Research Article

Fine dust emissions from softstone quarrying in Malta

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Summary. *The Lower Globigerina Limestone (softstone) provides stone blocks for the construction industry in Malta: primitive techniques are used to extract and convert limestone into such blocks. An analysis is presented of the work methods and practices employed by the industry, along with estimates of fine respirable dust (PM_{10}) emission from such techniques, to show that the rate of PM_{10} emission is 0.38 kg of limestone dust per building stone produced; taking into account mitigation of dust release during the wet months, it is estimated that the 67 active open pit quarries which lie in close proximity (0.2 to 2 km) to urban centres generate, annually, about 1200 t of PM_{10} dust. Considering that dust emission occurs mainly during the dry summer months, the average PM_{10} emission rate from quarries during this period is 11 500 mg m^{-2} day^{-1} which is well above international guideline values (100 – 350 mg m^{-2} day^{-1}). The main emission sources accounting for 97% of fine dust are the cutting tools (76%) used to extract the mineral from the quarry bed and the dressing tools (21%) that convert the blocks into 'fair-faced' stones suitable for use in construction. The reason why emission factors are so large is due to the fact that all dust generated is allowed to escape unchecked to atmosphere. It is concluded that in view of the magnitude of the emissions and the vicinity of sources to residential areas, the quarrying industry may be a significant factor contributing to the lowering of air quality on the islands with possible impacts on the health of the general population and, in a more serious manner, that of the quarrying community. Artificial water wetting of the quarry bed prior to extraction may provide an effective and relatively cheap mitigation measure during the dry weather when the problem of dust emission is at its worst.*

Keywords: *limestone, quarrying, PM_{10}, environment, dust, emission factors*

Introduction

With a total land area of c. 316 km^2 and a population of 389 000 (in 2001) (MPA, 2001a) Malta is one of the smallest and most populated countries. Limestone quarrying on the islands has played a central role in the country's economy from earliest known times: from the magnificent 5000-year old temples at Hagar Qim and Ggantija to the more recent and numerous churches, palaces and medieval fortifications, these edifices in stone testify to the importance of the industry and its effect on the social fabric of the inhabitants. In Malta, the main construction material is Globigerina Limestone (a softstone locally known as *franka*) and it has been used for any type of building from rural sheds to housing units to schools etc. During the last 60 years or so, roofing elements made from concrete have totally replaced limestone alternatives and concrete bricks are also being employed for building walls although for this use *franka* blocks remain a preferred choice. The Tertiary Globigerina Limestone Formation, which outcrops in several places in Malta and also in Gozo provides a soft, yellow biomicritic limestone from which 67 quarries (Mallia et al., 2002) are currently extracting material for the construction industry.

The quarries are situated mainly in the central and eastern areas of Malta (Figure 1) and occupy a total land area of 1.2 km^2 which represents almost 0.4% of the national land territory. The open-pit quarries are located in sites most of which lie within about 0.2 to 2 km from residential centres. Such a preponderance of quarrying activity occurring practically in the midst of urban development is probably unique to Malta. Nevertheless, any impacts which this industry has on the quality of the environment, especially the atmosphere, have not been hitherto evaluated. To our knowledge, this is the first attempt at quantifying emissions to air from softstone quarrying of fine respirable limestone dust, *i.e.* that component having nominal aerodynamic diameter < 10 μm (PM_{10}): such material is probably the most problematic waste arising from the industry. The need for industry to adopt measures for reducing the dust impact, which appears likely to have potential for affecting the health of both quarry workers and general population, is also discussed.

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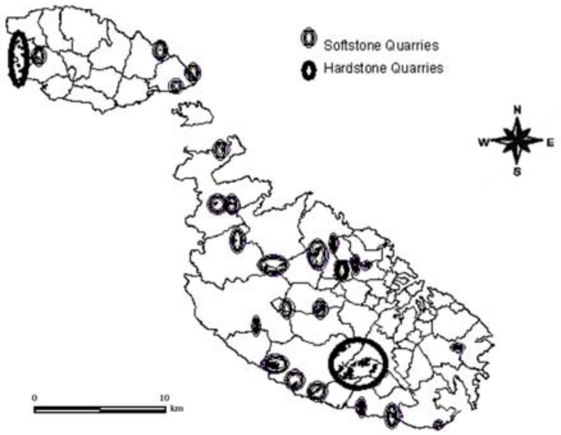

Figure 1: Location of softstone and hardstone quarries in Malta and Gozo (from Mallia et al, 2002).

