: Melted filter crucible (before and after heating at 900°C)

2. The medium porosity filter paper did not dissolve in solution, even when the experiment was repeated and with alternative methods. It is highly probable that the medium porosity filter paper used did not have dissolvable properties (figure D.6.2). This meant that the solution had traces of filter paper before even forming the precipitate, rendering any residue on the filter crucible incorrect due to the presence of the undissolved filter paper.

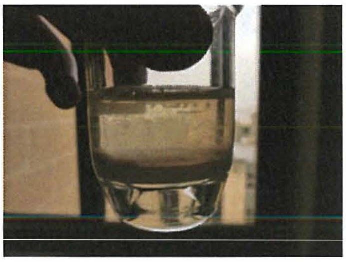


Figure D.6.2: Undissolved filter paper

Hence it was decided to use the BS method, where the same reagents are used and same reactions take place but different apparatus and techniques are used: specifically the burning of ashless filter paper without flaming, in a platinum crucible, as opposed to dissolving normal medium porosity grade filter paper in solution.

E.7 Chemical properties - ACID-SOLUBLE SULFATES — Operator: Author

E.7.1 Crushed waste concrete from Manuel Dimech bridge — 12-13/05/2011

Mass of test specimen, m_A (g)	5.0009	Mass of test specimen, m_B (g)	5.0008
Mass of precipitate, $m_{1,A}$ (g)	0.0110	Mass of precipitate, $m_{1,B}$ (g)	0.0130
Soluble sulfate content $SO_3 = m_{1,A} / m_A * 34.3$ (%)	0.0754	Soluble sulfate content $SO_4 = m_{1,A} / m_A * 41.16$ (%)	0.0905
Soluble sulfate content $SO_3 = m_{1,B} / m_B * 34.3$ (%)	0.0892	Soluble sulfate content $SO_4 = m_{1,B} / m_B * 41.16$ (%)	0.1070
AVG Soluble sulfate content SO_3 (%)	0.0823	AVG Soluble sulfate content SO_4 (%)	0.0988

E.7.2 Crushed waste concrete from conventional aggregate (Ballut) — 12-13/05/2011

Mass of test specimen, m_A (g)	5.0001	Mass of test specimen, m_B (g)	5.0005
Mass of precipitate, $m_{1,A}$ (g)	0.0015	Mass of precipitate, $m_{1,B}$ (g)	0.0018
Soluble sulfate content $SO_3 = m_{1,A} / m_A * 34.3$ (%)	0.0103	Soluble sulfate content $SO_4 = m_{1,A} / m_A * 41.16$ (%)	0.0123
Soluble sulfate content $SO_3 = m_{1,B} / m_B * 34.3$ (%)	0.0123	Soluble sulfate content $SO_4 = m_{1,B} / m_B * 41.16$ (%)	0.0148
AVG Soluble sulfate content SO_3 (%)	0.0113	AVG Soluble sulfate content SO_4 (%)	0.0136

BS 1881 : Part 124 : 1988: Methods for analysis of hardened concrete. clause 10.3. (BSI)

Appendix F

Waste Generation inventory

for local case studies: Numerical Data

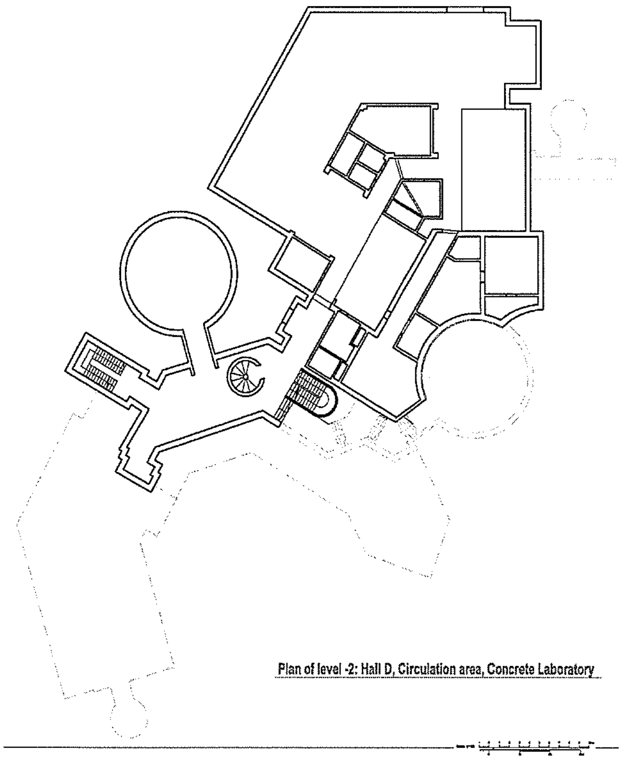
F Waste Generation Inventory: Numerical Data

F.1.1 Waste inventory for demolition of Faculty for the Built Environment Tal-Qroqq

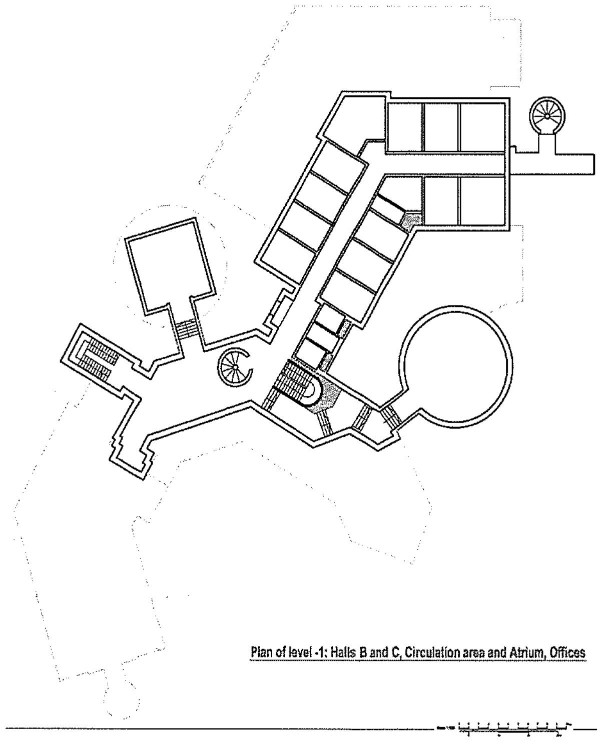
EWC	Material	Element Description	Qty	Area (m^2)	Height/ Length (m)	Volume, V (m^3)	Density ρ, (kNm^{-3})	Weight V*ρ,(kN)
Level -2: Basement: Hall D, Circulation area, Concrete Laboratory								
17 01 01	Concrete (C25)	ground slab	1	1185.00	0.25	296.3	25	7406.3
17 01 01	Concrete (C25)	roof slab	1	321.00	0.3	96.3	25	2407.5
17 01 01	Concrete	screed (roof of Hall B)	1	321.00	0.1	16.1	24	385.2
17 05 04	Sand	torba (for levelling)	1	321.00	0.02	6.4	19	122.0
17 05 04	Stone Masonry	parapet wall	1	22.00	1.10	24.2	27	653.4
17 05 04	Stone Masonry	walls (excl. windows/doors)	1	171.90	3.0	497.4	27	13430.3
17 01 01	concrete	columns	4	0.07	4.0	1.1	25	28.3
17 02 02	Glass	windows, doors	14	-	0.004	0.56	25	14.0
17 04 02	Aluminum	windows, doors	14	-	0.018	0.32	27	8.6
17 04 05	Metal	garage door	1	-	2.50	0.75	77	57.8
17 02 01	Wood	doors	26	-	2.10	1.34	3.5	4.7
17 01 03	gres, terrazzo, travertine	tiles	1	260.00	0.01	2.6	21	54.6
Level -1: Halls B and C, Circulation area and Atrium, Offices								
17 01 01	Concrete (C25)	ground slab (excl. shafts)	1	841.50	0.3	252.5	25	6311.3
17 01 01	Concrete (C25)	roof slab (Hall B, skylight)	1	56.00	0.3	16.8	25	420.0
17 01 01	Concrete	screed (roof of Hall B)	1	56.00	0.1	2.8	24	67.2
17 05 04	Sand	torba (for levelling)	1	56.00	0.02	1.1	19	21.3
17 04 05	steel	space frame (incl. purlins, without cladding)	1	340.00	0.8	272.0	78.5	85.0
17 04 05	metal	cladding	1	340.00	-	0.6	78.5	51.0
17 04 05	steel	columns (not composite)	12	0.0001	6.5	0.009	78.5	0.7
17 04 05	steel	bracing bars	5	0.0028	-	0.36	78.5	28.3
17 05 04	Stone Masonry	walls (excl. windows/doors)	1	187.10	3.0	542.65	27	14651.6
17 01 01	concrete	block work (toilets)	1	4.20	3.0	12.94	18	234.3
17 04 05	metal	railings (stairs)	1	0.02	6.0	0.38	77	29.3
17 02 02	Glass	windows, doors, atrium	35	-	0.004	1.34	25	33.5
17 04 02	Aluminum	windows, doors, atrium	35	-	0.018	3.39	27	91.5
17 02 01	Wood	windows, doors	22	-	-	0.79	4	2.8
17 08 02	Gypsum	soffit (corridor& toilets)	1	76.00	0.01	0.76	15	11.4
17 01 03	gres, terrazzo, travertine	tiles	1	650.20	0.01	6.5	21	136.5
Level 0: Hall A, Circulation area and Atrium, IT lab, Offices								
17 01 01	Concrete (C25)	ground slab (excl. shafts)	1	1068.00	0.3	320.4	25	8010.0
17 05 04	Stone Masonry	walls (excl. windows/doors)	1	232.10	3.0	677.65	27	18296.6
17 01 01	concrete	block work (toilets)	1	4.20	3.0	12.94	18	234.3
17 01 01	Concrete (C25)	roof slab (Hall A, offices)	1	464.00	0.3	139.2	25	3480.0
17 01 01	Concrete	screed (roof slab)	1	464.00	0.1	23.2	24	556.8
17 05 04	Sand	torba (for levelling)	1	464.00	0.02	9.3	19	176.3
17 01 01	concrete	columns	11	0.07	4.0	3.1	25	77.8
17 01 01	Concrete (C25)	beams	6	3.50	0.3	6.3	25	157.5

EWC stands for European Waste Catalgoue - Materials are labelled when dismantled/demolished for disposal or reuse.
Densities are taken from EN 1991, Annex A. Unit conversion: 0.1tonne = 1kN = 100kg

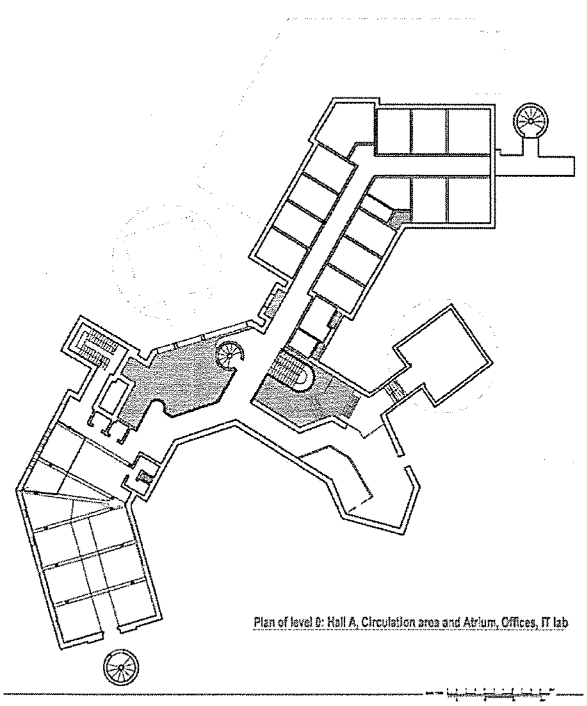
Appendix F.1.2 Plans of Faculty for the Built Environment, University of Malta



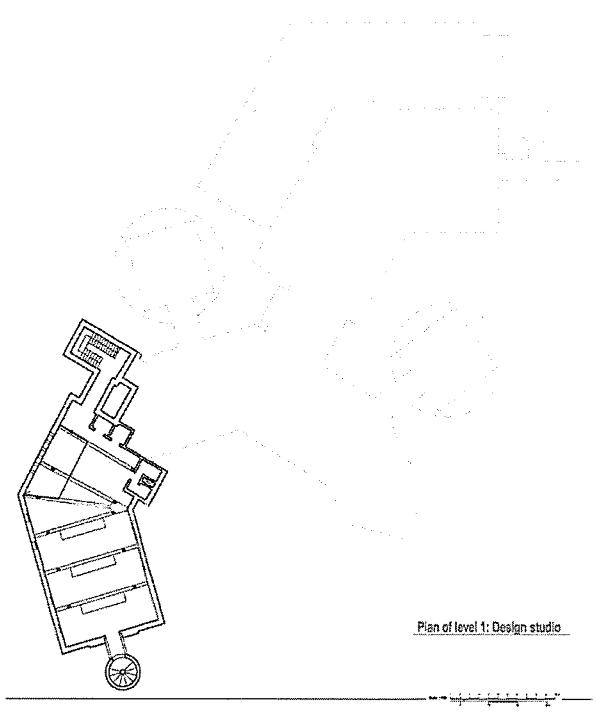
Plan of level -2: Hall D, Circulation area, Concrete Laboratory



Plan of level -1: Halls B and C, Circulation area and Atrium, Offices



Plan of level 0: Hall A, Circulation area and Atrium, Offices, IT lab



Plan of level 1: Design studio

F.2.1 Waste inventory for demolition of Block of apartments — Qormi

EWC	Material	Element Description	Qty	CSA/Area (m^2)	Height/ Length (m)	Volume, V (m^3)	Density ρ, (kNm^{-3})	Weight V*ρ,(kN)
Level -2: Basement garage								
17 01 01	Concrete (C25)	ground slab (incl. ramp)	1	135.40	0.25	33.9	25	846.3
17 01 01	Concrete (C25)	beams	3	0.70	0.4	0.8	25	21.0
17 01 01	Concrete (C25)	stairs	1	3.11	0.4	1.2	25	31.1
17 01 01	Concrete (C40)	precast planks (part of ceiling)	10	5.80	0.3	17.4	25	435.0
17 05 04	Stone Masonry	walls	1	17.53	2.5	43.8	27	1183.3
Levels -1, 0, 1, 2: Typical floor								
17 01 01	Concrete (C25)	ground slabs (including flush beams)	3.5	114.00	0.3	119.7	25	2992.5
17 01 01	Concrete (C25)	front balcony slabs	2	8.79	0.3	5.3	25	131.9
17 05 04	Stone Masonry	walls (excl. windows/doors)	4	19.28	3.0	68.02	27	1836.5
17 05 04	Stone	balcony courses	4	0.69	0.26	0.7	27	19.4
17 04 05	Wrought iron	balcony railings	4	-	1.1	0.04	76	2.9
17 02 02	Glass	windows, doors	4	-	0.004	0.07	25	1.6
17 04 02	Aluminum	windows, doors	4	-	0.018	0.20	27	5.4
17 02 01	Wood	doors	4	-	2.10	2.81	3.5	9.8
17 05 04	Sand	torba (for levelling)	4	94.72	0.02	7.6	19	144.0
17 01 03	Tiles (floors, bathrm walls)	tiles	4	95.08	0.01	3.8	21	79.9
Level 3: Penthouse								
17 01 01	Concrete (C25)	ground and roof slabs	2	87.89	0.3	52.7	25	1318.4
17 01 01	Concrete	screed (roof)	1	87.89	0.1	4.4	24	105.5
17 01 01	Concrete (C25)	terrace slab	1	17.13	0.3	5.1	25	128.5
17 05 04	Stone Masonry	walls (excl. windows/doors)	1	10.36	3.0	37.57	27	1014.4
17 05 04	Stone	balconies/roof courses	1	14.32	0.26	3.7	27	100.5
17 04 05	Wrought iron	balcony railings	1	-	1.1	0.03	76	2.2
17 02 02	Glass	windows, doors	1	-	0.004	0.02	25	0.4
17 04 02	Aluminum	windows, doors	1	-	0.629	0.63	27	17.0
17 02 01	Wood	windows, doors	1	-	2.10	0.6	4	2.1
17 05 04	Sand	torba (for levelling)	2	94.66	0.02	3.8	19	71.9
17 01 03	Tiles (floors, bathrm walls)	tiles	1	95.02	0.01	1.0	21	20.0

Material (mixed origins)	Total by vol. (m^3)	% by volume	Total by mass (tonnes)	% by mass
Concrete (insitu, precast, screed)	240.6	58.0	601.0	57.1
Stone (block work, torba)	165.2	39.8	437.0	41.5
Glass (windows, doors)	0.1	0.0	0.2	0.0
Tiles (floor, walls)	4.8	1.1	10.0	0.9
Wood (windows, doors)	3.4	0.8	1.2	0.1
Metals (wrought iron, aluminum)	0.9	0.2	2.8	0.3
Total	414.9	100.0	1052.1	100.0

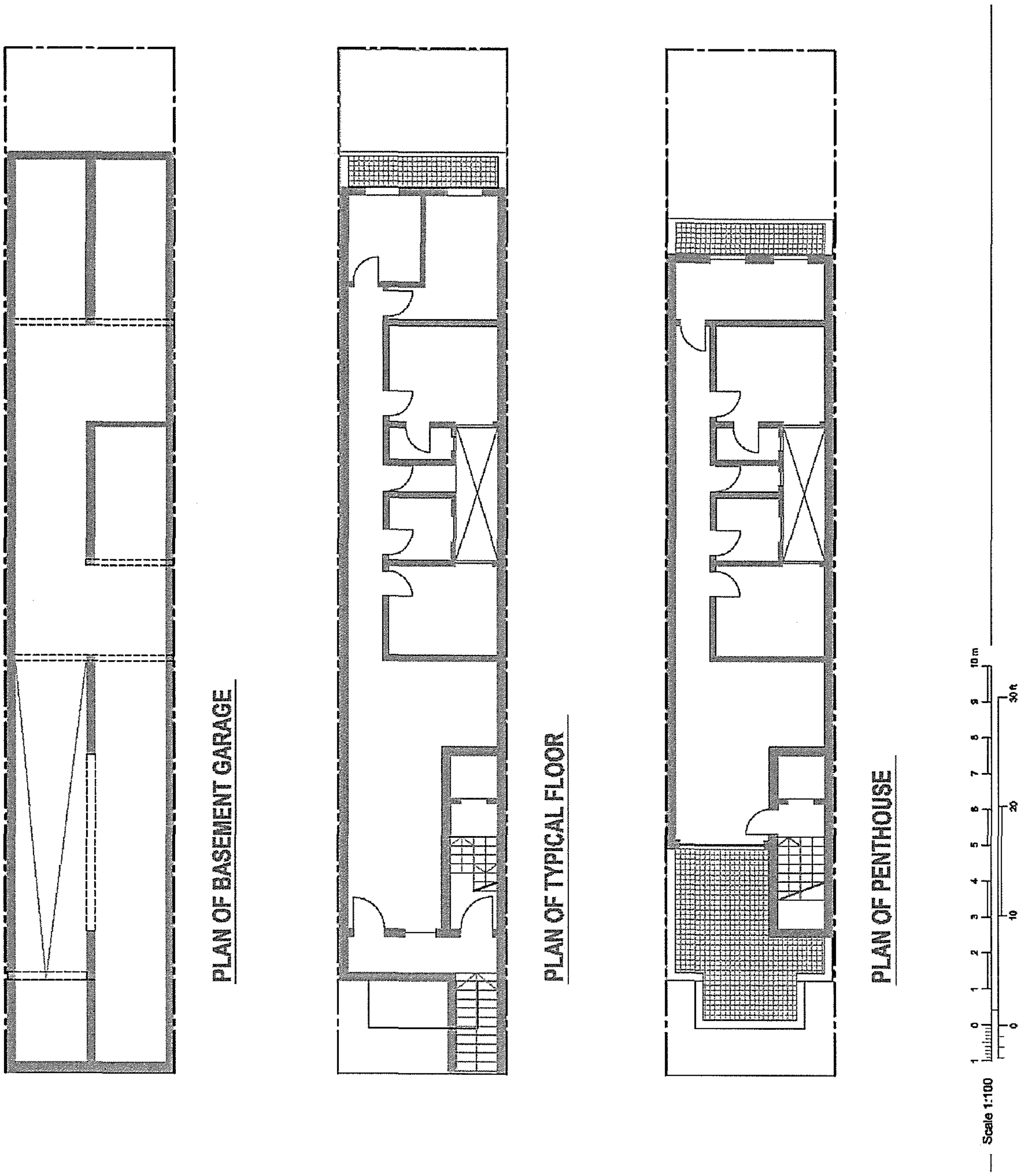
EWC stands for European Waste Catalgoue - Materials are labelled when dismantled/demolished for disposal or reuse.
Densities are taken from EN 1991, Annex A. Unit conversion: 0.1tonne = 1kN = 100kg

17 04 05	Wrought iron	railings (stairs,'bridge')	1	0.02	36.7	0.7	76	55.8
17 02 02	Glass	windows, doors	35	-	0.004	0.28	25	7.0
17 04 02	Aluminum	windows, doors	35	-	0.018	0.10	27	2.7
17 02 01	Wood	windows, doors	1	-	-	0.0	4	0.0
17 08 02	Gypsum	soffit (corridor& toilets)	1	76.00	0.01	0.76	15	11.4
17 01 03	gres, terrazzo, travertine	tiles	1	831.70	0.01	8.3	21	174.7
Level 1: Design studio								
17 01 01	Concrete (C25)	ground and roof slab	2	333.00	0.3	199.8	25	4995.0
17 01 01	Concrete	screed (roof slab)	1	166.50	0.1	8.3	24	199.8
17 05 04	Sand	torba (for levelling)	1	166.50	0.02	3.3	19	63.3
17 05 04	Stone Masonry	parapet wall (bridges)	2	0.96	1.10	2.1	27	57.0
17 01 01	Concrete (C25)	beams	6	3.50	0.3	6.3	25	157.5
17 01 01	Concrete (C25)	clerestory	3	1.76	1.0	5.3	25	132.0
17 05 04	Stone Masonry	walls (excl. windows/doors)	1	53.05	3.0	253.00	27	6831.0
17 01 01	concrete	columns	11	0.07	4.0	3.1	25	77.8
17 01 01	Concrete (C25)	beams	6	3.50	0.3	6.3	25	157.5
17 04 05	Wrought iron	railings	1	0.02	6.0	0.1	76	9.1
17 02 02	Glass	windows, doors	-	-	0.004	1.84	25	46.0
17 04 02	Aluminum	windows, doors	-	-	0.018	5.94	27	160.4
17 02 01	Wood	windows, doors	4	0.05	2.10	0.4	4	1.5
17 01 03	tiles	tiles	1	166.50	0.01	1.7	21	35.0

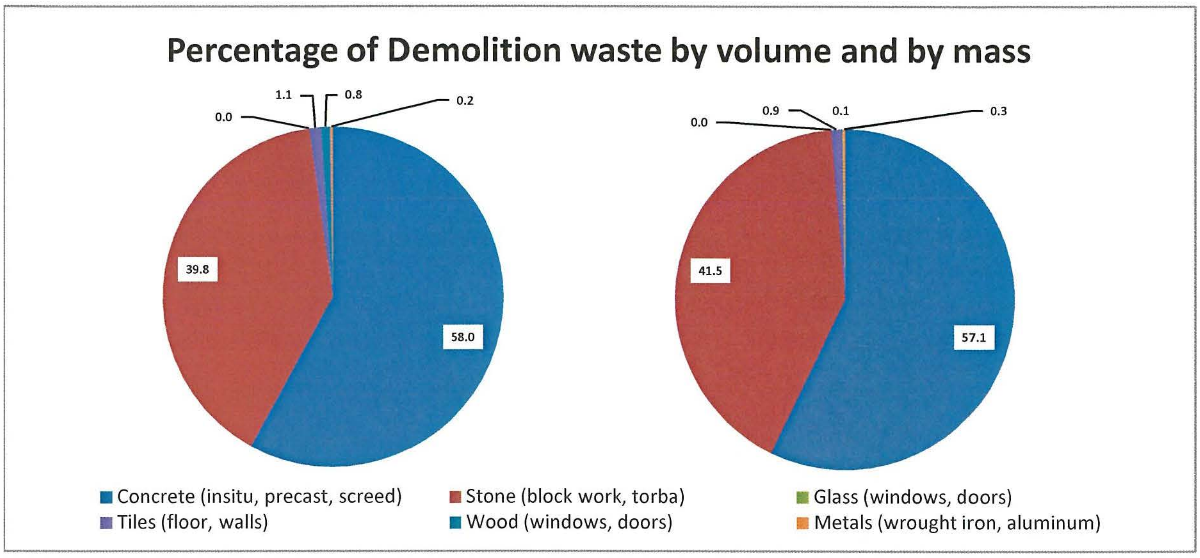
Material (mixed origins)	Total by vol. (m^3)	% by volume	Total by mass (tonnes)	% by mass
Concrete (insitu, block work, screed)	1429.0	38.0	3549.6	39.0
Stone (block work,torba)	2017.2	53.7	5430.3	59.7
Glass (windows, doors, curtain walls)	4.0	0.1	10.1	0.1
Tiles (floor)	19.1	0.5	40.1	0.4
Wood (windows, doors)	2.6	0.1	0.9	0.01
Gypsum (soffit)	1.5	0.04	2.3	0.03
Metals (wrought iron, steel, aluminum)	284.8	7.6	58.0	0.6
Total	3758.1	100.0	9091.2	100.0

