Thermo-economic Analysis of Porous Building Materials with Admixtures

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Abstract

Most buildings in many nations of the world including African countries are built with porous materials especially sandcrete blocks. It has been observed that various factors including presence of admixtures affect the engineering properties of the blocks. Recent reports show that admixtures are being introduced into these blocks to achieve different purposes including cost reduction and strength enhancement. In the process, some vital properties are traded-off. 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 energy conservation and other environmental consequences. This paper reports the effects of percentage substitution of the constituents of sandcrete block with coconut husk ash, crushed glass, and granite fines on its thermophysical properties. It was observed that the presence of the admixtures slightly increases the thermal conductivity and the thermal diffusivity but decreases the specific heat capacity and the thermal effusivity. Attendant effect on air conditioning load estimated shows that the load increases with the percentage substitution of the admixtures with granite fines having the highest increase of about 10% at 25% substitution. Recommendations are also made on the techno-economical suitability of these admixture-based blocks in building applications.

Keywords: *sandcrete blocks, admixtures, thermophysical properties, air-conditioning load*

Notations

A:	area of material perpendicular to heat flow (m^2)
c :	specific heat capacity (J/g K)
k	thermal conductivity (W/m K)
Q:	heat flux (W)
ΔT:	temperature change (K)
Δx:	sample thickness (m)

Greek symbols

α:	thermal diffusivity (m^2/s)
β:	thermal effusivity ($W/m^2\ K\ s^{1/2}$)
θ:	change in temperature (K)
ρ:	density (kg/m^3)

1. Introduction

Hollow sandcrete blocks containing a mixture of sand, cement and water are used extensively in many countries of the world especially in Africa. In many parts of Nigeria, sandcrete block is the major cost component of the most common buildings. The high and increasing cost of constituent materials of sandcrete blocks has contributed to the non-realization of adequate housing for both urban and rural dwellers. Hence, availability of alternatives to these materials for construction is very desirable in both short and long terms as a stimulant for socio-economic development. In particular, materials that can complement cement in the short run, and, especially, if cheaper, has been of great interest.

A number of investigations had been carried out to determine the viability[1,2], compressive strength increase [3,4], possibility of reducing cost [5] and the water absorption characteristics [6,7] of building materials with the use of admixtures. The change is found to depend on the admixture's grain structure or interstitial arrangement within the main material and other microstructural parameters including the volumetric fraction of each constituent, the shape of the particles, and the size distribution of the particles. However, the thermal characteristics of the construction materials of a space are important in evaluating air conditioning load and ventilation requirements among other heat transfer related activities within the building. This is necessary to provide a given level of occupants' thermal comfort within the building and over the annual climatic cycle.

The admixtures considered in this work are coconut husk ash (CHA), crushed glass and granite fines. A large amount of agricultural wastes are produced every year around the world. The use of these wastes as raw material to substitute mineral aggregates provides an interesting alternative to meet the challenge of disposal and support environmental sustainability. Coconut ash is a waste product obtained from coconut and is produced in significant quantity on a global basis. While it is utilized as fuel in some regions, it is regarded as a waste in others thereby causing pollution; due to problem with disposal. Hence, its profitable use in an environmentally friendly manner will be a great solution to what would otherwise be a pollutant. A significant amount of glass waste is also produced in many urban societies. Granite fines are obtained from crushed granite that is available in large quantities in many parts of the world especially Sub-Saharan Africa.

2. Materials of the sandcrete blocks

The sandcrete blocks used in this investigation were made of sand, cement and water. Sharp river quartzite sand that is free of clay, loam, dirt, and any organic or chemical matter was used. It was sieved with the 3.35mm zone of British Standard test sieves. The particle size distribution of the sand is shown in Fig.1. 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) was obtained from the West African Portland Cement Company, Ogun State, Nigeria with properties conforming to BS 12 [8] commonly used for producing building blocks. The water employed in mixing the blended cement and sand was fresh, colourless, odourless, tasteless and free from organic matter of any kind.

