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Concrete blocks for thermal insulation in hot climate

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Abstract

Heavy use of electric power has become essential for cooling purposes and comfort inside buildings in the Gulf area where outdoor temperatures in summer can reach up to 60 °C. The use of insulating materials is not popular, despite their long-term financial benefit, due to the fact that installation of such materials is expensive and requires skilled labour. With the absence of obligatory legislation in most countries in the region with regard to the use of material with high thermal resistance in construction, development of simply handled concrete blocks with high thermal insulation properties becomes a necessity. Description of the current systems used in construction to produce masonry walls with high thermal insulation properties is presented in this paper. Research concerned with the development of lightweight concrete (LWC) blocks for thermal insulation either by using different hole arrangements or by using indigenous and by-product materials is reviewed. The research currently conducted by the authors to develop lightweight concrete blocks for thermal insulation is briefly highlighted.

Keywords: Temperature; Concrete; Thermal analysis; Lightweight blocks

1. Introduction

Sultanate of Oman is situated in the south east corner of the Arabian Peninsula. Oman is located in hot and arid climatic conditions where, in summer, the outdoor temperature can reach up to 60 °C with relative humidity of about 70% or more. Most buildings in the country are built at present with external walls, known as single skin walls, made of concrete solid blocks or hollow-blocks with two holes. Such walls are characterised by low thermal resistance. The temperature inside such buildings without cooling is very high especially in summer. Therefore, heavy use of electric power is mandatory for the operation of air conditions. Where there is air-conditioning, the energy consumption is very high. This situation can extend for over 6 months a year.

From an economic and environment conservation point of view, it is more beneficial to design buildings with high thermal insulation characteristics than the practice currently followed in the construction of buildings. This will result in long-term benefit of reducing the cost of cooling as well as reducing the pollution of the environment due to heavy use of fuel.

Use of cavity or double skin walls with insulating materials like chip boards contributes to some extent in reducing the high cost of air conditioning in summer. These materials due to their high cost are limited to government offices and commercial complexes. However, in residential buildings, schools and other constructions, the use of such systems is not recognised and the traditional method of construction of using single skin walls is still dominant.

It is well known that the thermal conductivity of concrete is much higher than the thermal conductivity of air. By introducing holes or air-gaps in the concrete block, the thermal conductivity of concrete block can be reduced. As

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the number of air-gaps is increased, the thermal conductivity is reduced. Therefore, research was focused on the development of ordinary concrete blocks with different arrangements of holes, which were characterised by good thermal resistance [1,2].

The use of lightweight aggregate with low thermal conductivity in the production of lightweight concrete (LWC) blocks can provide an alternative cost-effective solution. Lightweight aggregate can be processed natural material, processed by-product or unprocessed material. With large number of voids in the aggregate, lightweight aggregate concrete possesses a relatively higher thermal insulating efficiency than the normal concrete. Therefore, lightweight concrete has superior properties such as lightness in weight, and good thermal insulation, but has a disadvantage of low mechanical properties which makes them suitable only as non-load-bearing walls. In recent years, there has been focus on utilising new local and by-product materials such as polystyrene beads and charcoal in the manufacturing of lightweight concrete blocks. Such materials are considered as waste, which are discarded without useful reuse. Development of LWC blocks with high thermal insulation properties using by-products and waste materials as lightweight aggregates can have dual benefits, reducing the cost of construction and providing an alternative safe way of utilising a waste material. The latter can help in conserving of the environment.

2. Current thermal insulation masonry wall systems

At present many types of hollow concrete blocks are manufactured, but with little attention to the thermal resistance of the units. Two types of standard blocks are manufactured in the Sultanate of Oman for the construction of single skin masonry walls and partitions. The first type is a 200×200×400-mm solid block while the second type is a 200×200×400-mm hollow block with two holes each measuring 110×75×200 mm. External walls constructed from these blocks are characterised by high thermal conductivity in which the temperature within buildings without cooling is very high especially in the summer.