Work methods at softstone quarries and associated dust emissions

Limestone blocks are extracted from the quarry bed and 'dressed' (given three fair faces) using rotary steel cutting tools. No attempt is made at controlling dust released. Judging by visible observation, these operations are the ones that generate most dust. Not only is a substantial quantity of limestone turned into a fine powder through the grinding processes involved in both operations, but the material so produced is ejected into the air, both as the cutting machine moves along the cut lines of the quarry face and as limestone blocks pass through the dressing machine. The dressed stones are loaded onto trucks for use offsite: this loading operation entails some dust emission although more dust is generated from loading, by mechanical shovel, of limestone wastes, fine cuttings (*xaħx*) and other stone debris that is removed from the quarry either for use off-site (as backfill) or for disposal to landfill. Finally, as material is conveyed away from the quarry in trucks, dust is again raised from the action of wheels on the unconsolidated materials constituting the surface of these dirt roads.

Limestone extraction from softstone quarries is performed using circular saws (Figure 2a), operating at 1500 revolutions per minute, that make horizontal cuts followed by other saws that make vertical cuts into the bedrock (Figure 2b), resulting in the formation of blocks of material having a thickness of either 23 or 15 cm, but the same length (56 cm) and height (26 cm). The blocks require finishing (or 'dressing') and this is performed using a machine (Figure 3) with three mutually perpendicular grinders to remove any edges or imperfections from three contiguous faces parallel to the long axis thus forming 'fair faced' building stones. The blocks issuing from the dressing machine are generally loaded directly onto trucks by conveyor and are transported away for use as construction material in truckloads of about 300 23 cm-blocks or 400 15 cm-blocks. Stockpiling of blocks occurs to a very limited extent involving about three to four thousand blocks that are kept in an area of the quarry away from active stone extraction. The cutting/grinding machinery is electrically driven, powered either from the mains or using diesel generators. The production of stones generates a significant quantity of fine limestone powder from the cutting and dressing processes and the rudimentary machinery employed is not equipped to control dust. The heavier fraction of dust collects next to the cutting and dressing machines and a small part of this material, referred to locally as "*xaħx*", is used in making mortar, although a significant fraction is discarded as a solid waste product. The finer fraction remains airborne and may be dispersed from the quarry pit by wind action and convective flow. In the dry months during stone extraction and dressing, the visibility in the pit is so low that the workers can barely be seen. It has also been noticed that when the quarry bed and the extracted stones are humid from rain, there is barely any visible dust since the damp cuttings clump together and drop to the ground practically without formation of airborne fines. It is clear that the simple expedient of water wetting of the bed rock prior to extraction of limestone would afford one method of eliminating the fine dust problem but the industry hasn't felt the need to respond to the problem, possibly because it is not regarded as being significant or as having potential for affecting occupational or environmental health.

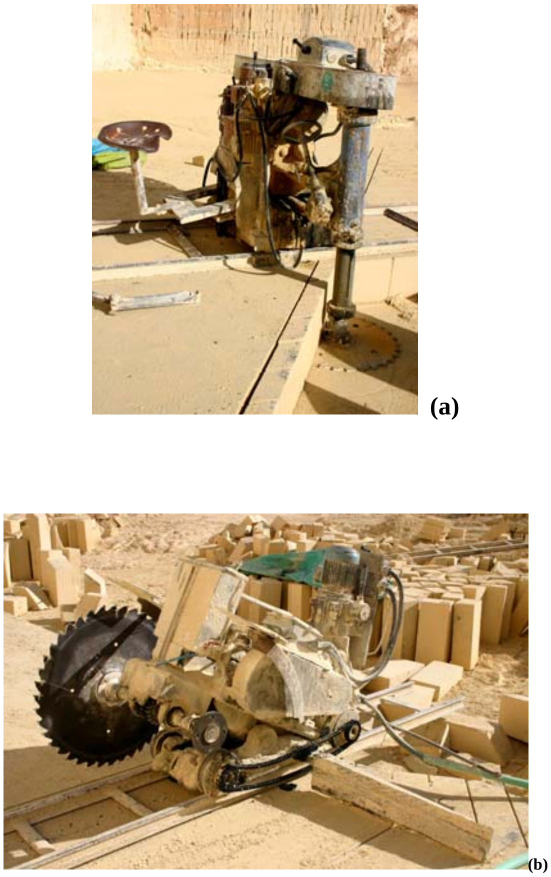

Figure 2. Typical cutting machines as used in softstone quarrying: (a) machine used to make horizontal cuts through bedrock and (b) machine used for vertical cuts.

