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Thermal and Hygrothermal Properties of Porous Building Blocks Produced with Crushed-Glass Blended Cement

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Abstract: *The quest to enhance physical properties, increase varieties and reduce costs of the material constituents of sandcrete blocks have led to the substitution of traditional materials with alternative admixtures.* One of such admixtures is glass particulates as researched in this work. *This work examined the effects of a partial replacement of cement with crushed glass on the thermal and hygrothermal characteristics of hollow sand-cement-glass blocks produced with 1:6 and 1:8 sand-cement mix ratio. The substitution of crushed glass by volume of the cement was varied in steps of 5% to a maximum of 25%. The results revealed that, for both mix ratios, as percentage of crushed glass substituted increased, there was an increase in the density, water absorption coefficient, thermal conductivity, thermal diffusivity, thermal conductance, thermal admittance and the heat transfer rate. But the porosity, specific heat capacity, thermal resistivity, thermal effusivity, thermal resistance and thermal insulance decreased as the crushed glass content increased. The overall thermal effect of the crushed glass partially replacing cement in a porous building block is that it loses the thermal insulating advantage leading to occupants' discomfort year-round. Therefore, it should be used with caution; for partitioned walls rather than as external walls and that not more than 5%.*

Keywords: *cement, crushed glass, sandcrete block, thermal, hygrothermal.*

1. INTRODUCTION

In many parts of Africa, hollow block is the major cost component of most buildings. Particularly in Nigeria, most of the buildings are being constructed with hollow sandcrete blocks [1]. However, the high and increasing cost of the constituent materials of these blocks and the scarcity of cement in rural areas have contributed to the non-realization of adequate and affordable housing for both urban and rural dwellers. Hence, availability of alternatives to these materials for construction has been a great desire in both short and long term as a stimulant for socio-economic development. In particular, admixture materials that could complement the increasingly expensive cement in the short run, and, especially, if cheaper, will be of great interest to the construction industry.

Over the years, attempts have been made to substitute construction materials with supplementary cementing materials (SCMs) such as powdered mineral and burnt agricultural wastes. Mo *et al.*, gave an overview of the effect of some of them on lightweight aggregate concrete [2]. Oyekan and Ganesan *et al*. reported effects of rice husk ash blended cement on the properties of concrete [3, 4]. Adesanya and Raheem developed a corn cob ash blended cement [5]. Oil palm kernel shell ash on mansory blocks was examined by Muntohar and Rahman [6]. Broken or crushed glass as a replacement for cement to strengthen concrete structures was reported by Falade [7]. Effect of metakaolin on properties of hollow concrete blocks were investigated by Rezende *et al.*, on sandcrete blocks by Kolovos *et al.*, and Ibrahim and Ocholi [8, 9, 10]. Others studies include that on fly-ash by Seo *et al.*, granite fines by Oyekan and Kamiyo and coconut husk ash with peanut shell ash by Nimityongskul and Daladar [11, 12, 13]. However, amidst these investigations, some vital properties of the new blocks were not considered. Prominent among these traded-off properties apply to the thermal characteristics of the blocks which determine the thermal comfort within the built space in addition to other energy conservation and environmental consequences. Energy requirements of residential and commercial buildings are known to be influenced by the construction materials and by design [14]. In both temperate and tropical regions, thermophysical properties of building materials are of significant importance because they have strong influence on the heating or cooling load within a building and hence the capacity of the mechanical equipment required to provide thermal comfort within the building over the annual climatic cycle. In addition, durability of structures with admixtures used for construction in swampy areas or environment prone to flood has been of concern to building professionals [15]. This paper investigates experimentally the

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effect of partially replacing cement with crushed glass on the thermal and hygrothermal properties of sandcrete blocks. The replacement is by volume within the range 5–25% at intervals of 5.

