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HEAT TRANSFER CHARACTERISTICS OF LOCALLY MANUFACTURED HOLLOW CONCRETE BLOCKS

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ABSTRACT: The paper is focused on the investigation of the thermal properties of traditional local building blocks with the aim of understanding its resistance to the transfer of heat. The building blocks under test shall be hollow concrete blocks (HCBs) manufactured by a local company. The hot box method technique shall be applied to obtain values of the thermal conductivity of the respective HCBs being tested. Dimensions and weight of these blocks shall be recorded and compression testing carried out. The correlation between thermal conductivities and compression strength shall provide useful information on the thermo-physical behaviour of these building elements. The first part of this paper reports on the actual setup of the hot box. It is then followed by the description of the testing methodology adopted and calculations applied to obtain values for comparisons between the different HCBs tested. The final part of the paper is then focused on the discussion of results and the ultimate conclusions. The aim is to succeed in obtaining a correlation between U-values of existing local HCBs, their density and compressive strength, which will enable future extrapolation of results, based on simple measurements such as density.

Keywords: Heat transfer, hot-box, hollow concrete blocks.

1 INTRODUCTION

Energy consumption has become an ever-growing concern worldwide due to the increase of private demand and industrial consumption. Energy use in the building sector takes between 20% to 40% of the total demand in the EU and the other developed countries [1]. 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), which fixed the year 2020 as the start of a new era, whereby all new and significantly renovated buildings have to be "nearly zero energy" [2], through improved construction materials, more efficient services and renewable energy installations.

In the Mediterranean and south European regions, hollow concrete blocks are by far the most popular construction material used nowadays. 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. Masonry enclosures play an important role in the economic weight of the building's construction expenses. However, one also has to seriously consider the lifetime energy costs, in order to reach a compromise that provides an affordable building while minimising energy expenditures. Designing building envelopes with minimised heat losses reduces energy consumption and helps to meet the sustainable energy goals.

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 lightweight, improved thermal and acoustic insulation, as well as ease of ventilation are few of the hollow block envelope characteristics that make hollow concrete blocks an attractive construction element. Consequently, concern about improvements in their thermal qualities is resulting in numerous studies.

Locally, there has been only a limited number of studies on the thermal properties of HCBs. The goal of this study is to identify and analyse the path of heat transfer through hollow concrete masonry units and correlate it to the physical properties of the same blocks. This may result in a statistical correlation, whereby the density of the HCB may be sufficient to estimate its U-value and structural strength.

For the assessment of thermal characteristics, the hot box method according to BS EN1934:1998 is being used. All thermal tests are being carried out at the Institute for Sustainable Energy, University of Malta. Compression testing of the HCBs is based on BS 6073-2:1981. These tests are being carried out at the Faculty of the Built Environment, University of Malta.

2 LITERATURE REVIEW ON HOT BOX METHOD OF MEASUREMENT

The paper presented by E.A. Adam et al. evaluated the thermo-physical properties of stabilised soil building blocks [3]. In their study, the authors pointed out the basic requirements for both good thermal insulation and structural strength of building blocks. The better of these two properties is not always easy to match as they are opposed one to the other as far as which mixture of materials best provides the optimum conditions for it. Whilst thermal insulation requires porosity for best results, strength reaches its maximum at maximum density. Adam et al. carried out the testing using a guarded hot box with wall specimens constructed from nominal 140mm thick solid or hollow stabilised soil blocks. The experimental results showed that the stabiliser has a significant effect on the thermal conductivity of the blocks. It was shown that lime stabilised soil blocks exhibit lower k-values than those of cement within the same soil type. These values varied according to the response of each soil type to the stabiliser added to it and the effect it had on its density.