However, in order to reduce the energy consumption during summer, cavity and double skin walls should be used. Construction of cavity walls requires the erection of two thin walls separated by an air-gap and braced with metal ties as shown in Fig. 1 [2]. For durability considerations, ties are made of stainless steel, which increases the cost. Double skin walls are similar to cavity walls but polystyrene or a thermal insulation board is inserted between the two walls, which fills the air-gap. The introduction of the air-gap or the thermal board reduces the heat transfer through the wall which improves the thermal resistance of the wall. Despite the fact that

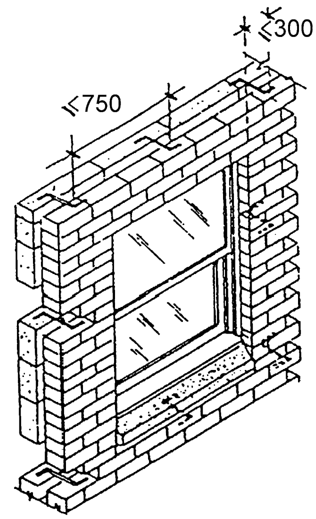


Fig. 1. Cavity wall.

these walls possess lower thermal insulation characteristics than single skin walls, they are costly and more labour and time consuming.

However, due to the method of construction of cavity walls, many thermal bridges are introduced [2]. The thermal bridges in external cavity walls will render the thermal resistance of the whole enclosure much lower than that assigned for the cavity wall itself, because much more heat flows through thermal bridges than through the cavity wall. Therefore, the best way to obtain lower thermal conductivity in such walls would be by introducing many air-gaps, cavities, holes, etc. into the wall. The air-gaps seem to be the most reliable medium for thermal insulation inside the wall since they do not change the thermo-insulating parameters [3].

3. Wall-units with improved thermal resistance

The thermal bridges effect on the wall can significantly be reduced by introducing as many air-gaps or holes as possible in the block or wall unit which leads to a great improvement in the thermal resistance of masonry walls. Pierzchlewicz [2] developed 13 concrete wall-units (i.e. blocks) with different hole configurations and investigated the thermal properties and compressive strength of these blocks. Fig. 2 shows some of the investigated wall-units.

Two kinds of concrete wall-unit were produced, one with aligned holes while the other with staggered holes. The thicknesses of the shells of the hollow block and the widths of the holes were assumed to be 30, 35 and 40 mm. The basic idea behind using staggered holes was to attain elongation of the heat flow path through the wall. The direct heat flow through vertical transverse joints was avoided by cancelling vertical joints fully filled with