EWC stands for European Waste Catalgoue - Materials are labelled when dismantled/demolished for disposal or reuse.
Densities are taken from EN 1991, Annex A. Unit conversion: 0.1tonne = 1kN = 100kg

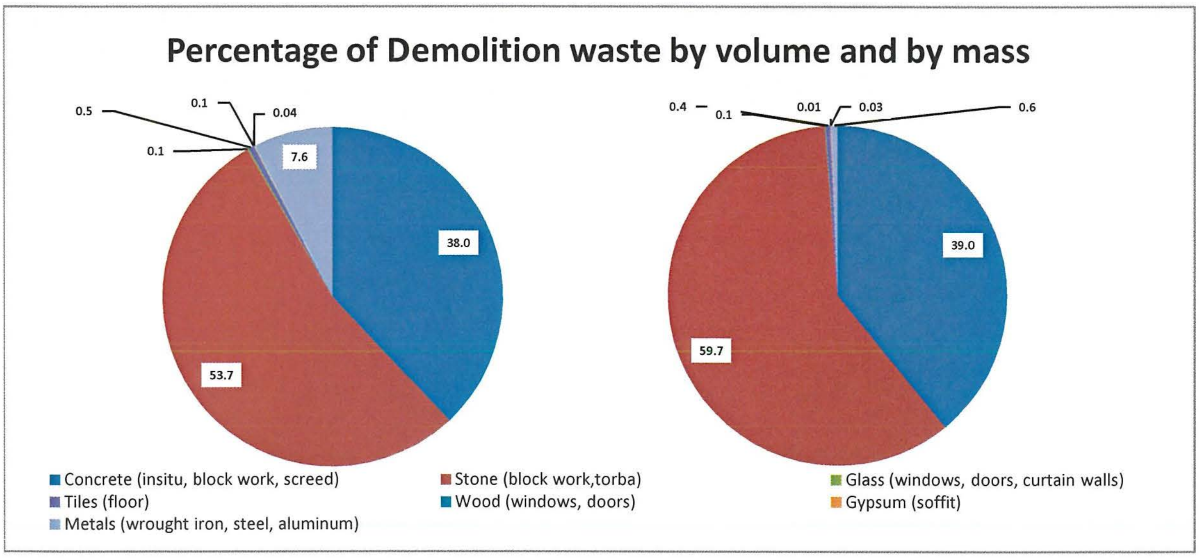
Appendix F.2.2 Plans of Block of Apartments, Qormi



Block of apartments with 4 floors, penthouse and basement garage — Qormi



Faculty for the Built Environment — Tal-Qroqq



Densities are taken from EN 1991, Annex A

Appendix G

Proposed Guidelines for recycling of aggregates in Malta

Appendix G Proposed Guidelines for Recycling of Aggregates in Malta

Instructions on how to read Appendix

This appendix is divided into three columns per page. The central column describes how the Der Österreichische Baustoff-Recycling Verband, Austrian Guidelines in the right column have been adapted to the Maltese guidelines in the left column. Alphabetical references in left and right columns, written as, for example, [a], refer to notes in the central column. Numerical references in the central column, written as, for example, [1] are for other international guidelines which are fully referenced in section 1 of this appendix.

Field of application of Proposed Maltese Guidelines

The guideline sets quality standards to determine the type of assessments which need to be carried out on recycled aggregates (RA). Once a RA is graded according to its quality, it can be used in applications including mainly bound or unbound general concrete or road applications and bulk filling. RA may consist of crushed concrete of different types, stone and tiles, which are the main waste generated from local Construction and Demolition. RA from asphalt, rubber, polystyrene and glass may also exist and may be used with the RA being considered in this guideline for the applications mentioned; however they are not from building materials and are therefore not being assessed in this guideline. However, once enough research has been carried out at the university on these RA, specifications may be added to these guidelines, since the same principles would apply. Some sections within these guidelines still require further research to be complete. These are specified accordingly.

The main material which has been researched in this dissertation is crushed recycled concrete aggregate mixed with conventional stone aggregate. Limitations of these guidelines are discussed in the middle column, where necessary.

Disclaimer: The guideline document is a first attempt compiled on the basis of the methodology and data presented in this dissertation. Its use and application are to be considered in terms of the limitations and constraints indicated in this dissertation.

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Note that the main division of sections in this guideline is proposed in the F.I.R. (2004) document 'Recommendation Guidelines for Quality Assessment of Recycled Building Materials':

1. Recovery
2. Storage
3. Processing
4. Quality category
5. Constructional engineering assays
6. Composition of the material
7. Environment compatibility
8. Inspection (Internal and external)

The F.I.R. document is available at www.fir-recycling.nl/Products/0ca00d26/1/Products.aspx. The Austrian guidelines are also based on this method of division of sections.

1. References to international and local standards and guidelines

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2. Abbreviations and definitions

F.I.R.	Fédération Internationale du Recyclage (International Recycling federation)
I.C.E.	Institution of Civil Engineers
WRAP	Waste and resources Action Programme

More definitions can be found in Appendix A of this dissertation [8].

'Demolish, clear and build' sites are sites where the structures or infrastructures are demolished prior to the erection of new ones. [4, p10]

'Demolish and clear' sites are sites with structures/infrastructures to be demolished, but on which no new construction is planned in the short term. [4, p10]

'Renovation' sites are sites where the interior fittings (and possibly some structural elements as well) are to be removed and replaced. [4, p10]

'Greenfield' building sites are undeveloped sites on which new structures or infrastructure are to be erected. [4, p10]

'Road build' sites are sites where a new road (or similar) is to be constructed on a greed field or rubble free base. [4, p10]

'Road refurbishment' sites are Sites where an existing road (or similar) is to be resurfaced or substantially rebuilt. [4, p10]

Contaminations/Impurities may include dirt, humus (ground surface), clay, gypsum, wood, plastics, paint, paper, glass, metals and textiles. [8]

Foreign materials are building material waste which have potential to be recycled aggregate but are collected in the wrong stockpile that is recycled aggregate of another material, intended possibly for a different application. For example, asphalt in a batch dedicated to storage of concrete only. [8]

Hazardous and potentially hazardous items (for human health or processing of RA) that may be encountered on construction/demolition sites are the following: solvent-based concrete additives, damp proofing chemicals, adhesives, tar-based emulsions, asbestos-based materials (asbestos, asbestos cement), mineral fibres (insulation), some paints and coatings, treated timber, resins, plasterboard (gypsum board), electrical equipment containing toxic components, CFC-based refrigerants, CFC-based fire fighting systems, radionuclides, biohazards, part empty or empty gas bottles (from cutting, welding and so on), grouting materials containing PCBs or tar-containing building materials [2,4].

Treatment of waste is any physical, thermal, chemical or biological process, including sorting, that changes the characteristics of the waste in order to reduce its volume or hazardous nature, facilitates its handling or enhances its recovery. [10]

Pre-treatment includes processes such as hand-picking of valuable pieces (wood and plastic), electro-magnetic removal of metals, screening to remove undersize and oversize material (if sizes cannot be handled by the final processing equipment), removing undesired organic materials and so on. [16]

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
<u>3 General Requirements</u> **3.1 Recovery: Deconstruction, assessment and quantification of incoming waste materials.** Construction and demolition waste (C&DW) [a] can be generated from several types of sites. The site type which generates most waste is the above-ground 'Demolish, clear and build' site [b]. Another type is 'Road refurbishment' site [c] which has different handling requirements since different types of waste are generated. In the case of circulation areas such as roads, paths, parking areas and aerodromes [d], bituminous materials are also to be considered. Materials may be in crushed and cut form. Materials to be processed as recycled aggregate (RA), can be of 1. Building origins [e]: These may consist of mineral demolition waste such as concrete (cast in situ/precast of different grades), mortar, stone and building ceramics or a mixture of these. 2. Road or civil engineering origins [f], may consist of a) unbound building materials, such as materials for the construction of dams, filling materials, excavation materials, bases b) hydraulically bound building materials, such as road pavements/kerbs, pipes, slabs/beams, concrete blocks, un/reinforced concrete c) bituminous bound building materials, such as bases, covering layers 3. Other origins other than those mentioned in 1 and 2, may consist of: a) Secondary stone aggregate from returned fresh concrete b) Waste products from concrete factories [g]	[a] Definition in section 2. [b] 'Demolish, clear and build' sites are most common in Malta, since being densely populated; space for building is an issue. [c] More types and definitions in section 2. [d] The term 'railway tracks' used in [2] is excluded since these are not used in Malta. [e] Materials discussed in Austrian guidelines [2]. [f] Materials discussed in Austrian guidelines [1]. [g] These may include cutoffs from precast concrete elements, failed elements such as precast hollow core slabs which fail in shear, unused block work and so on.	**<u>General Requirements</u>** **Recovery** Demolition waste which can be reused or recycled mainly results from the demolition of over-ground buildings and civil engineering and engineering constructions as well as from the demolition of circulation areas such as roads, paths, parking areas, aerodromes and railway tracks. [d] The materials [e] to be processed may consist of mineral demolition waste such as bricks, concrete, mortar, stone and building ceramics or may be a mixture of these materials. The material to be processed may exist in crushed and cut form.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
Any waste which cannot be processed due to contaminations should also be treated [a, g] before it is sent to a land fill. On-site sorting of demolition waste helps to improve the quality [b] of recycled building materials and also reduce this problem; however it may not always be possible or feasible. Demolition of a structure is to be treated as a deconstruction, where possible, so that the resulting quality of the inputs of the recycling plant will be of high purity levels. [c] In this way, mixing, polluting and/or damage to the material are minimal. When the demolition waste, or waste from the other site types, is processed, the impurities [g] may only lie below a limit of 1% of total mass [f]. If there are any contaminations [g] suspected, for example because of the origin of the material, which cannot be proven, the waste has to be sorted out in every case from the recycling process. Dangerous substances [g] must not be contained.	[a] Treatment is to be carried out according to landfill directive [10]. [b] In Austria, ÖNORM B 2251 (Guide for recycling oriented Demolition) exists for pure selection of materials. These do not exist yet locally. Possibility for on-site sorting is very is site specific since problems may arise due to project deadlines or even possibly site restrictions locally. International research [9] confirms that on-site sorting improves quality of final product since materials of same type are stored together and not with those of possibly a lower quality. On-site processing on the other hand may prove to be less quality-enhancing. [c] [5] Deconstruction is dismantling of individual construction elements, carried out in the reverse order of the construction process. This is ideally designed for before project initiation, however no such effort is done locally because there is no valid reason to do so, as yet. Local traditional construction is mainly by load bearing walls which imposes a problem for deconstruction techniques. Careful handling is required when demolished materials are to be salvaged for reuse/recycling purposes. [f] [1, 2, 6: Table 2, 7, 8] [g] Definition in section 4.	In this regard fundamentally it has to be pursued the aim to produce pure materials by selecting, for example according to ÖNORM B 2251. On-site sorting of demolition waste helps to improve the quality of recycled building materials [b]. The processed demolition waste has to be almost free of impurities. If there are any impurities they have to be sorted out so that the content of impurities in recycled building materials will be lower than 1 mass percent. [f] If there are any contaminations suspected, for example because of the origin of the material, the respective demolition waste has to be sorted out in every case from the recycling process if the required pureness cannot be proven. Dangerous waste such as asbestos, asbestos cement, grouting materials containing PCBs or tar-containing building materials may not be contained.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
There is a responsibility that any kind of controlled waste must comply with the duty of care [a]. Waste transfer notes are ideally documented including all waste transferred and recorded for at least two years. The following are some guides of compliance with duty of care: - Suitable waste containers, such as skips, intermediate bulk containers (IBCs) or drums are to be used for safe and secure storage of waste materials. Containers are to be in good condition and clearly labelled for future holders. Any old labels are to be removed if containers are reused. - It is important to ensure that waste is not blown away by using covers/nets or at risk of not being reused or causing contamination run off due to precipitation [b]. - The storage, at the place where the size reduction (crushing/grinding) of concrete or tiles for further use, is carried on is permissible if the total quantity of such waste so stored at that place at any one time does not exceed a mass which is to be indicated by the authorized person. The storage of C&D/W prior to imminent reuse on a site is allowed if the waste in question is suitable for use for the purposes of relevant work on the site. In the case of waste which is not produced on the site, it is not to be stored there for longer than three months before relevant work starts. Exceptions may be made if specific conditions are met. [c]	[a] In foreign countries there is a legal responsibility toward the environment when handling waste, which is referred to as duty of care. [15] This means that it is stored, transported and disposed of without harming the environment and it is to be carried out by authorised personnel only. Locally the term 'waste producer responsibility' is used in the MEPA website. [b] It is very important that RA is protected from precipitation as much as possible since this may lead to possible chemical contaminations (chlorides and sulfates). [c] This is an extract from the local Landfill directive whereby some legal issues are mentioned. [10, clauses 10 and 24]	This page has been left blank intentionally, since no data relevant to this section in the proposed local guideline is mentioned in the Austrian guidelines.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.2 Delivery, sorting, storage and processing **3.2.1 Delivery: Assessing ncoming waste materials, keeping them free from impurities.** For better communication with the recycling plant to process the material, the waste manager is to assess and estimate the amounts and types of wastes that will be generated from commencement to completion of the project at hand, at the particular site type. Standard C&DW management forms can be used for better handling [a]. Once the amount of waste is known, the right number of delivery trucks can be summoned. It is important to remember the bulking effect when large volumes of waste are collected. Hence, it is recommended to quantify data by mass and also by volume. Documentation of first inspection of the material [b] is to include origin of waste and identification of waste products as per European Waste Catalogue (EWC) [c]. Pre-sorting of the waste regarding its usability should be made immediately at the delivery [d]. Storage and transportation are to be carried out such that breakage, segregation or cause in deterioration of quality of RA is prevented. Also, material is to be protected from vandalism, theft and accidental damage. [e] Hazardous substances [f] are to be collected separately from other waste and discarded appropriately in sealed, labeled containers. Tar containing road demolition waste and asbestos containing cement products are to be rejected immediately.	[a] Several guidelines for waste management plans [4, 11, 12, 13, 14] can be referred to implement efficient methods of handling waste inventories. An example of a waste inventory [8] for a typical block of local apartments can be found in Appendix F.2. The more the detail, the better, however very rough estimates are also considered to suffice. [b, d] The method suggested in [1] for detection of contaminations of coal-tar is not used in Malta. [c] A copy of all possible C&DW with their corresponding EWC number can be found in Appendix H in this dissertation [8]. [e] Reference to [16] [f] Definition in section 2.	**Delivery, sorting and processing** **Delivery** At the delivery the origin and possible contaminations of the demolition waste have to be evaluated and documented in the frame of a first inspection. A first evaluation and pre-sorting of the waste regarding its usability have to be made immediately at the delivery [b,d]. In particular, it has to be ensured that only appropriate and authorized materials are taken over. [1] Moreover, in the frame of the receiving inspection mixed asphalts containing coal-tar should be sorted out. In order to detect contaminations of coal-tar in a rapid way the "paint spraying method with fluorescence under UV-light" according to the FGSV-working paper Nr 27/2(2000) may be applied. The threshold value of this method is approximately 50 mg PAH/kg. [b] Tar containing road demolition waste and asbestos containing cement products have to be rejected.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.2.2 Pre-treatment sorting and storage: Raw materials to be stored separately to achieve good product quality. Treatment of material waste [a] facilitates handling and enhances its recovery. Crushing and sorting may be done on-site using mobile crushers or off-site at a fixed recycling centre where large stockpiles may be accumulated. The pros and cons [b] of different methods should be assessed to aid a waste manager in deciding which method is most feasible. In the crushing process, economy of coarse aggregate production can be maximized by balancing types of crushers [c]. It is common practice to crush the inert material twice, using primary and secondary crushers, followed by separation of impurities and washing of aggregates. Caution should be taken with mobile crushers since, although often more economical in that they avoid transporting C&D/EW away from site, they are rarely sophisticated enough to remove all impurities [d]. To obtain properties suitable for use in higher value applications it is suggested that materials are separated before crushing also. Pre-treatment [a] is done so that processing can be as effective as possible in producing an acceptable product and so that any potential damage to crushing equipment is avoided.	[a] Definitions in section 2. [b] Appendix I in this dissertation [8] lists the pros and cons of on-site or off-site crushing and sorting. [c] Reference to [17] [d] Reference to [16]	This page has been left blank intentionally, since no data relevant to this section in the proposed local guideline is mentioned in the Austrian guidelines.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
It is good practice to store materials separately into colour-coded groups: - white for gypsum - grey for inert waste (concrete/stone/mixed RA) - red for mixed waste - black for asphalt - blue for metal - green for wood - brown for packaging - orange for hazardous waste [a] Although difficulty arises in doing so, separating materials as much as possible increases their quality and allows better chances for materials with strict restrictions covered in the present version of the BSI codes (e.g. max of 5% asphalt).	[a] The waste colour coding is the one developed by the I.C.E. Waste Awareness Construction [18]. A slight alteration has been suggested - the colour representing mixed waste has been changed from black to red. This way a separate colour for asphalt, black, can also be used, as used by WRAP [19]. Stone masonry is also included as an inert material. Note that the colour-coding system used by WRAP consists of only three colours: black for asphalt, white for concrete, red for mixed waste (mostly bricks).	This page has been left blank intentionally, since no data relevant to this section in the proposed local guideline is mentioned in the Austrian guidelines.
In addition to the recommendations for storage in section 3.1 for duty of care, the following [b] should be considered where possible: - Separate storage of RA from conventional aggregate (NA) - Separate storage of RA of different fines grade - Recycled coarse aggregates to be used in a saturated and surface dry condition, owing to their high water absorption. It might be necessary to provide sprinkler facilities to maintain the pile at required moist condition. - There is the risk that fine aggregates, in time, are caked [c] when unhydrated Portland cement and hydrated lime are present in fine RA. Hence, fine aggregates should not be stored for a longer period of time than is necessary.	[b] These are instructions by the Building Contractor's Society of Japan (1978) as cited in [20]. [c] Aggregate cake formation is a cake of retained aggregates composed of many small primary colloidal particles. Source: http://pam.eng.hawaii.edu/papers-pdf/ASKim009_RYuan_Aggregate_Cake.pdf	

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
Pre-sorting is followed by classification according to the material quality. In case of doubt, the materials are to be classified in a lower quality class or sorted out.		**Sorting** [a] The delivered materials have to be pre-sorted in order to classify them according to their quality. Pre-sorted materials have to be stored separately. In case of doubt, the respective material possibly has to be classified in a lower quality class or sorted out. [b] The fact sheets: "Transfer stations for mineral demolition waste, Asphalt and Concrete Demolition Waste" and "Mobile Processing of Building Demolition Waste" are to be complied with. In case of doubt the material shall, where possible, be assigned to a lower grade or separated out.
3.2.3 Processing Processing of the waste is done according to its future application as a product. Materials to be processed require their own specific processing plants and plant parts. [a] Table G.1 shows the list of what building materials (products) can be used for, depending on the grade they are assigned to. The three main uses are in concrete building applications, roads or bulk filling.	[a] The tables with applications are provided in the following pages as table G.1, table G.2 and table G.3 separately for the proposed local guidelines and for the Austrian guidelines since they could not fit in one page in three columns.	**Processing** For the processing of the materials processing plants and plant parts appropriated for the intended use of the respective product have to be applied (see table 2). [c] Note: The recycling of waste resulting from demolition of over-ground buildings is regulated by the „Guideline for recycled building materials made of waste resulting from demolition of over-ground buildings" for the fields of application „cement bound masses" and "unbound masses". In order to win as much as possible pure wastes from the demolition of buildings the demolitions should be carried out according to the guide "Recycling-Oriented demolition" (regarding ÖNORM B 2251 Demolition works). [b]
3.2.4 Post-treatment storage The recommendations mentioned in section 3.2.2, pre-treatment storage, for good handling and storage, are to be considered here too. Recycled building materials have to be stored separately according to grades and quality classes. Deteriorations in quality (e.g. contaminations, mixing, de-mixing) are to be avoided.	[b] The documents in reference [2] do not exist as yet in Malta.	**Storage** Recycled building materials have to be stored separately according to grades & quality classes. In this regard it has to be ensured that deteriorations in quality (e.g. contaminations, mixing, de-mixing) are avoided. Note: In connection with the storage of demolition material for processing and with recycled building materials that have been produced, account is to be taken of the criteria contained in the Austrian Building Material Recycling Association's fact sheet "Transfer stations for mineral demolition waste, asphalt and concrete demolition waste. [b]

Table G.1: Application and use of recycled aggregates from C&DW (Proposed Maltese Guidelines)

Applications [c]			Concrete only			Asphalt mix	Mix of concrete with conventional aggregate (or unbound stone)															
	Buildings / roads / bulk		R_{C100-}			R_{C50+} R_{A50-}	R_{C35-} + R_{U65+}						R_{C15-} + R_{U85+}									
			G-C	R-C	F		G-B1	G-C	RA-1	R-B1	R-C	F	G-A	G-B1	G-B2	G-C	R-A1	R-A2	R-B1	R-B2	R-C	F
	Hydraulically bound construction methods	Prestressed or water-retaining											■									
		Structural					■		■	■			✓				■		■			
		Lean	■	■			✓	■	✓	✓	■		✓	✓	✓	■	✓	✓	✓	✓	■	
	Roads [a]	Wearing course					■		■	■			■				■	■				
		Intermediate binding course and Base course				○ [b]	■		✓	■			■	■	■		✓	✓	■			
		Sub-base (foundation) course	■	■			■	■	✓	✓	■		■	■	■	■	✓	✓	✓	✓	■	
	bulk	Fill and embankment	✓	✓	■		✓	✓	✓	✓	✓	■	✓	✓	✓	✓	✓	✓	✓	✓	✓	■

✓ Qualified
■ Qualification must be proven
○ Future research required

[a] Road construction should be expanded further due to different types of constructions carried out locally

- Flexible type: axle-loading is transmitted down the pavement structure, high loading at the top (use of high quality material) and low loading at the bottom
- Rigid type: normally concrete roads where loads are supported by reinforced concrete slabs (not used locally)
- Composite type: bituminous layer (overlay) on top of a concrete layer. The only instance this was used is with Zabbar Road in Fgura. (personal communication with Mr. Briffa at TM)

Reference to Demicoli (2004) [26] and Azzopardi (2004) [27] for road applications should be made.

[b] Mix ratios with R_A and R_C and R_U with possibly R_G, R_B and other recycled aggregates should be investigated further before being included in this table.

[c] Illustrated applications in Appendix K of this dissertation [8]. Read section 6.1 before Appendix K.