Figure 3. Typical dressing machine as used in sofstone quarries.

An experiment was conducted to measure directly the concentration in air of particulate matter with aerodynamic diameter nominally less than 10 μm (PM_{10}) generated by cutting limestone blocks using a typical tool as employed locally for the purpose. This was in order to obtain an order-of-magnitude estimate of the emission factor for PM_{10} particles associated with the limestone block cutting operation.

The tools employed for cutting blocks off the quarry face and those involved in the dressing operation are very similar and this suggests that dusts generated from both might possess similar size distributions. This hypothesis was tested by collecting dust generated from both cutting and dressing operations in local quarries and analyzing the particle size distributions in each. Moreover, the particle size distribution of deposited dust collecting on unpaved access roads in quarries was also analysed.

Materials and methods

(a) Experimental determination of nominal PM_{10} emission from softstone cutting

The cutting tool consisted of two electrically-powered rotary blades, each of width 4 mm and diameter about 30 cm, which cut into the stone block from opposite ends as the block moves on a steel surface. The blades of this cutting tool are of similar shape but smaller in width than those employed for limestone block manufacture. The tool is, however, actually used for cutting stone blocks to size on site during construction. The cutting tool had no provision for collecting dust. The tool was placed centrally in a window-less chamber[*] of dimensions 1.9 m x 2.7 m x 5.3 m having limestone walls and a concrete ceiling and provided with a wide steel plate door for access. An electric fan was placed at ground level pointing upwards in order to provide turbulence of the inside air without causing visible disturbance of deposited dust.

A Lecker low volume air sampler (Model LVS3) containing a 47 mm diameter glass fibre filter (Whatman) was placed in the chamber about 2.5 m from the cutting tool and the collecting head was placed at a height of 1 m: the experiment was repeated six times, in three of which the sampler was placed at the front of the chamber and in the other three at the back to correct for uneven distribution of airborne dust. The filter paper was equilibrated in a constant humidity glove box and weighed inside the box to the nearest 0.1 mg and it was then inserted in a clip-seal polythene sachet pending use in the low volume sampler.

The limestone used for the experiment was a dry block (moisture content = 1.2 %) extracted from a limestone quarry in Qrendi. Each experimental run consisted of cutting a segment of stone with cross section 17 cm x 3 cm, an operation which generated 20.4 cm^3 pulverized limestone. After each cut, the airborne fine dust produced inside the chamber was sampled using the low volume air sampler for a measured period of approximately 15 minutes: the rate of air sampling was 2.3 m^3 h^{-1} and during the sampling period, the concentration of suspended fines in the chamber decreased from a maximum value to nearly zero. Prior to each run, the 'background' airborne dust was measured by passing air through the sampler for 15 minutes and the mass of dust so collected was deducted from that obtained in the subsequent experimental run. Each loaded filter paper was replaced in the polythene sachet and taken back to the constant humidity box for re-equilibration and weighing.

(b) Determination of size distribution and moisture content of dust from quarries

A size distribution analysis was carried out on dust generated in three quarries, two of which are located in Qrendi (quarry nos. 15 and 55) and the other at Siggiewi (known as "extension to quarry no. 15"). Samples were collected from both cutting and dressing machines while working on stones that were wet from previous heavy rainfall. No visible dust was emitted in the cutting and grinding processes and it was thus concluded that most of the fine dust had collected with the coarser material as a result of water damping. The moisture content of dust was measured by drying at 110°C to constant mass. About 30 g of dried dust was analyzed granulometrically using brass laboratory test sieves (Endecotts Ltd.) for the larger sizes and an LS Coulter Counter (Model LS100Q) for the size fraction smaller than 45 μm. The Coulter Counter provided direct values for the dust fractions Ø < 10μm and 10μm < Ø <45μm (Ø is the particle diameter), whereas the mechanical sieves allowed measurement of the total fraction Ø < 45 μm as well as four larger-sized fractions, namely, 45μm < Ø < 63 μm, 63μm < Ø < 125 μm, 125μm < Ø < 500 μm and 500μm < Ø. It is noted that data on particle size distribution obtained with the sieves and Coulter Counter do not refer to aerodynamic particle sizes and cannot be directly compared with data on airborne dusts obtained using size-selective air samplers.

