Institute for Sustainable Energy, UNIVERSITY OF MALTA

SUSTAINABLE ENERGY 2015:
THE ISE ANNUAL CONFERENCE
Tuesday 17th March 2015, Dolmen Resort Hotel, Qawra, Malta

ISBN No. 978-99957-853-0-7

DEVELOPMENT OF A THERMALLY IMPROVED HOLLOW CONCRETE BLOCK

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ABSTRACT: The paper is focused on the comparison of the compression strength and thermal insulation of improved prototypes of hollow concrete building blocks to traditional local building blocks, with the aim of developing a new product for the local market that meets the demand for better insulated buildings. The building blocks under test are hollow concrete blocks (HCBs) manufactured by a local company. The heat flow meter method and infrared method techniques are applied to obtain values of the thermal conductivity of the respective HCBs being tested. Dimensions and weight of these blocks have been recorded and compression testing carried out. The correlation between thermal conductivities and compression strengths of the standard and prototype HCBs shall provide useful information on the thermo-physical behaviour of these building elements. The paper reports on the actual setup of the insitu test cells, followed by the description of the material characterisation, the thermal testing methodologies developed and the compression and dimensional testing carried out. The aim is to succeed in obtaining an innovative block with an improved U-value of at least 10% over existing standard local HCBs without reducing the standard minimum characteristic compressive strength of 7.5 N/mm^2.

Keywords: Heat transfer, heat flow meter, infrared, hollow concrete blocks.

1 INTRODUCTION

Society today is facing one of the most significant and pervasive issues of the twenty-first century: *Energy*. The ever-growing demand for energy with 40% dependence on oil and 85% dependence on fossil fuels is generating concerns of critical public, economic, environmental and social issues [1]. This interdisciplinary field of concerns requires that citizens, governments and industry leaders understand the many facets, challenges and uncertainties of energy use. It is only in this way that we can develop energy systems to transform the patterns of our energy production and consumption.

Energy use in the building sector takes between 20% to 40% of the total demand in the EU and the other developed countries [2]. In Malta, most of the energy used in buildings is essentially electrical energy and it is mainly consumed for space heating and cooling, lighting and water heating, as well as for other uses such as appliances. Information gathered from the National Statistics Office (Malta) shows that the average electricity consumption, for the years 2010-2013, based on the billed consumption data, showed that rresidential buildings accounted for 33.6% of Malta's electrical energy production, compared to 36.7% for commercial and public services and 29.8% for industrial uses [3]. Following international agreements, such as the Kyoto Protocol and EU commitments to reduce energy consumption and carbon dioxide emissions, a number of directives and legislations have been implemented. One of the most important EU directives for buildings is the 2010/31/EU recast of the 2002 Energy Performance of Building Directive (EPBD). The EPBD has fixed 31st December 2020 as the start of a new era, whereby all new and significantly renovated buildings have to be "zero net-energy", through improved construction materials, more efficient services and renewable energy installations [4]. One of the most important changes brought about by the recast was the reduction of the floor area for which the directive shall apply, both for new and renovated buildings.

In humid climatic regions like Malta, where the cooling season may be as long as the heating season, energy demands for space conditioning within buildings has become a key issue for most energy policies. A detailed study, carried out as part of the Masters programme followed for this Project, clearly illustrates that in a typical Maltese household the energy required for heating and cooling accounts for approximately 68% of the total energy consumed, when compared to 5% for lighting and 27% for the use of hot water and other electrical devices. These results show the importance of focusing on the reduction of the demand for heating and cooling in buildings, which is mainly governed by the degree of insulation of the building's envelope.

In the Mediterranean and south European regions, hollow concrete blocks are by far the most popular construction material used nowadays. Masonry enclosures play an important role in the economic weight of the building's construction expenses. However, one also has to seriously consider the operational energy costs in order to reach a compromise between the capital needed to build and the expenses required to condition the indoor climate. Designing building envelopes with minimised heat losses reduces energy consumption and helps to meet the sustainable energy targets, which are becoming more stringent as time passes by. Despite the rising awareness of energy efficient building materials, there still remains a great challenge towards widespread acceptance of green building concepts. This may be a result of a number of issues, amongst which, high production and manufacturing costs, lack of governmental information and incentive programmes and lack of improved building energy codes, all of which greatly affect the growing consumer market.