2. METHODOLOGY

The sandcrete blocks used in this investigation are made of sand, crushed glass blended cement and water. Sharp river quartzite sand free of clay, loam, dirt, and any organic or chemical matter was used. Wet sieving analysis which is in accordance with BS 1377-3 [16] was used. The sand has a specific gravity of 2.66 and an average moisture content of 0.90%. The coefficient of uniformity of the sand is 2.95. Ordinary Portland cement (OPC) from the Larfarge Cement Company, Ogun State, Nigeria with properties conforming to international standard BS 12 [17] and local standard NIS 439 [18] commonly used for producing building blocks in Nigeria was used in the study.

The water used in mixing the blended cement and sand is fresh, colourless, odourless, tasteless and free from organic matter of any kind. The crushed glass used is obtained from BETA Glass Company, Agbara, Ogun State, Nigeria. Figure 1 shows the particle size analysis of the sand used.

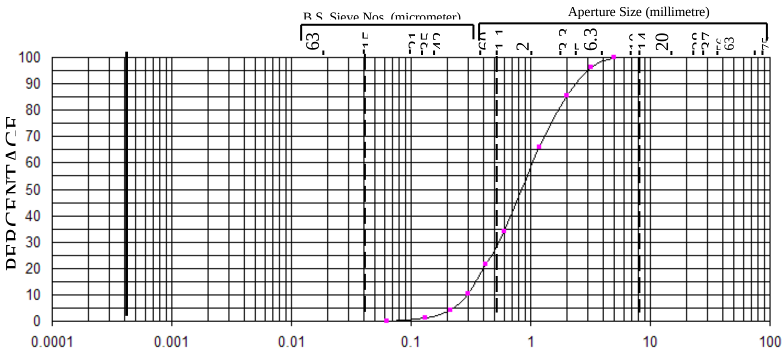

Figure 1. The particle size analysis of the sand

Table 1: Chemical analyses of ordinary portland cement and crushed glass

PARAMETER	PORTLAND CEMENT (%)	CRUSHED GLASS (%)
Silica (SiO_2)	18.26	73.26
Aluminium oxide (Al_2O_3)	4.68	1.32
Ferrous oxide (Fe_2O_3)	0.40	0.51
Calcium oxide (CaO)	66.06	11.57
Magnesium oxide (MgO)	2.13	0.32
Sodium oxide (Na_2O)	0.52	12.32
Potassium oxide (K_2O)	0.49	0.34
Silica Ratio [SiO_2 /(Al_2O_3 + Fe_2O_3)]	3.59	40.03
Aluminium Ratio [Al_2O_3/ Fe_2O_3]	11.7	2.59
$\sum$ (SiO_2 +Al_2O_3 + Fe_2O_3)	23.34	75.09

From the chemical analysis of crushed glass, Table 1, carried out at the Chemistry Laboratory of the University of Lagos, Lagos, Nigeria, the sum of SiO_2, Al_2O_3 and Fe_2O_3 is 75.09%. This value is higher than 70%, the minimum percentage requirement for pozzolans as specified in ASTM C618-19 [19]. It therefore implies that crushed glass will be a good pozzolan. The sum value compares favourably with that of other admixtures such as rice husk ash which has 76% [3] and corn cob ash which has 78% [5].

The blocks (all hollow) were produced with an immersion poker vibrating machine. Standard mix proportion of 1:6 as specified by BS 2028 [20] is adopted. However, a mix of 1:8 was also considered because it is commonly used by many local sandcrete block producers. An average water/cement ratio of 0.6 is adopted in the mix. As shown in Figure 2, the size of the block is 225 mm x 225 mm x 450 mm with one-third of the volume void so as to produce the type of hollow sandcrete blocks commonly used for construction of buildings in Nigeria. The replacement of cement with crushed glass is varied in steps of 5% to a maximum of 25%.

The production of the blocks was done with the materials turned over by hands a number of times until an even colour and consistency were attained. Water is added through a fire hose. The mix is further turned over to secure adhesion, then rammed into the machine moulds and compacted. After removal from the machine moulds, the blocks were left on pallets under cover in separate rows, one block high and with a space between two blocks for the curing period. They were daily watered to keep them wet throughout the period.