Using the same techniques, dust collected from the surface of unpaved quarry access roads was also

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[*] Actually, the chamber was a small garage cleared and converted for the purpose.

analysed: the dust was sampled from the tracks defined by truck tyre markings in these roads.

Results and discussion

(a) Nominal PM_{10} emissions from cutting of softstone

Table 1 shows the results obtained in the sampling of PM_{10} dust generated by cutting softstone using the tool as described in the experimental section. During each sampling period, the visibly-dusty atmosphere in the chamber cleared completely before the period had elapsed and this was confirmed by the value of airborne dust measured in the background runs (filter numbers 1, 3, 5, 7, 9 and 11): these were typically between 1 and 2% of the values for dust generated during the cutting operation. It is most likely that airborne dust collecting in the chamber settles out through sedimentation, particle aggregation and collision with walls and ceiling of the chamber. The last column in Table 1 refers to the 'nominal' concentration of PM_{10} dust generated as a result of the cutting operation. The calculation assumes that the airborne particles remained at some fixed mean nominal value throughout the measuring period which was between the maximum value obtaining immediately after the cutting process and the nearly-zero value after approximately 15 minutes of air sampling. This nominal concentration is likely to be an underestimate of the true (maximum) value, but it suffices for the purposes of this paper, which is intended primarily to provide an 'order-of-magnitude' estimate of the environmental impact from dust generated by softstone quarrying.

Filter Number	**Volume of air sampled (m^3)**	**Mass of PM_{10} dust (mg)**	**Nominal corrected PM_{10} concentration ($mg\ m^{-3}$)**
1	0.67	0.2	-
2	0.72	31.4	43.6
3	0.67	0.3	-
4	0.68	32.8	48.2
5	0.64	0.1	-
6	0.7	34.2	48.9
7	0.58	0.4	-
8	0.63	32.3	51.3
9	0.64	0.4	-
10	0.67	33.1	49.4
11	0.65	0.8	-
12	0.65	31.1	47.8

Table 1. Results obtained from six consecutive limestone cutting experiments together with the measurements of background airborne dust.

The data obtained when the sampler was in the front part of the chamber (filter numbers 1 to 6; nominal PM_{10} concentration = 46.6 ± 2.9 mg m^{-3}) and those obtained from the back area (filter numbers 7 to 12; nominal PM_{10} concentration = 48.6 ± 2.0 mg m^{-3}) show that airborne dust in the chamber was reasonably uniformly dispersed throughout. Preliminary runs involving larger cut volumes of limestone produced nominal dust concentrations that did not increase proportionately with the mass cut, showing that significant particle aggregation and rapid settling was occurring at higher dust concentrations.

From Table 1, the mean nominal PM_{10} concentration is 47.6 ± 2.5 mg m^{-3}. The total mass of PM_{10} dust generated in the chamber for every cut is (47.6 mg m^{-3})(28 m^3) = 1333 mg; taking the density of Globigerina limestone (Camilleri, 1991) as 1900 kg m^{-3}, the mass of limestone ground away per cut is (2.04 x 10^{-5} m^3)(1900 kg m^{-3}) = 0.039 kg and this yields a nominal PM_{10} emission rate for cutting limestone equal to 34.2 kg / Mg pulverized rock.

(b) Size distribution of dust from quarries

Table 2 lists data from the three quarries as it pertains to the cutting and dressing machine in each quarry. For quarries 1 and 2, the data for the dressing machine is the average from two separate samples collected on different dates. In all cases (except where indicated), the limestone was humid with moisture content varying from 8.9 to 23% and with a mean value of 15% . Dry stone from quarry 2, with moisture content 0.74%, on dressing produced dust with composition as shown in parenthesis.

The data show that both cutting and dressing machines generate an appreciable quantity (mean value 18%) of respirable dust (of diameter < 10 μm) which precipitates out of the air immediately or soon after it forms: this is true not only for wet conditions, when little or no dust emissions are visible to the eye during the grinding operations, but also when the stones are dry: it appears that a considerable fraction of fine dust particles are scavenged out of the air by the larger particles, presumably by impaction, and this factor helps to lessen the dust impact from the machines.

