Effect of Crumb-Rubber Aggregate on Thermal Performance of Masonry Hollow Concrete Blocks

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ABSTRACT

The thermal benefits of masonry hollow concrete blocks containing crumb-rubber (CR) particles from waste automobile tyre as partial replacement for mineral coarse aggregate (granite) was investigated with the aim of exploring its prospect and also proffering a solution to the environmental problems constituted by waste tyres. Replacement was made at 5%, 10%, 15%, 20% and 25% by volume using a mix ratio of 1:1.5:3 and water-cement ratio of 0.42. Compacting factor, density, and compressive strength of masonry hollow concrete were determined according to specifications while the thermal properties were measured using KD 2 Pro thermal properties analyzer. The cost of masonry concrete per cubic meter and unit blocks increased with increase in crumb rubber content which is attributed to the high cost of crumb rubber as a result of high cost of processing. Compacting factor, density and compressive strength of masonry hollow concrete blocks decreased with increase in crumb rubber content, Thermal conductivity of masonry concrete (1.380W/mk) have been greatly reduced to 0.610W/mk indicating 55.8% reduction with 25% crumb rubber content which makes it a better insulator while the specific heat capacity of masonry hollow concrete blocks (2.830 MJ/m^{3}k) have been reduced to 1.606MJ/m^{3}k indicating 43.3% reduction which may adversely reduce thermal mass effect. Other thermal properties such as thermal resistivity increased by 55.8%, thermal diffusivity decreases by 53.8% while thermal effusivity decreases by 55%. The result indicates that the potential use of such composite material for building applications is viable in term of reduction in heating/cooling loads which may results in energy saving.

Keywords: Blocks, Concrete, Masonry, Thermal properties and Cost.

1. INTRODUCTION

Enormous quantities of solid waste materials are generated all over the world every year and are classified into hazardous and non-hazardous waste materials. As the population of the world grows so does the amount and type of waste materials generated. One of such materials is automobile waste tyres which are non-biodegradable. According to Yang *et al.* (2000), each year about 9 million tonnes waste rubber-tyres are disposed of all over the world, which was also estimated to be around 1 billion tyres withdrawn from use in the world annually according to Erdogan *et al.* (2010).

Ebewele *et al.* (1990) reported that an estimated 5 million scrap tyres from trucks, cars and motorcycles existed in Nigeria in 1983 with an annual generation rate of 15% each year. About 37 million scrap tyres are estimated to exist in Nigeria by 2018. In Nigeria, one of the most common ways of disposing waste tyres is through open field disposal, open air combustion most especially in our abattoir and local commercial quarry where they serve as source of fire for processing slaughtered animals and mining activities. Scientists, engineers and technologists look out for using different types of solid waste as alternative for some ingredients of civil engineering materials such as asphalt and concrete according to

Khalid *et al.* (2008). Many researchers have studied and developed various recycling methods for re-use of waste rubber-tyres in construction materials. Some of these methods are: use of waste rubber-tyres in asphalt concrete mixture; use of waste rubber-tyres in some plastic and rubber products; utilizing waste rubber-tyres in portland cement concrete; use of waste rubber-tyres as a visco-elastic material for vibration dampers and utilizing waste rubber-tyres in ordinary cement mortar according to Yunping *et al.* (2010).

Early studies on the use of waste rubber-tyres in asphalt mixes, sealants and rubber sheets were very promising. They showed that rubberized asphalt had better skid resistance, reduces fatigue cracking and achieved longer pavement life than conventional asphalt (Adams *et al*., 1985; Esch 1984; Estakhri 1990; Khosla and Trogdon 1990). Thermal properties of most cementitious materials are found to change with the presence of admixtures (Cisse and Laguerbe, 2000; Okpala, 1993). The change is found to depend on the admixture's grain structure or interstitial arrangement within the main material and other micro structural parameters including the volumetric fraction of each constituent, the shape of the particles, and the size distribution of the particles (ACI 122R-14). The thermal properties that influence the temperature rise and distribution in a concrete structural section are: thermal conductivity, specific heat capacity, thermal expansion and mass loss (Neville, 1996). According to ACI 122R (2014), these properties depend on the type of aggregate, aggregate fraction temperature, composition of the concrete mix with admixture (if any) and method of curing.