Locally, there are a number of new construction materials and modern building masonry technologies that lend themselves in achieving high levels of thermal performance through their geometry and form. Figures 1 and 2 below give two examples of products and technologies already available on the local market.

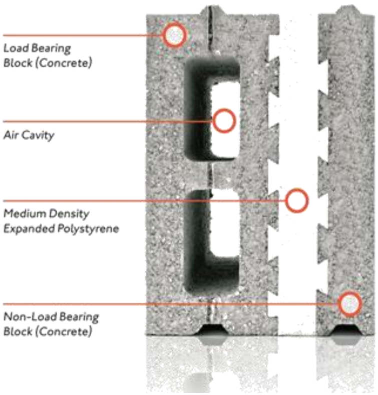

Figure 1: AB ThermaBlock with a low U-value but a large thickness sacrificing available space, deviating from standard dimensions and form and thus requiring a different manufacturing process.

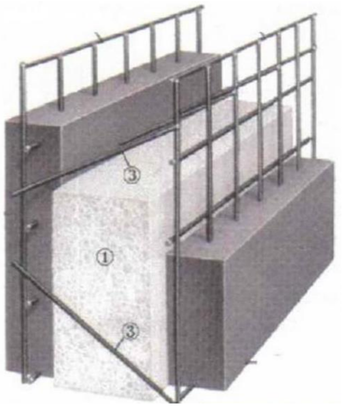

Figure 2: EVG-3D Malta providing very good thermal insulation and economical use of material but deviating from the standard local construction system thus requiring new expertise.

Although highly effective in improving the U-value, these products and technologies do not actually address the conductivity value of the load bearing element itself, but achieve it through the introduction of additional insulating material. The ThermHCB project, of which this study forms part, was launched — under the Malta Council for Science and Technology (MCST) 2012 R&I Programme – specifically to address this concept, by developing an innovative HCB with enhanced thermal properties, while keeping the dimensions and structural strength of the local standard HCB. The objective of the project is to manufacture an innovative product that is structurally very similar to the traditional HCB but having improved thermal properties and made available on the market at a competitively reasonable price.

2 MATERIAL CHARACTERISATION

The main factors that influence heat transfer in hollow concrete block walls are the size, position and shape of voids, the geometrical characteristics of the mortar joints and the thermal conductivities of the constituent materials. The last of these factors is the first objective of this study. The type and percentage of raw materials used to form the concrete mix achieving the optimum balance between the structural strength and the thermal properties of the block was to be identified. The basic mixture of the prototype HCBs was based on:

1. Binders - cement and other additives like HC1,
2. Fillers - hard stone aggregate and sand, and
3. Insulation materials - expanded clay and perlite.

The initial batches of ThermHCB were prepared based on long periods of acquired experience of the manufacturer R&A Sons Ltd. in this field. The first three prototypes manufactured for testing purposes were 230 mm thick single type HCBs encoded as

HCB-1, HCB-2 and HCB-3. Corresponding cubes of these prototypes were also manufactured in order to be tested for compression strength. A standard 230 mm thick single type HCB, encoded as HCB-N, was also manufactured in order to be used as a benchmark.

The characteristic compression strength of HCB-N was found to be 5.4 N/mm^2, which fell short of reaching the desired compression strength of 7.5 N/mm^2, although it could still be used as a load bearing block, depending on the design made by the architect and the characteristics of the building itself. Three other batches of standard mix designs, encoded as HCB-N1, HCB-N2 and HCB-N3, were then manufactured with varying amounts of cement content. Compression strength testing results showed that batch HCB-N2 almost met the characteristic compression strength requirement of 7.5 N/mm^2 and was thus set as a benchmark for the optimisation of the ThermHCB prototypes over standard HCBs.

On the other hand, the best ThermHCB mix that had been manufactured so far (HCB-2) achieved a characteristic compressive structural strength of 5.1 N/mm^2 and had the best improved thermal properties of 6.4% (using the HFM method insitu results) over the standard block used for the insitu construction of the standard test wall. In order to achieve the targets of the project with the minimum set of experiments, a more rigorous experimental approach, known as the Taguchi method, was applied to optimise the ThermHCB mixture [5].