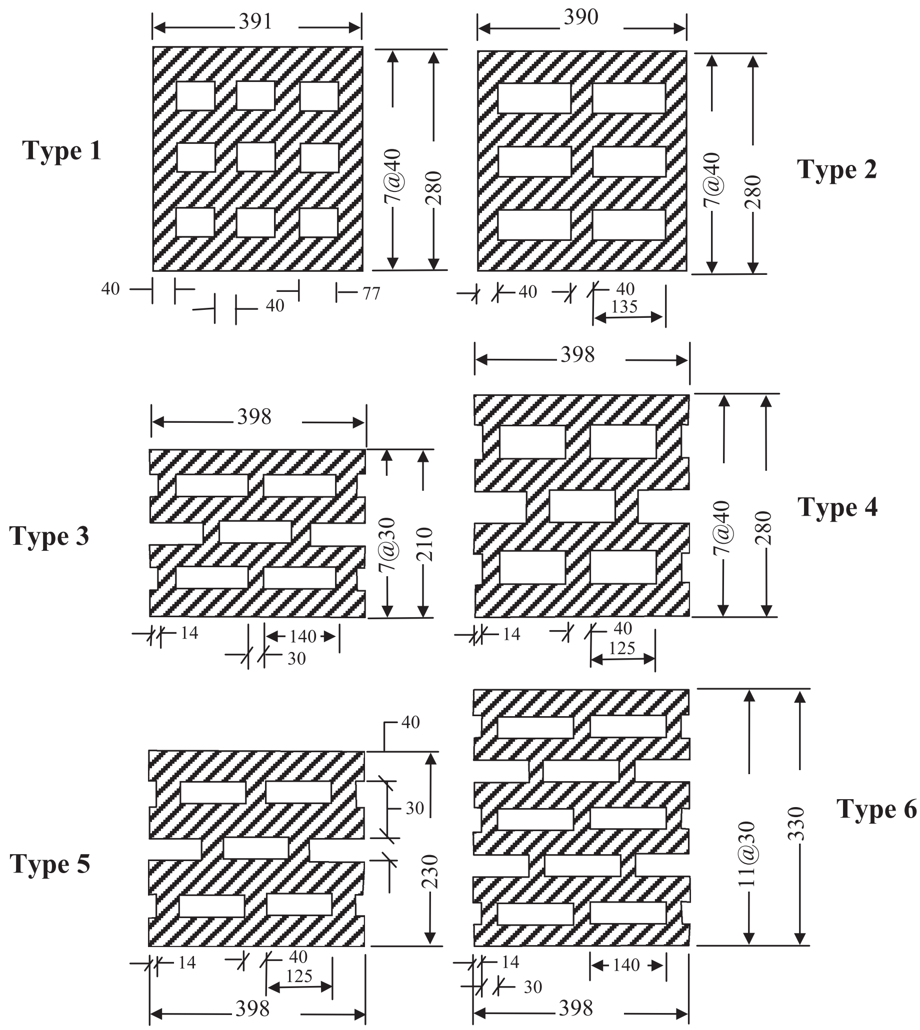


Fig. 2. Some types of hollow blocks developed by Pierzchlewicz [1,2].

mortar and introducing pockets filled with mortar as shown in Fig. 3. This method creates air contained in the holes which does not affect its thermal parameters in the course of time. The construction of walls made of hollow blocks is much easier than the construction of cavity walls where it is necessary to build two leaves of wall and tie them properly. Also the proposed wall-units were handy and easy to lay in the masonry walls. Thermal conductivity study conducted on these wall-units indicated that the thermal resistance of the wall-units with staggered holes was 1.5 to 2.6 times higher than those made of hollow blocks with aligned holes and 2.1 to 3.4 times higher than those made of solid blocks, assuming the walls were of the same thickness.

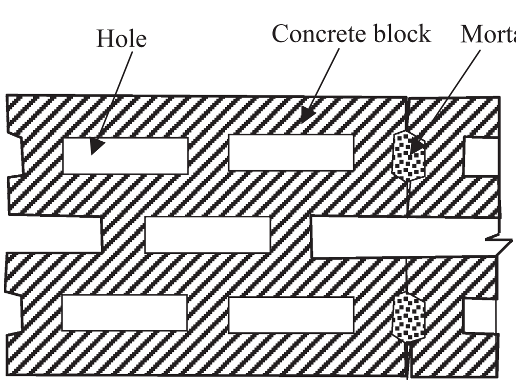


Fig. 3. Detail of vertical joint with mortar pockets.

Blocks made of staggered holes performed better, having thermal conductivity between 0.57–0.68 W/mK compared with blocks made of aligned holes in which the thermal conductivity was between 0.87 and 0.92 W/mK. Solid blocks were found to have the highest thermal conductivity of 1.2 W/mK.

Recently, a new interlocking concrete block was developed by Abdelhamid [4] for residential construction in hot desert climate. The main criteria used to develop the new system were thermal and structural efficiency, minimum quality control on the job site and speed of construction using unskilled labour. The block had three chambers: an outer chamber to accommodate insulation, a middle chamber to accommodate reinforcing steel and an inner chamber to accommodate electrical conduits and piping. The block is 390 mm long by 190 mm high by 300 mm thick. The faceshell thickness is 30 mm and the web thickness is 30 mm. The thickness of the inner and outer chambers is 40 mm whereas the thickness of the middle chamber is 100 mm. Tongue and groove concept was used for interlocking of the blocks in the vertical plane. There was no interlocking in the horizontal plane of the block. Staggering was used to provide continuity. Wall assemblies made of the proposed concrete block were tested for thermal response from which it was found that the thermal conductivity of the wall was 0.375 W/m^2 °C. This value was found to satisfy the target thermal design requirements for comfortable interior temperature without the need for mechanical air-conditioning. As a result of the thermal insulation efficiency of the tested wall, a prototype one-storey building was constructed consisting of two bed rooms, a family room, a dinning room, a kitchen and two bath rooms with an inner open court. Vaults and domes were chosen for the roof to minimise direct exposure to sun light. Small openings in the vaults and domes were provided to obtain effective ventilation and air exchange. The new insulated block was used to build the exterior walls to provide targeted thermal efficiency while interior walls were built using conventional concrete masonry blocks. Actual thermal measurements of the prototype building affirm the thermal efficiency of the proposed building system. The indoor temperature achieved using the proposed insulated interlocking concrete masonry wall system was around 25 °C which is within the identified comfort zone (25–35 °C) without the need of mechanical air-conditioning. The results obtained clearly demonstrated the effectiveness of the proposed system in maintaining comfortable indoor temperature.