Table G.2: Application and use of recycled building materials. Source: Austrian Green Guideline [1], Table 2

Building material						Type of recycled crushed granular aggregate: asphalt (RA) I	RA II	RA III	RA IV	concrete (RB) I	RB II	RB III	RB IV	asphalt and concrete mix (RAB) I	RAB II	RAB III	RAB IV	Concrete and/or Asphalt and/or ≤ 50% (RM) or ≥ 50% (RG) Stone (natural/recycled) (RM RG) I	RM RG II	RM RG III	RM RG IV	Quality class - environmental compatibility	Location
Application	Aggregates	Concrete	Up to C12/15, no specific properties		ÖN B 4710-1	☑	☑			O	☑			O				O				B B	lhs hs
Application	Aggregates	Concrete	From C 12/15		ÖN B 4710-1					☑	☑											B B	lhs hs
Application	Aggregates	Asphalt			RVS 08.97.05	O	☑	☑		O	☑	☑		O	☑	☑		O	☑	☑		B B	lhs hs
Application	Road base	Base course	Cement bound		RVS 08.17.01	☑	☑	☑		✓	☑	☑		✓	☑	☑		✓	☑	☑		B A	lhs hs
Application	Road base	Base course	unbound	B	RVS 08.15.01	✓1)	✓2)			✓	☑			✓3)	☑			✓3)	☑			B A	lhs hs
Application	Road base	Base course	unbound	NB	RVS 08.15.01	✓1)	✓2)			✓	☑			✓3)	☑			✓3)	☑			B A+	lhs hs
Application	Road base	Sub base course		B	RVS 08.15.01					✓	✓			✓3)	✓3)			✓3)	✓3)			B A	lhs hs
Application	Road base	Sub base course		NB	RVS 08.15.01					✓	✓			✓3)	✓3)			✓3)	✓3)			B A+	lhs hs
Application	Bulk	Bulk material/ Trench filling material		B	RVS 8.03.01 4)	☑	☑	☑	☑	✓	✓	✓	☑	✓	✓	✓	☑	✓	✓	✓	☑	B A	lhs hs
Application	Bulk	Bulk material/ Trench filling material		NB	RVS 8.03.01 4)	☑	☑	☑	☑	✓	✓	✓	☑	✓	✓	✓	☑	✓	✓	✓	☑	A A+	lhs hs

Notes

Type of recycled crushed aggregate

RA recycled crushed granular asphalt
RAB recycled crushed granular asphalt/concrete mix
RB recycled crushed granular concrete
RM mixed recycled crushed granular material consisting of concrete and/or asphalt and stone (natural and/or recycled) with a max. percentage ≯ 50%
RG mixed recycled crushed granular material consisting of stone (natural and/or recycled) with a min. percentage > 50% and concrete and/or asphalt

1) In accordance with RVS 08.15.02
2) In accordance with RVS 08.97.04

3) ≤ 50% asphalt content
4) Approval of the customer required

✓ = suitable
☑ = proof of suitability to be provided
O = additional tests required for proof of suitability

B = with base course
NB = no base course
hs = hydro-geologically sensitive area
lhs = less hydro-geologically sensitive area

Table G.3: Application and use of recycled building materials. Source: Austrian Green Guideline [2], Table 2

		Building material	RMH		RS	RZ	RHZ	RH
		Grade	III	IV	III	III	II	III
Application	Hydraulically bound building methods	Bricks and hollow blocks	–	–	–	√	√	√
		Concrete	○	–	–	☑	☑	☑
		Lightweight concrete	○	–	–	☑	☑	☑
		Screed and screed filling	○	–	–	☑	☑	☑
		Subsoil improvement/stabilisation	○	–	–	–	–	–
	Unbound construction methods	Bulk (Filling)	√	☑	–	–	–	–
		Filling of pipe trenches and covering of pipes	√	☑	–	–	–	–
		Bedding material for pipe areas	☑	–	√	–	–	–
		Backfilling and covering of structures	√	☑	–	–	–	–
		Sports facility construction as base course and mineral surfacing	☑1)	–	–	√	√1)	☑1)
		Substrates for planting purposes (aggregate)	☑1)	–	–	√	√1)	☑1)
		Building materials in the construction of landfill sites	√	☑	–	–	–	–
		Drainage material	○	–	–	–	–	–
	free-flowing, self-compacting trench filling materials		○	○	–	–	–	–

Notes

Type of recycled crushed aggregate

RMH – from recycled mineral waste from demolition of above-ground constructions

RS – sand

RZ – coarse and fine aggregate (sand) from brick

RHZ - coarse and fine aggregate (sand) from brick from above ground constructions

RH – coarse and fine aggregate (sand) from above ground constructions

1) Proportion of brick is to be specified.
√ = suitable
☑ = Proof of suitability is to be provided
○ = additional tests required for proof of suitability

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.3 Designation of recycled aggregates **3.3.1 Designation of materials** EN 12620:2002+A1 requires the proportions of constituent materials in coarse recycled aggregate to be determined in accordance with a visual sorting test in accordance with EN 933-11. This allows the producer to declare conformity with the categories for constituents of coarse recycled aggregate in EN 12620:2002+A1 [a]. Constituent materials [b] in coarse RA are the following: R_C Concrete, concrete products, concrete masonry units, mortar R_U Unbound aggregates, natural stone, hydraulically bound aggregate R_B Aerated non-floating concrete, tiles [d] R_A Bituminous materials R_L Lightweight (<1.0Mgm^{-3}) Note that the following constituents materials R_G Glass **X** Other, including: cohesive clay, and soil, wood, plastic and rubber, gypsum plaster and miscellaneous, including metals **FL** Floating materials (measured by volume) listed in EN933-11 are not used as RA but are given a nomenclature solely for sorting and labeling purposes. However note that <u>glass, polystyrene beads, tiles and rubber</u> are currently being investigated at the University of Malta for use as RA in concrete. Bulk material [e] is also a material which can be reused/recycled.	[a] Reference to [21] [b] It is important to note the differences in nomenclatures used in EN and ONORM (Austrian) standards, due to mainly translation purposes. See Definition in section [c] The Austrian guidelines list also mix of ratios for coarse aggregates originating from concrete, stone and asphalt [1] and ratios for both coarse and fine aggregates originating from concrete, stone and brick [2]. This is applied later on for the local guidelines. [d] In EN 12620:2002+A1, R_B includes clay masonry units (brick, tiles), calcium silicate masonry units which have been omitted as they are not found locally. Although aerated non-floating concrete is not used locally, it may become common once the demand for it increases. Tiles (not specifically clay ones) have been added to the list. [e] Bulk material is excavation waste or sieved material as per technical requirements used for fill. [f] RZ and RHZ (include bricks) are not applicable to Malta	**Designation of recycled building materials** **Designation of materials [1] [c]** **RA** recycled crushed granular asphalt **RAB** recycled crushed granular asphalt/concrete mix **RB** recycled crushed granular concrete ('beton') **RM** mixed recycled crushed granular material consisting of concrete and/or asphalt and stone (natural and/or recycled) with a max. percentage ≯ 50% **RG** mixed recycled crushed granular material consisting of stone (natural and/or recycled) with a min. percentage > 50% and concrete and/or asphalt Bulk materials (according to BAWP [bundesabfallwirtschaftsplan] Austrian Federal Waste Management Plan) : Harmless materials resulting from excavation into frost-proof, gravel and drainage bases which in contrast to materials resulting from excavation into normal ground do not represent a naturally grown ground or sub-base but are produced, for example by sieving, in order to fulfill technical requirements. **Designation of materials [2] [c]** **RMH** Recycled mineral waste resulting from demolition of above-ground constructions **RS** Recycled sand **RZ** Recycled brick sand; recycled granular brick [f] **RHZ** Recycled brick sand resulting from above-ground constructions; recycled granular brick resulting from above-ground constructions [f] **RH** Recycled above-ground construction sand, recycled granular materials from above-ground construction

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
Sub classes [a] can be also used when further separation of materials is economically feasible, physical space allows for it, if time allowed for scheduled project permits and if material is known. R_{CN} Normal reinforced concrete R_{CP} Precast planks or other high grade concrete R_{CM} Concrete masonry units R_{CL} Lean concrete (C12/15) R_{UU} Unbound aggregate R_{UP} Natural stone (Coralline Prima type - angular) [b] R_{US} Natural stone (Coralline Sekonda type - round) [b] R_{UH} Hydraulically bound aggregate X_C Cohesive materials (clays and soils) X_M Miscellaneous (wood, metal, rubber, plastic) X_G Gypsumboard and plaster Any combination of mixes is to be written as per section 3.3.4. It is important to note that the EN933-1 does not list a category for fine aggregate. However, it is important to do so since some applications do not require coarse aggregate. It is usually not recommended to use recycled fine aggregate due to increased water absorption and more probable contaminations being present. However it the event that the quality is good enough, the nomenclature to be used is a subscript 'F' following the given subscripts, in any of the above.	[a] A similar approach for subclasses is used in prEN933-11, whereby the subscripts are numbers not letters. It should be noted that in the case of a demolition, if the collection of original drawings of project with structural details are available, they should be used to aid in the sorting of materials and separation process. [b] This distinction is made in reference [28].	This page has been left blank intentionally, since no data relevant to this section in the proposed local guideline is mentioned in the Austrian guidelines.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.3.2 Grades - Engineering classification scheme Once the aggregates are processed and classified according to material type, they can be tested for quality and hence graded according to their application. The main applications [b] that the classification in tables G.1 and G.4 is based upon are the following: **<u>For use of RA in general purpose concrete</u>** **Grade G-A:** **Prestressed concrete or concrete element RC 30/37 to RC40/50** (BS8500-2 Table 3) in exposure classes X0,XC1-4, XD1-2, XS1 **Grade G-B:** **Structural element (concrete C20/25 to C28/35)** Containing reinforcement or embedded metal in exposure classes X0,XC1-2 **Minor-structural element (C20/25)** Containing reinforcement or embedded metal in exposure classes X0,XC1 **Grade G-C: Non-structural element (lean concrete) (C12/15 TO C16/20)** Not containing reinforcement or embedded metal in exposure class X0 **<u>For use of RA in road construction/renovation</u>** **Grade R-A: Wearing course** (max size aggregate of 12.5mm) **Grade R-B: Intermediate binding course and base course** **Grade R-C: Sub-base (foundation) course in roads** **<u>For use of RA for other purposes (lowest quality)</u>** **Grade F: Fill and embankment**	[a] Refer to tables G.2 and G.3. [b] It should be noted that the classification scheme is only partly based on the Austrian guidelines, as other literature has been reviewed. Also, the scheme has been modified to suit local applications. [c] Illustrations of these applications summarized from AggRegain [22] can be found in Appendix K. The dissertation carried out by Camilleri, E. (2011), [8], is the research behind the derivation of this scheme. Final quality of product may be written as the following example extracted from Chapter 8 of [8]: Recycled concrete aggregate (RCA) from crushed waste of <u>Manuel Dimech Bridge</u> of grading <u>≤10mm</u> can be used with a replacement ratio of <u>≤35%</u> for <u>structural, minor-structural or unreinforced concrete</u> with maximum recycled aggregate concrete (RAC) strength of <u>C28/35</u> in exposure classes <u>X0, XC1 and XC2</u> with conventional aggregate (NA) of 24-hour water absorption (WA_{24}) of not more that <u>4.5%</u> for a final blend ratio of water absorption for NA and RCA of <u>5.0%</u>. Quality of this material is set at a grade not more than <u>G-B1</u>. The critical parameters hindering achievement of a higher grade are <u>water absorption and chloride content</u>.	**Grades: Engineering classification scheme** According to the field of application indicated in table 2 [a], recycled building materials are classified in: **Grade I**: Frost-proof and frost resistant building materials for unbound base courses and sub-base courses (according to RVS 08.97.04, RVS 08.15.01) and for the construction of hydraulically and bituminous bound bases (according to RVS 08.17.01). **Grade II**: Frost-proof and frost resistant building materials for unbound sub-bases (according to RVS 08.15.01) and hydraulically bound base courses (according to RVS 08.17.01) **Grades III, IV**: Building materials for hydraulically bound base courses, agricultural and forestry road constructions, parking areas, noise protection embankment, fillings, filling materials for roadside ditches, subsoil improvement.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.3.3 Quality classes: Environmental compatibility No data on hydro-ecologically delicate areas exists locally, as yet and hence further research needs to be carried out to be able to complete this section.		**Quality classes: Environmental compatibility** In order to protect the environment, and especially ground waters, recycled building materials are classified in the quality classes A^+, A and B according to the fields of application indicated in tables 2 and 3. **Quality class A^+** - Building materials which can be used in unbound form without covering layer in hydro-geologically delicate areas. **Quality class A** - Building materials which can be used in hydro-geologically delicate areas in bound form or in unbound form with covering layer or in hydro-geologically less delicate areas in unbound form without covering layer. **Quality class B** - Building materials which can be used in hydro-geologically less delicate areas in bound form or in unbound form with covering layer or as aggregates in unbound form also in hydro-geologically delicate areas. **Quality class C** - These are building materials that a) are used only for civil engineering purposes within a landfill site compartment for non-hazardous waste under the following conditions: - they are necessary in terms of building technology - are suitable in terms of building technology - are used to the required extent and are shown on the plans. Examples: - peripheral embankments shown on the plans - drainage layers referred to in the landfill site project Landfill site roads and levelling layers are not regarded as fulfilling civil engineering purposes.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
3.3.4 Composition of the designation of RA Designation of RA [a] produced according to this guideline consists of: Material designation with content of material (if known) in brackets Grade Grading curve field $(R_{A5-} + R_{UP50+} + R_{CP2C-} + X_{M1-})$ **G-B1 9/18** The above is a typical An example using the designation in 3.3.1 for a genuine recycled aggregate with a mix of Less than 5% bituminous material with More than 50% of natural stone (prima) and Less than 20% of precast concrete from planks with Less than 1% of other miscellaneous foreign material (metal rebar) With Grade G-B1 of grading size 9/18 **4 Structural engineering properties - grading provisions** The requirements pertaining to RA are laid down in the grading provisions. Table G.1 lists the properties to be tested according to grades specified in section 3.3.2.	[a] Note that the percentage (e.g. less than 50%) nomenclature is used in the published document [21] for BS EN 12620:2002+A1. Note that from the waste inventory exercise carried out for a typical block of apartments made entirely out of different concrete types in table 4.2 of [8], the following nomenclature would be adopted. $(R_{CP5-} + R_{CN60-} + R_{CM30-})$ **R-C 9/18** This represents a mix of Less than 5% precast concrete from planks with Less than 60% of normal reinforced concrete and Less than 30% concrete masonry units With Grade R-C of grading size 9/18	**Composition of the designation of recycled building materials** The designation [a] of recycled building materials produced according to this guideline consists of: Material designation, grade, grading curve field, quality class Example: RB II 0/32 A^{+} **Structural engineering properties - grading provisions** The requirements pertaining to recycled building materials are laid down in the grading provisions. Table 1b lists the properties to be tested according to grades III and IV. The tests on recycled building materials from building demolition waste extend to include: ▪ Recovery and delivery ▪ Processing and storage ▪ Particle size distribution ▪ Water content ▪ Loose bulk density (dry) ▪ Specific heat resistance (dry) ▪ flowability in "as delivered" condition ▪ particle density ▪ Foreign constituents ▪ Impurities ▪ organic contamination (proportion of humus) ▪ proportion of brick

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
The tests [a] on RA from C&DW include: - Particle-size distribution - Flakiness index - Oven-dry particle density - Oven-dry bulk loose density - Water absorption - Resistance to fragmentation: Los Angeles value - Acid- and water-soluble chlorides - Acid- and water-soluble sulfates - Foreign materials content - Fines content	[a] Some researchers [9] indicate that if a strong correlation is found between different properties, then the number of tests to be carried out can be reduced to save time, since some tests are very time consuming. For example, the author of the dissertation [8] has found a strong correlation between particle density and water absorption. Hence it could be recommended that only water absorption be tested. Further research is required in this area. [b] Wherever recycled asphalt aggregate is mentioned in the Austrian guidelines, future research is required in Malta to provide similar specifications.	The requirements pertaining to recycled building materials are laid down in the grading provisions. Table 1 lists the properties to be tested according to grades I, II, III and IV. For recycled building materials of unbound and hydraulically bound materials, and those with a maximum asphalt granulate content of 50%, the tests cover: ▪ Recovery and delivery ▪ Processing and storage ▪ Resistance to fragmentation ▪ Purity (impurities) ▪ Particle size distribution ▪ Foreign constituents ▪ Frost stability and resistance The tests where recycled granular asphalt [b] is concerned are ▪ Recovery and delivery ▪ Processing and storage ▪ Particle size distribution ▪ Grain size distribution ▪ Frost stability ▪ Foreign constituents ▪ Purity (impurities) ▪ Binder content

Table G.4a: Structural engineering properties and material composition (Proposed Maltese Guidelines)

Use of RCA				In concrete elements (hydraulically bound)					In road construction/renovation (hydraulically/bituminously bound/unbound)					For other (unbound)
Application description				Prestressed or water-retaining (highest quality)	Structural (>C20/25) and minor-structural (C20/25) Containing reinforcement or embedded metal			Non-structural (lean concrete) Not containing reinforcement or embedded metal	Wearing course (40mm road surfacing) MSA is 12.5mm		Intermediate binding course and Base course MSA is 20mm		Sub-base (foundation) course (usually unbound) MSA is 31.5mm	Fill and embankment (unbound) (lowest quality)
Grade				G-A	G-B1	G-B2	G-B3	G-C	R-A1	R-A2	R-B1	R-B2	R-C	F
Exposure class [a]				X0, XC1-4, XD1-2, XS1	X0, XC1, XC2			X0	X0, XC1, XC2					n/a
Strength classes [a]				≤ C30/37, C32/40, C35/45, C40/50	≤ C20/25, C25/30, C28/35 [C20/25 not to be used in XC2]			C12/15, C16/20 [o]	C16/20 to C25/30					n/a
[e] Replacement ratio (RCA instead of NA)				≤ 15% ± 2%	≤ 35%	≤ 15% ± 2%	≤ 10% ± 2%	≤ 100%	≤35%	≤15% ± 1%	≤35%	≤15% ± 1%	≤ 100%	≤ 100%
Final blend ratio due to different water absorptions of NA and RA according to replacement ratio				[c] 3% with NA of WA_{24}2.5	[d] 5% with NA of WA_{24}4.5			NR	[b] 4% with NA of WA_{24}3				[b] NR	n/a
Test		Property	units											
MSA EN 933-1	Geometrical	Particle-size Distribution	Not applicable	EN 12620	EN 12620			EN 12620	Series 800, EN 13242		Series 800, EN 13242		Series 800, EN 13242	NR
MSA EN 933-3	Geometrical	Maximum flakiness index	%	[m] FI_{35}	[m] FI_{35}			[m] FI_{35}	[b] FI_{25}		[b] FI_{25}		NR	NR
MSA EN 197-6	Physical	Minimum oven dry particle density, ρ_{rd}	Mgm^{-3}	2.0	2.0			NR	2.0		2.0		NR	NR
MSA EN 1097-3	Physical	Minimum loose bulk density	Mgm^{-3}	[n] 1.0	[n] 1.0			<1% = 1.0 [o]	1.0		1.0		NR	NR
Tam et al (2008)	Physical	Maximum water absorption	% by mass of dry aggregate	WA_{24} 5.5	WA_{24} 6	WA_{24} 7.5	WA_{24} 9	WA_{24} 14	WA_{24} 6	WA_{24} 9.5	WA_{24} 6	WA_{24} 9.5	[b] NR	NR
MSA EN 1097-2	Mechanical	Maximum Los Angeles value	%	[f] LA_{40}	[f] LA_{40}			[f] LA_{40}	[g] LA_{20}		[b] LA_{35}		[b] LA_{35}	NR
MSA EN 1744-5	Chemical	Maximum water-soluble chloride content	% by mass of aggregate	$Cl_{0.01}$	$Cl_{0.03}$ (sulfate resisting cement) $Cl_{0.05}$ (all other)			$Cl_{0.1}$	$Cl_{0.1}$		$Cl_{0.1}$		$Cl_{0.1}$	NR
MSA EN 1744-1	Chemical	Maximum acid-soluble chloride content	% by mass of aggregate	$Cl_{0.01}$	$Cl_{0.03}$ (sulfate resisting cement) $Cl_{0.05}$ (all other)			$Cl_{0.1}$	$Cl_{0.1}$		$Cl_{0.1}$		$Cl_{0.1}$	NR
MSA EN 1744-1	Chemical	Max water-soluble sulfate content	% by mass of aggregate	[i] $WS_{0.2}$										WS_1
MSA EN 1744-1	Chemical	[h] Max acid-soluble sulfate content	% by mass of aggregate	[k] AS_1										AS_1
Visual Test/EN 1744-1	Content	Max foreign materials content	%	[k] 1 or 0.5 for organic										
MSA EN 933-9	Content	Fines content	%	f Declared										NR

Footnotes on next page

Table G.4b: Structural engineering properties and material composition (Proposed Maltese Guidelines)

Notes to table G.4a:

This table should be read together with Appendix K, where the applications are illustrated.

Fines content should be declared by manufacturer or specifier to justify any high levels. Where presence of gypsum is known to or strongly believed to be present, fines content should be minimal or else fine aggregate not used at all for recycling purposes except for bulk filling. However leaching of sulfates should also be controlled. Further investigation is required.

[a] Reference: BS8500-2 Table 3, BS8500-1 Table A.1, EN 1992-1-1 Table 4.1, EN 206-1 Table F.1, International standards

[b] Reference: Transport Malta and Series 900. NR stands for no requirement.

[c] Reference: BS 8007 clause 6.2.2

[d] Reference: EHE specifications in Spanish standard for NA

[e] Adjustments may be made to increase the replacement ratio if NA of excellent quality, such as foreign aggregate, is being used, e,g, basalt

[f] Reference: BS 8500-2 clause 4.3

[g] Reference: TM and Series 900 clause 2

[h] Acid-soluble sulfates for material obtained by crushing hardened concrete (of known composition) that has not been in use e.g. surplus precast units or returned fresh concrete, need not be checked according to BS 8500-2, Table 2.

[i] Limits suggested in proposed amendment to EN12620, are for sulfate tests carried out according to EN1744-1

[j] Reference: BS 882, EN 206-1 and [8]

[k] BS 8500-2 Table 2

[m] PD 6682-1:2009

[n] Reference: EN 933-11

[o] Reference: Belgian standard

Table G.5: Application and use of recycled building materials. Source: Austrian Green Guideline [1], Table 1

	Recycled building material	RA	RB	RAB	RM	RG
	Grade	Grade I				
Structural engineering properties	Particle size distribution	to be specified	as per Fig. 1-4			
	Fragment size distribution	as per Fig. 1-4	-			
	Frost stability	f_3; f_5[1]; f_7[1]; f_9[1]; f_{12}[1]				
	Resistance to fragmentation	LA_{NR}	LA_{40}			
	Water absorption	-	≤4% by mass[2,3]		≤2% by mass[2,3,4]	≤2% by mass[2,3]
	Resistance to freeze-thaw cycle	F_4[5]	F_4[6]			
Material composition	Foreign constituents	≤ 5% by mass[7]	≤ 5% by mass			
	Impurities	≤ 1% by mass				
	Binder content	≥ 3.5% by mass	-			
	Mixing ratio	-		to be specified, <50% asphalt content		

	Recycled building material	RA	RB	RAB	RM	RG
	Grade	Grade II				
Structural engineering properties	Particle size distribution	-	as per Fig. 5-9			
	Fragment size distribution	as per Fig. 5-9	-			
	Frost stability	f_3; f_5[1]; f_7[1]; f_9[1]; f_{12}[1]				
	Resistance to fragmentation	LA_{NR}	LA_{40}			
	Water absorption	-	≤4% by mass[2,3]		≤2% by mass[2,3,4]	≤2% by mass[2,3]
	Resistance to freeze-thaw cycle	F_4[5]	F_4[6]			
Material composition	Foreign constituents	≤ 12% by mass				
	Impurities	≤ 1% by mass				
	Binder content	≥ 3.0% by mass	-			
	Mixing ratio			to be specified, <50% asphalt content		

	Recycled building material	RA	RB	RAB	RM	RG
	Grade	Grade III				
Structural engineering properties	Particle size distribution	-	as per Fig. 10-14			
	Fragment size distribution	as per Fig. 10-14	-			
	Frost stability	f_{NR}				
	Resistance to fragmentation	LA_{NR}				
	Water absorption	-				
	Resistance to freeze-thaw cycle	F_{NR}				
Material composition	Foreign constituents	≤ 12% by mass				
	Impurities	≤ 1% by mass				
	Binder content	-				
	Mixing ratio	-	to be specified			

	Recycled building material	RA	RB	RAB	RM	RG
	Grade	Grade IV				
Structural engineering properties	Particle size distribution		Max. grain size to be specified			
	Fragment size distribution	Max. fragment size to be spec.	-			
	Frost stability	f_{NR}				
	Resistance to fragmentation	LA_{NR}				
	Water absorption	-				
	Resistance to freeze-thaw cycle	F_{NR}				
Material composition	Foreign constituents	≤ 25% by mass		≤ 33% by mass		
	Impurities	≤ 1% by mass				
	Binder content	-				
	Mixing ratio	-		to be specified		

1) If the fines content in the grain mixture exceeds 3% by mass, ÖNORM B 4810 shall be observed.
2) The water absorption test shall be performed using GK 4-32.
3) F_4 shall be deemed to have been complied with if these limit values are met.
4) If the concrete content of the material is greater than 50% by mass, the requirement for RB shall be used for the water absorption, provided the application is not covered by ÖNORM B 3132.
5) As the starting materials for RA are frost-resistant in origin, this test is unnecessary; F_4 is therefore met for grades I and II.
6) Evidence of water absorption.
7) Corresponds to the 'purity' requirement in RVS 08.97.04.

Note: The scope of Table 1 is the basis for obtaining the quality mark for recycled building materials.

