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ScienceDirect

Energy Procedia 62 (2014) 180 – 189

Energy Procedia

6th International Conference on Sustainability in Energy and Buildings, SEB-14

Overview of testing methodologies for thermally improved hollow-core concrete blocks

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Abstract

In construction, hollow-core concrete blocks (HCBs) offer a number of advantages over solid blocks, such as lighter weight and improved thermal and acoustic insulation. However, the relative high value of the overall heat transfer coefficient (U-value), makes them less attractive for use in new buildings in Europe, given that these must approach the net-zero energy performance level by 2020. In this respect, a project has been developed in Malta, which aims at producing a new HCB having the same physical dimensions and load bearing characteristics as a standard locally-produced HCB, but with improved thermal properties. The project (ThermHCB) is being co-financed by the Malta Council for Science and Technology (MCST) under the 2012 R&I National Programme. ThermHCB project is divided into a number of Work Packages covering the whole process from developing the HCB, manufacturing, testing and optimizing the final commercial product. This paper focuses on one aspect of this project, namely on the testing methodologies that are being proposed and implemented, for the load bearing as well as thermal characterization of the HCBs. In the latter, two procedures are being adopted to compare the thermal properties of standard and prototype HCBs, using infra-red techniques and heat flow methodology. Comparisons shall be made to verify whether the infra-red method, which offers faster measurement techniques, provides U-value results that are sufficiently accurate.

Selection and peer-review under responsibility of KES International

Keywords: building envelope; hollow-core concrete block; insitu; heat flow; infra-red; Malta

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Selection and peer-review under responsibility of KES International
doi:10.1016/j.egypro.2014.12.379

1. Introduction

Energy use has become an ever-growing concern worldwide, especially for buildings, which consume between 20 and 40 % of the total energy consumption in developed countries, including EU Member States [1]. Following the EU Energy Performance of Buildings Directive (EPBD) of 2002 and its recast 2010/31/EU, all new and renovated buildings shall be “nearly zero energy” after the year 2020 [2].

In hot/humid climatic regions like Malta and the Mediterranean, where the cooling season may be longer than the heating season, cooling energy demand for buildings has become a key issue for most energy policies. Many researches have been done and are still being carried out to provide new building materials and simple ways of selecting appropriate building envelopes with the right thermo-physical properties. Locally, two leading construction companies have already introduced two distinct thermally improved construction systems on the market: the EVG-3D Malta and Thermablock Malta. The former is based on a core of expanded polystyrene strengthened by a web of galvanised wire mesh that can be blasted by concrete mix on both sides of the wall. The latter is a composite HCB that integrates an expanded polystyrene layer and an outer concrete layer to the standard HCB. ThermHCB Project takes a different approach, whereby no specialised machinery is needed and no extra-wide blocks are used.

Two types of limestone are found on the Maltese Islands: globigerina and coralline. The globigerina (mostly found to the south as large flaky slabs) is a soft rock, relatively easy to work and has formed the bulk of Malta's building material over the years. The harder, more crystalline, coralline stone (found more to the North and in the Island of Gozo) has been used on the more important buildings. The typical local construction for the external building envelope was based on two single masonry leaves separated by an air cavity. This provided a substantial amount of thermal control inside the buildings, due to the fact that any heat absorbed by the outer stone leaf, would find it difficult to travel through the air cavity into the inner leaf adjacent to the interiors of the building spaces (and *vice-versa*). The challenge with this type of construction lied in the 10% bond-stones, which offered an easy path for heat transfer through the wall. With more and more stone masonry blocks being utilised during the building boom back in the 1980s-1990s, many quarries have been exhausted. Hollow-core concrete blocks have nowadays become the main building masonry units used locally.