Chen et al. acknowledged through their study, the challenge that exists to measure summer condition thermal transmittance (SCTT) as opposed to winter condition thermal transmittance (WCTT) [4]. This results from the fact that the lower temperature difference between indoor and outdoor temperatures leads to smaller heat flows, in turn requiring more accurate measurements, calibration and uncertainty analysis. In their study, they presented a potential alternative solution to use a reversed orientation method, through the use of a calorimetric hot box, such that the metering box simulates the warm outdoor condition. This method was also applied by McCabe et al., who tested SCTT with hot boxes designed for WCTT tests [5].

Baig and Antar reported that both the increased number of cavities in the layout of the block as well as the cavity layouts has a direct effect on reducing the heat flux without compromising the strength of the building block [6]. Kumar specified constraints on the thickness of any shell to be not less than 11mm and that of any web to be no less than 8mm [7]. This ensured minimum requirements to sustain the entire structural integrity of the block. The effect of the profile of the cavities was also reported by Diaz et al. [8, 9]. Interesting to mention as well, is the effect of thermal radiation on the total heat transfer rate across cavity blocks. Li et al. addressed this issue and reported from their investigations that the significance of the thermal radiation on the total heat transfer rate across clay bricks ranges between 4.6 to 25.8 % depending on the layout of the cavities [10]. Likewise, the main idea in Antar's work was to calculate heat transfer rate across a building block taking into account the effect of thermal radiation [11]. The latter is significant when the heat transfer coefficient is relatively small or when there is substantial temperature difference between the surfaces. The author concluded that for single cavity block, the total heat transfer rate is increased by 30% if radiation is considered. The highest heat transfer rate observed was when using single wide cavity blocks. In his conclusions, Antar recommends building blocks with multiple narrow cavities rather than wide cavities. This reduces the aspect ratio which decreases the convection heat transfer effects.

A local study, carried out by Stephen Pulis investigated the measurement of thermal characteristics of local HCBs [12]. In his work, Pulis obtained U-values for 230mm thick double density type HCBs of 2.2422W/m^{2}K. His chosen method of measurement was the guarded hot plate method. His work was carried out on samples cut to size directly from typical concrete blocks. U-values were then determined using the CIBSE combined calculation procedure, which calculates the upper and lower limit values of thermal resistance and takes their average as the effective resistance value. This method, also referred to as the Combined Method, is the one set out in Document F [13].

Another local study on thermal characteristics of HCBs was carried out by Nathan Vella [14]. Vella investigated the thermal advantages of an improved design of a traditional 230mm thick double density HCB. In his work, he attempted to even out the errors arising from the use of the parallel flow method by omitting the effect of mortar joints in his calculations. He also opted to consider one dimensional steady heat flow in his experiments, which may be true within the central region of the wall. Although Vella proved that the proposed block (having three cavities and two reflective sheets) gave a U-value (2.87W/m^{2}K) of approximately 60% that of the traditional block (4.66W/m^{2}K)[1], this could only be achieved by changing the whole manufacturing production line, which would involve added financial burden on any manufacturing company. When it comes to practical handling and positioning on site and

[1]*Vella used the internal area of walls when calculating the actual heat loss. If the external areas were used instead, the U-value of the traditional 230mm thick double density HCB would have gone down to a value which is comparable to the value obtained by Pulis [12].*

construction at corners, the proposal presented some drawbacks.

3 HOT BOX MEASUREMENT TECHNIQUE

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 of that element divided by the difference in temperature across itself. The greater the U-value the greater the heat loss through the element. Determining the U-value is an essential part of building envelopes and for this reason these should be determined realistically. 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 Hot box setup

The heat flow meter hot box method, based on document BS EN1934:1998, allows for a reproduction of boundary conditions of a test element which is enclosed between two different environments kept at constant temperatures [15]. The heat transfer through the specimen is then monitored at steady-state conditions. The resistance value (R) is calculated using the analysed data according to the methodology set out in Section 3.3. The experimental setup used to carry out the measurements consisted of the following:

- Hot and cold climatic chambers
- Test specimen HCBs
- Measuring devices
- Heating system

Climate Chambers: A custom-made chamber was used for this experimental research work. This is a hot box situated inside the laboratory of the Institute for Sustainable Energy in Marsaxlokk. Figure 1 below shows a photograph of the setup.