4. Lightweight concrete blocks with high thermal insulation properties

Lightweight concrete (LWC) refers to any concrete produced with density of less than 2000 kg/m^3. According to the classification given by RILEM/CEB [5], LWC for structural purposes is defined as concrete with density range of 1600–2000 kg/m^3 and strength grade not less than 15 MPa. LWC used for insulation purposes may provide strength as low as 0.5 MPa and a density of less than 1450 kg/m^3. The main advantages of LWC over normal-weight concrete are the following:

(a) It provides reduced dead load of structure, which can lead to a reduction in the foundation size and in the supporting column size as well.
(b) It provides high thermal insulation for buildings.
(c) It enhances the inherent fire resistance of buildings.

It is well known that the thermal behaviour of concrete is related to its density. By lowering the density of concrete, a lower thermal conductivity can be achieved. Therefore, by creating air-bubble or voids in the concrete, lightweight concrete with low thermal conductivity can be produced. Lightweight aggregates are the paramount factor in the production of LWC. These are broadly classified into three types: natural materials (pumice, diatomite, expanded clay or expanded shale, etc.), processed by-products (foamed slag, sintered pulverised fuel ash) or un-processed materials. The selection of LWC is controlled by the properties required in the finished product: density, cost, strength, and thermal conductivity. Lightweight aggregates possess high void ratio due to their porous nature which results in good thermal insulation properties when mixed in concrete.

Research in recent years has been focused on the potential uses of waste and by-product materials on the manufacturing LWC with high thermal insulation properties. Polystyrene beads, vermiculite and leca are some of the by-product materials which are used as lightweight aggregates in the production of LWC blocks. These materials are characterised by very low thermal conductivity. Typical values of physical properties of some materials are shown in Table 1 [5]. In some cases, other materials such as aluminium powder are added to the mix in small proportions in order to generate air bubbles in aerated concrete. Finding a useful and cost-effective utilisation of such materials can help in protecting the

Table 1
Typical physical properties of some lightweight aggregates used in LWC

(1) Leca		
Bulk density for size:	up to 4 mm	560 kg/m^3
	4–8 mm	415 kg/m^3
	8–12 mm	305 kg/m^3
Voids ratio for size:	up to 4 mm	44%
	4–8 mm	48%
	8–12 mm	45%
(2) Polystyrene foam		
Bulk density		36 kg/m^3
Water adsorption		0.2% by volume
Thermal conductivity		0.03 W/m
Coefficient of expansion		7×10^{-6}
(3) Vermiculite		
Bulk density		64 to 160 kg/m^3
Shape		accordion-shaped granule
Colour		light to dark brown
pH (in water)		6 to 9
Fusion point		1200 to 1320 °C
Thermal conductivity		0 to 0.06 W/m

environment as well as reducing the cost of construction. For instance, expanded polystyrene beads are often used as packing material. This leads to a large amount of waste material which is not biodegradable. This material could be granulated and used as lightweight aggregate for concrete. Although much work has been done on the effect of using lightweight aggregates on the mechanical properties of concrete, very little research has been done on thermal conductivity.