Table G.6: Application and use of recycled building materials. Source: Austrian Red Guideline [2], Table 1

<table>
<tr><th colspan="2">Recycled building material</th><th>RS</th><th>RMH</th><th>RZ</th><th>RHZ</th><th>RH</th><th>RMH</th></tr>
<tr><th colspan="2">Grading</th><th colspan="5">Grade III</th><th>Grade IV</th></tr>
<tr><td rowspan="7">Structural engineering requirements</td><td>Particle size distribution</td><td>as per Fig. 1</td><td>as per Fig. 2-8
D ≤ 63, G_A 75
G_F 80
G_C 80-20</td><td>as per Fig 2-8</td><td>as per Fig. 2-8
G_C 80-20
G_C 85/20 [2]</td><td>as per Fig. 2-8</td><td>Max. grain size to be specified</td></tr>
<tr><td>Water content</td><td>5-12 % by mass</td><td>-</td><td colspan="3">-</td><td>-</td></tr>
<tr><td>Loose bulk density (dry)</td><td>to be specified</td><td>-</td><td colspan="3">-</td><td>-</td></tr>
<tr><td>Specific heat resistance (dry)</td><td>≤ 6.0 km/W [1]</td><td></td><td colspan="3">-</td><td>-</td></tr>
<tr><td>Flowability in “as delivered” condition</td><td>apparently not prone to clumping</td><td>-</td><td colspan="3">-</td><td>-</td></tr>
<tr><td>Particle density</td><td colspan="2">-</td><td colspan="3">ρ_{rd} to be specified [2]</td><td></td></tr>
<tr><td>Foreign constituents</td><td>RA ≤ 10% by mass [3]</td><td>≤ 12% by mass</td><td colspan="3">≤ 5% by mass</td><td>≤ 12% by mass</td></tr>
<tr><td rowspan="3">Material composition</td><td>Impurities</td><td>≤ 1% by mass [4]</td><td colspan="5">≤ 1% by mass</td></tr>
<tr><td>Organic contaminants (humus content</td><td colspan="2">-</td><td colspan="3">lighter than colour coating solution [5]</td><td>-</td></tr>
<tr><td>Proportion of brick</td><td colspan="2">-</td><td>85% by mass</td><td>33-85% by mass</td><td>< 33% by mass</td><td>-</td></tr>
</table>

1) This is regarded as having been complied with when loose bulk density in a dried state ≥ 1.15 Mg/m³
2) Is to be listed pursuant to ON B 3131 when used as an additive
3) RS 0/4 with max. 10 M-% RA-content may be used, if no ambient warming takes place (for example, through cable) and possible solidification is accepted.
4) Impurities are to be determined in respect of particle size fraction 2/D following EN 933-5.
5) in accordance with ÖNORM EN 1744-1

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
4.1 Engineering properties and material composition of RA The requirements regarding engineering properties and material composition are regulated according to table G.4. Grading curve ranges apply to materials as they are on their delivery. If the grading curve ranges are not complied with, a sample area shall be used to demonstrate that the compactability and load bearing capacity are adequate. [a] **4.1.1 Particle size distribution** Refer to table G.7 for tables to be used to plot grading curves to be applied in Malta. These are extracts from EN 12620, EN 13242 and Series 800 [d]. Examples of their applications can be found in Appendix B.1 of [8].	[a] Refer to tables G.5 and G.6. [b] Refer to table G.8a-c for grading curves of Green Guideline [1]. [c] Refer to table G.8d-e for grading curves of Red Guideline [2]. [d] Reference to [23, 24, 25]	**Engineering properties and material composition of recycled building materials** The requirements regarding engineering properties and material composition are regulated according to table 1 [a]. Grading curve ranges apply to materials as they are on their delivery. If the grading curve ranges are not complied with, a sample area shall be used to demonstrate that the compactability and load bearing capacity are adequate. [a] [1] **Grain-size distribution** [b] Figures 1 – 14 show the grading curve ranges. **Grading curves of grade I:** The grading curve of grade I corresponds to the RVS 08.15.01 (issue October 2005) See figs 1-4. **Grading curves of grade II:** See figures 5 - 9. **Grading curves of grade III:** See figures 10 – 14 [2] **Particle size distribution** [c] Figures 1-8 illustrate the grading curve ranges. **Grading curve ranges for RS**: The grading curve of Fig 1. **Grading curve ranges of grade III**: See figures 2-8.

Table G.7: Grading envelopes. (Proposed Maltese Guidelines)

Table on the right are extracts from EN 12620: 2000 Tables 2 and 3.

Refer to standards for more details.

Table 2 — General grading requirements

Aggregate	Size	Percentage passing by mass					Category G^{d}
		$2D$	$1{,}4D^{a\,b}$	D^{c}	d^{b}	$d/2^{a\,b}$	
Coarse	$D/d \le 2$ or $D \le 11{,}2$ mm	100 100	98 to 100 98 to 100	85 to 99 80 to 99	0 to 20 0 to 20	0 to 5 0 to 5	$G_C85/20$ $G_C80/20$
	$D/d > 2$ and $D > 11{,}2$ mm	100	98 to 100	90 to 99	0 to 15	0 to 5	$G_C90/15$
Fine	$D \le 4$ mm and $d = 0$	100	95 to 100	85 to 99	–	–	G_F85
Natural graded 0/8	$D = 8$ mm and $d = 0$	100	98 to 100	90 to 99	–	–	$G_{NG}90$
All-in	$D \le 45$ mm and $d = 0$	100 100	98 to 100 98 to 100	90 to 99 85 to 99	–	–	G_A90 G_A85

[a] Where the sieves calculated are not exact sieve numbers in the ISO 565:1990 R 20 series then the next nearest sieve size shall be adopted.

[b] For gap graded concrete or other special uses additional requirements may be specified.

[c] The percentage passing D may be greater than 99 % by mass but in such cases the producer shall document and declare the typical grading including the sieves D, d, $d/2$ and sieves in the basic set plus set 1 or basic set plus set 2 intermediate between d and D. Sieves with a ratio less than 1,4 times the next lower sieve may be excluded.

[d] Other aggregate product standards have different requirements for categories.

Table 3 — Overall limits and tolerances for coarse aggregate grading at mid-size sieves

D/d	Mid-size sieve mm	Overall limits and tolerances at mid-size sieves (percentage passing by mass)		Category G_T
		Overall limits	Tolerances on producer's declared typical grading	
< 4	$D/1{,}4$	25 to 70	± 15	G_T15
≥ 4	$D/2$	25 to 70	± 17,5	$G_T17{,}5$

Where the mid-size sieve calculated as above is not an exact sieve size in the ISO 565:1990/R20 series then the nearest sieve in the series shall be used.

NOTE Overall limits and tolerances for the most common product sizes are illustrated in annex A.

Table in middle column are extracts from EN 13242: 2000 Tables 2 and 3.

Refer to standards for more details.

Table in right column are extracts from Series 800.

Refer to standards for more details.

Table 2 — General grading requirements

Aggregate	Size mm	Percentage passing by mass					Category G
		$2D^{a}$	$1{,}4D^{b\,c}$	D^{d}	$d^{c\,e}$	$d/2^{b\,c}$	
Coarse	$d \ge 1$	100	98 to 100	85 to 99	0 to 15	0 to 5	G_C 85-15
	and $D > 2$	100	98 to 100	80 to 99	0 to 20	0 to 5	G_C 80-20
Fine	$d = 0$	100	98 to 100	85 to 99	–	–	G_F 85
	and $D \le 6{,}3$	100	98 to 100	80 to 99	–	–	G_F 80
All-in	$d = 0$	-	100	85 to 99	–	–	G_A 85
		100	98 to 100	80 to 99	–	–	G_A 80
	and $D > 6{,}3$	100	–	75 to 99	–	–	G_A 75

[a] For aggregate sizes where D is greater than 63 mm (e.g. 80 mm and 90 mm) only the oversize requirements related to the 1,4 D sieve apply since there is no ISO 565/R20 series sieve above 125 mm.

[b] Where the sieves calculated as 1.4 D and $d/2$ are not exact sieve sizes in the ISO 565/R20 series then the next higher or lower sieve size respectively shall be adopted.

[c] For special uses additional requirements may be specified.

[d] The percentage passing D may be greater than 99 % but in such cases the manufacturer shall document and declare the typical grading including the sieves D, d, $d/2$ and sieves in the basic set plus set 1 or basic set plus set 2 intermediate between d and D. Sieves with a ratio less than 1,4 times the next lower sieve may be excluded.

[e] Limits for the percentage passing d can be modified to 1 to 15 for G_C 85-15 and 1 to 20 for G_C 80-20 where necessary to ensure a well graded aggregate.

Table 3 — Categories of overall limits and tolerances for coarse aggregate at mid-size sieves

D/d	Mid-size sieve mm	Overall limits and tolerances at mid-size sieves (Percentage passing by mass) where $D/d \ge 2$		Category GT
		Overall limits	Limit deviations on manufacturer's declared typical grading	
<4	$D/1{,}4$	25 to 80	± 15	$GT_C25/15$
		20 to 70	± 15	$GT_C20/15$
≥4	$D/2$	20 to 70	± 17,5	$GT_C20/17{,}5$
No requirement				GT_{NR}

When the mid-size sieves calculated in the above is not an exact sieve size in the ISO 565/R20 series then the nearest sieve in the series shall be used.

TABLE 8/2:

Granular Material Type 1 Range of Grading

ASTM sieve size	Percentage by mass passing
50.0 mm	100
37.5 mm	70 – 100
25.0 mm	60 – 80
12.5 mm	40 – 65
4.75 mm	22 – 47
2.36 mm	15 – 40
0.30 mm	5 - 20
0.075 mm	0 – 5

The particle size shall be determined by the washing and sieving method of BS 812: Part 103

TABLE 8/3:

Granular Material Type 2 Range of Grading

ASTM sieve size	Percentage by mass passing
50.0 mm	100
37.5 mm	70 – 100
25.0 mm	60 – 100
12.5 mm	40 – 80
4.75mm	22 – 62
2.36 mm	15 – 50
0.30 mm	5 – 25
0.075 mm	0 – 10

The particle size shall be determined by the washing and sieving method of BS 812: Part 103

Table G.8a: Grading envelopes. Source: Austrian Green Guideline [1]

Grading curves for

Grade I: Fig 1-4

Grade II: Fig 5-6

1) For RA, this figure applies to the fragment size distribution

Fig. 1: Grading curve range 0/22 for top roadbases, grade I, RA[1]), RB, RAB, RM, RG

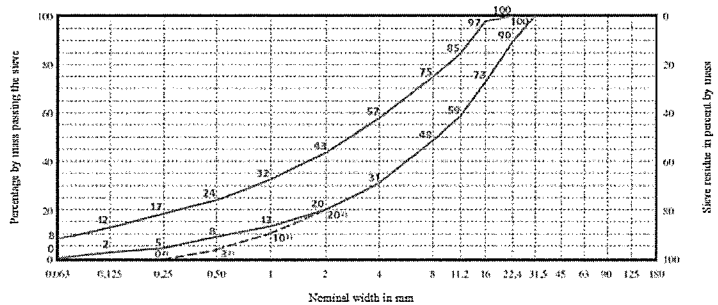


Fig. 2: Grading curve range 0/32 for top roadbases, grade I, RA[1]), RB, RAB, RM, RG

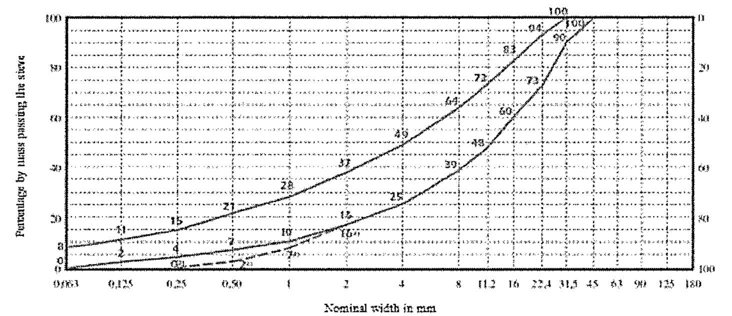


Fig. 3 Grading curve range 0/45 for top roadbases, grade I, RB, RAB, RM, RG

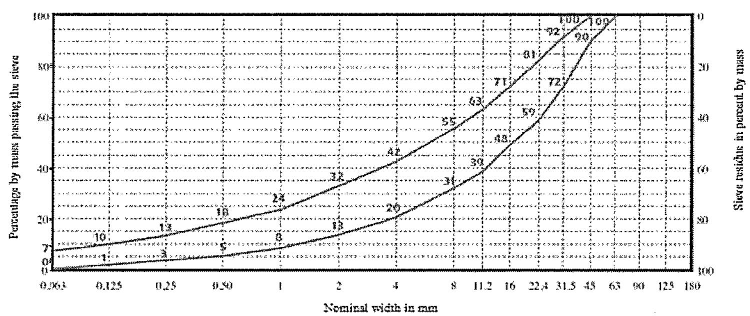


Fig. 4: Grading curve range 0/63 for top roadbases, grade I, RB, RAB, RM, RG

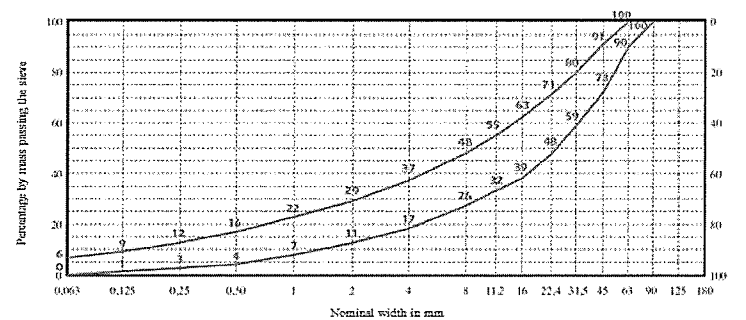


Fig. 5: Grading curve range 0/22 for roadbases, grade II, RA[1]), RB, RAB, RM, RG

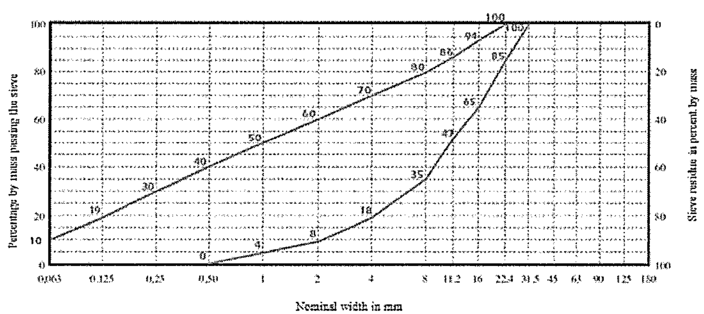


Fig. 6: Grading curve range 0/32 for roadbases, grade II, RA[1]), RB, RAB, RM, RG

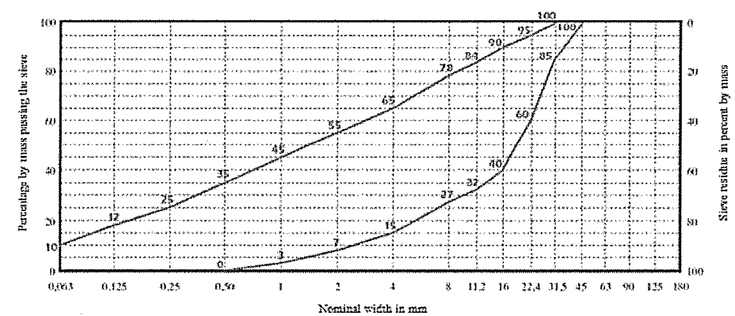


Table G.8b: Grading envelopes. Source: Austrian Green Guideline [1]

Grading curves for Grade II: Fig 7-9 Grade III: Fig 10-12 1) For RA, this figure applies to the fragment size distribution	See figures below

Fig. 7: Grading curve range 0/45 for roadbases, grade II, RB, RAB, RM, RG

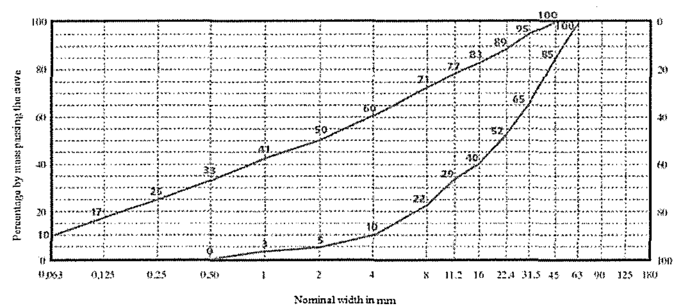


Fig. 8: Grading curve range 0/63 for roadbases, grade II, RB, RAB, RM, RG

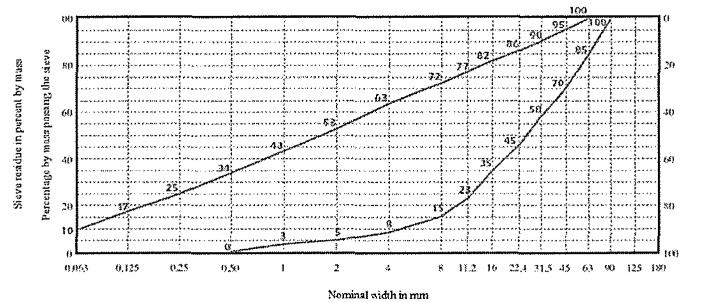


Fig. 9: Grading curve range 0/90 for roadbases, grade II, RB, RAB, RM, RG

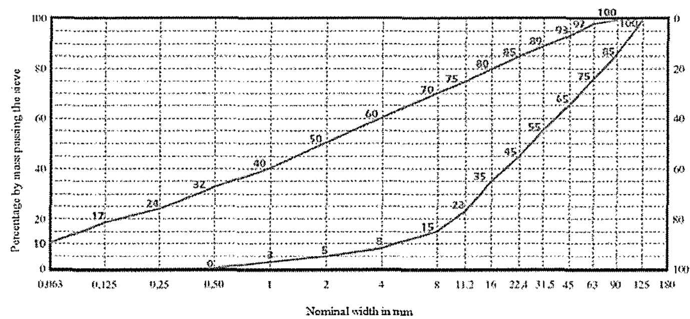


Fig. 10: Grading curve range 0/22 for roadbases, grade III, RB, RAB, RM, RG

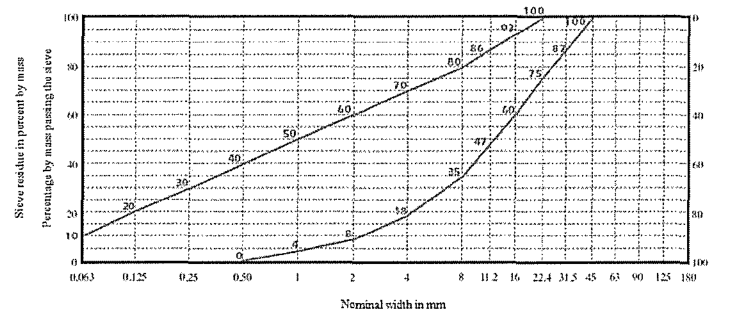


Fig. 11: Grading curve range 0/32 for roadbases, grade III, RA[1], RB, RAB, RM, RG

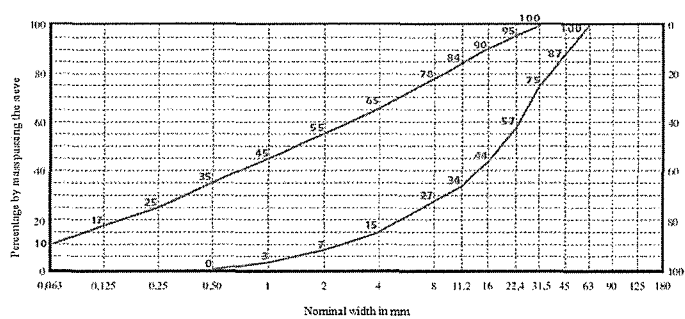


Fig. 12: Grading curve range 0/45 for roadbases, grade III, RB, RAB, RM, RG

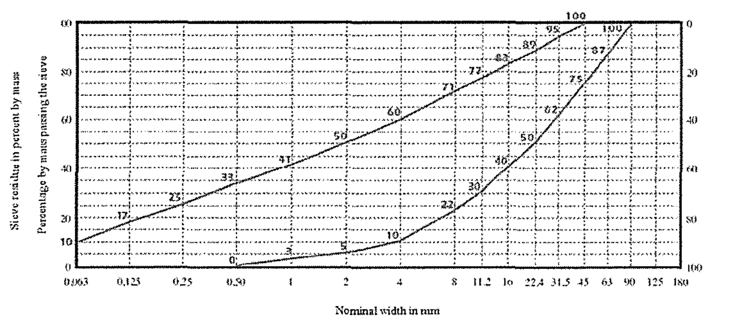


Table G.8c: Grading envelopes. Source: Austrian Green Guideline [1]

Grading curves for Grade III: Fig 13-14

Fig. 13: Grading curve range 0/63 for roadbases, grade III, RB, RAB, RM, RG

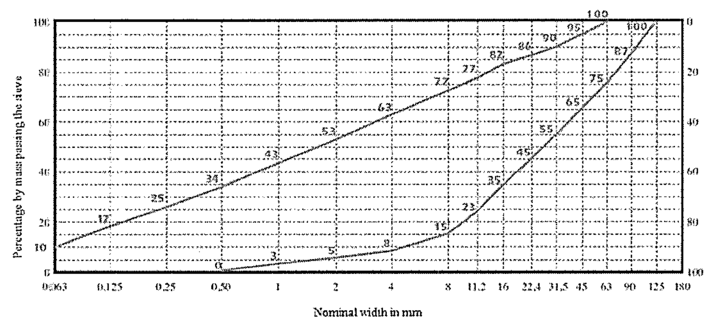


Fig. 14: Grading curve range 0/90 for roadbases, grade III, RB, RAB, RM, RG

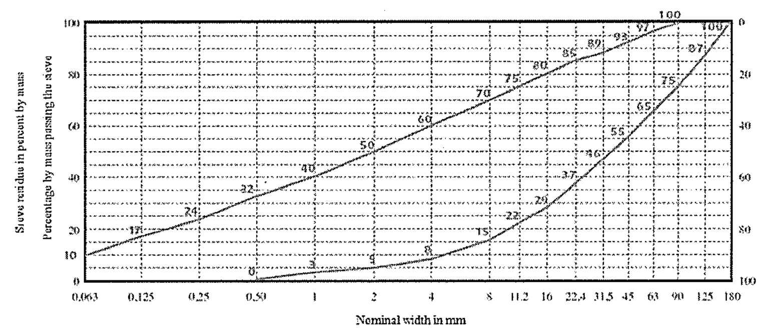


Table G.8d: Grading envelopes. Source: Austrian Red Guideline [2]

Figure 1: grading curve range 0/4 for RS

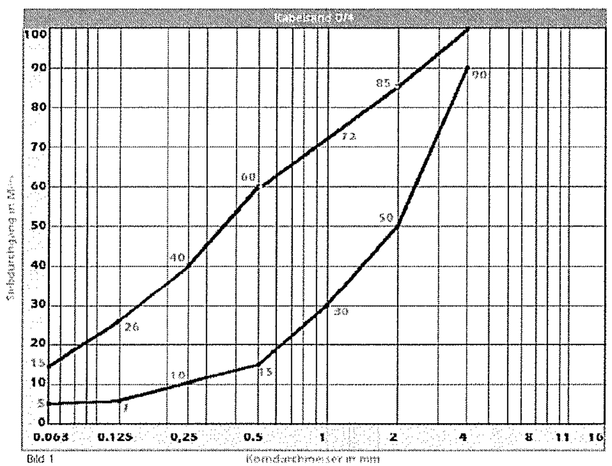


Figure 2: grading curve range 0/4 for grade III

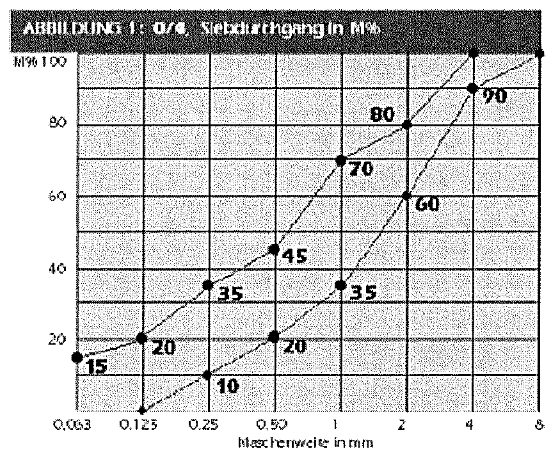


Figure 3: grading curve range 0/8 for grade III

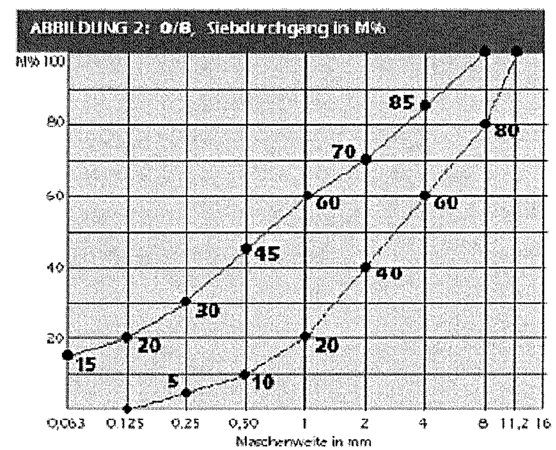


Table G.8e: Grading envelopes. Source: Austrian Red Guideline [2]