The Taguchi method is a strategically designed experiment to determine the optimum mix design configuration for the desired responses whilst still being able to maintain an insight of the overall effects of the control factors. Responses of a product are the desired characteristics which are influenced by a number of parameters. For an effective Taguchi's factor design methodology, the objective is to choose control factors that are most robust and least sensitive to noise factors [5]. Orthogonal Arrays (OA) are a special set of Latin squares, constructed by Taguchi to layout the product design experiments. The advantages of using Taguchi OA over a factorial design approach are:

1. Easy interpretation of experiments with a large number of factors,
2. Determination of the contribution of each factor on the target characteristics, and
3. Reduction of the number of experiment configurations to be studied.

For our initial study, two control factors were considered, cement content and lightweight expanded clay aggregate (LECA)/coarse aggregate ratio at two different levels. In order to reduce the number of rigorous tests, an L_4 orthogonal array in the Taguchi method was adopted yielding four trial experimental mixes (HCB-2, HCB-4, HCB-5 and HCB-6) to be used for the optimisation process. The test data was analysed using MINITAB statistical software in order to obtain the significance of each factor on achieving better thermal performance for the desired compressive strength. Thermal and compressive strength test results showed that even if the ingredients were to be adjusted to their optimum levels, the goals set for this project could still not be reached. Clearly, the heat transfer through the air gaps was quite significant and has limited the capacity of the single HCB from reaching superior thermal properties.

In order to counteract this condition, two measures were taken: a structurally stronger LECA aggregate was introduced in the ThermHCB prototype concrete mix so as to improve the compressive strength and double (230 mm thick) masonry design was selected so as to improve the thermal transmittance. Three batches, including one for the standard design and two for the ThermHCB design, encoded as HCB-N4, HCB-7 and HCB-8 respectively, were then manufactured. Compressive strength results for ThermHCB prototypes HCB-7 and HCB-8 reached and surpassed the compressive strength requirement set for the project. HCB-7 exhibited a 7.5% U-value improvement when compared to results obtained for HCB-N4. With these results in hand, the second stage of the HCB development was started aiming at meeting the full objectives of the project. Table 1 below shows all the batches manufactured up to this stage of the study.

Batches manufactured during Stage 1		**Date of Manufacture**
Conventional HCBs HCB-N4 (double)	HCB – N	27th August 2013
	HCB – N1	17th February 2014
	HCB – N2	23rd April 2014
	HCB – N3	23rd April 2014
	HCB – N4	31st July 2014
ThermHCBs HCB-7 and 8 (double)	HCB – 1	27th August 2013
	HCB – 2	27th August 2013
	HCB – 3	27th August 2013
	HCB – 4	23rd April 2014
	HCB – 5	23rd April 2014
	HCB – 6	23rd April 2014
	HCB – 7	31st July 2014
	HCB – 8	31st July 2014

Table 1: Manufacturing dates of the conventional and ThermHCB batches during Stage 1

3 THERMAL TESTING

3.1 Thermal transmittance

The thermal transmittance (U-value) of a building element is defined as the rate of heat transfer at steady-state, through one square metre area per degree change in temperature. The higher the U-value, the higher is the heat transfer through the element. Determining the U-value is an essential part of building envelopes and for this reason these should be determined in situ. Thermal transmittance values can be calculated theoretically but very often there is a huge difference between the predicted and measured U-values. There are a number of reasons why predicted values differ from measured transmittance values, of which one can include: variations in material thermal properties (moisture content) and thermal bridges which allow greater heat flow through these regions.

3.2 Thermal testing setup

Two field test cells were constructed at the Institute for Sustainable Energy in Marsaxlokk, to carry out insitu thermal experiments. Figures 3 and 4 below show the design of the setup, whereby two fully insulated test cells were built with the sample test walls being placed on their northern sides. The test wall models, with dimensions of 1.8 m by 1.8 m, were composed of 230 mm cement-based hollow core block masonry having a north-facing orientation. Also, a polycarbonate shielding was placed at a distance of 0.25 m from the test, to protect the test wall from wind and rain. The polycarbonate sheet did not block natural ventilation because sufficient gaps were left at the bottom and top sides. Hence, it was possible to assume that all tests were carried out with similar conditions, in as far as solar radiation, wind and humidity ingress control.