Park and Chisholm [6] investigated the thermal conductivity of polystyrene aggregate concrete with densities of 600, 800 and 1000 kg/m^3. Investigations were also made on mixes containing fly ash, at same densities, to study its effect on the workability, and other properties of the mixes. Results indicated that thermal conductivities of 0.133, 0.217 and 0.3 W/m °C were achieved for mixes with densities of 600, 800 and 1000 kg/m^3, respectively. Also results showed that addition of fly ash had negligible influence on thermal conductivity. Thermal conductivity of concrete was calculated empirically based on Arnold chart [7].

The effect of charcoal powder addition on the thermal conductivity of lightweight concrete was studied by Resheidat et al. [8]. The charcoal powder was added as partial substitute of the Portland pozzolanic cement in the concrete mix. The ratio of charcoal powder to the cement ranged from 2.5% to 10%. The water-to-cement ratio was 0.5. Concrete specimens were subjected to accelerated curing and later to heat treatment at 300 °C for different heating times to create porous concrete. Results showed that the addition of charcoal powder reduces the thermal conductivity of concrete. This reduction was more significant at percentages higher than 2.5% charcoal contents. Thermal conductivity decreased as the heating time was increased for different percentage of charcoal.

Demirboğa and Gül [9] studied the effect of expanded perlite aggregate, silica fume and fly ash on the thermal conductivity of lightweight concrete. Both expanded perlite (EPA) and pumice aggregates (PA) were used in the manufacturing of lightweight concrete samples. To determine the effect of silica fume (SF) and class C fly ash (FA) on the thermal conductivity of lightweight aggregate concrete, SF and FA were added as replacement for cement by decreasing the cement weights in the ratios of 10%, 20% and 30% by weight. The highest thermal conductivity of 0.3178 W/mK was observed with samples containing only PA and plain concrete. It decreased with the increase of SF and FA as replacement for cement. The lowest value of thermal conductivity, which is 0.1472 W/mK, was obtained with the samples prepared with EPA replacement of PA and 70% cement+30% FA replacement of cement. Use of EPA in place of PA induced a decrease of 43.5% in thermal conductivity of concrete. Also results showed that both SF and FA had a decreasing effect on thermal conductivity although FA was more effective than SF in decreasing the thermal conductivity.

The mechanical, physical, acoustic and thermal properties of lightweight concrete made from leca, polystyrene foam and vermiculite as aggregates were investigated by Abdel-Reheem et al. [5]. Aerated concrete was also produced and tested with aluminium powder which was used to generate air bubbles in the aerated concrete. Thirteen mixes with different proportions of leca, polystyrene foam and vermiculite were prepared. Concrete block specimens with 100×100 mm and thickness 50, 100, and 150 mm were used for measuring the thermal conductivity. A casting-steel box 500×333×15-mm thickness was used for measuring the thermal properties. The box walls were insulated from inside by 100-mm thermo-bricks. A heating coil was connected inside the box in front of the test specimen and was connected with an electric current source and a switch. Two thermocouples were connected on two parallel faces of the concrete test block. The test specimen was exposed to a given high temperature at one face, while the temperature at the other face was recorded at different times.

Results indicated that the percentage of heat transmission for the mixes prepared with ordinary gravel, leca, polystyrene foam, vermiculite and aluminium powder were 15.3%, 14.2%, 17.7%, 12.9%, and 10.4%, respectively, which reflects the superiority of aerated concrete in resisting high temperature.

5. Current research on development of lightweight concrete blocks with high thermal insulation properties

An on-going research project investigating the possibility of developing lightweight concrete blocks which can be used for cladding and serve the purpose of thermal insulation was started by the authors [10,11]. The blocks were produced from two indigenous materials: vermiculite (VerBlock) and polystyrene beads (PolyBlock1) which were used as lightweight aggregates with different proportions in the mix. The mechanical and thermal properties of the two types of blocks were compared with blocks manufactured commercially as thermal insulation blocks (PolyBlock2) and ordinary concrete blocks. Fig. 4 shows the different types of blocks while Fig. 5 shows different tests conducted to determine the thermal and mechanical properties of the investigated blocks.