The inclusion of processed waste rubber-tyre in concrete could also make the material a better thermal insulator, due to better thermal insulating properties of rubber-tyre which could be very useful especially in the wake of energy conservation requirements Tantala *et al.* (1996). Benazzouk *et al.* (2008) conducted an investigation of the thermal conductivity of a lightweight construction material containing rubber waste particles. The test was carried out in a dry state using a transient plane source (TPS) technique. The effect of the rubber particles ratio on the thermal conductivity of cement composite, the experimental investigation revealed that the addition of rubber particles reduces the material unit weight and furthermore the thermal conductivity of the composite have been improved significantly.

The effect of crumb-rubber from waste automobile tyres on the thermal performance of masonry hollow concrete block is the aim of these investigation and also proffering solution constituted by waste tyre by converting waste into resources.

2. METHODOLOGY

2.1 Materials

Crumb rubber masonry hollow concrete block units (CR-MHCBU) consists of cement, natural aggregate (fine and coarse), waste crumb rubber-tyre derived aggregate and water. A general-purpose blended limestone portland cement CEM II (42.5R MPa) that conforms to BS EN 197-1:2011 with a specific gravity (*G)* of approximately 3.15, was sourced from retail outlet in Zaria, Nigeria was used for this study. Ordinary tap water (potable drinking water) sourced from Civil Engineering Laboratory Ahmadu Bello University, Zaria Nigeria was used for all concrete mixes and curing. Natural sharp river quartzite sand smaller than 4.76mm but larger than 75µm that is free of clay, loam, dirt and any organic or chemical matter with average specific gravity of 2.65 and bulk density of 1454 kg/m^3 was used as fine aggregate. The fine aggregate (sand) falls in zone two (medium sand) according to BS EN 12620:2002+A1:2008 specification. Natural crushed (granite) with nominal maximum sizes of 9.52-10 mm sourced from a local commercial quarry with average specific gravity of 2.66 and bulk density of 1635 kg/m^3 was used as coarse aggregate.

Coarse rubber aggregate (crumb rubber) from scrap tyres with nominal maximum sizes of 4 - 8mm, specific gravity of 1.14 and bulk density of 528 kg/m^3 was used for this research. Crumb rubber surface treatment method by soaking in sodium hydroxide (NaOH) solution was adopted for this research due to its effectiveness in enhancing the hydrophilic properties of the rubber and increasing the intermolecular interaction forces between rubber and calcium silicate hydrate (C-S-H) gel which enhances strength of the composite matrix as reported in the literature (Mohammadi, 2014).

2.2 Mix Proportions

The mix design for the masonry concrete was based on an Absolute volume method according to BS EN 206:2013+A1:2016 design, a mix ratio of 1:1.5:3, compressive strength of 30N/mm^2 at 28 days (Grade 30 Concrete) with water/cement ratio of 0.42 and aggregate/cement ratio of 4.5:1 were used to produce a trial mix which was tested for compacting factor, strength, density and finishing properties. The mix was eventually subjected to adjustment, adopted and applied to all the concrete mixes. A total number of six (6) mixes were prepared: One control mix with no crumb rubber aggregate and five concrete mixes in which the 9.52-10 mm coarse aggregate (granite) was replaced by crumb rubber aggregate at 5%, 10%, 15%, 20% and 25% by volume. The mix proportions were constant in terms of mix design ratio, water/cement ratio, sizes, type of natural and crumb rubber-tyre aggregate used for the study. A total of 36 masonry hollow concrete blocks (450 x 225 x 225) mm specimens (average of six samples per mix) were tested for compressive strength and thermal properties after 28 days of curing in water. Table1 show the mix proportion.

Table 1: Quantity of Materials to a Cubic meter of Concrete (Control Mix)

Mix Ratio	W/C Ratio	A/C Ratio	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
1:1.5:3	0.42	4.5	411.29	616.94	1,233.87	179.56