Statistical analysis (Friedman's test) showed that the size distribution of deposited dust generated from tools in use in the three different quarries were not significantly different (respective p-values for dust from cutting and dressing tools in the three quarries = 0.203 and 0.565; for the null hypothesis, $p > 0.05$) and also that particle distributions of deposited dust from the cutting and dressing machines were statistically indistinguishable (for the fractions of dust with diameter, in μm, < 1.5 and 1.5 – 10, the respective p-values = 0.717 and 0.307; similar results were obtained for larger dust sizes; for the null hypothesis $p > 0.05$). The data therefore suggests that the dust emitted from cutting and dressing tools has similar size distribution and the nominal emission factor for PM_{10} dust for both types of tool was taken as identical: this is not unreasonable given that the rotary blades employed in each tool are very similar. Moreover, the emission factor was assumed to be the same as that obtained from the cutting tool employed in the experiment described in (a) and again this assumption is reasonable in view of the similarity of cutting tools involved.

Dust from the access roads (Table 3) also had a statistically indistinguishable size distribution from that of dust deposited near the working tools. It is interesting to note that the fine dust content of unpaved roads within quarries is not significantly higher than that found next to the cutting and dressing machines and this suggests that surface material on these roads is constantly being replenished from the quarry face through wind transport.

Particle Diameter (Ø) (μm)	**% fraction by mass of dust**					
	Quarry 1		**Quarry 2**		**Quarry 3**	
	Cutting	**Dressing**	**Cutting**	**Cutting**	**Dressing**	**Cutting**
Ø > 500	4.6	4.8	6.4	2.6 (14.6)	1.8	4.1
125< Ø < 500	10.8	11.2	11.7	10.7 (20.5)	10.8	17.5
63 < Ø < 125	47.9	42.6	37.3	45.0 (26.5)	34.2	27.1
45 < Ø < 63	15.3	14.1	18.3	17.4 (15.3)	20.6	17.0
10 < Ø < 45	8.1	10.0	9.7	8.3 (8.9)	11.2	11.2
Ø < 10	13.2	18.3	16.7	16.1 (14.6)	21.3	22.9
Ø > 500	4.6	4.8	6.4	2.6 (14.6)	1.8	4.1

Table 2. Size distribution of deposited humid dust (mean moisture content 15%) from limestone cutting and dressing machines in three quarries in Malta. For quarry 2, the data in parenthesis refers to dust generated from dry stones (moisture content 0.74%).

Quarry	**Dust % fraction (in μm)**					
	Ø< 10	**10 < Ø <45**	**45<Ø<63**	**63< Ø <125**	**125<Ø<500**	**Ø > 500**
1	11.0	3.8	5.2	13.1	15.8	51.0
2	21.8	11.1	19.8	31.8	11.0	4.4
3	13.2	10.9	18.3	35.6	16.2	5.7

Table 3. Size distribution of (wet) deposited dust (moisture content 7 – 23%) from unpaved access roads in quarries

Modelling fine dust emissions from quarrying

There is a dearth of available data on the properties of local materials and methods to allow accurate prediction of dust emissions from each of the operations involved in the sofstone industry. Besides new data presented in this paper, published information on comparable systems from other countries has also been used in order to obtain an estimate of total fine dust (PM_{10}) emission from softstone quarrying. Calculations were based on a virtual typical quarry where the open pit has a footprint of 20 000 m^2 and a depth of 75 m and then this data was used to estimate total emissions as applicable to the softstone quarrying industry as a whole.

(a) Fine dust emission from limestone cutting and dressing of stones

In this model, it was assumed that all limestone blocks measure 56 by 26 by 23 cm. It was further assumed that the 12 mm rotary blade forms a cut in the limestone bed that is 1.3 cm thick: this value is supported by actual measurements in a quarry which gave values in the range 1.25 and 1.35 cm (*n* = 5). When the blade makes a cut parallel to the opposite faces, with dimensions 56 by 26 cm (faces A_1 and A_2) of incipient blocks in the quarry bed, it grinds away from the bedrock and pulverizes a cuboid of limestone of volume V_A equal to [(0.013 m)(0.56 m)(0.26 m)] or 1.89 x 10^{-3} m^3; similarly, a cut parallel to opposite faces B_1, B_2 of dimensions 56 by 23 cm, would remove a volume V_B equal to 1.67 x 10^{-3} m^3, while a third cut parallel to the remaining set of faces, C_1, C_2, of dimensions 23 by 26 cm, would remove volume V_C equal to 7.77 x 10^{-4} m^3. To detach a single block from the quarry bed will thus theoretically require the removal of a total volume $V_t = 2(V_A+V_B+V_C)$ which amounts to 0.00876 m^3 of pulverized rock. However, limestone blocks are not removed singly from the quarry bed but in groups involving several stones: indeed, for the purposes of this analysis it is convenient to regard stone extraction as involving *theoretical* removal of a three-dimensional array of stones where a series of cuts will cause each block to form simultaneously with six other nearest neighbours: thus, any single cut in the quarry face will make possible the release of two adjacent blocks of limestone. Therefore, the volume of rock cuttings formed per block produced is equal to ½ V_t or 0.00438 m^3. To this volume, an additional element of limestone of volume V_s equal to $4(0.0065)^2(0.56 + 0.013)$ also actually requires removal during the grinding process representing four cuboids along the edges of each extracted block. The total volume of rock cut per block extracted is therefore 0.00448 m^3. This model ignores the situation at the boundaries of the quarry but the error is small since only a very small proportion of blocks constitute the boundary layer for a typical quarry.