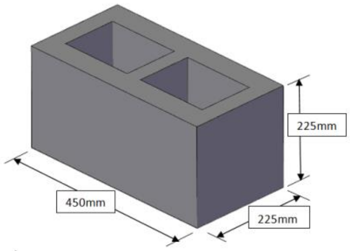

Figure 2: Dimensions of the hollow sandcrete block

The thermal conductivity of the blocks was determined using the guarded hot plate box according to ASTM C177-19 [21]. The determination of the specific heat capacity of the sandcrete blocks was obtained using the adiabatic calorimetric technique. For accurate results, necessary precautions were taken at every stage of the experiment and for each procedure to keep error within 10%. The condition of the laboratory where the experiment was performed was about 27^{0}C dry-bulb temperature and relative humidity of about 50%.

3. RESULTS AND DISCUSSION

3.1 Results of the Hygrothermal Properties

The changes in the values of the hygrothermal properties of the blocks with percentage substitution of crushed glass are presented in graphical forms in Figures 3, 4 and 5.

3.1.1 Effect on density

Figure 3 shows that partial substitution of cement with crushed glass results in increasing effect on the density of the sandcrete blocks for both mix ratios. Understandably, the 1:8 block with more sand and glass is heavier 1:6 block. The density of the block increases almost at same rate for every 5% crushed glass substitution of cement in both mix ratios. The value of the density of the control block (0%) is just about 2% less than that of the 25% substitution. Change in the density of a block is known to have effect on its thermal mass [22].

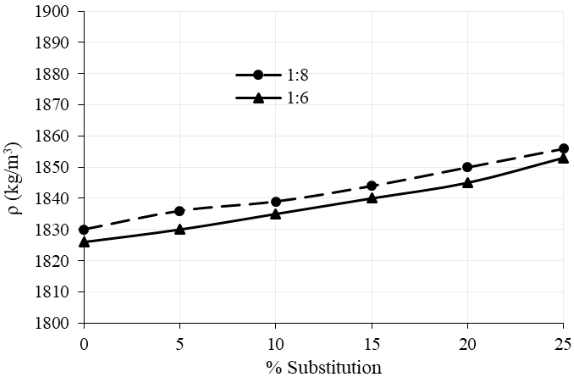

Figure 3: Density against percentage substitution of crushed glass

3.1.2 Effect on porosity

The volume of liquid absorbed by a porous medium is an indication of its pore volume and it is a good approximate measure of its porosity. The variation of porosity with percentage substitution of the crushed glass for both mix ratios is presented in Figure 4. The results show that, for both mix ratios, all the blocks containing the crushed glass are less porous than that of the block without the glass (0%). There was about 6% drop in the value of porosity when the crushed glass replaced only 5% volume of cement. But further volumetric addition of the admixture gradually decreases porosity. For the 1:8 mix ratio block, with 25% substitution, the porosity level reduced from 11.8% in the control block to 7%. This decrease in porosity shows that addition of the crushed glass closes up the pores in the blocks, possibly due to the particle size of the crushed glass in comparison with that of sand.

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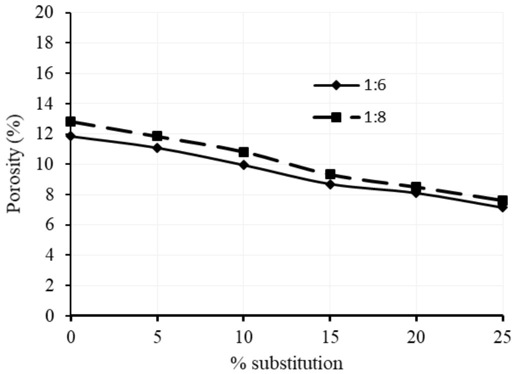

Figure 4: Porosity against percentage substitution of crushed glass

3.1.3 Effect on water absorption coefficient

For external walls in tropical humid climate, water-resistance ability of the blocks must be considered in order to minimize penetration of moisture or rain water into the interior of the building. Water absorption coefficient of the blocks is therefore tested using the partial immersion method. The principle behind the method is that a material that allows liquid moisture diffusion through its boundary surface would change its weight with time when it is brought in contact with liquid water. In Figure 5, water absorption coefficient of the blocks marginally increases with the content of the crushed glass substituted. This implies that replacing cement with glass particulates opens up the blocks and hence increase water inflow. Therefore, such blocks are not to be used in swampy or flood-prone areas.