In order to determine the thermal conductivity of the blocks, a guarded hot box was constructed in accordance with ASTM C236-89 [12]. The box was constructed from plywood plates and was insulated from inside with 100-mm-thick polystyrene panels (Fig. 5c). The specimen was located on the sixth side of the box. An electric heater with a fan was used to heat the box from inside. Two thermocouples were stuck on the inside and outside of each face of the box. A data logger was used for the

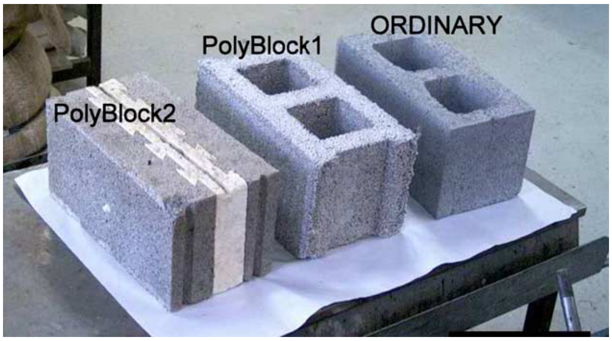


Fig. 4. Different types of blocks.

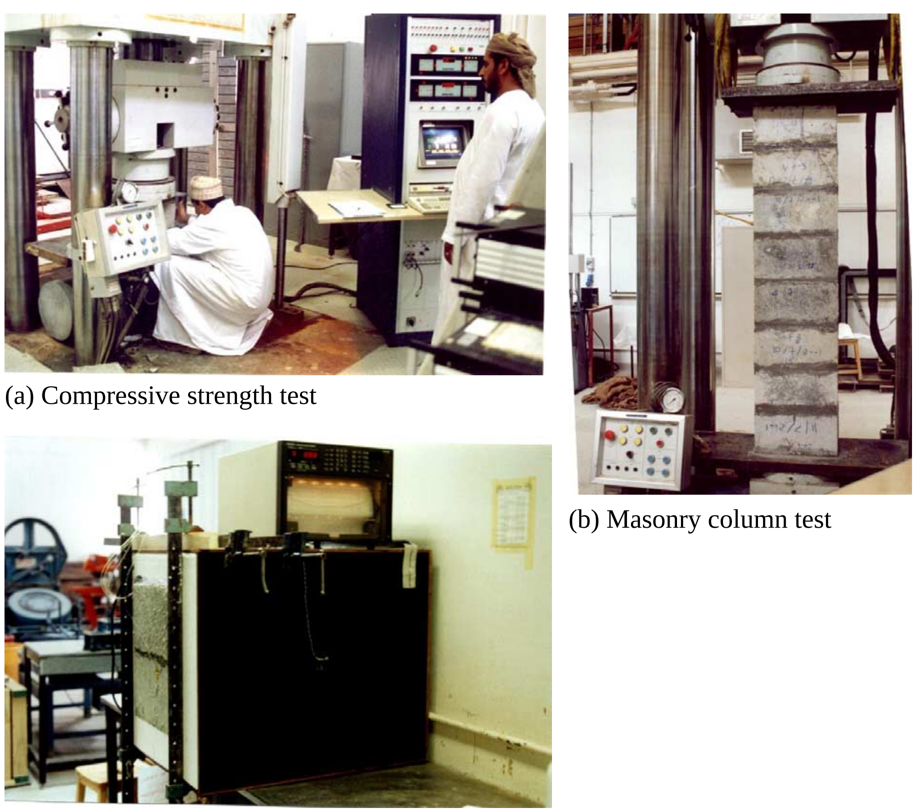
monitoring of the temperature measured by the thermocouples. Steady state conditions were reached in about 10 h. The interior of the box was kept at about 52 °C. The Fourier heat conduction equation was used to calculate the thermal resistance of all sides of the box and the heat flux through the sides.

By comparing three types of concrete blocks for thermal insulation, it was found that polystyrene beads was a better material to be used as lightweight aggregate for making blocks. Blocks-type PolyBlock1 (hollow) was found to be superior to PolyBlock2 (solid) in terms of weight, and had comparable thermal conductivity, K from 0.626 to 0.616 W/m°C as shown in Table 2. In addition, it provided reasonable compressive strength satisfying the requirement for non-load bearing masonry.