One test cell (Test Cell 2, on the right hand side, Figure 3) has a standard local HCB wall, whilst the test wall in the other cell (Test Cell 1, on the left hand side, Figure 3) is replaced after every test with a different prototype HCB wall.

Figure 3: Northern side view of insitu test cells with polycarbonate sheeting protecting the test walls

The test cells were carefully insulated on top, bottom and all sides using made-to-measure 150 mm thick expanded polystyrene (EPS) sheets, complimented with tongue and grooved system joints. The joints were further sealed with EPS beads and an acrylic-based sealer to reduce thermal bridging at the junctions

In this way, and by taking the readings of the central HCB of the test wall, uni-directional heat flow could be assumed for the analysis, when steady state is reached. The test rooms were thermally controlled, to keep a constant interior temperature, using separate fan heaters and electronic temperature controllers.

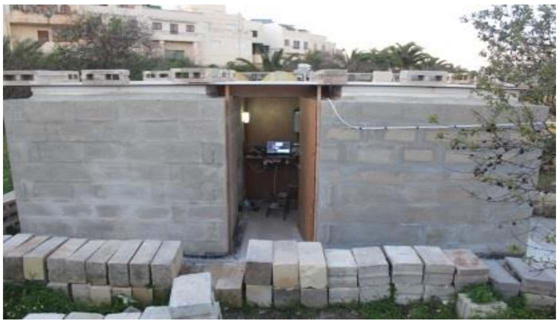

Figure 4: Southern side view of insitu test cells showing the data monitoring equipment area

A separate laboratory hot-box setup was also upgraded to be used for testing the standard and prototype HCBs at the Institute for Sustainable Energy. The hot box was originally developed by Dr. Mario Fsadni, during his tenure at University. The upgrades included repairs to the heating and cooling systems, replacement of the controllers, complete replacement of all thermocouples by isolated ones to reduce noise, upgrade of hardware and software and introduction of heat flux sensors for measuring heat flow through the test walls. Figure 5 below shows a view of the enclosure of the hot-box being used with one test wall on the left hand side.

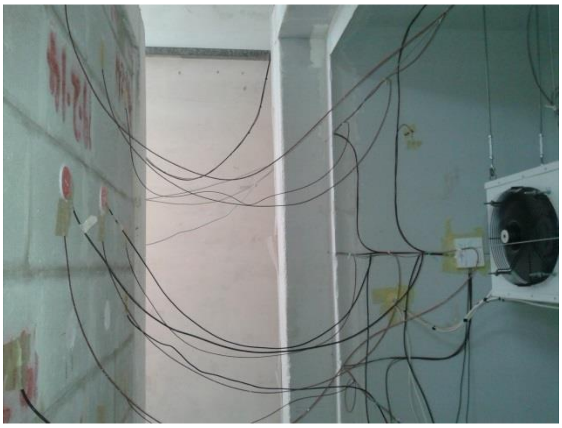

Figure 5: Sectional view of the hot-box setup

Insitu U-value results of the different hollow concrete blocks were then compared to the ones obtained for the same blocks tested in the hot-box setup under controlled laboratory conditions. This ensured a certain level of control on the results being obtained throughout the study.

3.3 Thermal testing methodologies

In this study, research was carried out on two thermal testing methodologies: the heat flow meter method and the infrared method. These separate methodologies were used to quantify the thermal performance (i.e. the U-value) of the prototype HCBs tested insitu.

The heat flow meter method was performed in accordance to ISO standard 9869 Part 1. This method makes use of heat flux sensors, which are made of thin thermally resistive plates with thermocouples, arranged in such a way that the electrical signal given by the sensors is directly proportional to the heat flow per square metre through the plate and subsequently the wall surface under it. Figures 6, 7 and 8 below illustrate equipment used for the monitoring and data collection for the heat flux meter methodology.

Figure 6: View of the data monitoring equipment used for the heat flow meter method as part of the Hukseflux TRSY01 datalogger system

Figure 7: View of the heater unit used to maintain constant temperature inside the test cells

Figure 1: View of the Hukseflux HFP01 heat flux sensors used to measure the heat flux through the building blocks being tested

The infrared method makes use of an infrared camera to capture thermograms of the interior surface of the test wall in order to calculate the U-value of the building elements. The infrared method being developed by Kato et al [6] – a method which would eventually contribute towards the development of ISO WD 9869 Part 2 – was adopted in this study. Figures 9 and 10 below illustrate the equipment used for the infrared technique.