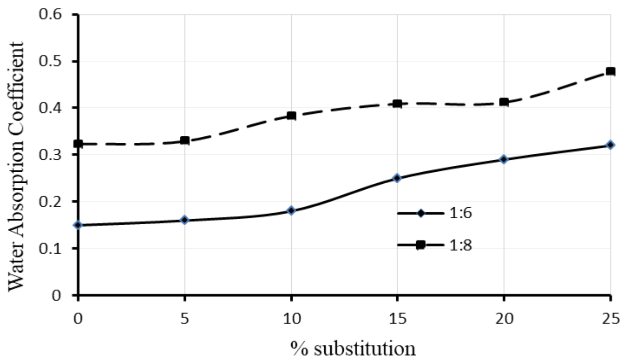

Figure 5: Water absorption coefficient against percentage substitution of crushed glass

3.2 Results of the Thermal Properties

Thermophysical properties of most cementitious materials are found to change with the presence of admixtures [14, 23]. In predicting the thermal performance of buildings constructed with such materials, it is necessary to consider the dynamic effects of this variation. The properties investigated on this study are the thermal conductivity (k), specific heat capacity (c), thermal diffusivity (α), thermal effusivity (β), thermal resistance (R-value), thermal conductance (C-value), thermal admittance (h_a), thermal insulance (i_t) and thermal resistivity (r_t) of the blocks. The variations of these properties with percentage substitution of crushed glass are presented in Figures 6-14. The thermal conductivity of the blocks was determined using the Guarded Hot Plate Box conforming to the requirements of ASTM C177-19 [21]. The determination of the specific heat capacity of the sandcrete blocks was through the adiabatic calorimetric technique. To ensure the results were as accurate as possible, necessary precautions were taken during the measurements. Results obtained are compared with those reported for rice-husk-ash (RHA) blended blocks in [24].

3.2.1 Effect on thermal conductivity (k)

In Figure 6, for both mix ratios, it is observed that the value of the thermal conductivity increases with the quantity of the crushed glass added. But those of blocks made with 1:6 mix ratio is higher than corresponding block with 1:8. The value of the thermal conductivity of the 25% crushed glass block with 1:6 mix ratio is 4% higher than that of the block without glass (0%). The higher k value obtained for the block is as a result of the higher thermal conductivity of glass. Similar increase is obtained for blocks containing rice husk ash [24]. It is worthy of note however that highly conducting block is undesirable for construction of buildings where thermal comfort of occupants is paramount because it increases the heat transfer rate into the building space during the day.

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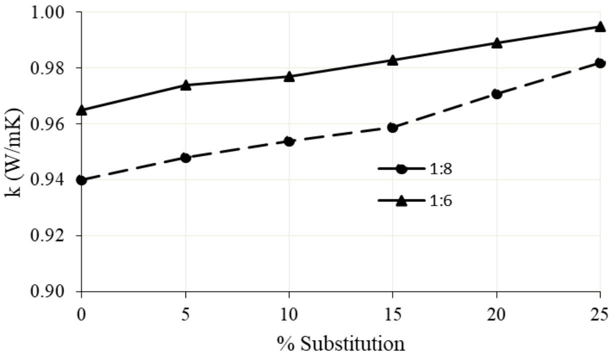

Figure 6: Thermal conductivity against percentage substitution of crushed glass

3.2.2 Effect on specific heat capacity (c)

The variation of the specific heat capacity against percentage crushed glass substitution, Figure7, indicates that all the blocks with the admixture have slightly lower values than that of the block. In the 25% block, the value of the specific heat capacity is 20% and 25% less than that of the 0% block for the 1:8 and 1:6 mix ratio respectively. This is because the quantity of crushed glass with slightly lower heat capacity than sand is more in the former than in the latter mix ratio. This implies, blocks with crushed glass have lower heat energy storing capacity and lower thermal mass than those without it. In a tropical environment, at evenings, these blocks will lose heat gained during the day faster, thereby making the building space more comfortable overnight and less energy consumed for mechanical cooling. This results agrees with those of Kamiyo and Oyekan [24] and Oktay *et al*. [25] that observes that specific heat capacity of a cementitious block decreases as its density increases.