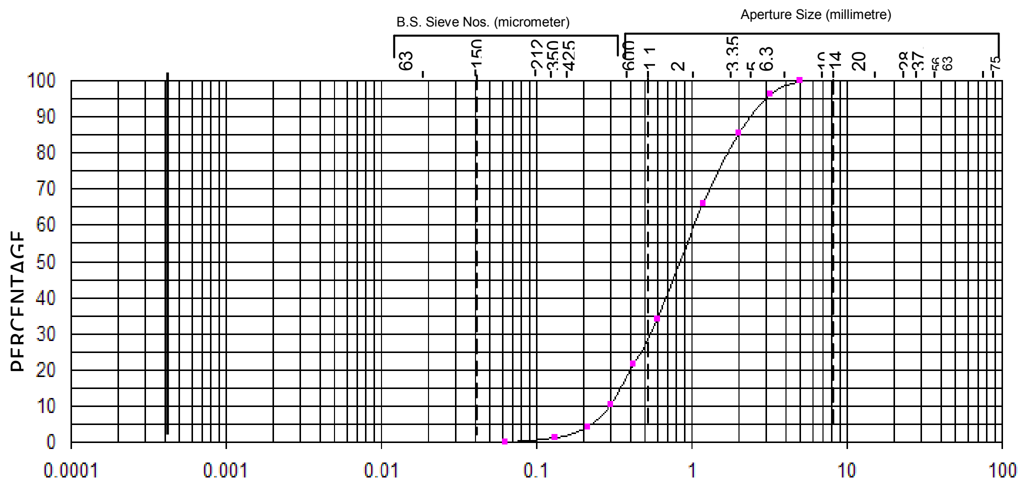

Figure 1: Particle Size Distribution of Sand

Coconut shells used for this experiment were collected from a threshing site at Epe, Lagos State, Nigeria. The shells were burnt into ash in a controlled gas furnace at the Federal Institute for Industrial Research, Oshodi, Lagos and sieved in order to remove all particles that do not pass the 45µm test sieve [9]. Table 1 shows the chemical analyses of the CHA and of the Portland cement substituted. The crushed glass used was obtained from BETA Glass Company, Agbara, Ogun State, Nigeria. The chemical analysis of the crushed glass is presented in Table 1. The granite fines was obtained from the limestone quarry in Ogun State of Nigeria. The specific gravity of the granite fines is 2.7 and the average moisture content is 0.32%. The coefficient of uniformity of the granite fines is 10.7.

Table 1: Chemical analyses of coconut husk ash, cement (OPC) and crushed glass.

Parameter	Coconut husk ash (%)	Cement (%)	Crushed Glass (%)
Silica (SiO_2)	3.0	21.0	73.26
Aluminium oxide (Al_2O_3)	1.2	5.22	1.32
Ferrous oxide (Fe_2O_3)	0.002	4.75	0.51
Calcium oxide (CaO)	5.0	64.73	11.57
Magnesium oxide (MgO)	0.0002	2.01	0.32
Sodium oxide (Na_2O)	1.14	0.19	12.32
Sulphite ($SO_3^{2-)}$	0.02	1.48	0.24
Chromium Oxide ($Cr_2\ O_3$)	-	-	0.11

From the chemical analysis of CHA, the sum of SiO_2, Al_2O_3 and Fe_2O_3 is 4.2%. This value is far less than the minimum percentage requirement for pozzolanas which is 70% [10]. It therefore implies that the CHA is less pozzolanic than that of cement unlike crushed glass which has 75% and rice husk ash which has 76% [11].

3. Production of the Sandcrete Blocks

Hollow blocks were produced with a vibrating machine. The standard mix proportion is 1:6, but a mix proportion of 1:8 was also considered because it is commonly used by many local sandcrete block producers. The size of the block, as shown in Fig.2, was 225mm x 225mm x 450mm with one-third of the volume void. The replacement with the admixture was by volume, as well as the batching of cement and sand.

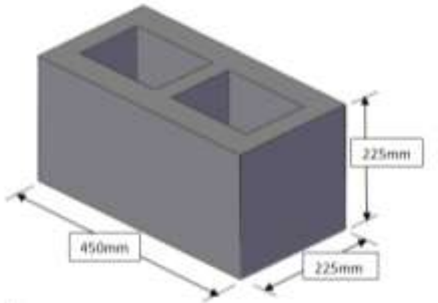

Figure 2: Hollow sandcrete block

Hand mixing was employed during the production of the blocks. The materials were turned over a number of times until an even colour and consistency were attained. Water was added through a fire hose. The mix was 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 throughout the curing period. They were kept wet during this period by watering daily. The laboratory condition is 27 ± 2^0C DB, 50 ± 5% RH.

4. Thermophysical Properties

Thermophysical properties of most cementitious materials are found to change with the presence of admixtures [12,13]. In predicting the thermal performance of buildings, it is necessary to consider the dynamic effects of this variation. The properties investigated are the thermal conductivity, specific heat capacity, thermal diffusivity and thermal effusivity of the blocks.