Figure 1: Hot box setup inside the laboratory at the Institute for Sustainable Energy, University of Malta

The temperature in the hot chamber is regulated by means of a 2 kW electric heater and two circulating fans. Temperature is controlled by means of an electronic thermostat. The entire hot box setup is surrounded by a temperature controlled space through the use of one split air-conditioning unit. The heat losses through the box walls are kept to a minimum by using 50 mm thick expanded polystyrene (EPS) enclosed within a frame-work of timber.

Test specimen HCBs: Double density 230mm thick HCBs were placed in the hot box separating the hot and cold chambers. The test blocks are based on a standard size block measuring 480mm by 280mm by 230mm and having two cavities. They were individually placed within a cut-out of insulation made of expanded polystyrene (EPS) sheets, as shown in Figure 2. The units were suspended in place through the use of a pulley system. They were placed face down, so as to ensure that heat transfer occurs through the web and cavity in a uni-directional fashion. To reduce the effect of thermal bridges, the upper part of the test unit was sealed using EPS blocks taped on to the surrounding thick EPS base sheets.

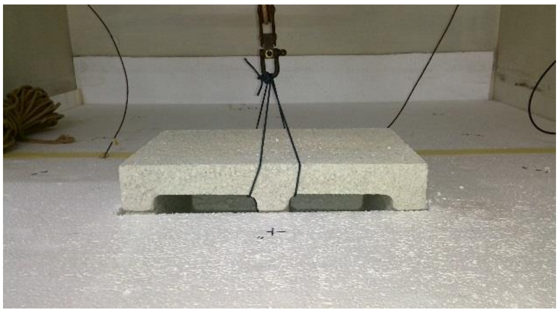


Figure 2: Individual HCBs placed within a cut-out of expanded polystyrene sheet, suspended in place through the use of a pulley system. (Hot box setup in the laboratory at the Institute for Sustainable Energy, University of Malta)

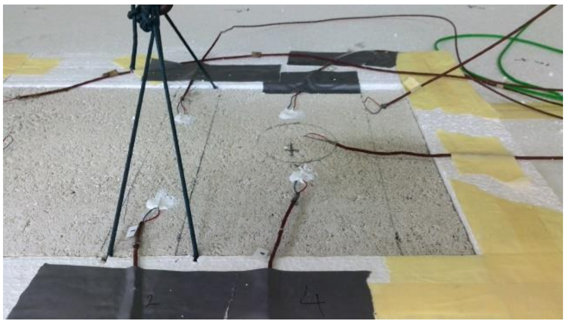
The standard test blocks consisted of a mixture of sand, cement, water, coarse and fine aggregates as manufactured by R.A. & Sons Manufacturing Ltd. The HCBs used for these experiments were stored under the same ambient conditions, so as to reduce error variations due to moisture content in specimens. All samples were stored outside on timber pellets and covered by thick plastic sheets, to avoid direct contact with rain and night time condensation

Measuring devices: Ten type-T shielded thermocouples, with a temperature range of -250^{o}C to 350^{o}C and specific error limit of 0.5^{o}C or 0.4% of the reading, whichever is larger, were used to measure temperatures on different locations of the test specimen masonry unit. Shielded thermocouples maintain electrical ground from the probe sheath to the instrument and reduce noise caused by grid frequency. The thermocouples were mounted on the test HCB using thermal paste and tape, using glue on either side of the tape to ensure proper contact.