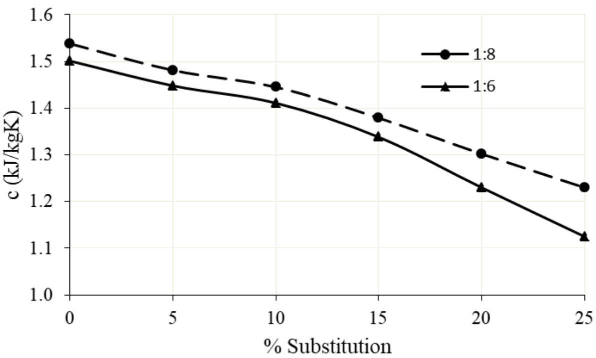

Figure 7: Specific heat capacity against percentage substitution of crushed glass

3.2.3 Effect on thermal diffusivity (α)

When a material is exposed to a fluctuating thermal environment, how quickly the material respond to changes in temperature is a measure of its thermal diffusivity. It shows the unsteady nature of thermal diffusion within the material. Therefore, material with high thermal diffusivity will quickly adjust its temperature to the level of that of its environment. Figure 8 shows that the values of the thermal diffusivity of all the blocks are slightly higher than that of the control block (0%) with the blocks made with 1:6 mix ratio higher than similar block with 1:8. The reducing values of both density and the specific heat capacity with crushed glass content caused the thermal diffusivity value to increase. In effect, sand-cement blocks made with crushed-glass-blended cement will undergo a somehow faster temperature change or allow more rapid heat flow than those without the admixture. In [24], the thermal diffusivity of RHA-blended blocks is reported to gradually increase with RHA substitution.

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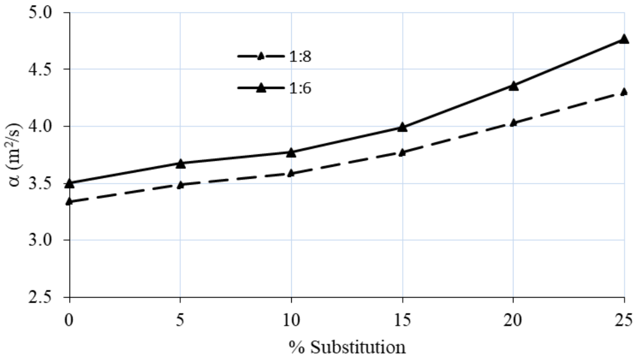

Figure 8: Thermal diffusivity against percentage substitution of crushed glass

3.2.4 Effect on thermal effusivity (β)

Thermal effusivity, otherwise called heat penetration coefficient, shows how rapidly a material absorbs or dissipates heat. When the material is touched with hands, there is that feeling of 'warm' or 'cold'. In Figure 9, the thermal effusivity value decreases as the percentage crushed glass content increases. The β value of the 25% crushed glass block for the 1:6 mix ratio, which is the lowest, is almost 12 percent more than that of the control block. In practical terms, the higher thermal effusivity of the blocks made with crushed-glass-blended cement increases its ability to conduct heat away from the building space faster. Hence, the air-conditioning load and the period of thermal comfort without the use of mechanical equipment will be reduced.