In this research work, the potential applicability of ThermHCB blocks as thermally enhanced building blocks is studied. ThermHCB (part-financed by the Malta Council for Science and Technology (MCST), being co-ordinated by Galea Curmi Engineering Services Ltd. in partnership with R.A. & Sons Manufacturing Ltd. and the University of Malta), is a project aiming at developing a building block with enhanced thermal properties, while keeping the standard dimensions and the same structural strength of the local HCB. It needs no new skills to build with and requires no added machinery on site. The percentage of raw materials used to form the concrete mix is being varied to achieve the optimum balance between the structural strength and the thermal properties of the block. In this assessment, two thermal testing methods are investigated in order to establish the correlation of the results obtained from each measurement technique.

- *The Heat Flow Meter Method:* using ISO Document 9869:1994: Part 1: Thermal Insulation – Building Elements – In-situ measurement of thermal resistance and thermal transmittance.
- *The Infra-red Method:* using the methodology presented in the paper [10]: Method of in-situ measurement of thermal insulation performance of building elements using infrared camera.

Nomenclature

HCB	hollow concrete block
HTCS	heat transfer coefficient sensor
HFM	heat flux meter
IR	infrared
ET	environmental temperature sensor

HF	heat flux (W/m^2)
T	temperature (°C)
L	wall thickness (m)
k	thermal conductivity (W/mK)
Q	heat flow (W)
A	heat transfer area of infra-red analysis region (m^2)
h	total heat transfer coefficient (W/m^{2}K)
Θ_n	internal controlled environmental temperature – using ET sensor (°C)
Θ_s	internal surface temperature of selected wall region for infra-red method (°C)
q_{hs}	heat flow density in infra-red method (W/m^2)
V_{sen}	voltage output of heat flux sensor (mV)
E_{sen}	sensitivity of heat flux sensor of infra-red method (mV/Wm^{-2})
Θ_{hs}	surface temperature of HTCS (°C)
U	thermal transmittance (W/m^{2}K)
Θ_{ni}	internal environmental temperature using thermocouple (°C)
Θ_{ne}	external environmental temperature using thermocouple (°C)

2. Survey on methodologies for measuring heat transfer through walls

To comply with the European strategies for energy performance of buildings regulations, it is essential to define effective methodological procedures to determine the thermal performance of building envelopes [3]. The method presented in ISO 9869 Part 1 is the only method validated by ISO standards to determine thermal transmittance of a building in-situ. Another less invasive method is the infrared technique presented and discussed by Kato et al. [10]. The aim of this method is to measure the U-values using an infrared camera. While the first method is already consolidated (ISO 9869 Part 1), the latter is still considered as a qualitative method and its potential has not yet been established.

2.1. Heat flow meter method

In the light of the importance of actual thermal performance after realisation of the building, in-situ measurements of heat flow have been of international concern. Cesaratto *et al.* have carried out simulations to evaluate the relative increase on the net heating energy demand when implementing the measured values with respect to the design values [4]. Differences between 11 and 14 % were noted. However, transient thermal techniques do have drawbacks. Desogus *et al.* highlighted the problematic issues of the non-invasive method of in-situ measurement, when using the heat flow meter technique, arising from measurement of surface temperatures and heat flux. They mention the fact that extended performance period, of at least 72 hours of measurement, is a requisite in order to calculate thermal resistance using the mean progressive method [5]. Although the authors concluded that even at critical temperature differences (of lower than 10 ^{o}C) the heat flux meter measurement was compatible with other values, the test wall thermal resistance value (R-value) measurement with an air temperature difference equal or higher than 10 ^{o}C between inside and outside is the most reliable method, as it is affected by the smallest error (9 %). Notwithstanding these drawbacks, the lightweight components and parts of the heat flow meter technique distinguish this method as the easiest one to test thermal parameters of building elements in-situ. Yesilata *et al.* pointed out the concern about the location of thermocouples and the quality of contact resistance between the latter and the surface of the sample in obtaining accurate measurement [6]. In the proposed dynamic measurement technique, the authors addressed the issues of minimising heat losses to the surroundings as well as reducing heat flow to one dimensional axial flow. The importance of mortar joints was stressed in the work of Tinker and Rourke [7]. In their paper, they stated how change of densities between the mortar joints and the actual block-work can result in cold bridging, which in turn reduces the thermal efficiency of what could be achieved by the actual blocks.