The mass of rock cut and converted into total dust is equal to 8.5 kg. Since each block has a mass of 64 kg, the mass of limestone dust generated per block is equivalent to 13.3 % by mass of extracted rock and the rate of total dust released during stone cutting is 133 kg total dust/Mg limestone blocks produced.

A typical stone dressing machine grinds away 0.64 cm from one of the larger faces of the block (measuring 56 cm by 26 cm) and 0.15 cm from the two contiguous faces with dimensions 56 cm by 22 cm: the volume of pulverized rock is therefore 1.3×10^{-3} m^3 which is equivalent to 2.5 kg limestone dust generated per block or 39 kg total dust/Mg limestone blocks produced. Assuming that the amount of PM_{10} dust generated for both cutting and dressing operations is 34.2 kg/ Mg pulverized limestone, we calculate an *emission factor,* $E_{c+d,\ n}$, being the amount of PM_{10} dust generated in the production of *n* fair-faced limestone blocks, as follows:

$$E_{c+d,n} = (0.29 + 0.085)n = 0.38n \qquad (1)$$

(b) Fine dust emission from limestone waste removal

Limestone wastage associated with *franka* quarrying is claimed to vary from almost 50% of production (Mallia et al., 2002) to about 20% and wastage depends on the presence of such features as bedding joints, fractures and so on in each quarry: using the lower, more conservative value, it follows that in producing *n* stones, (64 *n*/80)(20) kg = 16*n* kg limestone waste is formed. Transferring this waste, with front-end loader, from a pile onto a truck constitutes a batch drop operation for which the PM_{10} dust emission factor is given by the following empirical equation (USEPA, 1995):

$$E_{wr}\ \text{(in kg Mg}^{-1}\text{)} = [k\,(0.0016)(U/2.2)^{1.3}/(M/2)^{1.4}] \qquad (2)$$

where k is 0.35 for particle sizes < 10 μm, U is the wind speed and M is the moisture content. Taking the moisture content as 0.7% typical of the dry months when the problem of dust emission is greatest, and substituting for M in eq 2 using a value for 'typical' wind speed (Chetcuti et al., 1992) of 10 m sec^{-1} gives a value for the *emission factor for waste removal*, E_{wr} , equal to 0.017 kg Mg^{-1}. Thus the dust released from removal by haulage of limestone waste involved in the formation of *n* stones, $E_{wr,n}$ is given by:

$$E_{wr,\ n} = (16n)(0.017/1000) = 2.7 \times 10^{-4}\ n\ \text{kg} \qquad (3)$$

Since this emission factor is already much smaller than $E_{c+d,n}$, it was decided to ignore the ostensibly even smaller dust emission associated with loading of limestone blocks onto trucks, an operation which is carried out without actual 'dropping' of the material (which would damage the stones through fracturing and chipping).

(c) Fine dust emission from transport of stones by truck over unpaved road

Trucks travelling along unpaved temporary 'roads' through a quarry represent another source of fine dust emission. When a vehicle travels an unpaved road, the force of the wheels on the road surface is expected to pulverize the unconsolidated surface material by grinding: particles are also lifted and dropped from the rolling wheels and the road surface is exposed to strong air currents in turbulent shear with the surface. The atmospheric turbulence left behind the vehicle continues to act on the surface after the vehicle has passed. The quantity of dust emitted depends on the volume of traffic, the fraction of silt (here defined as particles < 63 μm diameter) in the road surface materials and the humidity of the road surface materials. The following empirical equation was used to estimate $E_{r,\ kt}$, the quantity of PM_{10} dust emitted per vehicle km travelled (USEPA, 1998)

$$E_{r,kt}\ \text{(in kg/vehicle km travelled)} = [0.2819\ k\ (s/12)^a(W/3)^b]/(M/0.2)^c \qquad (4)$$

where s is the surface material silt content (%), W is the mean vehicle weight (t), M is the surface material moisture content (%) and k, a, b and c are constants which for PM_{10} emissions have respective values 2.6, 0.8, 0.4 and 0.3.