Table 2
Properties of different types of blocks used for thermal insulation

Block type	Weight (kg)	Gross density, (kg/m^3)	Block strength (N/mm^2)	Column strength (N/mm^2)	K (W/m°C)
Ordinary	19.08	1193	5–15	5.48	1.60
VerBlock	18.68	1168	2.2	–	0.76
PolyBlock1	12.77	798	3.3	2.24	0.626
PolyBlock2	22.68	1418	10.2	7.56	0.616

The efficiency of the manufactured blocks is currently under investigation by building three rooms in order to monitor the thermal variation during summer. One room was constructed using ordinary blocks while the two others using PolyBlock1 and PolyBlock2. Heat transferred through the walls of the rooms is continuously monitored by thermocouples stuck on the outer and inner sides of the walls and connected to a data logger. The outside atmospheric temperature and the inside room temperature are also recorded. Sample results are shown in Fig. 6. The room built with developed blocks (Polyblock1) gave the lowest inside temperature compared with the other two rooms. These are preliminary results, and recording will continue during the whole of



(a) Compressive strength test

(b) Masonry column test

(c) Thermal conductivity test

Fig. 5. Different tests conducted on the blocks.

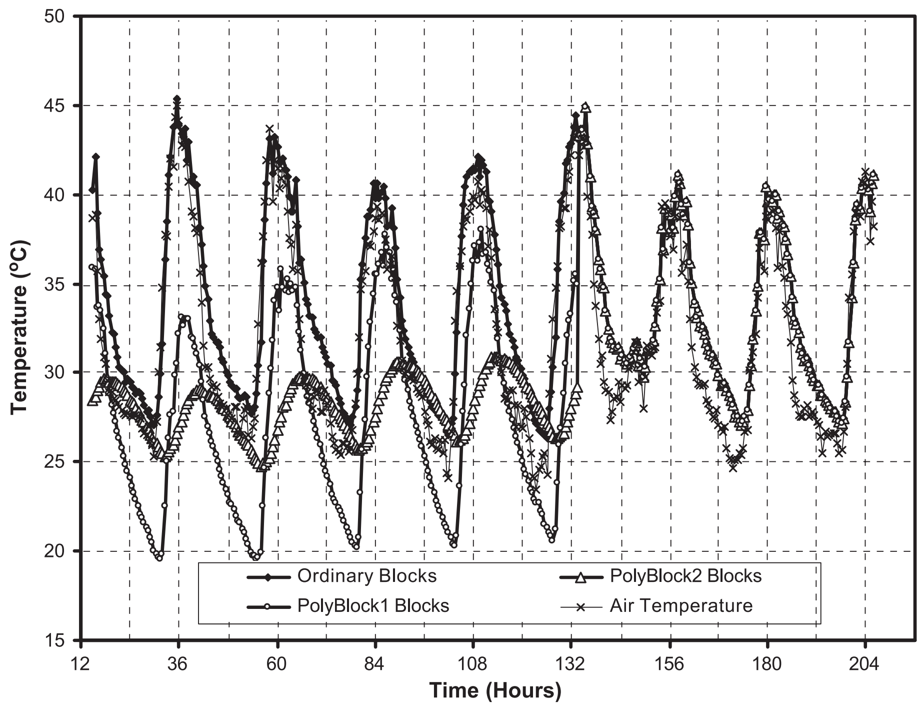


Fig. 6. Temperature inside rooms made from different blocks.

the summer season where temperature can reach more than 50 °C. When the analysis is complete, recommendations regarding the use of lightweight concrete blocks for thermal insulation in hot climate will be presented in a separate research paper.

6. Conclusions

The use of masonry walls with high thermal resistance has become of great importance in hot weather countries where temperature can reach high levels especially in summer. this can be achieved either by constructing double skin walls using ordinary blocks or manufacturing new blocks with low thermal conductivity. This can result in considerable reduction on the demand on electrical energy for cooling purposes.

This paper highlighted the recent research work concerning the development of concrete blocks for thermal insulation using different hole arrangements. The paper reviewed the attempts made to develop lightweight concrete blocks with thermal insulation properties using indigenous and by-product materials, with emphasis on the current research conducted by the authors in this field.

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