Anderson [8] pointed out the effects of moisture, air velocity, air infiltration, complex heat flow patterns at interfaces of different materials and differences between design and structure as built, on the discrepancies between design and measured values and hence the need for in-situ measurement techniques. The author concentrated mostly on how variations in internal and external temperature affect the result of the U-value. An important consideration given in Anderson's work was the effect of changes in mean temperatures. Changes in mean internal/external temperature over any day cause changes in the heat stored in the wall at the end of the day, thus affecting the measured heat flux integrated over the 24 hours. Thus one needs to be aware of the potential error from fairly small temperature changes. Variation in construction methods as well as quality and aging of materials are some other causes which can result in substantial variation in wall thermal performance when comparing laboratory and in-situ measurements. Condon *et al.* have stated in their study that between 20 and 30 % reduced values could be expected from laboratory measurements and standard calculations [9]. To this end, a reliable method of in-situ measurement validated by comparison with established laboratory test methods, as the one carried out in our study, is sensible and justified.

2.2. Infra-red method

The subject of the application of the infrared method has prompted several research studies to validate the infrared methodology as an effective method to determine U-value of building envelopes. In their study, Kato *et al.* presented a quantitative method to measure thermal transmittance of building envelopes using infrared thermography [10]. An HTCS was used to measure and simulate the heat flux resulting from convection and radiation incident on the test wall in-situ. The HTCS consisted of thermal insulation material, thin film heater and HFM attached to a copper plate. By measuring the surface temperature of the HTCS, wall surface temperature and inside environmental temperature with the infrared camera (IR camera), the thermal transmittance of the wall could be derived. Experimental results showed that U-value measurements for infrared thermography can be sufficiently guaranteed. The studies presented by Albatici and Tonelli involved on-site evaluation of thermal transmittance of building elements of a single family house, using both the heat flow meter and the infrared measurement techniques, based on the ISO 9869. The tests were carried out in the month of January and data was acquired every 15 minutes. For the heat flow meter method, results showed that the measured U-value is 59% higher, when compared to the calculated U-value, whilst more reliable results were obtained for the infrared method with values 31% higher than the calculated U-values. The main advantage of the IR technique over other relevant techniques is that it is not a point measurement but rather collects rapid data over large surfaces of the wall [11]. Hence a global thermographic image is analysed over the entire wall. On the other hand, this method does present some limitations such as the fact that measurements need to be taken during the evening to eliminate solar radiation effects on the readings. Furthermore, outside wind speeds have to be less than 1m/s so as to avoid out of control convective phenomena [11]. Dall 'O' *et al.* presented a study which involved the extensive use of infrared audits on 14 existing buildings located in Milan Province (Italy), made in different construction periods and characterised by different building technologies and thus, different energy performances [12]. Dall 'O' *et al.* investigated the application of infrared thermography to provide quantitative information on thermal transmittance of external walls. Results were evaluated by comparing actual known values of the walls with the measured values through thermography. It was concluded that results from field testing were reliable with a low margin of error.

3. Methodology

The preliminary experimental programme consisted of establishing three concrete mix designs, including different percentages of expandable clay, perlite and basalt. These mixes were classified as HCB-1, HCB-2 and HCB-3. In each mix design, the following materials were used: cement, mineral aggregates (local stone and sand), expandable clay and super plasticizer. The composition of the mix constituents is still undergoing optimisation and is subject to intellectual property rights and patent application. The main driving forces behind the pre-determined mix designs were affordability, availability, strength, thermal performance and workability. An attempt has been made to provisionally explore the structural and thermal behaviour of the preliminary HCBs, by carrying out compressive and thermal testing. The initial test results yielded a starting point to determine whether the innovative HCBs satisfy the main criteria, when compared to the performance characteristics of a standard HCB.