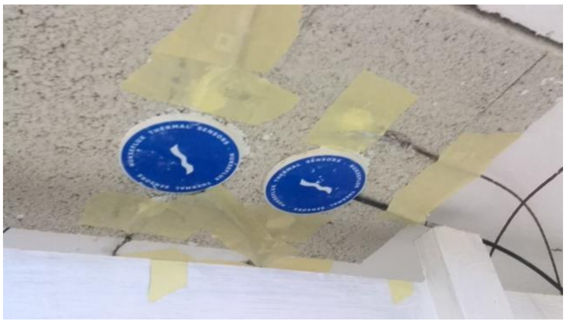
Two thermocouples in each chamber were used to monitor the air temperature inside the hot box. Also, a number of thermocouples were fixed on the HCB and inside the air gap, to read the temperature gradient across the block.

Two Hukseflux heat flux sensors, with thermal resistance of less than 0.00625 m^2K/W and temperature range of -30^oC to 70^oC, were fixed to the test unit, using thermal paste and plastic clips thus ensuring full contact to the HCB surfaces on the cold side.

Figure 3 indicates the setup of the test specimen unit and the measuring devices. It can be seen how the position of the thermocouples and the heat flux sensors is chosen over the centre of the web and cavity faces.



(a) Top face of the HCB with the type-T thermocouples installed on the web and the cavity faces.



(b) Bottom part of the HCB with the 2No heat flux sensors and corresponding thermocouples installed on the web and cavity faces.

Figure 3: Measuring devices installed on the test specimen HCB placed inside the hot box setup in the laboratory at the Institute for Sustainable Energy, University of Malta

The heating system: The applied heating load was generated by a 2kW electronically-controlled heater. Uniform heat exposure to all the surface areas of the sample was provided by the aid of two 17W fans. This ensured a uniform temperature over the sample block

Measurements: a National Instruments programme using LabVIEW software was used to gather all the data. The values analysed were those falling within the bracket of steady-state conditions and were then used for calculations of thermal resistances. The procedure adopted is the one established in Document F using the Parallel and Isothermal methods of calculation, also known as the upper and lower values, respectively [13].

3.3 Monitoring and analysis

This section describes the procedures adopted in this study to monitor and analyse the thermal transfer through the specimen HCBs. Procedures and problems described in ISO 9869, as well as in literature papers have been followed to develop the methodology and analyse the gathered data Monitoring of the HCBs in the hot box is still ongoing, in order to have a statistically meaningful batch of tests..

A data logging system making use of LabVIEW as the graphical programming platform is being used in the hot box setup. Readings are averaged over 3 minute intervals. The system allows for a period of time long enough for steady-state conditions to be reached.

Hukseflux HFP01 heat flux sensors are being used to measure heat flows through the selected HCBs. The actual sensor is the HFP01 thermopile, 80mm diameter and 5mm thick. This thermopile measures the differential temperature across its ceramics-plastic composite body. Working completely passive, HFP01 generates a small output voltage proportional to the local heat flux. Figure 4 depicts the type being described here from both sides, namely the hot and cold facets.

Figure 4: Hukseflux HFP01 heat flux sensor.

The value of thermal conductivity is obtained using the procedure set out below. The input variables are the monitored heat fluxes (HF) and temperatures (T), across the web of the test HCB. The resulting output variable is the thermal conductivity (k). The readings are taken at specified intervals and over a period sufficiently long to take into account the thermal capacity of the HCB. Moving averages of the heat flux (HF) and corresponding temperature difference (ΔT) were calculated over steady-state periods of at least 72 hours. This enables the calculation of the thermal conductivity through the material thickness (L) using equation (1) below:

$$k = HF*L/\Delta T \quad (1)$$

The value of the convective heat transfer coefficient, h_{air} is obtained from the equation:

$$HF_{cavity} = k*\Delta T_1/L_1 + h_{air}*\Delta T_2 + k*\Delta T_3/L_2 \quad (2)$$

where HF_{cavity} = heat flux through the cavity section of the HCB (W/m²); k = thermal conductivity of the concrete face shells of the HCB, calculated using equation (1); L_1 and L_2 are the top and bottom face shell thicknesses of the HCB; ΔT_1, ΔT_2 and ΔT_3 are the temperature differences across the top face shell, the air gap and the lower face shell, respectively.