(i) Thermal conductivity, k*,* the property that indicates a material's ability to conduct heat, was determined using the Guarded Hot Plate Box conforming to the requirements of ASTM C177 [14] through the Fourier heat equation

$$k = {Qt}/{A\Delta T} \tag{1}$$

(ii) Specific heat capacity, c, measures the thermal storage capacity of a material. Walls with high specific heat capacity will have a large thermal lag. This time lag effect contributes to shifting energy demand to off-peak periods and improves overall thermal efficiency. The specific heat capacity of the block was determined by the adiabatic calorimetric technique using the classical heat capacity equation

$$c = {Q}/{m\Delta T} \tag{2}$$

Thermal diffusivity, α, describes the heat transfer capability of a material relative to its heat storage ability. It is obtained through the relation

$$\alpha = {k}/{\rho c} \tag{3}$$

Thermal effusivity, β, measures the capacity of a material to absorb and release heat. The value of the thermal effusivity is useful in calculating the heat-accumulation capacity of material. It is calculated as

$$\beta = \sqrt{k\rho c} \tag{4}$$

5. Results and Discussion

The variation of the thermophysical properties with percentage substitution of the admixture, determined experimentally, are presented in Figs.3-6.

5.1 Effect on thermal conductivity

It is observed from Fig.3 that the addition of the CHA and crushed glass slightly increase the thermal conductivity of the blocks. Appreciable increase of thermal conductivity is observed with percentage increase in granite fines. However, the values of the thermal conductivity obtained are still within the standard range for cementitious materials [15]. The higher k values obtained after adding the admixtures could be from the products of their chemical reactions with cement during the hydration process. The products that increase the k value of the blocks are subject of further investigation. It is worthy of note that sandcrete block, being a non-metallic solid, is characterised by much variability as heat is transferred within it via lattice vibration.

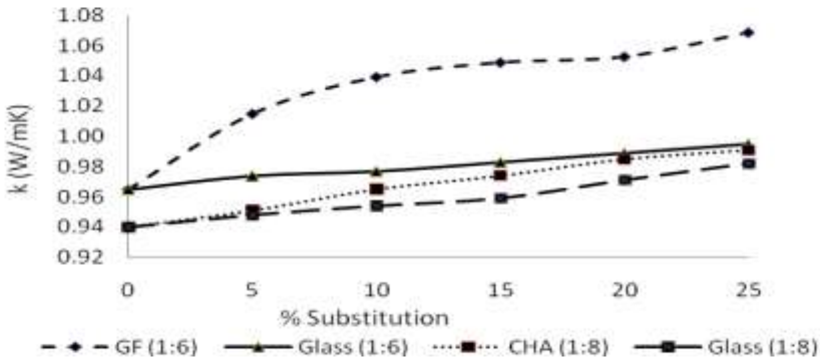

Figure 3: Thermal conductivity variation with % substitution of admixture.

Nonetheless, the increase in thermal conductivity implies increased conductive heat transfer through the blocks which consequently increase the cooling load of buildings they are built with and hence increase in cooling equipment capacity and costs. It shows that the admixtures considered in this study reduce the insulating quality of the block rather than enhance it. Nevertheless, these types of blocks may be used for partition walls within air conditioned buildings and for other applications where fast rate of heat transfer through walls is desired.

5.2 Effect on specific heat capacity

As shown in Fig.4, the substitution of the admixtures makes the sandcrete blocks to exhibit decreasing heat-storage capacity and hence lower thermal mass. In a tropical environment, these blocks will lose heat gained during the day faster, thereby making the building space comfortable for early sleep in the evening.

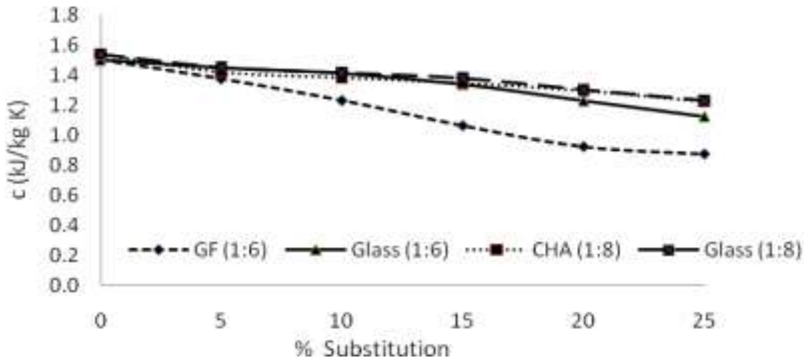

Figure 4: Specific heat capacity variation with % substitution of admixture.

5.3 Effect on thermal diffusivity

In a manner almost a mirror of the specific heat capacity plot, Fig.5, the values of the thermal diffusivity of all the blocks increases with the percentage admixture substitution. The reducing values of both density and the specific heat capacity of the blocks with the subsitution of the admixtures led to the increase. In essence, these types of sandcrete blocks will undergo a faster temperature change or allow more rapid heat diffusion than those without the admixture. Blocks containing crushed glass and CHA showed almost identical thermal diffusivity variations.