Figure 4: grading curve range 0/16 for grade III

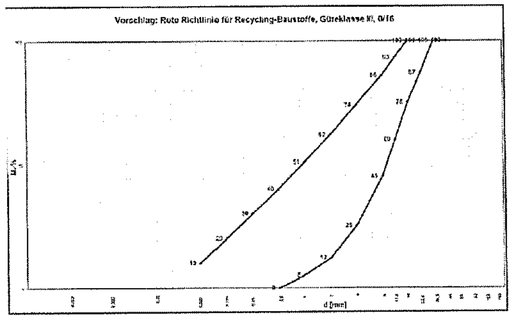


Figure 5: grading curve range 0/22 for grade III

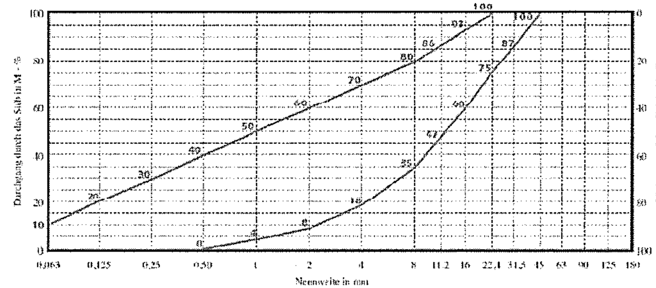


Figure 6: grading curve range 0/32 for grade III

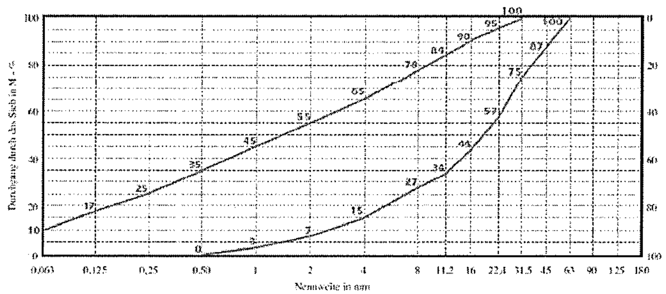


Figure 7: grading curve range 0/45 for grade III

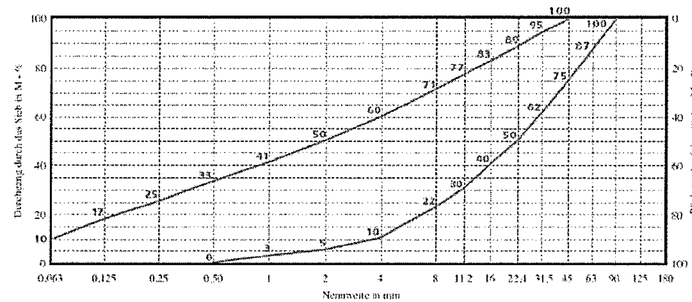
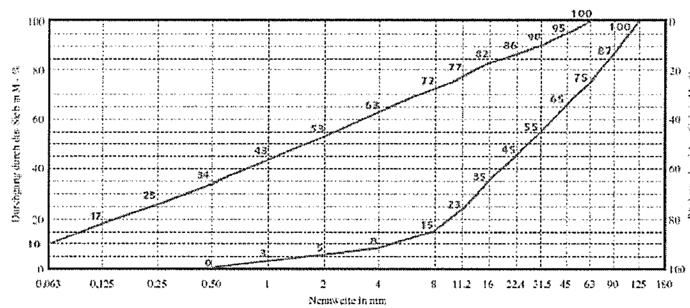


Figure 8: grading curve range 0/63 for grade III



Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
4.2 Foreign constituents See definition in section 2. **4.3 Impurities** See definition in section 2. **5 Environmental compatibility – quality regulations** No data is available; hence further research for Malta is required to complete this section.		**Environmental compatibility – quality regulations** The regulations regarding environmental compatibility have been prepared on the basis of the study "Recycling-Baustoffe; Regelung der Umweltverträglichkeit, Dezember 2002" – "Recycled building materials; regulation regarding the environmental compatibility, December 2002" carried out by the "Umweltbundesamt" (UBA) – "Austrian Environment Protection Agency" – at the request of the "Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft" (BMLFUW) - Ministry of Agriculture, Forestry, Environment and Water Management. **Quality of classes** Recycled materials produced in recycling plants are classified acc. to their composition in quality classes which are defined by means of a list of parameters and respective limit values (table 3). **Fields of application** In order to regulate the environmentally compatible use of recycled building materials it is necessary to determine forms of application according to hydro-geological conditions. Fundamentally, the use of recycled building materials of quality class A+ is permitted in water source preservation areas and in areas with frame conditions regarding water management. The use of recycled building materials of quality class A+, A and B is subject to defined conditions. This means that the quality of recycled building materials corresponds directly with the possible use (table 4). An area is to be considered less delicate in respect of hydro-geological conditions if it shows the following criteria: existence and sufficient efficiency of layers with low permeability or sufficient distance from ground waters. The application of recycled building materials in • water-source protection areas and • areas with fluctuating groundwater levels is prohibited **Foreign constituents** Foreign constituents are asphalt and gaseous concrete. Foreign components are predominantly of mineral origin and not contained in the definition of the relevant recycled building material pursuant to point 3.4.1. **Impurities** (contamination) may be caused by: • plastics, wood, paper, cardboard, metals • glass and glass building components • plasterboard sheets, wood wool lightweight building slabs • insulating materials, other non-hazardous waste

Table G.9: Environmental classification of recycled building materials. Source: Austrian Guidelines [1, 2], Table 3

Parameter	Unit	Quality class A+	Quality class A	Quality class B	Quality class C
Eluate					
pH-value		7.5–12.5 2)	7.5–12.5 2)	7.5–12.5 2)	6-13
Elec. conduct.	mS/m	150 1)2)	150 1)2)	150 1)2)	300
Chromium total	mg/kg TS	0.3	0.5	0.5	2
Copper	mg/kg TS	0.5	1	2	10
Ammonium-N	mg/kg TS	1	4 3)	8	40
Nitrite-N	mg/kg TS	0.5	1 3)	2	10
Sulphate-SO4	mg/kg TS	1,500	4,500	6,000 4)	10,000
HC index	mg/kg TS	1	3	5	50
∑ 16 PAH as per EPA	mg/kg TS	4	12	20	-

1) If the pH is between 11.0 and 12.5, the limit value for electrical conductivity is 200 mS/m
2) If this value is exceeded, see point 7.5.2.
3) The limit value is considered to have been complied with if the arithmetical mean of all test results from the last 12 months contains this value and, in the process, an individual value is exceeded by no more than a maximum of 65% of the limit value.
4) In the case of a Ca/SO4 ratio of ≥ 0.43 in the eluate, a limit value of 8,000 mg/kg TS applies

Table G.10: Environmental areas of use (minimum requirements). Source: Austrian Guidelines [1, 2], Table 4

Application form	Less hydro-geologically se sitive area	hydro-geologically sensitive area	within the landfill body 2)
in bound form or unbound with base course 1)	Quality class B	Quality class A	Quality class C
unbound without base course M	Quality class A	Quality class A+	Quality class C
in unbound form as an additive	Quality class B	Quality class B	Quality class C

1) Definition of the base course in accordance with RVS 01.02.11, principles, terms and definitions, structural engineering (September 1984)
2) Only in the case of landfill sites for non-hazardous waste

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
6 Applications **6.1 Application and use of RA** It is rather exhausting reading all the possible applications if listed at one go. Hence it is easier to read table G.1 and table G.4 with Appendix K of the dissertation [8] where illustrations of all applications are illustrated for ease of application. These applications been compiled and summarized from the AggRegain website [b]. Any further applications from the Austrian guidelines or other literature have been added at the end. It should be noted that the concrete road and stabilization techniques mentioned are not used locally and are therefore still provided but printed in grey not black.	[a] All documents mentioned are not used in Malta. [b] Reference to [22]	**6 Applications [a]** [1] **6.1 Application and use of recycled building materials** Recycled building materials may be used in pure form or in form of mixed materials consisting of aggregates made of natural stone or industrial byproducts such as • aggregates for unbound materials e.g. according to RVS 08.15.01 or RVS 08.15.02) • aggregates for hydraulically bound materials e.g. acc. to RVS 08.17.01 and so on • aggregates for bituminous bound materials acc. to RVS 08.97.05) Regarding the possibilities of use according to grades see sections 3.4.2 and 4.1 or according to quality classes see sections 3.4.3 and 5.2. Table 2 shows the possibilities of application and use of recycled building materials. [2] **6.1 Application and use of recycled building materials** Recycled building materials may be used on their own, or in conjunction with additives of natural stone/ industrial by-products, for • unbound construction methods, e.g. - Filling acc. to RVS 08.03.01 and noise barriers, road construction - Filling of pipe trenches and covering of pipes acc. to RVS 08.03.01 - bedding material for pipeline areas - Backfilling and covering of structures pursuant to RVS 08.03.01 - sports facility base course and lying area acc. to ÖNORM B 2606-2 - Substrate for grass acc. to ÖNORM L 1210 - Building materials used in the construction of landfill sites (cf. Act concerning the remediation of contaminated sites) - Drainage material • hydraulically bound construction methods, e.g. - (Wall) cavity blocks - Concrete in accordance with ÖNORM B 4710-1 - Light concrete in accordance with ÖNORM B 4200-11 - Screed pursuant to ÖNORM EN 13139 and so on - Subsoil improvement/stabilisation • free-flowing, self-compacting trench filling materials pursuant to Austrian Building Material Recycling Association guideline With regard to the possibilities for use dependent on the grade, see Table 2 or to the possibilities for use dependent on the quality class, see point 5.2.

Proposed Maltese Guidelines	Notes	Austrian Guidelines [1], [2]
6.2 Construction designs involving RA All RA which fall under the limits provided in table G.1 are considered to be of equal quality as conventional aggregate when used with the replacement ratios specified. The limits specified are all adapted for local use and compiled from standards used in Malta, based on EN or BS practices [a] and where roads are concerned confirmation of limits have been made with Transport Malta. **7 Grade and quality surveillance** The test methods and the frequency of monitoring for demonstrating compliance with the requirements and characteristics imposed have been laid down for the relevant grades and quality classes. These are the basis for obtaining the quality mark according to section 10; for obtaining the CE mark, the general provisions in EN 13242:2002 Annex C and ZA [c], EN 12620:2002 Annex H and ZA and EN 206-1 clauses 9 and 10 are also applicable.	[a] International standards have also been reviewed to comprehend the methodology of dealing with RA. The limits have been modified where necessary to suite the quality of aggregate used locally, especially when it comes to water absorption. [b] EN 13242 in conjunction with EN13285 is slowly being introduced locally, when it comes to road applications. Note that the sections following this apply for both the Austrian Guidelines and the proposed Local Guideline. Hence they shall only be reproduced once.	**Construction designs involving recycled materials** According to RVS 03.08.63 recycled building materials which meet the requirements laid down in RVS 08.15.01 or RVS 08.15.02 are considered of equal quality with natural building materials in respect of the use in unbound lower and sub-base courses. The layer designs shown in the tables 8 to11 of the RVS 03.08.63 may be made only of recycled building materials or may be constructed material and layers consisting of natural material. Construction designs which do not correspond with the RVS 03.08.63 must be declared and accorded as special designs. Note: Regarding construction type 3 of the RVS 03.08.63, table 8, the unbound sub-base course – restricted to load bearing classes III to VI – has definitely to be made of RA (recycled crushed granular asphalt) **Grade and quality surveillance** The test methods and the frequency of monitoring for demonstrating compliance with the requirements and characteristics imposed have been laid down for the relevant grades and quality classes. These are the basis for obtaining the quality mark pursuant to point 8; for obtaining the CE mark, the general provisions in EN 13242 are also applicable.

IMPORTANT: From here onwards only extracts from the Austrian guidelines are shown in the columns, as a continuation of the Proposed Maltese guidelines, with terms such as 'Austrian' changed to 'Maltese'. This is done since a Maltese agency with its own set of procedures does not exist. Logistics similar to those written should be adopted. They are being reproduced for now but are to eventually be modified to satisfy local requirements.

7.1 Initial inspection (proof of qualification)

The initial inspection serves to determine whether the monitoring requirements (e.g. possibility of internal monitoring in operation or by appointed laboratories, technical requirements, machinery) and the requirements laid down for recycled building materials can be complied with. Material samples shall be taken for the tests to be carried out in accordance with the testing provisions for the external inspection. A record of the sampling shall be taken and signed by those involved.

If the initial inspection produces a negative result, a repeat inspection shall be performed immediately. If the second repeat inspection is also failed, the material does not comply with the requirements of this guideline. The initial inspection shall be carried out once per business per type of granulate per intended granule size for delivery. The tests to be carried out are shown in Table G.12 of the testing provisions.

7.2 Internal monitoring

The recycling business is required to carry out internal monitoring and to ensure that compliance with the requirements imposed is monitored on a continuous basis. If the business is not in a position to carry out the internal monitoring itself, it must appoint a laboratory to do so. The test results shall be recorded.

The form used must show the following information:

- designation and origin of the material
- tests performed
- name of the tester, location and date
- evaluation of comparison with the requirements imposed
- defect report indicating rectification measures

If the internal inspection reveals that the test requirements laid down in the grading or quality provisions have not been met, the recycling business shall immediately take all possible operation measures to rectify the defects. Recycled building materials that do not meet the grading or quality requirements for their class shall either be reclassified or, if that is not possible, disposed of appropriately. The tests to be carried out are shown in Table G.14 of the testing provisions. The sampling records and inspection results from the internal inspections must be available in all cases.

7.3 External monitoring

The recycling business shall appoint testing offices authorised by the Quality Assurance Association for Recycled Building Materials to carry out the external monitoring.

These offices shall carry out the tests involved in the external monitoring. The purpose of external monitoring is to determine whether the requirements laid down for recycled building materials have been met. The tests shall be carried out at the frequency indicated in Table G.14, though in each case the second test may be omitted if there are no more than 20 production runs per calendar year per granule size for delivery. The sampling records and inspection results from the external inspections must be available in all cases.

7.3.1 External structural engineering inspection

Material samples shall be taken for the tests to be carried out in accordance with the testing provisions. A record of the sampling shall be taken and signed by those involved. If a parameter does not comply with the requirements of this guideline, a repeat inspection shall be carried out immediately, whereby only the relevant test need to be repeated, not the entire inspection. If a second repeat inspection is also failed, the recycled building material shall be reclassified into a different grade if possible, or, if not, shall be disposed of appropriately. The tests to be carried out are shown in Table G.14 of the testing provisions.

Table G.12: Testing provisions for initial inspection (proof of suitability and external monitoring). Source: Austrian Guidelines [1], Tables 5

GRADES I, II	Test pursuant to	1st ext. insp.	2nd ext. insp.	RA	RB	RAB	RM	RG
Particle size distribution	EN 933-1	x	x	I only	x	x	x	x
Fragment size distribution	EN 933-1	x	x	x			x	
Frost stability	B 4810	x		x	x	x	x	x
Resistance to frost	EN 1097-6/B 3132	x	x		x	x	x	x
Resistance to fragmentation	EN 1097-2	x	x		x	x	x	x
Foreign matter	see Chapter 7.5.1	x	x	x	x	x	x	x
Contamination	see Chapter 7.5.1	x	x	x	x	x	x	x
Binder content	EN 12697-1	x	x	x				
Mixing ratio	see Chapter 7.5.1	x	x			x	x	x
Environmental compatibility	see Chapter 5	x	x	x	x	x	x	x
GRADES III, IV	**Test pursuant to**	**1st ext. insp.**	**2nd ext. insp.**	**RA**	**RB**	**RAB**	**RM**	**RG**
Particle size distribution	EN 933-1	x	x		x	x	x	x
Fragment size distribution	EN 933-1	x	x	x				
Foreign matter	see Chapter 7.5.1	x	x	x	x	x	x	x
Contamination	see Chapter 7.5.1	x	x	x	x	x	x	x
Mixing ratio	see Chapter 7.5.1	x	x			x	x	x
Environmental compatibility	see Chapter 5	x	x	x	x	x	x	x

Table G.13: Testing provisions for internal monitoring. Source: Austrian Guidelines [1], Table 6

GRADES I, II	Test pursuant to	RA	RB	RAB	RM	RG
extraction, supply	visual, indicating: owner of waste, waste location, accumulation site, supplier	on each delivery				
Processing	visual inspection	daily				
Storage	visual inspection	daily				
Particle size distribution	EN 933-1	-	1x per week			
Fragment size distribution	EN 933-1	1x per week	-			
Resistance to fragmentation	EN 1097-2	-	2x per year			
Resistance to frost	EN 1097-6 / B 3132	-	2x per month			
Foreign matter	see Chapter 7.5.1	1x per week				
Contamination	see Chapter 7.5.1	1x per week				
Binder content	EN 12697-1	2x per month	-			
Environmental compatibility	see Chapter 5	2x per month				

GRADES III, IV	Test pursuant to	RA	RB	RAB	RM	RG
extraction, supply	visual, indicating: ■ owner of waste ■ waste location ■ accumulation site ■ supplier	on each delivery				
Processing	visual inspection	daily				
Storage	visual inspection	daily				
Particle size distribution	EN 933-1	-	1x per week			
Fragment size distribution	EN 933-1	1x per week	-			
Foreign matter	see Chapter 7.5.1	1x per week				
Contamination	see Chapter 7.5.1	1x per week				
Environmental compatibility	see Chapter 5	2x per month				

Table G.14: Testing provisions for initial inspection (proof of suitability and external monitoring) and internal monitoring (Proposed Maltese guidelines)

	Test pursuant to	1st ext. insp.	2nd ext. insp.	R_A	R_C	R_A+R_C	$R_A+R_C+R_{u50-}$	$R_A+R_C+R_{u50+}$
Particle size distribution	EN 933-1	x	x	I only	x	x	x	x
Fragment size distribution	EN 933-1	x	x	x			x	
Resistance to fragmentation	EN 1097-2	x	x		x	x	x	x
Foreign matter	see section 9.5.1	x	x	x	x	x	x	x
Contamination	see section 9.5.1	x	x	x	x	x	x	x
Binder content	EN 12697-1	x	x	x				
Mixing ratio	see section 9.5.1	x	x			x	x	x

	Test pursuant to	R_A	R_C	R_A+R_C	$R_A+R_C+R_{u50-}$	$R_A+R_C+R_{u50+}$
extraction, supply	visual, indicating: owner of waste, waste location, accumulation site, supplier	on each delivery				
Processing	visual inspection	daily				
Storage	visual inspection	daily				
Particle size distribution	EN 933-1	-	1x per week			
Fragment size distribution	EN 933-1	1x per week	-			
Resistance to fragmentation	EN 1097-2	-	2x per year			
Foreign matter	see Chapter 7.5.1	1x per week				
Contamination	see Chapter 7.5.1	1x per week				
Binder content	EN 12697-1	2x per month	-			

7.3.2 External inspection of environmental compatibility

Environmental compatibility table still needs to be researched.

7.4 Record-keeping obligations and labelling

The records must ensure that the input materials used for each batch can be traced. They must also document what internal and external monitoring applies to the material in question. The labeling must in all cases show what input materials were used to produce the RA in question. In addition, the label shall show the grade and quality class of the product.

7.5 Testing methods

7.5.1 Testing of foreign matter, contamination and mixing ratio

Foreign matter, contamination and the mixing ratio shall be tested as per EN standards, with the test particle size fractions being 4 to maximum grain size. The indication of the results shall apply for 4 to maximum grain size. The materials are sorted visually into:

- particles that are foreign matter
- particles that are contaminants

To determine the mixing ratio, it is also necessary to determine:

- particles that can be regarded as asphalt fragments
- particles that can be regarded as concrete fragments
- stone (natural and/or recycled)

7.5.2 Testing of pH and electrical conductivity

Local experiments per EN standards are to be used.

7.5.3 Testing of PAHs (EPA)

Local experiments per EN standards are to be used.

7.5.4 Internal inspection of environmentally relevant criteria

As part of the internal inspection, which shall be carried out twice a month for the recycled building material in question, the following parameters shall be analysed in each case: Total content: Σ16 PAH pursuant to EPA; Eluate: pH value, electrical conductivity, chromium, copper.

7.5.5 Quality assurance

Sampling should be carried out as per EN 932-1.

7.5.6 Simplified testing methods

Simplified testing methods may be used if the business produces building materials in compliance with the guideline that are the same in terms of nature, grading and quality class, but have different grain sizes. In such cases the building material with the smallest maximum grain size shall be subject to the entire internal or external monitoring process, while the other building material(s) need only be tested with regard to particle size distribution and frost stability. If it can be shown that a quality-assured building material is produced in a quantity of less than 10 000 tonnes per year per delivered granule size, only one external inspection shall be required in the first six months. One external inspection shall also be carried out each calendar year.

8. Obtaining the quality mark

Recycled building materials that comply in full with the requirements this guideline and meet the testing requirements may be labelled with the "quality mark for recycled aggregates" of the Maltese Quality Assurance Association for Recycled Building Materials, which still needs to be initiated. Manufacturers whose recycled building materials are labelled also guarantee compliance with the above-mentioned environmental compatibility requirements

8.1 Preconditions for obtaining the quality mark

The quality mark for recycled building materials may only be awarded, on request, to members of the Association.

8.2 Initial inspection (proof of qualification)

The initial inspection (proof of suitability) shall be carried out by a laboratory chosen by the applicant from the most up-to- date version of the list of testing offices appointed by the Association. The testing office cannot be changed during the course of a calendar year.

Subsequently, the applicant and the chosen testing office shall enter into an agreement regarding initial inspections and external inspections for each operating site, and shall send this agreement to the Association. On initial inspection, all the conditions for the selected grade/quality class and for the selected type of building material must be met in full.

The tests to be carried out are shown in Table 14 of the testing provisions. The result of the successful initial inspection shall be recorded by the testing office in the standardized results log, signed and stamped. As part of this, it shall be assessed whether all the relevant conditions have been met (e.g. possibility of internal monitoring, technical conditions, machinery, and compliance with technical requirements). The laboratory shall send the complete test report and the associated completed results log to the Association. If a parameter does not meet the requirements in this guideline, only the relevant test need be repeated, and not the entire inspection.

The formal application for the quality mark constitutes a declaration of obligations that the applicant fills in, signs and sends to the Association. It shall indicate the building materials to which the application relates, the inspector for the internal monitoring and the external testing office.

8.3 Conferring the quality mark

On receipt of the agreement, the declaration of obligations and the positive proof of suitability (test report and results log) by the Association, the application shall be examined by the Board.

If this examination has a positive outcome, the Chairman of the Association shall award the quality mark for the recycled building material to which the application relates (not for one transaction) produced by an operating site and for the specific grade/quality class.

8.4 Using the quality mark

The quality mark may only be used once it has been awarded by the Association. The quality mark shall indicate the class of recycled building materials in question. It may be included on price lists and such like in accordance with the guidelines and implementing provisions.

A party using the quality mark shall list recycled building materials that are not monitored in accordance with these quality and testing provisions separately, or label them as such.

8.5 Internal monitoring

The internal monitoring of the quality-assured products must be carried out, in accordance with the declaration of obligations, either by the member business itself or by an appointed laboratory. Each manufacturer shall keep an operating log and a results log. The nature and frequency of the tests are shown in Table G.14. The operating log and the results log shall be sent to the Association regularly (quarterly, or at least every six months). If the quantity threshold of internal monitoring tests is not attained, the operating log shall be submitted to the Association. If the internal monitoring is carried out by an appointed laboratory, any change of laboratory shall be notified immediately.

8.6 External monitoring

The member business shall have an external inspection carried out by the laboratory indicated in the declaration of obligations at the frequency indicated in Table G.14. The business itself is responsible for ensuring that the required number of inspections is carried out. The laboratory in question may choose the date of this inspection itself.

The tests to be carried out are shown in Table G.14 of the testing provisions. The laboratory carrying out the external inspection shall send a copy of the test report and the associated completed 'results log' form from the external inspection to the Association. The results log must show that the inspection was passed. The laboratory carrying out the external inspection must also not whether the operating log and results log for the internal inspections have been completed correctly. It shall be possible to change from the laboratory indicated in the declaration of obligations to another laboratory at the end of the year, or if the former laboratory is removed from the Quality Assurance Association's list.

8.7 Penalties for infringements

If defects are found in the quality assurance, the Board shall apply penalty measures, depending on the severity of the infringement. These shall usually be:

- additional requirements as part of the internal monitoring
- increased external monitoring
- warning
- temporary or permanent withdrawal of the quality mark

The aforementioned measures may also be applied in combination.
The quality mark shall be withdrawn temporarily or permanently from users who repeatedly or seriously contravene the proper use of the quality mark or the quality and testing provisions.