2.3 Experimental Procedure

Tests were conducted to assess the compacting factor of the freshly relatively dry mixed masonry concrete (control mixes) and that of crumb rubber masonry concrete mixes at the department of civil engineering concrete laboratory Ahmadu Bello University (A.B.U) Zaria in accordance with BS EN 12350-4:2009. The density and compressive strength of the hardened masonry hollow concrete block samples were established in accordance with BS EN772 -13 (2000) and BS EN 772 -1:2011+A1:2015 respectively after 28 days of standard curing with water. KD 2 Pro thermal properties analyzer by Decagon Devices, Inc. (2011) was used to measure the thermal conductivity *(k)*, thermal resistivity *(ρ)*, thermal diffusivity (α) and volumetric specific heat capacity (c) of masonry hollow concrete block samples after 28 days of standard curing with water; while the thermal effusivity *(β)* were computed from the relationship between thermal conductivity, density and specific heat capacity given in Equation 1.

$$\beta = \sqrt{k\rho C} \tag{1}$$

Where:
β is the effusivity
k is the thermal conductivity
ρ is the density of the sample
c is the specific heat capacity

3. RESULTS AND DISCUSSION

3.1 Workability, Density and Compressive Strength

The compacting factor (C.F) was observed to decrease significantly. Control masonry concrete mixes had C.F of 0.84 (low workability) while the 25% crumb rubber mix had C.F of 0.77 (very low workability) indicating 8.3% reduction. The modified masonry concrete mixes exhibited lower densities than the reference mix, it was deducted that density reduces by 19% and this was expected, as the specific gravity of crumb-rubber, at 1.14, is less than that of natural coarse aggregate (granite), at 2.66. The addition of crumb-rubber aggregates in concrete mixes decreased the compressive strength significantly by 49% with percentage increase in the crumb-rubber tyre particles up to 25%. However, the minimum strength required for masonry hollow concrete block can still be attained for both load bearing and non-load bearing applications.

3.2 Thermal Properties

Masonry hollow concrete blocks (450 x 225 x 225) mm specimens were tested for the thermal properties using a KD2 Pro thermal properties analyzer. Average results obtained from the experimental measurement of thermal properties of crumb rubber masonry concrete are presented in Figure 1 and 2.

3.2.1 Effect on thermal conductivity *(k)* (Wm/k)

The results indicate that the value of concrete thermal conductivity decreases with an increase in the percentage of crumb rubber aggregate thereby improving their insulating value (R-value) which is attractive and indicates high potentials for development most especially for tropical, temperate and cold climate where low thermal conductivity construction materials are desirable in optimizing the heating/cooling load within the building space and hence capacity of the mechanical equipment required in handling the load thereby enhancing thermal comfort. Heidari (2009) estimates that each degree reduction in heating/cooling loads results in 7% energy saving.

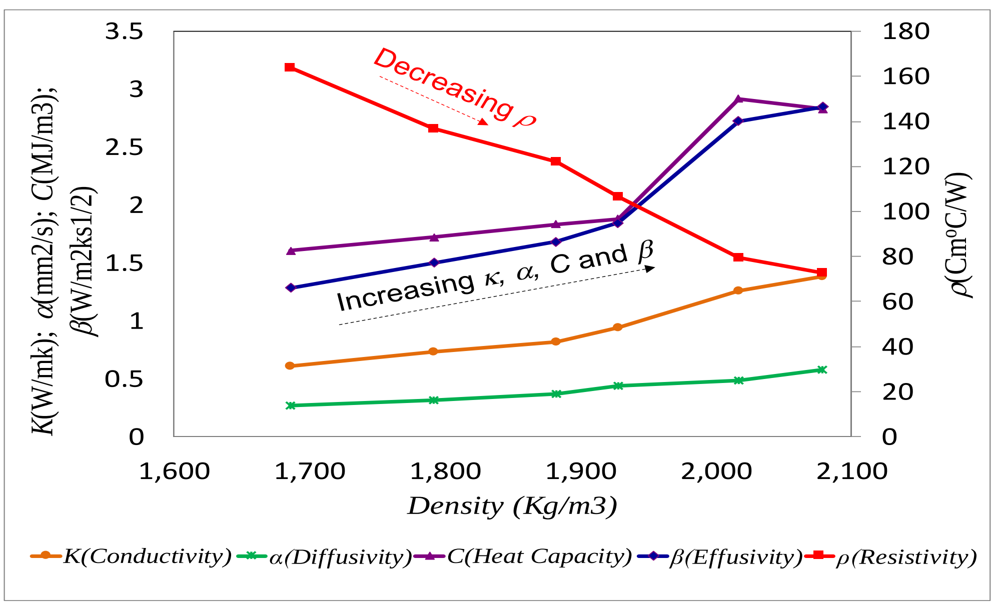

Figure 1: Variation of Thermal Properties with Density of Masonry Hollow Concrete Block Units