From Table 3, the silt content (Ø < 63 μm) for access roads is seen to vary between 20 and 51%, with a mean of 38%. Thus, the following values were used in eq (4): s = 38%; M = 0.7% (dry conditions); W = 30 t, being the average weight of a loaded truck (40 t) and that of an empty truck (20 t). Substituting in the given equation yields a value for $E_{r,kt}$ of 3.2 kg/vehicle km travelled. The distance travelled by trucks on their way in and out of the virtual quarry can be estimated from its physical size. Allowing for tortuosity, the travel distance is about 400 m per trip inside the quarry. To transport stones or waste rock away from the quarry, a truck needs to enter empty and leave full and hence to travel 800 m per load of product. If one truck carries 300 stones, then for *n* stones, the travel distance on unpaved road is 0.0027*n* km and the corresponding PM_{10} emission is given by

$$E_{r,\ n}\ \text{(in kg)} = E_{r,kt}\,(0.0027 + 0.0008)n = 0.011n \qquad (5)$$

In eq. 5, the emission factor also includes the contribution (second term in the brackets) made by trucking away to landfill the limestone waste arisings associated with the production of *n* stones based on a wastage rate of 20% of production as used earlier.

(d) National emissions and implications

Table 4 summarizes the estimated PM_{10} emissions from the various sources as they pertain to the virtual quarry. It is evident that stone cutting and dressing produce over 97% of the fine dusts, of which 76% is contributed by the cutting process; dust raised during transportation of stone over unpaved road contributes 2.8% and the handling of solid wastes accounts for an almost insignificant fraction of total emissions. For a typical production rate, *n*, of 900 stones per day, the total PM_{10} dust released from the virtual quarry is 351 kg. Since the surface area of the quarry is 20 000 m^2, the rate of emission is 17550 mg m^{-2} day^{-1}. For a 30-day month with 22 working days, the time-weighted monthly average is 12870 mg m^{-2} day^{-1} which is 129 times the guideline level (100 mg m^{-2} day^{-1}) proposed as being likely not to provoke complaints at peak periods (Vallack and Shillito, 1998). Comparable guideline criteria (Williams, 1986; QUARG, 1996) from the USA and Australia range from 133 to 350 mg m^{-2} day^{-1}.

Process	**PM_{10} dust emitted in production of *n* stones (kg)**
Stone cutting and dressing	0.38*n*
Limestone waste removal (batch drop operation)	0.00027*n*
Stone transport over unpaved road	0.011*n*

Table 4 Estimated emissions of fine (PM10) limestone dust from operations involved in softstone quarrying in virtual quarry

Since only dust associated with waste removal and wind whipping on the access road is dependent on the size and geometry of the quarry pit and wind conditions, and since these sources are both minor contributors, it is seen that the term $E_{c+d,n}$ in eq. 1 can be used to yield a good estimate of total fine dust emission from the quarrying industry as a whole *based solely on stone extraction information*. The total annual current production of softstone in Malta (Mallia et al., 2002) is 400 000 m^3: since only 87.4% of rock is potentially convertible into blocks (to allow for volume removed in the cutting process and assuming only blocks of volume 0.0335 m^3 are manufactured), this would generate a total number of blocks equal to (0.874)(400 000)/(0.0335) = 10.4 x 10^6 stones. The PM_{10} dust emission during the cutting process is (10.4 x 10^6)(0.29)/(10^3) = 3016 t. Assuming 25% of production is discarded as waste (which is low according to Mallia et al (2002) but probably more realistic than the value 50% quoted in the reference), then the dust released in dressing is [(0.75)(10.4 x 10^6)(0.085)/(10^3)] = 663 t. Hence, ignoring the minor emission sources, we estimate that national softstone production could generate 3679 t a^{-1} of PM_{10} dust. However, since production of dusts is largely suppressed during the wet months, namely, September through April for which the mean daily rainfall is > 0.4 mm (Chetcuti et al, 1992), we can applying a wet-month correction factor of (12-8)/12 = 0.33 to the national emission rate to yield a yearly 'rain-mitigated' total emission of 1214 t a^{-1}. Since the total land taken by quarries (Mallia et al., 2002) is 1.2 km^2, and considering only the four dry months during which emissions are significant, the daily average emission rate[*] during this period is 11 500 mg m^{-2} day^{-1} which is well above international guideline values (100 – 350 mg m^{-2} day^{-1}). Even if taken over the whole year, the daily average emission rate (3679 mg m^{-2} day^{-1}) remains unacceptably high.