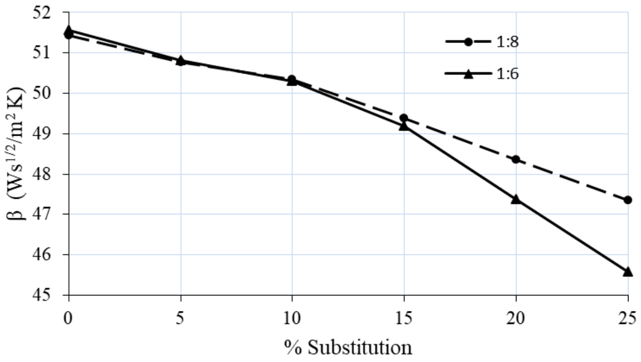

Figure 9: Thermal effusivity against percentage substitution of crushed glass

3.2.5 Effect on thermal resistance (R-value)

A 5 percent crushed glass substitution reduced the thermal resistance of the sand-cement block by 0.9% in the 1:6 mix ratio block and by 0.8% in the 1:8 mix ratio block. Further gradual drops were observed as percentage substitution of crushed glass in the block is increased. Figure 10 indicates that at 25% substitution, the block's resistance to heat flow drops to 0.874 K/W and 0.886 K/W for the 1:6 and 1:8 mix ratios respectively. This means that for every 5% substitution of cement with crushed glass and approximating a linear relationship, the sand-cement block loses its ability to resist heat flow averagely by 0.6%.

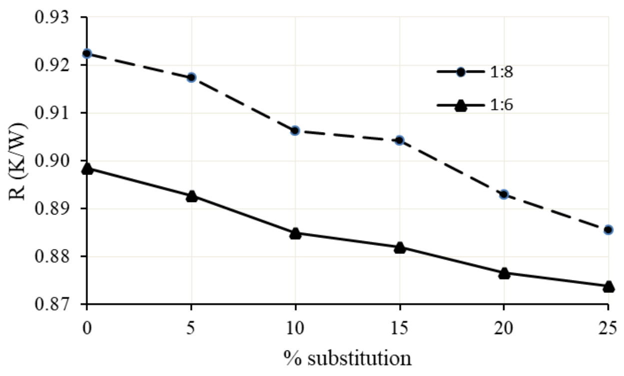

Figure 10: Thermal resistance against percentage substitution of crushed glass

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3.2.5 Effect on thermal conductance (C-value)

Thermal conductance is the reciprocal of the block's thermal resistance. In Figure 11, thermal conductance of the crushed-glass-blended block increased by 0.6% when 5% crushed glass substitutes the cement in the 1:6 mix. The increase is consistently gradual until it reaches 1.448W/K. Similar increasing rate is observed for the 1:8 mix. This imposes an increase in heat flow through the walls of the space built with the blocks and hence, an increase in the air-conditioning load during the day but cools the space faster during the night.

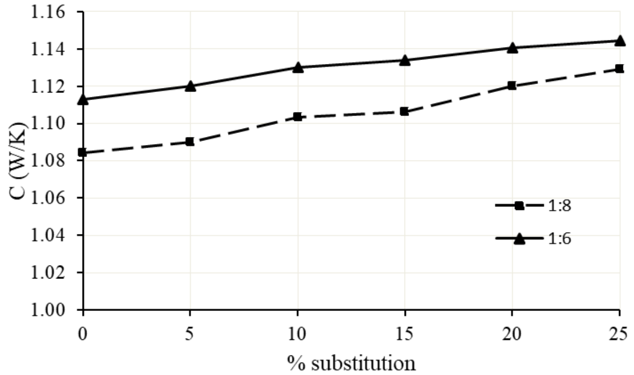

Figure 11: Thermal conductance against percentage substitution of crushed glass

3.2.6 Effect on thermal admittance (h_a)

Thermal admittance is the measure of a material's ability to exchange heat rapidly to its environment in response to a cyclic change in temperature. Figure 12 shows a marginal increase in the value of the thermal admittance of the block with the percentage crushed glass substitution. At a constant block thickness, the thermal admittance increases at the same rate as the thermal conductivity of the block.