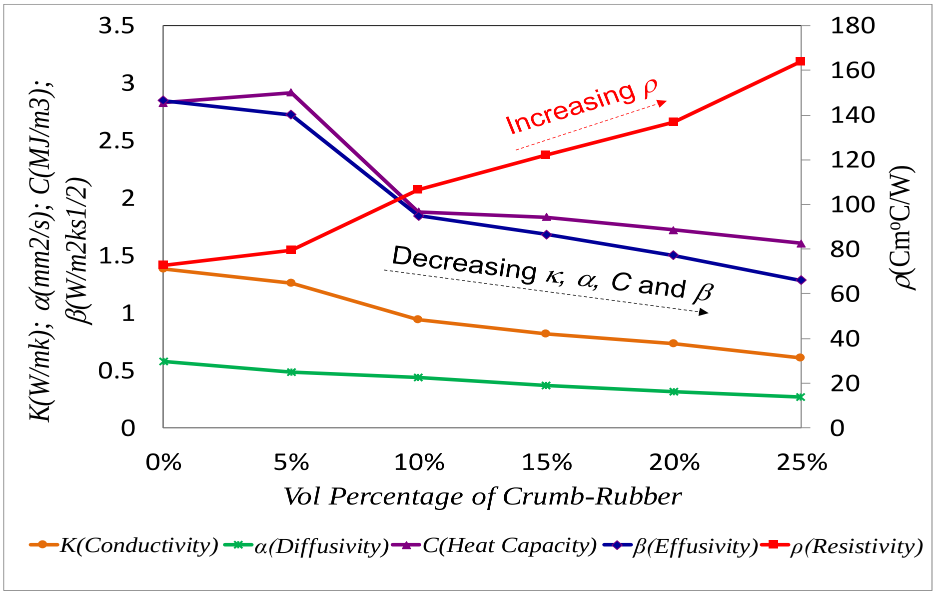

Figure 2: Variation of Thermal Properties with Crumb Rubber Content (%) in Masonry Concrete Block Units

3.2.2 Effect on thermal resistivity *(ρ)* (Cm°c/W)

Thermal resistivity of masonry concrete has been greatly enhanced by 55.8% with 25% rubber particles content, which indicates an increase in resistance to heat flow through the concrete making it a better insulator.

3.2.3 Effect on volumetric heat capacity (Cv) (MJ/m^{3}k)

Heat capacity of masonry concrete with 5% rubber particles content was observed to have increased slightly by 3% before a steady decline to 43.3% with higher rubber particles content up to 25%. Increase in specific heat capacity (heat energy storing capacity) signifies increase in thermal storage mass which is desired for heating building most especially in the cold climate but not much desired in temperate and hot climate while low specific heat capacity signifies lower thermal mass (reduction in heat storage capacity) ACI 122R (2014).

3.2.4 Effect on thermal diffusivity (α) (mm^2/s)

The thermal diffusivity of control masonry concrete mixes (0% rubber mix) measured was 0.576mm^2/s while 25% crumb rubber-masonry hollow concrete blocks have thermal diffusivity of 0.266mm^2/s. Thermal diffusivity of the masonry hollow concrete block decreased by 53.8% with 25% rubber particles content, which implies a decline in the ability of the masonry hollow concrete block to undergo a temperature change when exposed to a fluctuating thermal environment. Material with low thermal diffusivity like the crumb rubber masonry hollow concrete blocks will respond slowly to an imposed temperature difference and are effective thermal mass elements in a building (ACI 122R-14). Thermal performance is also characterized in terms of thermal diffusivity, for mass concrete applications. Concrete with a high thermal diffusivity will rapidly adjust its temperature to match that of its surroundings. Therefore, often a low thermal diffusivity is preferred so that the concrete may act as a heat sink/source to buffer temperature extremes experienced during a diurnal cycle Bentz *et al*. (2011).