The party concerned shall be granted a hearing before any measures are imposed. In urgent cases, the Chairman of the Association may provisionally withdraw the quality mark with immediate effect. This shall be confirmed by the Board within 14 days.

8.8 Appeals

Within 14 days of a penalty notice being issued, the user of the quality mark may lodge an appeal against the notice with the Board of the Association. If the appeal is rejected, justifications shall be provided.

8.9 Surrender or withdrawal of the quality mark

In the event of surrender (end of production, transfer to a different grade) or withdrawal of the quality mark, the award certificate shall be returned immediately, in accordance with the implementing provisions.

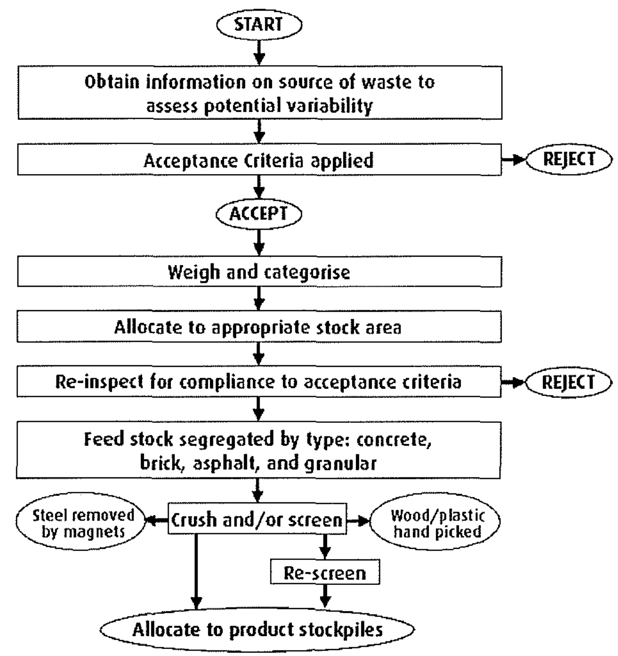
8.10 Regranting

If the right to use the quality mark is withdrawn, a reapplication may be submitted at the earliest three months after withdrawal. The procedure shall be based on point 8.3 of these guidelines, but the Board may impose additional conditions.

8.11 Preprinted forms

The following preprinted forms may be ordered from the Association:

- application form for Association membership
- form for agreements ("inspection contract")
- Declaration of obligations
- Results log (payment due)
- operating log (payment due)



Flow chart for acceptance and processing of inert waste.
Source:
www.wrap.org.uk/downloads/0083_Quality_Protocol_A4.2aec6f17.87.pdf

Appendix H

European Waste Catalogue

Appendix H Extracts from European Waste Codes v. 1.1 (EWC v.1.1)

01 Wastes resulting from exploration, mining, quarrying & physical & chemical treatment of minerals

01 01 Wastes from mineral excavation

01 01 02 wastes from mineral non-metalliferous excavation
Brine, Coal, Colliery spoil, Quarry spoil, Mine waste, Slate, Sodium chloride, Graphite, Calcium carbonate, Chalk, Overburden

17 Construction and demolition waste (including excavated soil from contaminated sites)

17 01 Concrete, bricks, tiles and ceramics

17 01 01 concrete:
Building rubble, wet concrete, concrete blocks, concrete floor tiles, concrete slurry, cement products

17 01 03 tiles and ceramics: Ceramics, china, floor tiles of ceramic or slate, roof tiles of clay or slate, clay and terracotta land drain pipes

17 01 06* mixtures of, or separate fractions of concrete, bricks, tiles & ceramics containing dangerous substances
Bricks, Building rubble, contaminated concrete or aggregate, Ceramics, Gravel, floor tiles of ceramic or slate, roof tiles of clay or slate

17 01 07 mixtures of concrete, bricks, tiles and ceramics other than those in 17 01 06
Bricks, Building rubble, Aggregates, Ceramics, Gravel, Hardcore, Road metal, Rubble

17 02 Wood, glass and plastic

17 02 01 wood: Wooden chairs, Cork, untreated timber, hardboard, wood cuttings, wooden doors

17 02 02 glass: Fibreglass, glass fibre, Resin-reinforced glass fibre products, vitreous enamels

17 02 03 plastic: Cones (roadworks), baled plastic waste, dry cellophane - dry, plastic chairs, corrugated plastic sheets, plastic laminates, low/high density polyethylene, mixed plastics, plastic film/pipes/sheeting, plastic windows

17 02 04* glass, plastic and wood containing or contaminated with dangerous substances
Fibreglass, glass fibre, glass, mixed plastics, plastics, polythene, polyurethane, polypropylene, polystyrene, resin-reinforced glass fibre products, timber railway sleepers, treated timber, contaminated ducting/piping, glassware

17 03 Asphalt, tar and tarred products

17 03 01* bituminous mixtures containing coal tar
Bitumen, Coal tars, Asphalt (containing tar), organic acid tars, Acid tars n/o/s, Mastic, Pitch, Tar residues, Tar macadam

17 03 02 bituminous mixtures containing other than those mentioned in 17 03 01
Bitumen, Asphalt (containing tar), Mastic, Pitch, Tar macadam

17 03 03* coal tar and tarred products
Bitumen, Coal tars, Asphalt (containing tar), Acid tars - organic, Acid tars n/o/s, Pitch, Tar residues

17 04 metals (including their alloys)

17 04 01 copper, bronze, brass: Brass scrap, copper waste and scrap, water heater elements

17 04 02 aluminium: Aluminum cladding and scrap, metal windows

17 04 03 lead: Lead waste and scrap, lead pipes

17 04 04 zinc: Zinc waste and scrap

17 04 05 iron and steel: Cast iron waste and scrap, metal doors, ferrous metal scrap and turnings, Iron scrap, Iron corrugated sheets, Steel, steel (of reinforced concrete), steel scrap, Ferrous swarf, steel cladding/pipes/wool, metal scrap, metal

17 04 06 tin: Tin waste and scrap

17 04 07 mixed metals:
Safety metal barriers, metal chairs, ferrous and nonferrous mixed/metal scrap, metal furniture

17 04 09* metal waste contaminated with dangerous substances
Ferrous metal scrap/turnings, iron scrap/corrugated sheets, steel, steel scrap, ferrous swarf, steel cladding/pipes/wool, Metal scrap (ferrous/non-ferrous), mixed ferrous and nonferrous

17 04 10* cables containing oil, coal tar and other dangerous substances
Cable stripping waste, coal tars, electrical cable/wire, wire (plastic coated) soft and hard drawn, wire (galvanised coated) soft and hard drawn

17 04 11 cables other than those mentioned in 17 04 10
Cable stripping waste, coal tars, electrical cable/wire, wire (plastic coated) soft and hard drawn, wire (galvanised coated) soft and hard drawn

<u>17 05 Soil (including excavated soil from contaminated sites), stones and dredging spoil</u>

17 05 03* soil and stones containing dangerous substances
Building rubble, contaminated clay/sand/soil/rock, stone, sub soil, excavated/crushed rock, sand, soil, soil and stones (mixed)

17 05 04 soil and stones other than those mentioned in 17 05 03
Building rubble, contaminated clay/sand/soil/rock, stone, top/sub soil, excavated/crushed rock, sand, soil, soil and stones (mixed), vermiculite

17 05 05* dredging spoil containing dangerous substances:
Contaminated silt and dredgings, Contaminated silt/dredgings, silt

17 05 06 dredging spoil other than those mentioned in 17 05 05
Contaminated silt and dredgings, Contaminated silt/dredgings, silt

<u>17 06 insulation materials and asbestos-containing construction materials</u>

17 06 01* insulation materials containing asbestos
Asbestos, Asbestos - fibrous, Asbestos - insulation products

17 06 03* other insulation materials consisting of or containing dangerous substances

17 06 04 insulation materials other than those mentioned in 17 06 01 and 17 06 03

17 06 05* construction materials containing asbestos (#)
Asbestos, Asbestos - bonded, Asbestos sheets - corrugated, Asbestos - bonded,

<u>17 08 gypsum-based construction material</u>

17 08 01* gypsum-based construction materials contaminated with dangerous substances

17 08 02 gypsum-based construction materials other than those mentioned in 17 08 01

17 09	other construction and demolition wastes
17 09 01*	construction and demolition wastes containing mercury
17 09 02*	construction and demolition wastes containing PCB (for example PCB containing sealants, PCB-containing resin-based floorings, PCB containing sealed glazing units, PCB-containing capacitors)
17 09 03*	other construction and demolition wastes (including mixed wastes) containing dangerous substances
17 09 04	mixed construction & demolition wastes other than those mentioned in 17 09 01, 17 09 02 and 17 09 03

Any waste marked with an asterisk (*) is considered as a hazardous waste pursuant to Directive 91/689/EEC on hazardous waste, and subject to the provisions of that Directive unless Article 1 (5) of that Directive applies.

As far as the landfilling of waste is concerned; Member States may decide to postpone the entry into force of this entry until the establishment of appropriate measures for the treatment and disposal of waste from construction material containing asbestos. These measures are to be established according to the procedure referred to in Article 16 of Council Directive 1999/31/EC on the landfill of waste (OJ L 182, 16.7.1999, p.1) and shall be adopted by 16 July 2002 at the latest.

Appendix I

Pros and cons of on-site or off-site sorting and crushing

Appendix I The pros and cons of on-site and off-site crushing and sorting

The choice as to whether crushing and sorting should be done on-site or off-site depends on many factors including:

i. availability (and ownership) of different machines
ii. quality of aggregate required on the demolition site itself
iii. space and time available on the demolition site
iv. haul distances between the site, the nearest available fixed processing site and other treatment and disposal sites

Below are listed the pros and cons of crushing and sorting on-site and off-site according to (Symonds et al, 1999).

Pros	**Cons**
...of on-site crushing and sorting a. Lower materials handling and transport costs b. Lower machinery capital costs c. Less transport disruption to surrounding areas (if recycled materials can be used on site)	...of on-site crushing and sorting a. Conflicts between site operations and space demands for materials and machinery b. Higher machinery operating costs per tonne of C&DW c. More local noise and dust nuisance d. Less flexibility about where/when recycled materials can be used e. Construction may be delayed
...of off-site crushing and sorting a. Easier to reduce and/or mitigate adverse environmental impacts on surrounding areas b. More practical to use a wider range of higher capacity equipment c. Lower machinery operating costs per tonne of C&DW d. Easier to control quality of recycled materials e. Possible to hold stocks, thereby making positive marketing of recycled materials easier	...of off-site crushing and sorting a. Proper control of demolition process essential (to avoid arrival of unknown quality materials) b. Higher materials handling and transport costs c. Higher machinery capital costs d. Fixed costs of recycling the site (land etc)

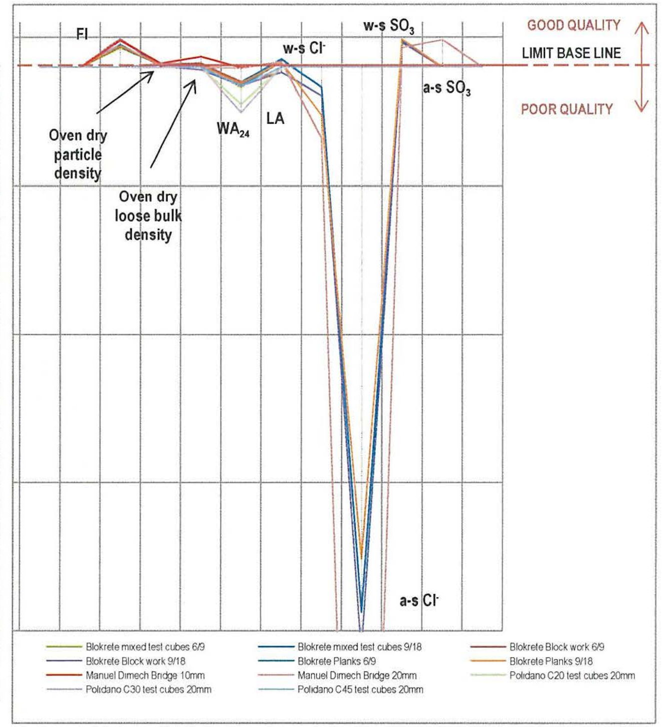
Appendix J

Study of critical parameters from results of RCA under proposed classification scheme

J.1 Results of RCA under proposed classification scheme for Grade G-A

GRADE G-A	APPLICATION : Prestressed or water retaining concrete element							Replacement ratio: ≤		15 ± 2	%
Relative values (± Limit ± Result) / Limit	Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit		35	2	1	5.5	40	0.01	0.01	0.2	1	
Base line		0	0	0	0	0	0	0	0	0	
Blokrete mixed test cubes 0/6	0 pass	0.00	0.07	0.28	-0.52	0.00	-0.70	-18.38	0.89	0.00	0
Blokrete mixed test cubes 6/9	0 pass	0.64	0.07	0.06	-0.70	0.25	-0.70	-18.38	0.89	0.00	0
Blokrete mixed test cubes 9/18	0 pass	0.73	0.05	0.10	-0.52	0.25	-0.70	-18.38	0.89	0.00	0
Blokrete Block work 0/6	0 fail	0.00	0.1	0.22	-0.65	0.00	-0.98	-19.72	0.80	0.00	0
Blokrete Block work 6/9	0 pass	0.89	0.09	0.12	-0.51	-0.18	-0.98	-19.72	0.80	0.00	0
Blokrete Block work 9/18	0 pass	0.93	0.015	-0.09	-0.65	-0.18	-0.98	-19.72	0.80	0.00	0
Blokrete Planks 0/6	0 pass	0.00	0	0.32	-0.56	0.00	-1.62	-16.59	0.93	0.00	0
Blokrete Planks 6/9	0 pass	0.67	0.065	0.05	-0.62	0.18	-1.62	-16.59	0.93	0.00	0
Blokrete Planks 9/18	0 pass	0.70	0.07	0.04	-0.56	0.18	-1.62	-16.59	0.93	0.00	0
Manuel Dimech Bridge 4mm	0 pass	0.00	0.11	0.12	-0.35	0.00	-2.40	-43.84	0.64	0.92	0
Manuel Dimech Bridge 10mm	0 pass	0.90	0.125	0.35	-0.02	0.17	-2.40	-43.84	0.64	0.92	0
Manuel Dimech Bridge 20mm	0 fail	0.00	0.12	0.00	-0.04	0.17	-2.40	-43.84	0.64	0.92	0
Polidano C20 test cubes 4mm	0 pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0 fail	0.00	-0.015	0.00	-1.27	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0 pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0 pass	0.00	-0.01	0.00	-1.55	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0 pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0 pass	0.00	0.05	0.00	-0.65	0.00	0.00	0.00	0.00	0.00	0

Results



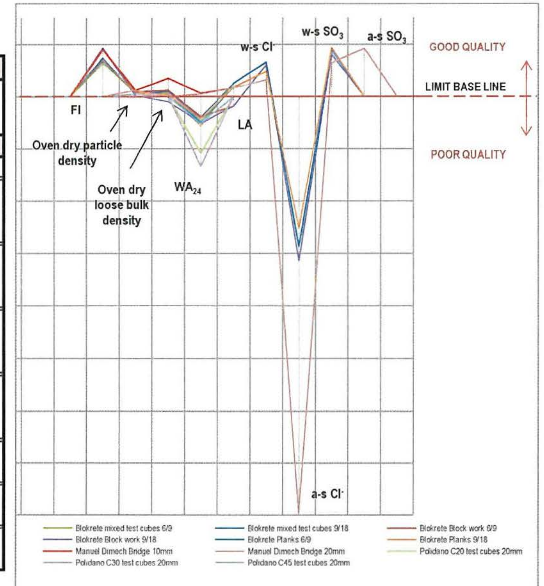
Note about this appendix

This appendix is a study of the results of experiments from this dissertation, Borg (1998) and Mifsud (2003) compared to the limits being proposed in the Guidelines in Appendix G.
Each individual grade (that is, G-A, G-B, G-C, R-A, R-B, R-C and F) which represent a particular type of application, is treated separately.
Relative values are calculated by subtracting the proposed limit for the grade by the result from the sample, divided by the limit. This is done for all the samples and all the

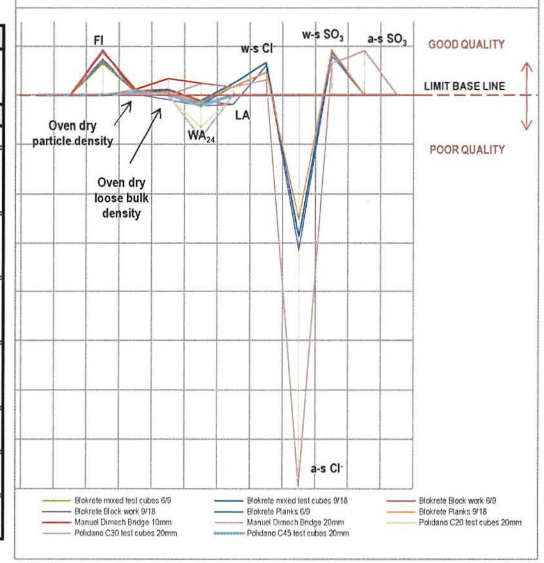
The properties with the largest relative values (discrepancies from the limits) are the critical properties for that application are can be observed in the graphs presented as being furthest away from the limit base line.

J.2 Results of RCA under proposed classification scheme for Grade G-B

GRADE G-B1		APPLICATION : Structural concrete element (reinforced)							Replacement ratio: ≤		35	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			35	2	1	6	40	0.05	0.05	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Results: Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	-0.40	0.00	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.64	0.07	0.06	-0.56	0.25	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.73	0.05	0.10	-0.40	0.25	0.66	-2.88	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	-0.52	0.00	0.60	-3.14	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.89	0.09	0.12	-0.39	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.93	0.015	-0.09	-0.52	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0	0.32	-0.43	0.00	0.48	-2.52	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.67	0.065	0.05	-0.49	0.18	0.48	-2.52	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.70	0.07	0.04	-0.43	0.18	0.48	-2.52	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	-0.23	0.00	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.90	0.125	0.35	0.07	0.17	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	fail	0.00	0.12	0.00	0.05	0.17	0.32	-7.97	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-1.08	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-1.33	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	-0.52	0.00	0.00	0.00	0.00	0.00	0



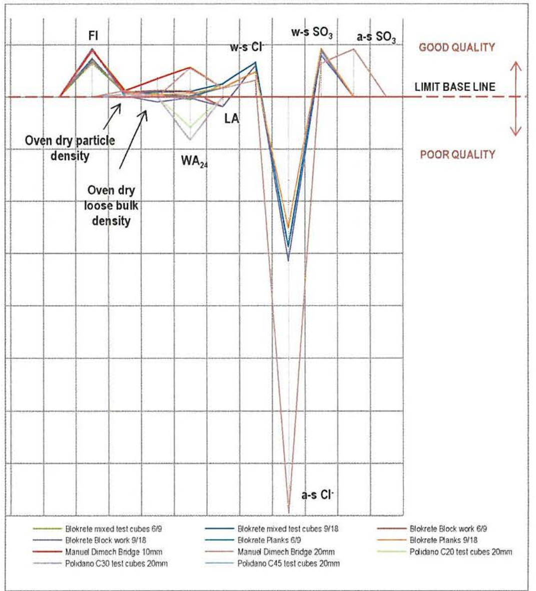
GRADE G-B2		APPLICATION : Structural concrete element (reinforced)							Replacement ratio: ≤		15 ± 2	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			35	2	1	7.5	40	0.05	0.05	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Results: Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	-0.12	0.00	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.64	0.07	0.06	-0.24	0.25	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.73	0.05	0.10	-0.12	0.25	0.66	-2.88	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	-0.21	0.00	0.60	-3.14	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.89	0.09	0.12	-0.11	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.93	0.015	-0.09	-0.21	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0	0.32	-0.15	0.00	0.48	-2.52	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.67	0.065	0.05	-0.19	0.18	0.48	-2.52	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.70	0.07	0.04	-0.15	0.18	0.48	-2.52	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	0.01	0.00	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.90	0.125	0.35	0.25	0.17	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	fail	0.00	0.12	0.00	0.24	0.17	0.32	-7.97	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-0.67	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-0.87	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	-0.21	0.00	0.00	0.00	0.00	0.00	0



J.3 Results of RCA under proposed classification scheme for Grade G-B and G-C

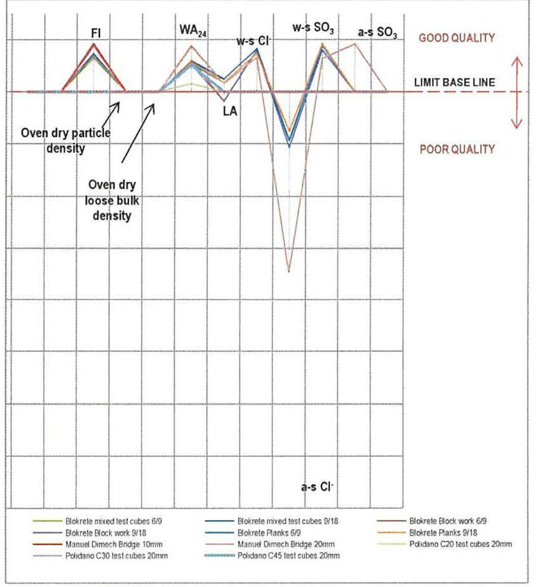
GRADE G-B3		APPLICATION : Structural concrete element (reinforced)							Replacement ratio: ≤		10 ± 2	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			35	2	1	9	40	0.05	0.05	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	0.11	0.00	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.64	0.07	0.06	-0.06	0.25	0.66	-2.88	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.73	0.05	0.10	0.11	0.25	0.66	-2.88	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	-0.02	0.00	0.60	-3.14	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.89	0.09	0.12	0.11	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.93	0.015	-0.09	-0.02	-0.18	0.60	-3.14	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0	0.32	0.07	0.00	0.48	-2.52	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.67	0.065	0.05	0.02	0.18	0.48	-2.52	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.70	0.07	0.04	0.07	0.18	0.48	-2.52	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	0.27	0.00	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.90	0.125	0.35	0.57	0.17	0.32	-7.97	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	fail	0.00	0.12	0.00	0.55	0.17	0.32	-7.97	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-0.58	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-0.83	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	-0.02	0.00	0.00	0.00	0.00	0.00	0

Results



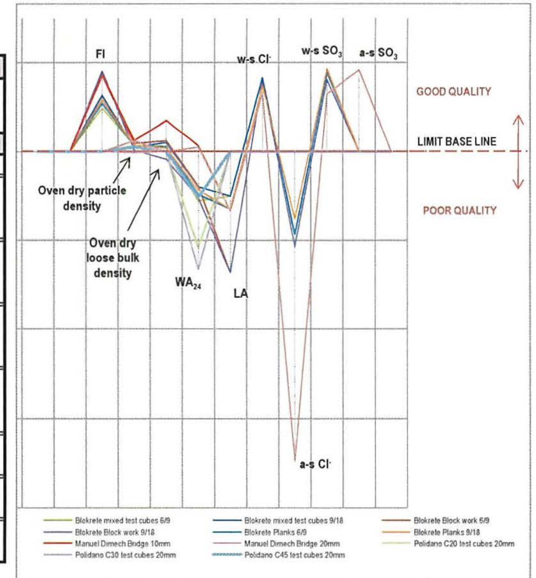
GRADE G-C		APPLICATION : Non-Structural concrete element (unreinforced)							Replacement ratio: ≤		100	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			35	NR	NR	14	40	0.1	0.1	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Blokrete mixed test cubes 0/6	0	pass	0.00	0.00	0.00	0.59	0.00	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.64	0.00	0.00	0.49	0.25	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.73	0.00	0.00	0.59	0.25	0.83	-0.94	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.00	0.00	0.52	0.00	0.80	-1.07	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.89	0.00	0.00	0.60	-0.18	0.80	-1.07	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.93	0.00	0.00	0.52	-0.18	0.80	-1.07	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0.00	0.00	0.57	0.00	0.74	-0.76	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.67	0.00	0.00	0.54	0.18	0.74	-0.76	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.70	0.00	0.00	0.57	0.18	0.74	-0.76	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.00	0.00	0.69	0.00	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.90	0.00	0.00	0.88	0.17	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	fail	0.00	0.00	0.00	0.87	0.17	0.66	-3.48	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.00	0.00	0.52	0.00	0.00	0.00	0.00	0.00	0