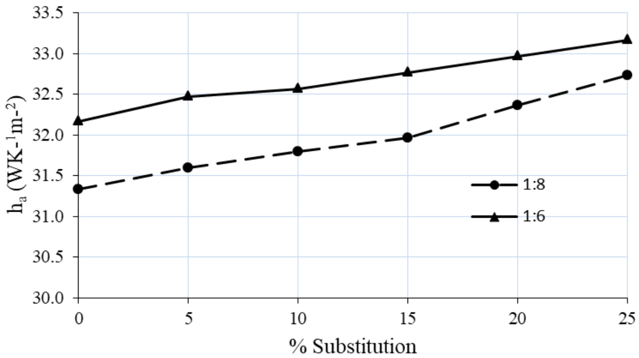

Figure 12: Thermal admittance against percentage substitution of crushed glass

3.2.7 Effect on thermal insulance (i_t)

Thermal insulance indicates the insulating power of a material. An insignificant drop is observed in Figure 13 for the thermal insulance of the blocks for both mix ratios as percentage glass substitution increases. The average difference in value of i_t for every 5% crushed glass substitution is about 0.0003K.m^2/W. In a direct inverse to the thermal admittance, the thermal insulance decreases as the crushed glass content increases.

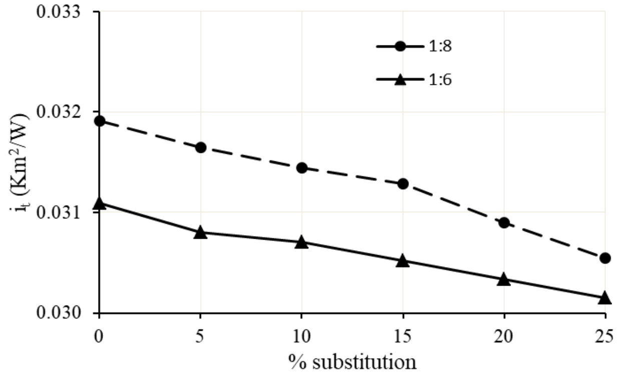

Figure 13: Thermal insulance against percentage substitution of crushed glass

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3.2.8 Effect on thermal resistivity (r_t)

Thermal resistivity shows the ability of a material to resist heat flow through it. Figure 14 shows that, for both mix ratios, there is a steady decrease in the thermal resistivity of the blocks with crushed glass as its percentage substitution increases. This implies that ability of the block to resist heat flow through it declines as the crushed glass content increases. The practical effect is that sandcrete blocks with crushed glass is more suitable for partition walls especially for buildings where human comfort is paramount.

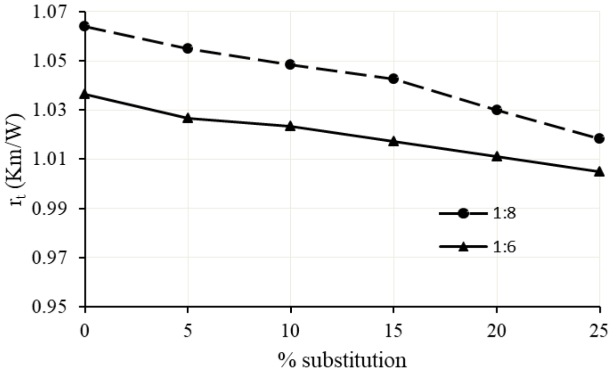

Figure 14: Thermal resistivity against percentage substitution of crushed glass

3.3 Case Study

Knowledge of the heat transfer characteristics of the materials used for a building has been of great value to engineers engaged in the analysis and design of building structures. It enables designers to be able to estimate the cooling load required to provide a given level of thermal comfort within the building and over the annual climatic cycle. This would help in sizing the cooling system required to maintain thermal comfort within the space and possibly extend the period of human comfort without reliance on mechanical system. These ultimately reduce the annual total energy cost in addition to other energy conservation and environmental consequences.

The heat gain through walls of a sample air-conditioned space, Figure15, was estimated with the aim of determining the effect of the changes in thermal properties on the cooling load and hence the energy demand by the air-conditioning system. The calculations were carried out for the space assumed built with the sandcrete blocks with crushed glass for both mix ratios.