3.2.5 Effect on thermal effusivity *(β)* ($W/m^2Ks^{1/2}$)

The thermal effusivity values measured are presented in Table 2, the control concrete mixes (0% rubber mix) have 2.849 $W/m^2Ks^{1/2}$ while 25% crumb rubber-masonry hollow concrete blocks have thermal effusivity of 1.285 $W/m^2Ks^{1/2}$. The result indicates that thermal effusivity of masonry hollow concrete block decreases with the partial replacement of rubber aggregate by volume of coarse aggregate in concrete. Thermal effusivity of masonry hollow concrete blocks have decreased by 55% with 25% rubber particles content, which indicates a reduction in the rate of heat absorption and release (heat exchange) of the composite material with its surrounding. Low thermal effusivity such as the one obtained for crumb rubber-masonry hollow concrete blocks will reduce its ability to conduct heat away from the building faster thereby reducing heating load most especially in cold climates but will be a disadvantage for tropical climates such as Nigeria due to increase in cooling load which implies increase in cost.

3.3 Economic Cost Analysis

The cost of the production of the crumb rubber masonry hollow concrete blocks was considered to consist of: Cost of constituent materials, labour and overhead.

3.3.1 Cost of constituent materials

The cost of material required to produce $1m^3$ of each of the mixes was obtained by summing up the products of the quantities of each constituent in a cubic meter of the mix using their respective current market price. The total cost was obtained by increasing the total cost of materials by 60% to incorporate the costs of labour and overhead. The quantities of material in kilogram per cubic meter of the mixes were obtained based on the average densities obtained for the mixes.

Table 2: Market Price of the Materials for CR-MHCBU

S/NO	Components	Cost/Kg (Naira)
1	Water	2.00
2	Cement	50
3	Sand	2.50
4	Granite	3.50
5	Crumb-Rubber	5.74

Table 2 reveals the current price of the constituent materials. These quantities are based on the respective densities of the various mixes. It should be noted that the cost of the materials varies greatly from locations to locations. The higher cost for crumb-rubber as against that for granite is as a result of the high cost of processing the waste tire from whole to crumb particles. The volume of a block is = $0.01467m^3$ and the number of blocks per m^3, N_b is therefore given as:

$$N_b = \frac{1}{0.01467} = 68.166 \tag{2}$$

The cost of a block, C_b is then given as:

$$C_b = \frac{C_m}{68.166} = 0.01467\,C_m \tag{3}$$

Where: C_m = is the cost per cubic meter of a mix.

3.3.2 Cost of masonry concrete per cubic meters (m^3) and hollow unit blocks

The cost per cubic meter of the mixes and the material cost of producing a block have been determined and presented in Figure 3. These costs as expected vary from one mix to another with the cost of masonry concrete per cubic meters (m^3) for the reference mix (0% CR) costing N22,465.97 while the cost per unit hollow concrete block is N329.58. Furthermore 5, 10, 15, 20 and 25% crumb rubber content cost N26, 922.70 & N394.96, N27,060.91 & N396.99, N27,199.10 & N399.01, N27,337.28 & N401.04 and N27,475.49 & N403.06 per cubic meter and per unit hollow concrete block respectively. It should be noted that these costs are relatively high when compared to commercially available block which is due to mix ratio adopted (1:1.5:3) in other to produce masonry hollow concrete blocks that will meet up to with the minimum compressive strength of 7N/mm^2 for load bearing and 3N/mm^2 for non-load bearing BS EN 771-3. The cost of processing crumb rubber increases the cost of the material when compared to aggregate sourced from natural source which significantly increases the cost of production of crumb-rubber concrete and the masonry units when compared to the cost of the reference materials produced. The cost of a standard vibrated 9'' sandcrete hollow block produce with a mix ratio of 1:6, minimum compressive strength of 3.45N/mm^2 (NIS: 87, 2004) is N280 per unit block while the cost of 9'' masonry hollow concrete blocks produce with mix ratio 1:3:3 and minimum compressive strength of 7N/mm^2 for load bearing and 3N/mm^2 for non-load bearing (BS EN 771-3) is N320 and N300 per unit respectively. However, as the amount of processing increases, the production costs and hence the price of the material also increases.

The cost of these crumb rubber is therefore at the higher end of the range given in Table 2. However, the processing requirements for crumb rubber aggregate used in masonry concrete are likely to be less stringent, raising the possibility that production costs could be reduced if there is sufficient demand for the material. It can be concluded that the economics of using crumb rubber from waste tyres in masonry concrete would have to change considerably for it to be viable as a cost-neutral in full or partial replacement for virgin materials.