Results

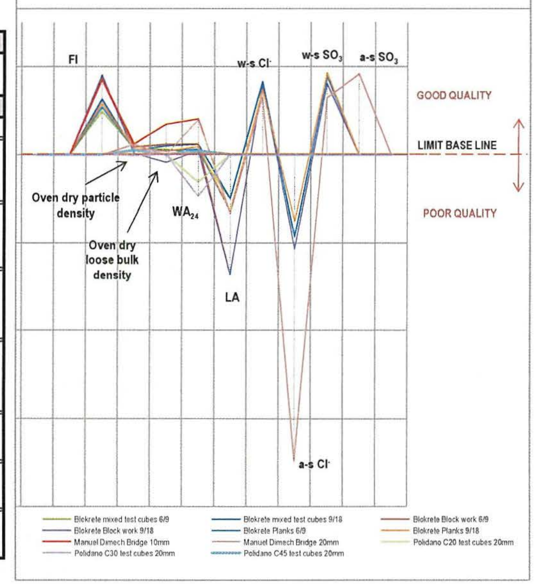


J.4 Results of RCA under proposed classification scheme for Grade R-A

GRADE R-A1		APPLICATION : Wearing course (road surfaces)								Replacement ratio: ≤		35	%
	Relative values (± Limit ± Result) / Limit	Particle size distribution		Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
	Proposed Limit			25	2	1	6	20	0.1	0.1	0.2	1	
	Base line			0	0	0	0	0	0	0	0	0	
Results	Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	-0.40	0.00	0.83	-0.94	0.89	0.00	0
	Blokrete mixed test cubes 6/9	0	pass	0.49	0.07	0.06	-0.56	-0.50	0.83	-0.94	0.89	0.00	0
	Blokrete mixed test cubes 9/18	0	pass	0.63	0.05	0.10	-0.40	-0.50	0.83	-0.94	0.89	0.00	0
	Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	-0.52	0.00	0.80	-1.07	0.80	0.00	0
	Blokrete Block work 6/9	0	pass	0.85	0.09	0.12	-0.39	-1.36	0.80	-1.07	0.80	0.00	0
	Blokrete Block work 9/18	0	pass	0.90	0.015	-0.09	-0.52	-1.36	0.80	-1.07	0.80	0.00	0
	Blokrete Planks 0/6	0	pass	0.00	0	0.32	-0.43	0.00	0.74	-0.76	0.93	0.00	0
	Blokrete Planks 6/9	0	pass	0.54	0.065	0.05	-0.49	-0.64	0.74	-0.76	0.93	0.00	0
	Blokrete Planks 9/18	0	pass	0.58	0.07	0.04	-0.43	-0.64	0.74	-0.76	0.93	0.00	0
	Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	-0.23	0.00	0.66	-3.48	0.64	0.92	0
	Manuel Dimech Bridge 10mm	0	pass	0.86	0.125	0.35	0.07	-0.67	0.66	-3.48	0.64	0.92	0
	Manuel Dimech Bridge 20mm	0	pass	0.00	0.12	0.00	0.05	-0.67	0.66	-3.48	0.64	0.92	0
	Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-1.08	0.00	0.00	0.00	0.00	0.00	0
	Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-1.33	0.00	0.00	0.00	0.00	0.00	0
	Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	-0.52	0.00	0.00	0.00	0.00	0.00	0



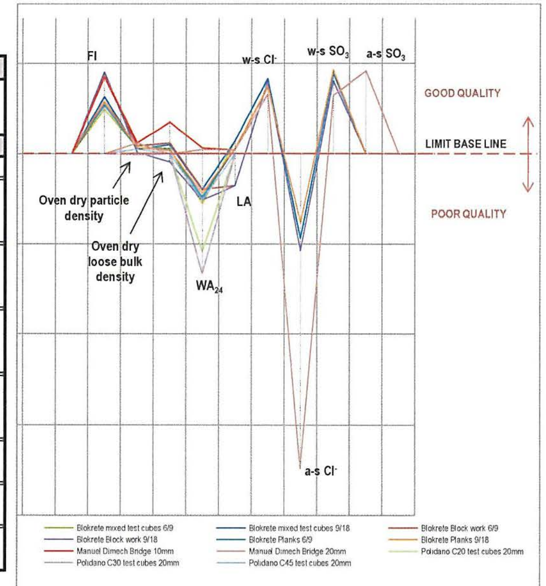
GRADE R-A2		APPLICATION : Wearing course (road surfaces)								Replacement ratio: ≤		15 ± 1	%
	Relative values (± Limit ± Result) / Limit			Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
	Proposed Limit			25	2	1	9.5	20	0.1	0.1	0.2	1	
	Base line			0	0	0	0	0	0	0	0	0	
Results	Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	0.12	0.00	0.83	-0.94	0.89	0.00	0
	Blokrete mixed test cubes 6/9	0	pass	0.49	0.07	0.06	0.02	-0.50	0.83	-0.94	0.89	0.00	0
	Blokrete mixed test cubes 9/18	0	pass	0.63	0.05	0.10	0.12	-0.50	0.83	-0.94	0.89	0.00	0
	Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	0.04	0.00	0.80	-1.07	0.80	0.00	0
	Blokrete Block work 6/9	0	pass	0.85	0.09	0.12	0.12	-1.36	0.80	-1.07	0.80	0.00	0
	Blokrete Block work 9/18	0	pass	0.90	0.015	-0.09	0.04	-1.36	0.80	-1.07	0.80	0.00	0
	Blokrete Planks 0/6	0	pass	0.00	0	0.32	0.09	0.00	0.74	-0.76	0.93	0.00	0
	Blokrete Planks 6/9	0	pass	0.54	0.065	0.05	0.06	-0.64	0.74	-0.76	0.93	0.00	0
	Blokrete Planks 9/18	0	pass	0.58	0.07	0.04	0.09	-0.64	0.74	-0.76	0.93	0.00	0
	Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	0.22	0.00	0.66	-3.48	0.64	0.92	0
	Manuel Dimech Bridge 10mm	0	pass	0.86	0.125	0.35	0.41	-0.67	0.66	-3.48	0.64	0.92	0
	Manuel Dimech Bridge 20mm	0	pass	0.00	0.12	0.00	0.40	-0.67	0.66	-3.48	0.64	0.92	0
	Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-0.32	0.00	0.00	0.00	0.00	0.00	0
	Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-0.47	0.00	0.00	0.00	0.00	0.00	0
	Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
	Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0



J.5 Results of RCA under proposed classification scheme for Grade R-B

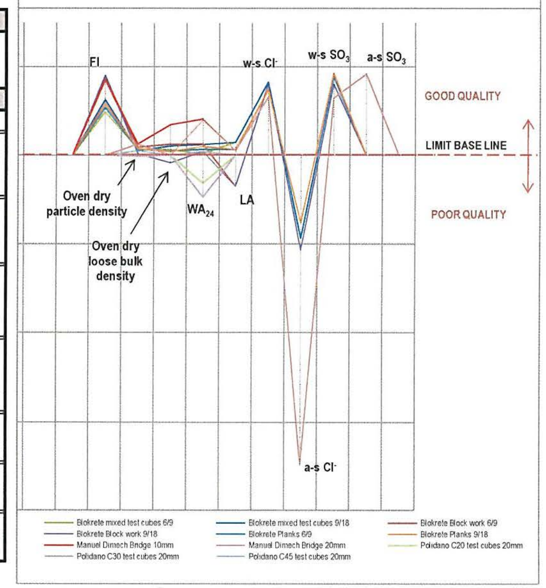
GRADE R-B1		APPLICATION : Intermediate binding course or Base course							Replacement ratio: ≤		35	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			25	2	1	6	35	0.1	0.1	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	-0.40	0.00	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.49	0.07	0.06	-0.56	0.14	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.63	0.05	0.10	-0.40	0.14	0.83	-0.94	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	-0.52	0.00	0.80	-1.07	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.85	0.09	0.12	-0.39	-0.35	0.80	-1.07	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.90	0.015	-0.09	-0.52	-0.35	0.80	-1.07	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0	0.32	-0.43	0.00	0.74	-0.76	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.54	0.065	0.05	-0.49	0.06	0.74	-0.76	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.58	0.07	0.04	-0.43	0.06	0.74	-0.76	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	-0.23	0.00	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.86	0.125	0.35	0.07	0.05	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	pass	0.00	0.12	0.00	0.05	0.05	0.66	-3.48	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-1.08	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-1.33	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	-0.52	0.00	0.00	0.00	0.00	0.00	0

Results



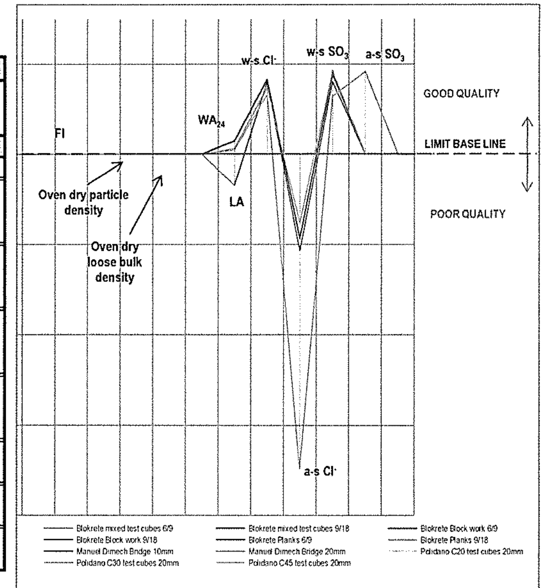
GRADE R-B2		APPLICATION : Intermediate binding course or Base course							Replacement ratio: ≤		15 ± 1	%
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			25	2	1	9.5	35	0.1	0.1	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Blokrete mixed test cubes 0/6	0	pass	0.00	0.07	0.28	0.12	0.00	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.49	0.07	0.06	0.02	0.14	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 9/18	0	pass	0.63	0.05	0.10	0.12	0.14	0.83	-0.94	0.89	0.00	0
Blokrete Block work 0/6	0	fail	0.00	0.1	0.22	0.04	0.00	0.80	-1.07	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.85	0.09	0.12	0.12	-0.35	0.80	-1.07	0.80	0.00	0
Blokrete Block work 9/18	0	pass	0.90	0.015	-0.09	0.04	-0.35	0.80	-1.07	0.80	0.00	0
Blokrete Planks 0/6	0	pass	0.00	0	0.32	0.09	0.00	0.74	-0.76	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.54	0.065	0.05	0.06	0.06	0.74	-0.76	0.93	0.00	0
Blokrete Planks 9/18	0	pass	0.58	0.07	0.04	0.09	0.06	0.74	-0.76	0.93	0.00	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.11	0.12	0.22	0.00	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.86	0.125	0.35	0.41	0.05	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	pass	0.00	0.12	0.00	0.40	0.05	0.66	-3.48	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	-0.015	0.00	-0.32	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	-0.01	0.00	-0.47	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.05	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0

Results

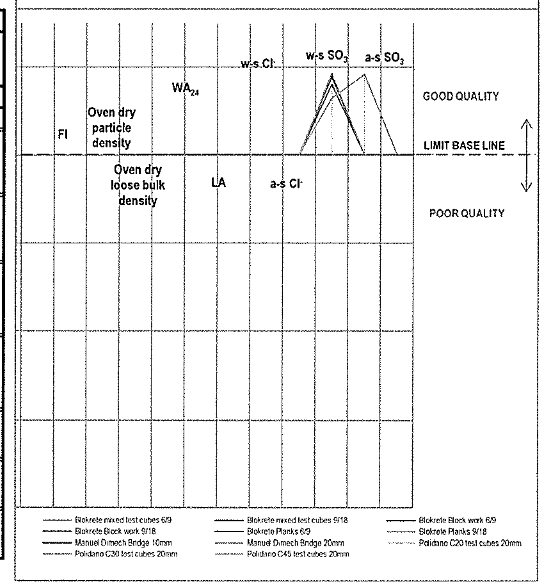


J.6 Results of RCA under proposed classification scheme for Grade R-C and F

GRADE R-C	APPLICATION : Sub-base (foundation) course								Replacement ratio: ≤	100	%	
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			NR	NR	NR	NR	35	0.1	0.1	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Results: Blokrete mixed test cubes 0/6	0	pass	0.00	0.00	0.00	0.00	0.00	0.83	-0.94	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	pass	0.00	0.00	0.00	0.00	0.14	0.83	-0.94	0.89	[illegible]	0
Blokrete mixed test cubes 9/18	0	pass	0.00	0.00	0.00	0.00	0.14	0.83	-0.94	0.89	[illegible]	0
Blokrete Block work 0/6	0	fail	0.00	0.00	0.00	0.00	0.00	0.80	-1.07	0.80	0.00	0
Blokrete Block work 6/9	0	pass	0.00	0.00	0.00	0.00	-0.35	0.80	-1.07	0.80	[illegible]	0
Blokrete Block work 9/18	0	pass	0.00	0.00	0.00	0.00	-0.35	0.80	-1.07	0.80	[illegible]	0
Blokrete Planks 0/6	0	pass	0.00	0.00	0.00	0.00	0.00	0.74	-0.76	0.93	0.00	0
Blokrete Planks 6/9	0	pass	0.00	0.00	0.00	0.00	0.06	0.74	-0.76	0.93	[illegible]	0
Blokrete Planks 9/18	0	pass	0.00	0.00	0.00	0.00	0.06	0.74	-0.76	0.93	[illegible]	0
Manuel Dimech Bridge 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	pass	0.00	0.00	0.00	0.00	0.05	0.66	-3.48	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	pass	0.00	0.00	0.00	0.00	0.05	0.66	-3.48	0.64	0.92	0
Polidano C20 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C20 test cubes 20mm	0	fail	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C30 test cubes 20mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 4mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0
Polidano C45 test cubes 20mm	0	pass	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0



GRADE F	APPLICATION : Fill and embankment								Replacement ratio: ≤	100	%	
Relative values (± Limit ± Result) / Limit		Particle size distribution	Flakiness index	Oven dry density	Loose bulk density	WA_{24}	Los Angeles	w-s chloride content	a-s chloride content	w-s sulfate content	a-s sulfate content	
Proposed Limit			NR	NR	NR	NR	NR	NR	NR	0.2	1	
Base line			0	0	0	0	0	0	0	0	0	
Results: Blokrete mixed test cubes 0/6	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.89	0.00	0
Blokrete mixed test cubes 6/9	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.89	[illegible]	0
Blokrete mixed test cubes 9/18	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.89	[illegible]	0
Blokrete Block work 0/6	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.80	0.00	0
Blokrete Block work 6/9	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.80	[illegible]	0
Blokrete Block work 9/18	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.80	[illegible]	0
Blokrete Planks 0/6	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.93	0.00	0
Blokrete Planks 6/9	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.93	[illegible]	0
Blokrete Planks 9/18	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.93	[illegible]	0
Manuel Dimech Bridge 4mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.64	0.92	0
Manuel Dimech Bridge 10mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.64	0.92	0
Manuel Dimech Bridge 20mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.64	0.92	0
Polidano C20 test cubes 4mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0
Polidano C20 test cubes 20mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0
Polidano C30 test cubes 4mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0
Polidano C30 test cubes 20mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0
Polidano C45 test cubes 4mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0
Polidano C45 test cubes 20mm	0	NR	0.00	0.00	0.00	0.00	0.00	[illegible]	[illegible]	0.00	0.00	0



Appendix K

AggRegain applications with Proposed Grades for RA in Malta

Appendix K AggRegain applications with Proposed Grades for RA in Malta

The author has compiled and summarised the applications from the AggRegain website, mentioned in section 3.1.9, in table format. However, two modifications are made which are additions to how they are presented in the website.

Firstly, few applications are in grey, signifying that they are not applicable to local construction methods. Since locally, we base most of our practice on that used in the UK, and also, since roads are designed as per most of the Specifications to road work in the UK, most of these applications are considered suitable for application in Malta.

Secondly, a list of grades is provided, such as R-A, R-B and so on. These are not specified in the website by AggRegain but are additions made by the author. These are the grades proposed for the local guidelines, as explained in Chapter 7, with say, R-A being of a higher quality than R-B and R-C. They are included since reference is made to these applications in the proposed guidelines. Therefore, if a RA is graded as R-B with the guidelines provided in Appendix G, then all applications with grade R-B or lower (that is, R-C and F) marked in this appendix apply to the aggregate being graded.

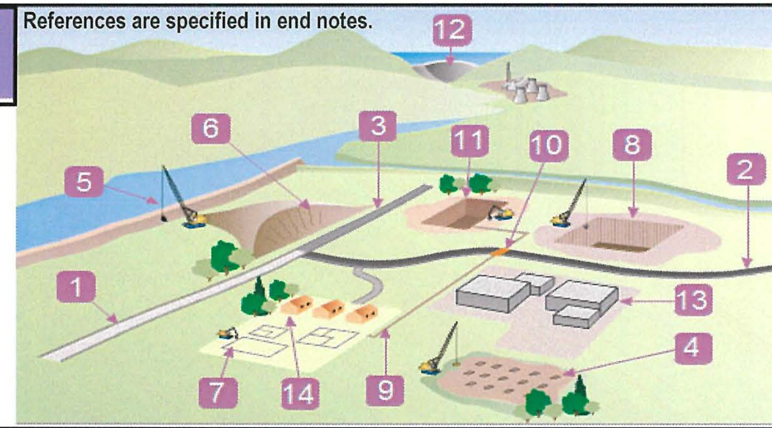
Note that the end notes at the end of the appendix are references made in the website.

Construction applications with recycled and secondary materials in accordance with Specification for Highway Works & BS & EN standards

Source: http://aggregain.wrap.org.uk/opportunities/applications

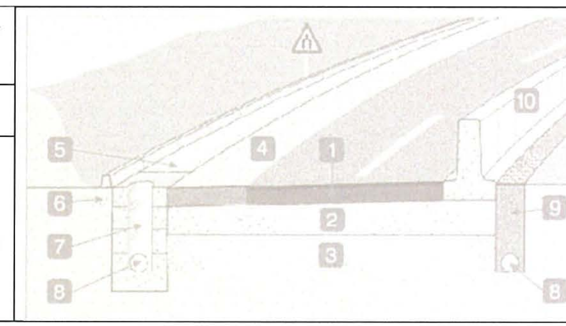
1 Concrete roads	8 Deep foundations
2 Bituminous roads	9 Utilities – new trenches
3 Hydraulically bound roads	10 Utilities – reinstatement in roads
4 Ground improvements	11 Concrete substructures

All replacement ratios of natural aggregate with RA are for coarse aggregate unless stated otherwise.



	1 CONCRETE ROADS		Replacement ratio and examples
1	1	concrete base [i]	≤20% RCA e.g. cold recycled cement bound material, continuously reinforced concrete base, wet lean concrete 1-4
	2	hydraulically bound sub-base (HBM)[ii]	Wide range of RA/RSA (DMRB HD35) without restrictions of origin e.g. cement bound granular material A of SHW
	3	granular capping [iii]	Wide range of RA/RSA (DMRB HD35), ≤100% e.g. Class 6F1, 6F2, 6F3, 6F4, 6F5
	4	pavement concrete [iv]	≤20% RCA e.g. for continuously or jointed reinforced concrete pavement, unreinforced concrete
	5	precast, unreinforced concrete kerbs and drainage channels [v]	RCA/RA where properties/ performance have been established by manufacturer
	6	concrete bedding for kerb [vi]	≤100% RA/RCA e.g. for GEN0 S1, ST1 S1
	7	precast, reinforced/ unreinforced concrete gully, manhole and inspection chamber units [vii]	RCA/ RA where properties/ performance have been established by manufacturer e.g. Channels, Manholes and inspection chambers, Pipes
	8	precast concrete pipes [viii]	
	9	granular drainage media [ix]	Wide range of RA/RSA (DMRB HD35), ≤100% e.g. for type A, B and C
	10	concrete safety barrier [x]	≤20% RCA (under circumstances). Refer to product standards for examples

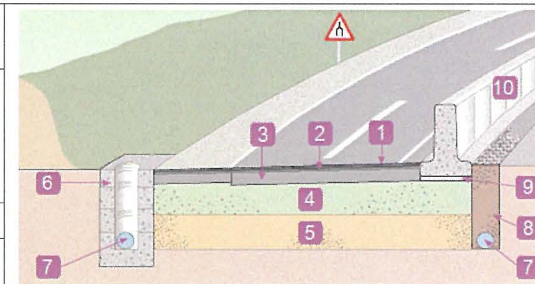
Illustration of constituents of concrete roads



All applications found on the AggRegain website are included here. Those which are in grey have been confirmed by Transport Malta that they are not practices carried out locally. Those which are carried out locally have a proposed Grade e.g. G-A adjacent to them. These grades should be read as an extension with the Proposed Guidelines for RA in Malta.

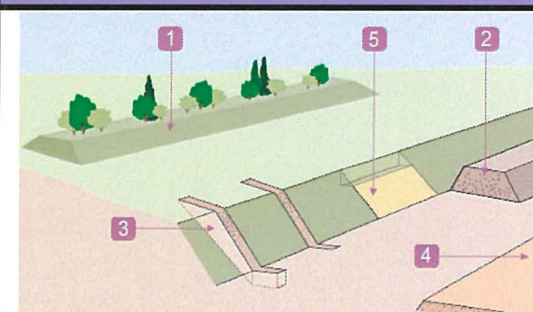
2	2 BITUMINOUS ROADS		Replacement ratio and examples
2	R-A	1 bituminous surface course [xi]	≤10% recycled asphalt & ≤100% RA e.g. stone mastic asphalt, hot rolled asphalt
2	R-B	2 bituminous binder course [xii]	≤50% recycled asphalt ≤100% in cold recycling, using foamed bitumen or bitumen emulsion e.g. Class 6F1, 6F2, 6F3, 6F4, 6F5
2	R-B	3 bituminous base [xii]	≤50% recycled asphalt, ≤100% in cold recycling, using foamed bitumen or bitumen emulsion e.g. EME2 base asphalt concrete, hot rolled asphalt
2	R-C	4 unbound sub base [xiii]	≤100% RA/ RSA are suitable and (HD35), excluding burnt colliery spoil, pulverised fuel ash and furnace bottom ash e.g. Type 1,2,4
2		5 granular capping [iii]	Wide range of RA/RSA (DMRB HD35) ≤100% e.g. Class 6F1, 6F2, 6F3, 6F4, 6F5
2	G-A G-B G-C	6 precast, reinforced or unreinforced concrete gully, manhole and inspection chamber units [xiv]	RCA/RA where properties/ performance have been established by manufacturer. Refer to product standards for examples
2	G-D	7 precast concrete pipes [xv]	
2	R-C	8 granular drainage media [xvi]	Wide range of RA/RSA (DMRB HD35), ≤100% e.g. type A, B, C
2	G-C	9 concrete bedding [xvii]	≤100% RCA e.g. for ST1 S1
2	G-A/B	10 concrete safety barrier [xviii]	≤20% RCA/ RSA (under circumstances). Refer to product standards for examples

Illustration of constituents of bituminous roads



6	6 EARTHWORKS – CUTTINGS		Replacement ratio and examples
6	R-C	1 landscaping and noise bunds [iii]	≤100% of wide range of RA/RSA (HD35) e.g. SHW Class 4
6		2 stabilising berm [iii]	≤100% RCA/RA/recycled asphalt e.g. SHW Class 1
6	R-C	3 granular drainage media [xix]	≤100% RCA/RA/recycled asphalt e.g. SHW type A, B, C
6		4 hydraulically bound capping [xx]	≤100% RCA/RA/recycled asphalt e.g. SHW Class 6E and 6R
6	R-C	5 benching [iii]	≤100% RCA/RA/recycled asphalt e.g. Class 6F5

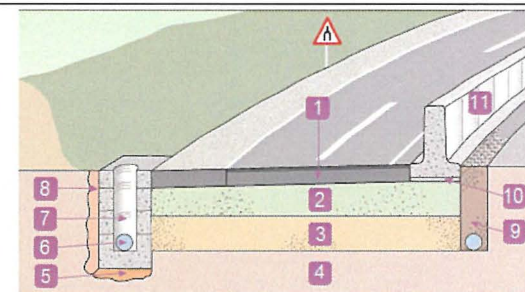
Illustration of earthworks cuttings



RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

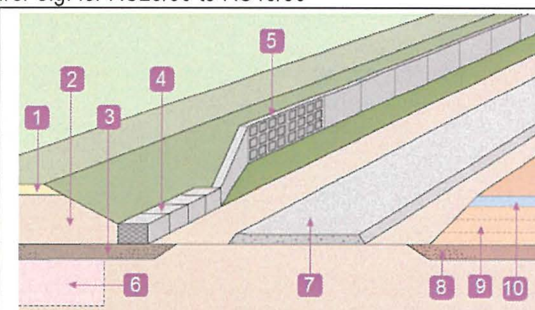
		3 HYDRAULICALLY BOUND ROADS	Replacement ratio and examples
3	R-B	1 hydraulically bound base [xxi]	≤100% RCA & RSA e.g. for SHW CBGM A-C, FABM 1-5, SBM 1-3
	R-B	2 hydraulically bound sub base [xxi]	
		3 hydraulically bound capping [iii]	Wide range of RA/RSA (DMRB HD35), ≤100% RCA/ RCA/ recy asphalt e.g. SHW Class 6E & 6R to form Class 9A & 9F
		4 hydraulically bound fill [iii]	≤95% RA & RSA imported to the site and stabilised with a hydraulic binder. In reality, the fill is more likely to be the existing material treated with in situ ground stabilisation techniques e.g. for SHW Class 6E and 6R
	R-B	5 concrete base [xxii]	≤100% RCA & RSA e.g. for ST4
	G-B/C	6 precast concrete pipes [xv]	RCA/RA where properties/ performance have been established by manufacturer. Refer to product standards for examples
	G-A/B/C	7 precast, reinforced or unreinforced concrete gully, manhole and inspection chamber units [xiv]	
	F	8 concrete backfill [xvi]	≤100% RCA & RSA e.g. for ST2
	R-C	9 granular drainage media [ix]	≤100% RCA/RA/recycled asphalt e.g. for SHW Type A, B or C
	G-C	10 concrete bedding [xvii]	≤100% RCA e.g. ST1
	G-A/B	11 concrete safety barrier [xxiii]	≤20% RCA (under circumstances). Refer to product standards for examples