3.1. Manufacturing process

The mixing process entails placing dry mixing materials in a concrete mixer for approximately two minutes. When all constituents are uniformly blended, water is added to the right amount to have the best workability. Part of the fresh mixture is used to fill cubic steel moulds (150mm) for testing purposes (as seen in Figure 1) and the rest is used to produce samples of the HCBs.

Due to the wide range of variability in the materials used in the innovative HCBs, a new methodical approach will be required to further optimize the chosen concrete mix. The approach will use Taguchi experimental design to systematically formulate concrete mix designs and determine optimum mixes for the desired responses, while understanding the influence of the chosen materials [13].

Fig. 1. Moulds used for cubic specimens.

3.2. Taguchi Method

Taguchi methods are statistical methods developed by Genichi Taguchi in the 1950s, in an effort to optimise the process of experimentation of robust systems, while keeping experimental costs at a minimum. The method aims to adjust the design parameters (known as control factors) to their optimal levels. For this project, the desired responses in the proposed block are to achieve minimum U-value at the prevailing compressive strength of not less than 7.5 N/mm^2. For this experimental programme, it is assumed that three control factors and two control levels per control factor are required, to understand the influence and interaction of the input parameters and desired responses. Therefore, a full set of experiments would require 2^3 different experiments, as opposed to four which are needed for the Taguchi version of the experiment. This methodology will thus reduce the number of tedious and costly tests, whilst maintaining an insight into the overall effects of the control factors and their interactions valid over the entire experimental region [14].

4. Development of experimental testing methodologies

4.1. Heat flow meter method

Figure 2 below shows the setup designed for an in-situ test bed, 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 1.8m by 1.8m, are composed of 230mm cement-based hollow core block masonry and have a north-facing sheltered elevation to reduce the effect of solar radiation on them. In order to protect the whole setup from direct sunlight, wind and rain, a polycarbonate shielding was installed to cover the whole top test area, as well as the front exposed sides of the two test walls, without blocking natural ventilation.

Fig. 2. In-situ test cells at the Institute for Sustainable Energy, Marsaxlokk.

The test data was monitored and analyzed, and values of the thermal resistances of the different building blocks under test, calculated according to the methodology adopted and described further down. Procedures and problems described in ISO 9869-1994 Part 1, as well as in literature papers, have been followed to develop the methodology for monitoring and analyzing results.

4.1.1. Monitoring and analysis

One test cell (Test Cell 2) has a standard local HCB wall, whilst the test wall in the other cell (Test Cell 1) is replaced after every test with a different prototype HCB wall. In this study, uni-directional heat flow is being assumed. To maintain functional equivalency of both the standard and prototype wall models, and hence ensure similar test room enclosures, it was necessary to carefully insulate the top, bottom and sides of the room model using made-to-measure expanded polystyrene (EPS) 3-sided boxes (for the two test cells) consisting of 150mm thick sheets complimented with a tongue and grooved system and further sealed at the joints using expanded polystyrene beads and an acrylic-based sealer to reduce thermal bridging at the junctions. The test rooms were thermally controlled, to keep a constant interior temperature, using separate fan heaters and electronic temperature controllers. The apparatus setup consisted of one heat flux sensor placed on the surface of each test wall together with two thermocouples, one on either side of the test wall. Figure 3 shows the setup used.

Fig. 3. Test cell construction in progress (a) ceiling level, left; (b) floor level and surrounding walls, centre; (c) capping of cavities of the hollow concrete block at top level, right.

A Hukseflux TRSYS01 system is being used to collect and store the data from both test cells simultaneously. Readings are averaged over 10 minutes or 24 hour intervals in-situ, for a period of time of not less than 72 hours, following steady-state conditions. The sensor locations were chosen so as to avoid possible thermal bridging spots close to corners. Heat flux and temperature sensors were thus located halfway between the two ends of the test wall and about halfway between floor and ceiling of the test cell walls. Heat flux sensors were mounted on the internal side of the wall models, so as to obtain the most stable signal possible and avoid the possibility of any lateral thermal heat flow not being accounted for. Two thermocouples were placed on the wall, one internally near the heat flux sensor and another externally at the same level as that of the sensor inside the test cell.