Figure 9: FLIR T640 Infrared Camera

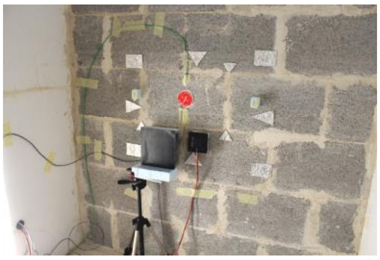

Figure 10: Thermal setup inside the test cell for both the infrared method

The use of two test cells was to carry out simultaneous insitu thermal testing on both standard HCB and ThermHCB walls under the same environmental conditions. This method of testing was possible when applying the heat flow meter methodology, but was not adopted for the infrared methodology due to costs. Funds available could not cover the purchase of two sets of infrared cameras to be set up in both test cells concurrently. U-values obtained from the infrared technique measurements were thus only compared to U-values obtained from measurements using the heat flow meter technique for the same test wall, with monitoring and collection of data taking place within the same period and thus under similar environmental conditions. This comparison strategy allows the validation of the infrared U-value measurements thus contributing towards the research and development of the ISO standard for thermal imaging, which is still in draft form.

Table 2 below shows the U-value results for both the heat flow and the infrared methododologies using the insitu collected data.

Mix Design Batches		**U-value (HFM method) W/m^2K**	**U-value (IR method) W/m^2K**	**Percentage improvement[5]**
Conventional HCBs	HCB-N1[2]	2.443 ± 0.026	2.298 ± 0.299	-
	HCB-N2[2]	2.500 ± 0.027	3.226 ± 0.419	-
	HCB-N3[2]	2.357 ± 0.025	3.028 ± 0.393	-
	HCB-N4[3]	2.465 ± 0.026	3.215 ± 0.418	benchmark
ThermHCBs	HCB-1[2,1]	2.289 ± 0.024	2.333 ± 0.303	no improvement
	HCB-2[2,1]	2.159 ± 0.023	1.913 ± 0.249	6.4%
	HCB-3[2,1]	2.197 ± 0.023	2.056 ± 0.267	2.5%
	HCB-4[2,1]	2.156 ± 0.023	2.470 ± 0.321	8.1%
	HCB-5[2,1]	2.140 ± 0.023	2.933 ± 0.381	7.7%
	HCB-6[2,1]	2.195 ± 0.023	2.585 ± 0.336	5.0%
	HCB-7[3,4]	2.280 ± 0.024	2.717 ± 0.353	7.5%
	HCB-8[3,4]	2.452 ± 0.026	3.205 ± 0.416	0.5%

[1] ThermHCB U-value is compared to HCB-N which corresponds to the standard HCB used in Test Cell 2.
[2] HCB batches manufactured using the Single (230 mm) geometric design.
[3] HCB batches manufactured using the Double (230 mm) geometric design.
[4] ThermHCB U-value is compared to HCB-N4 since test wall of Test Cell 2 has not yet been replaced with the Double geometric design.
[5] U-value percentage improvement is calculated by comparing insitu results obtained using the HFM method.

Table 2: U-value results calculated from insitu thermal testing

5 STRUCTURAL COMPRESSION TESTING AND DIMENSIONAL TESTING

Compression testing was done at the Laboratories of the Faculty for the Built Environment, in accordance to BS 6073-2:1981. Dimensional testing was also carried out in accordance to the procedures stipulated in BS EN 772-16: 2000 and BS EN 772-20: 200. Figure 11 below illustrates the setup used to perform compressive strength testing on HCBs.

Figure 11: Equipment set-up for compressive strength testing (fibre board rapid test BS 6073-1:1981)

Initially, compression and dimensional testing were performed on samples consisting of the standard batch (HCB-N) and the preliminary ThermHCBs (HCB-1, HCB-2 and HCB-3) together with their corresponding cubic specimens. Later during this study, further compression testing was performed on other batches of ThermHCBs (HCB-4, HCB-5 and HCB-6), manufactured in line with the Taguchi Method, and the other standard HCB batches (HCB-N1, HCB-N2 and HCB-N3). Dimensional testing was not carried out for these batches, as this test procedure had already been performed on the preliminary ones.