The value of the resistance of the air cavity is obtained through the equation:

$$R_{air} = 1/h_{air} \quad (3)$$

The Combined Method technique as presented in the Technical Guide F, Appendix B is used to obtain the values of the upper and lower limit thermal resistances. Given that surface temperatures are being recorded, standard internal and external surface resistances are added to calculate the resultant thermal resistance as explained in Document F [13]. The values of these resistances are widely used as 0.1 and 0.06 m²K/W, for the internal and external sides of a standard external wall.

The relationship between the concrete's thermal conductivity and its density shall unveil any correlation which exists between thermal conductivity and strength. Similarly, it is the intention to investigate the relationship between density and compressive strength. Figure 5 shows samples of HCBs that have undergone thermal testing and are being sent for compressive strength testing.

Figure 5: HCBs weighed and thermally tested ready to be taken for compression testing.

4 RESULTS

The experimental results of the investigations that have so far been completed are shown in Table 1 below.

Table 1: Comparison of U-values and strengths of locally manufactured double density 230mm thick HCBs

HCB	Block Density (kg/m^3)	Concrete k-value (W/mK)	Cavity h-value W/m^{2}K)	Block U-value (W/m^{2}K)	Comp. Strength (MPa)
No 1	33.1	0.541	24.378	2.4378	5.2
No 2	32.8	0.517	39.922	2.524	5.0
No 4	33.6	0.472	38.183	2.297	6.5
No 5	31.3	0.374	26.253	2.056	5.5

The graph in Figure 6 indicates a correlation between density and compressive strength. However, as seen from Figure 7, there are far too few test results available at this point of the study, to establish a marked correlation between the U-values and the densities of the HCBs.

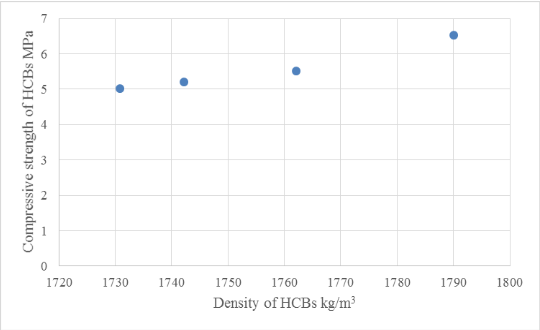


Figure 6: Correlation between the compressive strength and density of specimen HCBs

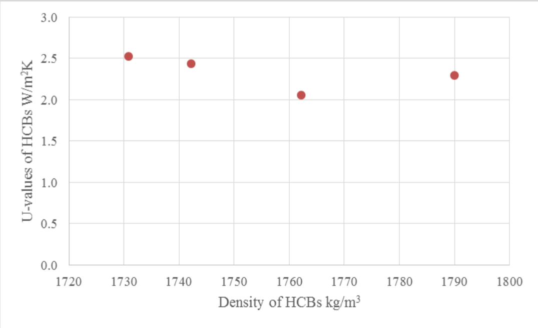


Figure 7: Distribution of test data between the U-value and density of specimen HCBs

5 CONCLUSIONS

This paper has provided an overview of local research work on the thermal properties of HCBs. It was shown that very little research has so far been carried out, especially with regards to the elemental heat transfer process through the solid parts and the cavities within the block.

A methodology has been set to calculate the convective heat transfer through the HCB and the U-value of a number of specimens have been calculated. Results showed close agreement with one particular local research that was carried out by Pulis [12].

A correlation between the compressive strength of the HCBs and their density was established. However, the U-values did not show clear correlation with density, possibly due to the small sample that has undergone testing so far.

6 ACKNOWLEDGEMENTS

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