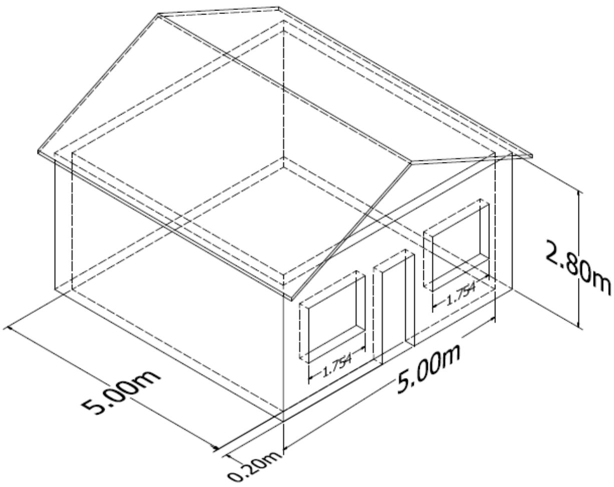

Figure 15: A sample air-conditioned space

Conductive heat transfer into the enclosure was estimated to be 40% of the total cooling load. The percentage increase in the cooling load for each percentage substitution of the crushed glass was calculated for a 24-hour operation over a year and presented in Figure 16.

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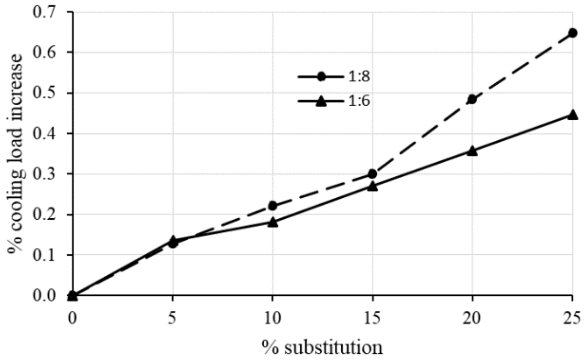

Figure 16: Percentage increase in space cooling load against percentage substitution of crushed glass

It is observed that the cooling load increases steadily with percentage increase in crushed glass content. Blocks with crushed-glass substituted blocks at the 1:6 mix ratio gives lower percentage increase than the 1:8 mix ratio as the substitution increases. The changes are higher for both mix ratios with a steady sharp increase after 10% substitution. The results suggest that, to minimize cost of mechanical cooling, blocks with low crushed glass content should be used.

The practical significance of these results is that the heat transfer characteristics of the sand-cement-crushed-glass blocks presented will be of a great value to building professionals engaged in the design and analysis of building structures. Designers would be able to properly size the heating/cooling equipment necessary to provide a given level of thermal comfort within the building and over the annual climatic cycle. As a result, there is reduction in the size of the air-conditioning system required to cool or heat the space, reduction in the thickness of the thermal insulator, and extension of the period of human comfort without reliance on mechanical air-conditioning. The above qualities reduce the annual energy cost in addition to other energy conservation and environmental effects.

4. CONCLUSION

The thermal and hygrothermal properties of building blocks produced with crushed-glass substituting cement within the range 5–25% at intervals of 5 have been investigated. The results show that sandcrete blocks with crushed glass-blended cement are of higher density but less porous than those purely sand-cement blocks. Also, the thermal characteristics of the block show an increase in the thermal conductivity, thermal diffusivity, thermal conductance and thermal admittance of the block with percentage substitution of crushed glass. On the other hand, as the crushed glass content increases, the specific heat capacity, thermal effusivity, thermal resistance, thermal resistivity and thermal insulance decrease. Buildings constructed with blocks made with crushed glass-blended cement will have higher cooling load as crushed glass content increase. The overall thermal effect of the crushed glass partially replacing cement in a porous building block is that it loses the thermal insulating advantage leading to occupants' discomfort year-round. Therefore, it should be used with caution; for partitioned walls rather than as external walls and that not more than 5%.

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