For the samples measured, it was shown that in general the overall length of the concrete masonry unit was on average 458 mm with a tolerance of +/- 0.9 mm, the average overall width, 230 mm, +/- 1.0 mm, and an average overall height of 280 mm +/- 1.2 mm. In all cases the concrete masonry units could be classed as type D3 as per recommendations given in EN 771-3: 2003, clause 5.2.2, Table 1. Testing also showed that concrete masonry units manufactured by the supplier (RA & Sons Manufacturing Ltd) have parallel faces and within very small variations.

The last compression testing for this first phase of the study was carried out on the ‘Double’ (230 mm) block design of the standard HCB-N4, and the ThermHCB prototypes HCB-7 and HCB-8. All structural compression and dimensional testing was carried out at the Faculty for the Built Environment, University of Malta. Table 3 below illustrates the compression test results obtained for all the batches mentioned above.

From these results an evaluation of the strength performance of ThermHCBs in relation to standard HCBs could be carried out.

	Characteristic strength N/mm^2	**Mean strength** N/mm^2	**Standard deviation** N/mm^2	**Max strength** N/mm^2	**Min strength** N/mm^2	**Range** N/mm^2	**Mean weight** kg	**Min weight** kg	**Max weight** kg
HCB - N	5.4	6.6	0.72	8.24	5.01	3.23	---	---	---
HCB - N1	6.1	7.2	0.69	8.70	6.10	2.60	---	---	---
HCB - N2	7.2	9.2	1.47	13.10	5.60	7.50	35.1	34.4	37.7
HCB - N3	5.3	7.5	1.32	9.70	4.80	4.90	33.4	32.7	34.4
HCB - N4	6.5	7.9	0.85	9.20	6.03	3.18	40.0	38.3	42.0
HCB - 1	6.1	7.6	0.91	8.77	5.80	2.97	---	---	---
HCB - 2	5.1	6.5	0.85	7.97	4.05	3.92	---	---	---
HCB - 3	4.1	5.1	0.65	6.16	3.99	2.16	---	---	---
HCB - 4	2.9	3.7	0.47	4.90	2.60	2.30	24.3	23.4	25.9
HCB - 5	3.1	4.1	0.59	5.50	3.10	2.30	26.6	25.7	28.2
HCB - 6	4.5	5.5	0.62	6.60	4.20	2.40	26.9	26.2	28.4
HCB - 7	7.1	9.9	1.70	12.69	6.92	5.77	35.5	33.5	37.5
HCB - 8	10.1	12.1	1.15	14.03	9.82	4.22	37.5	35.7	39.9

Table 3: Compressive strength test results of concrete masonry blocks

4 RESULTS, CONCLUSIONS AND FURTHER STUDY

This paper has provided an overview of the research work being carried out on the thermal properties of HCBs. Two methodologies have been set to calculate the heat transfer through the blocks. The U-value of a number of specimens have been calculated and the prototype which yielded the target compressive strength and the best thermal improvement over the standard HCB is now being pursued for further optimisation.

The study has been focused and planned around the improvement of the U-value of both the 'Single' (230 mm) and 'Double' (230 mm) hollow concrete block. Results have shown that the U-value improvement of at least 10% of the ThermHCB over the standard block cannot be attained with the 'Single' (230 mm) prototype hollow concrete block. Results also showed that the 7.5 N/mm² compression stress threshold could not be achieved for the single type. However, the block can still be used for load bearing walls within its limitations, according to the architect's design for any particular construction.

The second phase of this research work shall be focused on optimising the double 230 mm thick HCB, following the encouraging results of HCB-7. This will also be followed by a cost-optimisation for the mass production of the prototype. A feasibility study for commercialisation shall be conducted in order to prove whether the idea is commercially viable and thus determine if this concept can be further developed.

6 ACKNOWLEDGEMENTS

This work has been co-financed by the National Research and Innovation Programme 2012, of the Malta Council for Science and Technology, under grant agreement R&I-2012-058.

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