Illustration of constituents of hydr. bound roads

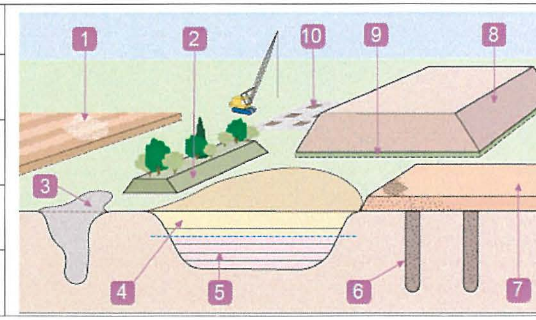


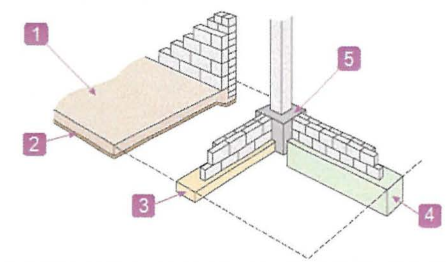
		5 EARTHWORK EMBANKMENTS	Replacement ratio and examples
5	R-C	1 granular capping [iii]	≤100% RCA/RA/RSA/recycled asphalt e.g. for Class 6F1, 6F2, 6F3, 6F4, 6F5
	F	2 general granular fill [iii]	≤100% Wide range of RA/RSA (DMRB HD35) e.g. for SHW Class 1A, 1B and 1C
	R-B	3 starter layer [iii]	≤100% RCA/RA/recycled asphalt e.g. for SHW Class 6A to 6D
	G-C	4 gabions [iii]	≤100% RCA e.g. for SHW Class 6G
	G-A/B	5 concrete crib wall or retaining wall [xxiv]	RCA where properties/ performance have been established by manufacturer e.g. for RC25/30 to RC40/50
	F	6 backfill to soft ground [iii]	≤100% RCA/RA/RSA/recycled asphalt e.g. for SHW Class 1A, 1B, 1C or Class 2B and 2C
	R-C	7 temporary working platform [xxv]	≤100% RCA/RA/recycled asphalt e.g. for 75/150mm granular material
	R-C	8 drainage layer [iii]	≤100% RCA/RA e.g. for SHW Class 6H
		9 strengthened embankment: reinforced soil [iii]	≤100% RCA/RA e.g. for SHW Class 6I and 6J
		10 hydraulically bound capping [iii]	≤100% RCA/RA/recycled asphalt e.g. for SHW Class 6E and 6R

Illustration of embankments



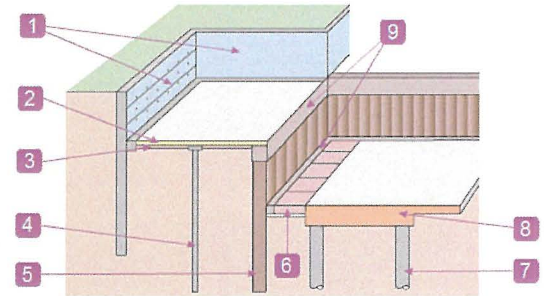
RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

		4 GROUND IMPROVEMENTS	Replacement ratio and examples	Illustration of ground improvements
4		1 stabilising of ground or fill [xxvi]	Using hydraulically bound materials this can be used to reduce amount of primary aggregates required. RA/RSA can be used to form part or all of stabilised layer e.g. SHW Classes 9A to 9F	
	R-C	2 landscaping [iii]	≤100% RCA/RA/recycled asphalt e.g. SHW Class 4	
	F	3 backfill to swallow holes/disused mine workings [iii]	≤100% of wide range of RA/RCA/RSA/recycled asphalt (HD35) e.g. any allowable material	
	F	4 backfill to soft ground, above water table [iii]	≤100% RA/RCA/RSA/recycled asphalt (HD35) e.g. SHW Class 6B and 6C	
	F	5 backfill to soft ground, below water table [iii]	≤100% RA/RCA/RSA/recycled asphalt/ well-burnt colliery spoil (HD35) e.g. SHW Class 6A	
		6 stone columns [xx]	≤100% of wide range of RA/RCA/recycled asphalt (HD35) e.g. selected material to specification	
	R-C	7 load transfer platform [iii]	≤100% of wide range of RA/RCA/RSA/recycled asphalt (HD35) e.g. SHW Class 6F1 to 6F5 capping materials	
		8 surcharge and reclamation layers [xxvii]	Not intended to form part of the permanent works and may consist of a wide range of materials. Reclamation material forms part of the permanent works. E.g. any materials complying with specification	
	R-C	9 working platform & compensation fill [xxviii]	Should comprise hard, substantially inert material such as unsaturated granular material with a maximum particle size of 200mm, and can include a wide range of RSA e.g. hardcore	
	F	10 dynamic compaction [xxix]	≤100% RA/RCA/recycled asphalt e.g. 200mm granular fill	

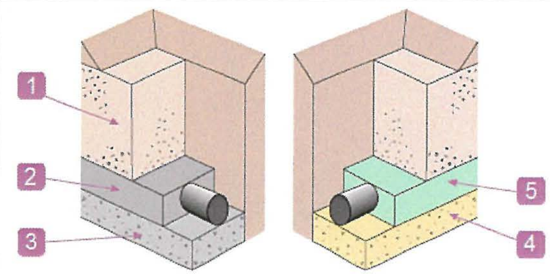
		7 SHALLOW FOUNDATIONS	Replacement ratio and examples	Illustr. of constituents of shallow foundations
7	G-A/B	1 raft foundation * [xxx]	≤100% e.g. RC25/30 to RC40/50	
	G-C	2 blinding concrete * [xxx]	≤100% e.g. GEN1 S3, ST2 S3	
	G-C	3 strip footing * [xxx]	≤100% e.g. GEN1 S3, ST2 S3	
	G-C	4 trench footing * [xxx]	≤100% e.g. GEN1 S4, ST2 S4	
	G-C	5 pad footing * [xxx]	≤100% e.g. GEN1 S3, ST2 S3	

* Recycled and secondary materials can also form parts of the fine aggregate and cementitious components of the concrete.
RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

8	8 DEEP FOUNDATIONS		Replacement ratio and examples	Illustration of constituents of deep foundations
	G-A	1 diaphragm & basement retaining walls [xxxi]	≤100% RCA e.g. RC30/37 to RC40/50	
	G-A/B	2 concrete ground bearing slab [xxxi]	≤100% RCA e.g. ST4, RC25/30 to RC40/50	
	G-C	3 blinding concrete [xxx]	≤100% RCA e.g. GEN1 S3, ST2 S3	
	G-A/B	4 precast concrete segmental pile [xxxii]	RCA where properties/performance have been established by manufacturer e.g. RC25/30 to RC40/50, Designed/Proprietary concrete	
	G-A	5 contiguous and secant bored pile walls [xxxiii]	≤100% RCA e.g. RC30/37 to RC40/50	
	G-A/B	6 precast concrete suspended slab [xxxiv]	RCA where properties/performance have been established by manufacturer e.g. RC25/30 to RC40/50, Designed/Proprietary concrete	
	G-A/B	7 reinforced bored piles [xxxv]		
	G-A/B	8 concrete ground beam and pile caps [xxxvi]	≤100% RCA e.g. RC25/30 to RC40/50	
	G-A/B	9 structural concrete propping and capping beams [xxxvi]		

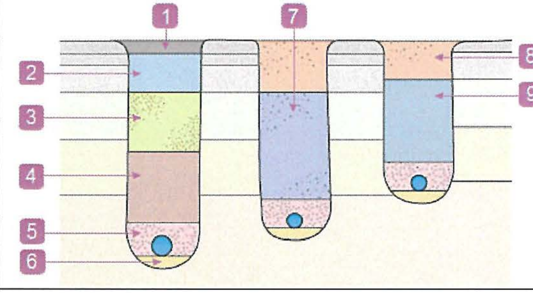


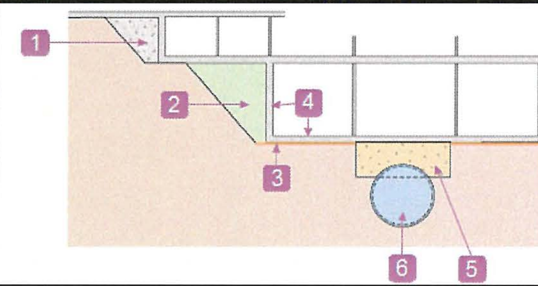
9	9 UTILITIES – NEW TRENCHES		Replacement ratio and examples	Illustration of constituents of new trenches
	F	1 lower trench fill [xxxvii]	≤100% RCA/RSA e.g. for SHW Type 8 lower trench fill (Class 1, 2 and 3 fill) (A higher grade of backfill may be required for load bearing and below roads, as shown in the Utilities reinstatement diagram)	
	G-C	2 concrete surround [xxxviii]	≤100% RCA e.g. Type S, Type T, Type Z (ST2 Concrete)	
	G-C	3 concrete bedding [xxxviii]	≤100% RCA e.g. Type A (ST4 Concrete)	
	F	4 granular or sandy bedding [xxxix]	≤100% RCA/RSA e.g. SHW Type B, F, N, S, and T	
	F	5 granular or sandy surround [xl]	≤100% RCA/RSA e.g. SHW Type S and T	



RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)

Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

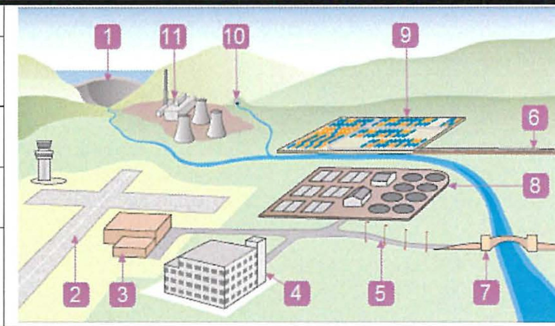
		10 UTILITIES – REINSTATEMENT IN ROADS	Replacement ratio and examples	Illustration of reinstatement in roads
10	R-A	1 bituminous surface course [xli]	≤10% recycled asphalt , ≤100% RA/RSA e.g. for Stone Mastic Asphalt, Hot Rolled Asphalt	
	R-B	2 bituminous binder/base course [xli]	≤50% recycled asphalt. In cold recycled mixes, using foamed bitumen or bitumen emulsion, recycled asphalt can contribute to 100% of the aggregate. e.g. Dense Asphalt Concrete Binder Course, Hot Rolled Asphalt	
	R-C	3 unbound sub-base [xlii]	≤100% RA/RSA e.g. for SHW Type 1, SROH GSB1	
	R-C	4 lower trench fill [xliii]	≤100% RA/RSA e.g. for SHW Type 8 Lower trench fill (Class 1, 2 and 3 fill), stabilised materials for fill (SMF)	
	R-C	5 utility apparatus surround [xliv]	≤100% RCA/RSA e.g. for SHW material Types S, T and Z; stabilised materials for fill (SMF)	
	R-C	6 utility apparatus bedding [xlv]	≤100% RCA/RSA e.g. SHW material Types B, F, N, S, T & Z, SMF	
	R-B	7 foamed concrete trench reinstatement [xlvi]	Recycled and secondary materials can form parts of the fine aggregate and cementitious components of the concrete providing they comply with the SHW. E.g. foamed concrete	
	R-A	8 concrete trench reinstatement [xlvii]	≤20% RCA e.g. SHW pavement quality concrete	
	R-B	9 hydraulically bound trench reinstatement [xlviii]	≤100% of wide range of RA/RSA e.g. for SHW Cement Bound Granular Mixtures (CBGM), Fly Ash Bound (FABM), Slag Bound (SBM) mixtures	

		11 CONCRETE SUBSTRUCTURES	Replacement ratio and examples	Illustration of concrete substructures
11	G-C	1 mass concrete backfill [xlix]	≤100% RCA e.g. for GEN1 S3, ST2 S3	
	F	2 granular backfill [iii]	≤100% RA/RCA e.g. for SHW Type 6N and 6P granular materials	
	G-C	3 blinding concrete [xlix]	≤100% RCA e.g. for GEN1 S3, ST2 S3	
	G-A/B	4 basement level structural concrete [xlix]	≤100% RCA e.g. for RC25/30 to RC40/50	
	G-B/C	5 mass concrete [xlix]	≤100% RCA e.g. GEN1 S3, ST2 S3, Designed or Proprietary concr	
	G-A/B	6 concrete tunnel lining [xlix]	≤100% RCA e.g. RC25/30 to RC40/50, Designed/ Proprietary concrete	

RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

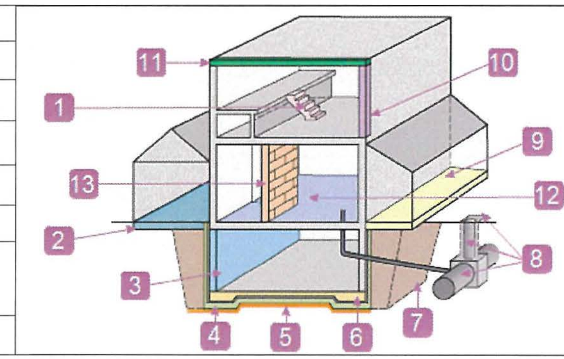
12	12 CONCRETE STRUCTURES		Replacement ratio and examples
	G-A	1 dam [xxxvi] 2 runway [xlix] 3 airport [l]	≤20% e.g. for RC40/50
	G-A/B	4 precast/in situ structural unit [li]	RA/RSA where properties/performance have been established by manufacturer e.g. for Designated, Designed/Proprietary concrete
	G-A	5 lighting columns [lii]	RA/RSA where properties/performance have been established by manufacturer e.g. for C30/37
	G-B/C	6 railway sleepers/cable covers [liii]	RA/RSA where properties/performance have been established by manufacturer e.g. for Refer to product specific standard
	G-A	7 piers, decks, abutments [liv] 8 water treatment works [lv] 9 ports [lvi]	≤20% RCA e.g. for RC40/50
	G-A/B	10 insitu concrete/precast tunnel lining [lvii]	RA/RSA where properties/performance have been established by manufacturer e.g. for RC25/30 to RC40/50, Designed or Proprietary Concrete
	G-A	11 power station [xxxvi]	≤20% RCA e.g. for RC40/50

Illustration of concrete structures

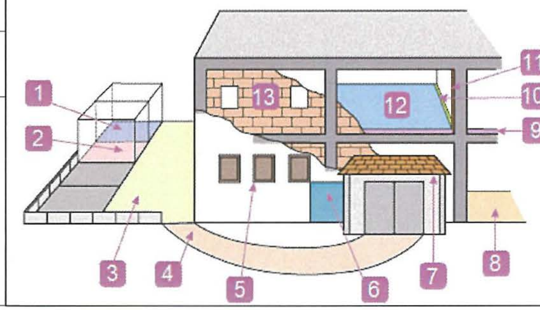


13	13 INDUSTRIAL BUILDINGS		Replacement ratio and examples
	G-A	1 precast concrete staircase [lviii]	RCA where properties/performance have been established by manufacturer. e.g. RC30/37 to RC40/50, Designed or Proprietary Concrete
	G-A	2 heavy duty industrial floor [xlix]	≤20% e.g. for RC40/50, Designed or Proprietary Concrete
	G-A	3 wall [xlix]	≤20% e.g. for RC40/50
	G-A/B	4 foundations [xlix]	≤20% e.g. for RC25/30 to RC40/50
	G-C	5 blinding concrete [xlix]	≤100% e.g. for ST2 S3, GEN1 S3
	G-A/B	6 slab [xxxvi]	≤20% e.g. for RC30/37
	F	7 fill to foundations [iii]	≤100% of wide range of RA/RCA/RSA e.g. SHW Class 6N and 6P
	G-B/C	8 precast concrete drainage pipes and manhole units [lix]	RCA where properties/performance have been established by manufacturer. e.g. Designated, Designed/Proprietary Concrete
	G-A	9 general industrial floor [xlix]	≤20% e.g. for RC40/50
	G-A/B	10 concrete column [xxxvi]	≤20% e.g. for RC35/45
	G-A/B	11 precast concrete structural beam [lx]	RCA where properties/performance have been established by manufacturer e.g. Designated, Designed/Proprietary Concrete
	G-B	12 concrete floor for foot/trolley traffic [xlix]	≤20% e.g. for ST4 S2, RC25/30 S2
	G-B/C	13 concrete block wall [lxi]	RCA where properties/performance have been established by manufacturer e.g. Designated, Designed/Proprietary Concrete

Illustration of industrial building



RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

14	Code	14 RESIDENTIAL BUILDINGS	Replacement ratio and examples	Illustration of residential building
14	G-A/B	1 garage floor, reinforced [xlix]	≤20% RCA e.g. RC35/45	
	G-C	2 garage floor, unreinforced [xlix]	≤100% RCA e.g. GEN3 S2	
	G-B/C	3 residential road pavement [lxii]	≤100% RCA/RA to replace coarse and fine e.g. Designated, Designed or Proprietary Concrete	
	R-C	4 landscaping and hard surface units [lxiii]	RCA/RA where properties/ performance have been established by manufacturer. e.g. Designated, Designed or Proprietary Concrete	
		5 masonry units [lxiv]		
		6 reconstituted stone elements/cladding [lxv]		
		7 roof tiles [lxvi]		
	G-C	8 internal floor [xlix]	≤100% RCA e.g. ST3 S2, GEN3 S2	
	G-A/B	9 precast concrete structural beam [lx]	RCA/RA where properties/ performance have been established by manufacturer. e.g. RC30/37 to RC40/50, Designed or Proprietary Concrete	
	G-A	10 precast concrete structural frame [lx]		
	G-A/B	11 precast concrete structural column [lx]		
	G-A/B	12 precast concrete floor units [lxvii]		
	G-B/C	13 concrete block wall [lxi]	RCA/RSA where properties/ performance have been established by manufacturer. e.g. Designated, Designed or Proprietary Concrete	

RCA (recycled concrete aggregate) RA (recycled aggregate) RSA (recycled secondary aggregate) SHW (Specification for Highway Works)
Designated Concretes mentioned are RC25/30 to RC40/50, GEN1 S3/S4, GEN0 S1 Standardized Prescribed Concretes are ST2 S3/S4, ST1 S1, ST4

References to Specifications

[i] SHW (Specification for Highway works) Series 1000 and BS 8500
[ii] SHW Series 800 and BS EN 14227-1
[iii] SHW Series 600
[iv] SHW Series 1000 and BS 8500
[v] BS EN 1340, BS EN 1433, BS EN 13369, BS EN 14992:2007
[vi] SHW Series 1000 and 1100 and BS 8500, BS 7533-6
[vii] BS EN 1917, BS 5911-3, BS 5911-4, BS EN 12620
[viii] BS EN 1916, BS 5911-1, BS EN 12620
[ix] SHW Series 500 and 710 and BS EN 13242:2002+A1
[x] SHW Series 400 and 1700, BS 6779-2 and BS 8500-2
[xi] SHW Series 900 clause 902
[xii] SHW Series 900 and BS 13043
[xiii] SHW Series 800, BS EN 13242, BS EN 13285
[xiv] BS EN 1917, BS 5911-3, BS 5911-4, BS EN 12620
[xv] BS EN 1916, BS 5911-1, BS EN 12620
[xvi] SHW Series 500 and 700 and BS EN 13242
[xvii] BS 8500-2 and SHW Series 500 and 2600
[xviii] SHW Series 400 and 1700, BS 6779-2, BS EN 1317 and BS 8500-2
[xix] SHW Series 500, 600 and 710 and BS EN 13242
[xx] SHW series 600 and 800
[xxi] SHW Series 800 and BS EN 14227
[xxii] BS 8500-2 and SHW Series 500 and 2600
[xxiii] SHW Series 400 and 1700, BS EN 1317-1, and BS 8500-2
[xxiv] BS 8500-2, BS EN 206, Highways Agency's DMRB BD 68/97
[xxv] BRE 470 Working platforms for tracked plant
[xxvi] SHW series 600 and 800, TRL 248, TRL 611
[xxvii] SHW, BRE Digest 276 "Hardcore"
[xxviii] BRE Digest 276 "Hardcore" and BRE Report 470 "Working platforms for tracked plant"
[xxix] ICE Specification for Ground Treatment, BRE Report 458 "Specifying Dynamic Compaction"
[xxx] BS 8500, BS EN 12620
[xxxi] BS EN 1997-1, BS EN 1992-1-1, BS EN 1538, BS 8500-2, BS EN 12620
[xxxii] BS 8500-2, BS EN 206, BS EN 12794, BS EN 13369, BS EN 14992
[xxxiii] BS EN 1997-1, BS EN 1997-1, BS EN 1536, BS EN 1992-1-1, BS 8500-2, BRE SD1, Specification for Piling and Embedded Retaining Walls
[xxxiv] BS 8500-2, BS EN 206, BS EN 1992-3, BS 8102, BS EN 13369, BS EN 14992
[xxxv] Designated Concrete RC30/37 to RC40/50
[xxxvi] BS EN 1992-1-1, BS 8500-2, BS EN 12620
[xxxvii] SHW Series 500 and 600, BS EN 13242
[xxxviii] SHW Series 500, BS 8500-2
[xxxix] SHW Series 500 and 700, BS EN 13242, and Civil Engineering Specification for the Water Industry (CESWI)
[xl] BS EN 13242 and CESWI
[xli] SHW Series 900, BS EN 13043, HAUC Specification for the Reinstatement of Openings in Highways (SROH)
[xlii] SHW Series 800, BS EN 13242:2002+A1, HAUC (SROH)
[xliii] SHW Series 500 and 600, BS EN 13242, HAUC (SROH)
[xliv] SHW Series 500, BS EN 13242, HAUC (SROH), Civil Engineering Specification for the Water Industry (CESWI)
[xlv] SHW Series 500, BS EN 13242, HAUC (SROH)
[xlvi] SHW Series 1000, HAUC (SROH), TRL Application Guide 39
[xlvii] SHW Series 1000, HAUC SROH
[xlviii] SHW Series 800, BS EN 14227, HAUC (SROH)
[xlix] BS 8500-2, BS EN 12620
[l] BS EN 1991-1-4, BS 8500-2, BS EN 1992-1-1, BS EN 12620
[li] BS EN 1991-1-4, BS EN 1992-1-1, BS 8500-2, BS EN 206, BS EN 12620, BS EN 13230, BS EN 13369, BS EN 14992
[lii] BS 8500-2, BS EN 206, BS EN 40-4, BS EN 13369, BS EN 14992
[liii] BS EN 206, BS 8500-2, BS EN 13230, BS EN 13369, BS EN 14992
[liv] SHW Series 1700, BS EN 1991-1-7, BS EN 1992-1-1, BS EN 1994, BS 8500-2, BS EN 12620
[lv] BS EN 1992-3, BS EN 1992-1-1, BS 8500-2, BS EN 12620, CESWI
[lvi] BS EN 1991-1-4, BS EN 1992-1-1, BS 8500-2, BS EN 12620
[lvii] BS 8500-2
[lviii] BS 8500-2, BS EN 206, BS 8103, BS EN 13369, BS EN 14992
[lix] BS 8500-2, BS EN 206, BS 5911, BS EN 13369, BS EN 14992
[lx] BS 8500-2, BS EN 206, BS EN 13225, BS EN 13369, BS EN 14992
[lxi] BS 8500-2, BS EN 206, BS EN 771-3, BS EN 13369, BS EN 14992
[lxii] BS 8500-2, BS EN 206, BS EN 1338, BS EN 13369, BS EN 14992
[lxiii] BS 8500-2, BS EN 206, BS EN 1339, BS EN 13369, BS EN 14992
[lxiv] BS 8500-2, BS EN 206, BS EN 845, BS 5642, BS EN 13369, BS EN 14992
[lxv] BS EN 206, BS EN 490, BS EN 771, BS 1217, BS EN 13369, BS EN 14992
[lxvi] BS EN 206, BS EN 490, BS EN 771, BS EN 13369,BS EN 14992
[lxvii] BS EN 206, BS EN 1168, BS EN 13224, BS EN 13369, BS EN 14992