The thermal conductivity and heat flux of the HCB test walls are correlated by the following equation:

$$k = HF * \frac{L}{\Delta T} \tag{1}$$

The thermal resistances are then obtained by using the Combined Method technique as presented in the Technical Guide F, Appendix B [15].

4.2. Infrared Method

The infrared experiment was conducted in accordance with the methodology presented by Kato et al. [10], to determine the thermal transmittance of the test wall built in-situ with the innovative blocks. Experiments were conducted during night time between 00:00 and 06:00, to exclude solar radiation, which might alter the surface temperature of the test wall [16].

The infrared camera was positioned as close to the test wall as is practical, to allow a good vision of the desired pre-measured area of the interior wall. This section of the wall was prepared with rubbed aluminium foils to help identify spatial locations and distances in the area that fits the thermography measured by the infrared camera. The aluminium foils are large enough to capture a representative portion of the internal background radiation and are placed in the plane of the wall region as shown in Figure 4 (a). The infrared camera was located so as not to affect the air flow characteristics of the test room, while allowing interior imaging of the test wall at near-normal incidence angle to alleviate its contribution towards background radiation. Both the HTCS and ET sensors were mounted near the centre of the desired region to be measured as shown in Figure 4 (a). A constant heating regime was maintained for the duration of the experiment by means of a fan heater inside the room set to 30°C. The interior fan heater was shielded with a wooden board in order to achieve a uniform background. Interior wall thermographic measurements were recorded every two seconds with the infrared camera and ancillary software, as shown in Figure 4 (b).

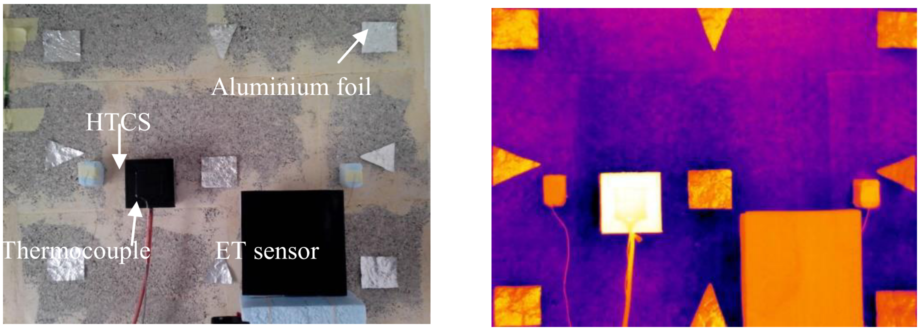

Fig. 4. (a) Scene of measurements on HCB wall (left); (b) Thermographic image (right).

To obtain useful quantitative measurements, thermograms were corrected for a number of parameters namely emittance and reflected apparent temperature. Reference emittance tests were conducted separately to determine the emissivity of both the test wall and black spray in comparison with a special adhesive tape of known emissivity. The reflected apparent temperature was determined by setting area measurement functions on aluminium foils for each recorded thermogram. Temperature measurements were carried out with emissivity set to 1.0 and distance 0.

Equation 2 is used to calculate Q across the selected region.

$$Q = Ah(\theta_n - \theta_s) \tag{2}$$

q_{hs} is calculated using equation 3.

$$q_{hs} = \frac{V_{sen}}{E_{sen}} \tag{3}$$

The value of h can then be calculated using equation 4.

$$h = \frac{q_{hs}}{\theta_{hs} - \theta_n} \tag{4}$$

The U-value of the test wall is calculated using equation 5.

$$U = \frac{Q}{(\theta_{ni} - \theta_{ne}) \times A} \tag{5}$$

4.3. Compression Testing

The hollow concrete blocks and concrete cubes were tested in accordance with BS EN772-1:2000. The compressive strength of the different concrete mixes used in the production of the prototype HCBs was obtained using a variation in the capping method. The concrete units were also measured in accordance with BS EN 772-20:200 to determine the flatness and parallelism of the HCBs being produced. The average length, width, height, shell and web wall thickness were measured for each sample. The mean value and the standard deviation of all the measurements were then computed for the entire batch.