Considering the number and geographical location of the quarry works, and the fact that the emissions are released in large open pits at sub-ground level, it is likely that airborne waste from this industry is affecting significantly the general air quality in Malta, particularly during the dry period. Routine air monitoring in Malta is a relatively recent activity and data for PM_{10} (collected by Malta Environment and Planning Authority using the beta attenuation technique) is particularly patchy; published information (Vella et al., 2002; Stacey and Bush, 2002) reveals that the 24-h EU standard limit value (50 μg m^{-3}) has frequently been exceeded with peak values >200 μg m^{-3}; also, exceedance occurs at most of the measurement sites including urban, rural and coastal locations. The data as currently available are not sufficient to allow evaluation of any spatial or temporal trends in ambiental PM_{10} as may be associated with quarry emissions.

Sea-salt and transboundary (especially Saharan) dust are expected to be important natural contributors to the airborne particles and probably the most problematic anthropogenic source is vehicle traffic since car ownership is high, with more than 250 000 vehicles on the roads in 2000 (MPA, 2001b). However, from our results it appears that softstone quarrying is another significant anthropogenic source of dust albeit providing a less toxic particulate pollutant than that from motor traffic. The contribution from quarrying has increased six-fold during the last 20 years as a result of increased "*franka*" production (Mallia et al., 2002). Limestone dust derives also from the Coralline Limestone (hardstone) industry where production output is actually larger by a factor of 1.8: it is likely however that dust emissions from this industry are lower in view of the different methods of extraction and processing.

The airborne dust contribution from softstone quarrying may be the most easily controllable component of PM_{10} in local air. As mentioned earlier, when the quarry bed and the extracted stones are humid from rain, there is no formation of visible dust during works in the quarry. Clearly, artificial water wetting as a dust suppression technique during the dry months would appear to constitute a technically sound solution, not entailing excessive cost, but providing significant environmental benefits. There may be factors which have to be considered if such a control measure is applied, e.g. increased handling difficulties of heavier (wet) blocks. A technical analysis of alternative dust suppression techniques is beyond the scope of this paper, but the need to control dusty emissions from quarrying appears to be indisputable.

Conclusions

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[*] One month taken to have 22 working days.

The softstone quarrying industry in Malta utilizes rather primitive techniques to extract and process limestone blocks that are used extensively in the construction industry as a main building material. The most problematic waste from quarrying is airborne dust since no control measures are in place. On the basis of a simple mathematical model, it is shown that the rates of total dust released during stone cutting and dressing are, respectively, 133 and 39 kg/Mg limestone blocks produced. It is also shown, experimentally, that the nominal PM_{10} dust generated during the cutting of limestone is 34.2 kg/Mg pulverized rock and that dust generated during both cutting and dressing operations has a practically identical size distribution. From this, it can be shown that, to produce n stone blocks, the quantity, in kg, of PM_{10} dust emitted is $0.38n$ and that this quantity is significantly greater than that released during transport of blocks by truck over unpaved road in the quarry ($0.011n$), and that involved in loading limestone waste on trucks for removal from the quarry ($0.00027n$). On the basis of this model, and using published limestone extraction information, it is estimated that the industry generates about 1200 t of PM_{10} dust per year. Since there are over 60 quarries situated within or very close to urbanized areas on Malta and Gozo, the air quality on the islands is likely to be significantly and negatively affected by these emissions, especially during the dry summer period. Insufficient information on air quality is available currently to establish any trends in PM_{10} levels as might confirm effects from quarry emissions. Airborne dust from quarries is visibly reduced to negligible quantities when the quarry bed and extracted limestone blocks are wet by rainfall suggesting artificial water wetting as an effective mitigation technique during dry weather. It is therefore concluded that work practices that include this or some other appropriate dust abatement measure would lead to a general improvement in local air quality through elimination of a major proximate source of airborne fine dust.

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