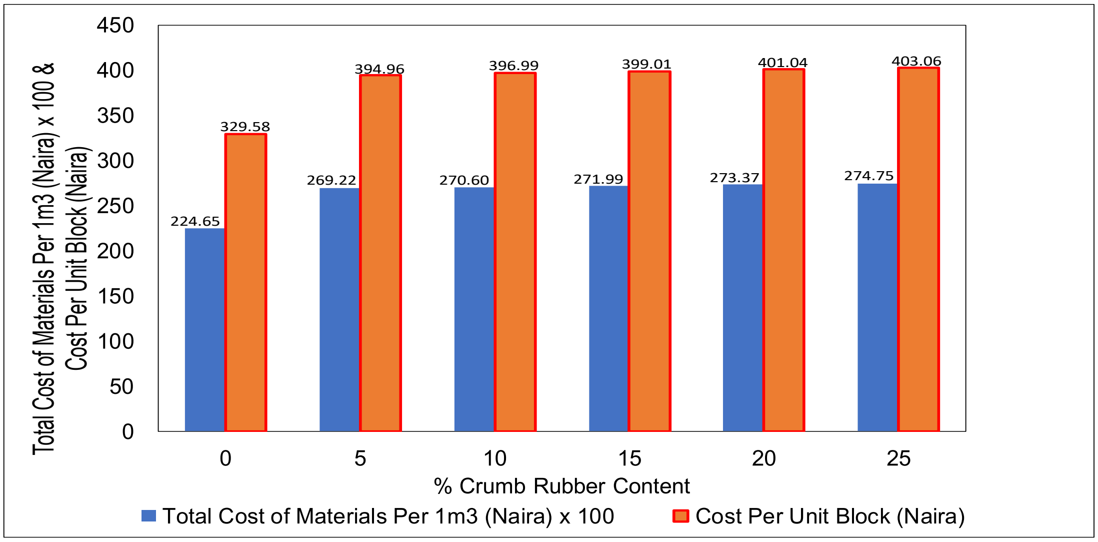

Figure 3: Cost Analysis of Crumb Rubber Masonry Hollow Concrete Block Units (CR-MHCBU)

However, when used as a building fabric or envelope to achieve a desired thermal control measures or comfort (reducing the rate of heat transfer through the envelope), the economic benefits in terms of potential energy cost reduction and savings could make it very economical in the long run compared to the standard hollow sandcrete and concrete blocks which will mostly require cooling loads in tropical region like Nigeria. Also comparing it with the cost of other prefabricated insulating materials, its installation and other related cost attached to it, the cost of the crumb rubber masonry hollow concrete might be of economic benefits for low cost housing projects.

4. CONCLUSION

The following conclusions are offered on the thermal prospect of masonry hollow concrete blocks containing crumb-rubber particles from waste automobile tyre as partial replacement for mineral coarse aggregate (granite) by volume:

i. The compacting factor (C.F) of masonry concrete was observed to decrease significantly by 8.3% while its density reduces by 19% and the compressive strength decreases significantly by 49% with 25% crumb rubber content.
ii. Thermal conductivity of masonry hollow concrete blocks decreases by 55.8%, with increase crumb rubber up to 25% thereby improving their insulating value (R-value) while the thermal diffusivity decreases by 53.8% with 25% crumb rubber content, which implies a decline in the ability of the composite material to undergo a temperature change when exposed to a fluctuation thermal environment.
iii. Volumetric heat capacity of masonry concrete with 5% crumb rubber content increased slightly by 3% before a steady decline to 43.3% with crumb rubber content up to 25%, while the thermal effusivity of concrete is reduced by 55% with crumb rubber particles content up to 25%, indicating a reduction in the rate of heat absorption and release (heat exchange) of the composite material with its surrounding.
iv. The cost of a standard crumb-rubber masonry hollow concrete block units is relatively higher than the price of a sandcrete and concrete block which is due to the mix ratio and the cost of processing crumb-rubber. This high cost have driven the cost of material (crumb-rubber) higher also, when used as a building fabric or envelope to achieve a desired thermal control measures or comfort the economic benefits in terms of potential energy cost reduction and savings could make it very economical in the long run compared to the normal sandcrete and concrete blocks.

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