The compressive strength of the HCBs was determined in accordance with BS6073-2:1981, although this standard has been withdrawn and replaced by BS 6073-2:2008. BS 6073-2: 1981 provides a routine rapid control method of compressive strength of blocks using fibre board test. In view of the recommendations found in BS 6073-2:1981, it was decided to adopt the fibre board method for testing of concrete masonry units for practical reasons.

5. Preliminary results

This research study is in its initial stages and tests are still ongoing. However, the first compressive strength and thermal results of the standard HCB and the three prototype walls are presented in Table 1 below. Compressive strength testing was carried out, after 28 days of air curing under normal laboratory conditions, on twenty specimens, produced for each batch. The overall average dimensions of the HCBs under test shown in Table 1 below were: 458mm (±0.9mm) x 230mm (±1.0mm) x 280mm (±1.2 mm). For all cases, the HCBs can be classed as type D3 as per recommendations given in EN 771-3:2003.

Table 1. Compressive strength and thermal results for standard and prototype HCB samples.

	Mean Strength N/mm²	U-value (HFM method) W/m²K	U-value (IR method) W/m²K
HCB – Standard	6.6	2.273	N/A
HCB - 1	7.6	2.289	2.748
HCB - 2	6.5	2.159	2.153
HCB - 3	5.1	2.197	2.294

Thermal testing was carried out for the period between February and April 2014 under in-situ conditions using the two chosen testing techniques, on the four different HCB wall models. Values measured from the heat flow meter method were obtained with internal test cell temperature of 40°C and using the moving average technique.

This is a distinct method of reducing the effect of random variation inherent in the collection of data taken over a specific length of time, computed by creating a series of averages of different subsets of the full data set. Monitoring of data used for measurement in the infra-red method was carried out between 00:00-06:00 hours on specific days, with an internal test cell temperature of 30°C.

HCB-2 prototype masonry units gave the best combination of results. With a mean compressive strength almost equal to that of local standard HCB, it gave an improved U-value of 2.16W/m^{2}K, calculated from measured data using the heat flow meter method. This value generated a 3.6% improvement over the established U-value of 2.24 W/m^{2}K for standard local HCBs as stipulated in the work of Pulis S. [17] and 5.0% improvement over the measured value of standard HCBs being tested in-situ in test cell 2. The discrepancy between the percentage improvements could be the result of differences in concrete mixes of the different standard blocks used for testing purposes. The infra-red method yielded a U-value of 2.15 W/m^{2}K for the HCB-2 test wall. The IR method showed a similar trend of U-values for the three prototypes, in comparison to the heat flow method, however they were not always close to them. More testing is needed to come to solid conclusions.

6. Conclusions

The starting point of this project has been to prepare three different concrete mixes and produce three different HCBs, with the scope of testing their compressive strength and thermal properties, in comparison to standard local HCBs. First results have shown that the compressive strengths of the beta-HCBs do not differ much from that of the standard HCB. On the other hand, the thermal test of HCB-2 using the heat flow meter methodology showed the best improved U-value when compared to the standard local HCB under test. Some differences in values obtained from the two measurement techniques require further validation. HCB-2 is being considered as the potential concrete mix for optimisation, using the Taguchi method. In this study, the control factors were chosen to be the quantity of cement, lightweight expanded clay aggregate (LECA) and perlite. The conclusions drawn from these experiments will be valid over the entire experimental region spanned by the control factors and their levels. Therefore, this strategy will increase the potential to strike the best balance between thermal and structural properties.

Acknowledgements

We acknowledge the co-financing provided by the National Research and Innovation Programme 2012 of the Malta Council for Science and Technology (MCST), under grant agreement R&I-2012-058, as well as the University of Malta for providing the necessary research environment.

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