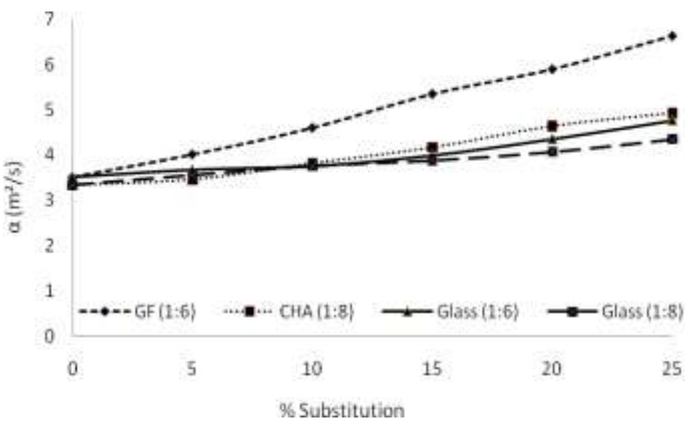

Figure 5: Thermal diffusivity variation with % substitution of admixture.

5.4 Effect on thermal effusivity

The thermal effusivity, β, in Fig.6, decreases slightly as the percentage substitution of the admixtures increases. In practical terms, these lower values increases the ability of the blocks to retain heat absorbed much longer than that of the block without the admixtures. This implies, whenever the surrounding temperature changes, blocks containing the admixtures tend to respond slowly. This is a disadvantage to human comfort in tropical clime because heat would be released from the block for much longer time in the evening thereby decreasing the period of thermal comfort without the use of mechanical cooling.

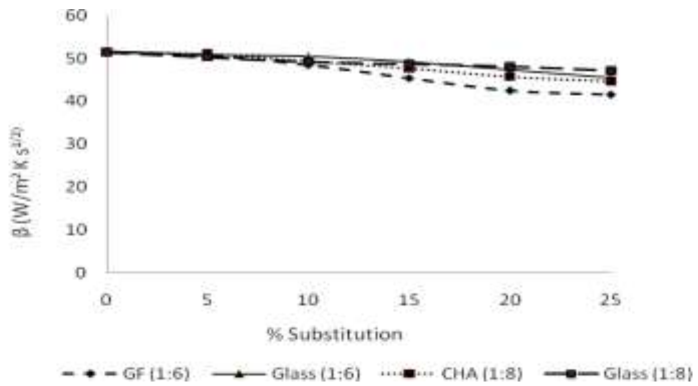

Figure 6: Thermal effusivity variation with % substitution of admixture.

6. Economic Analysis

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.

For economic analysis of the use of the admixture-based blocks considered in this study, the contribution from heat gain through walls of a sample space, Fig.7, was estimated with the aim of determining the effect of the changes in thermal conductivity 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 granite fines and crushed glass with 1:6 mix proportion and coconut hush ash and crushed glass with 1:8 mix ratio.

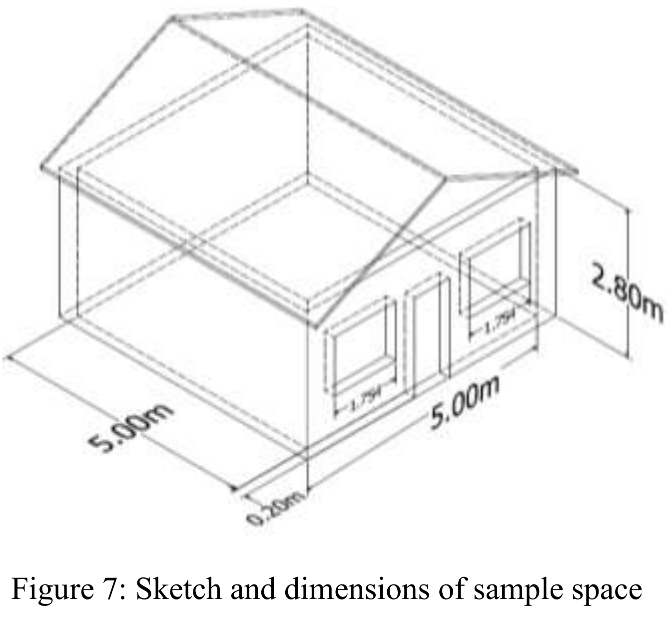

Figure 7: Sketch and dimensions of sample space

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 admixtures was calculated for a 24-hour operation over a year and presented in Fig. 8.

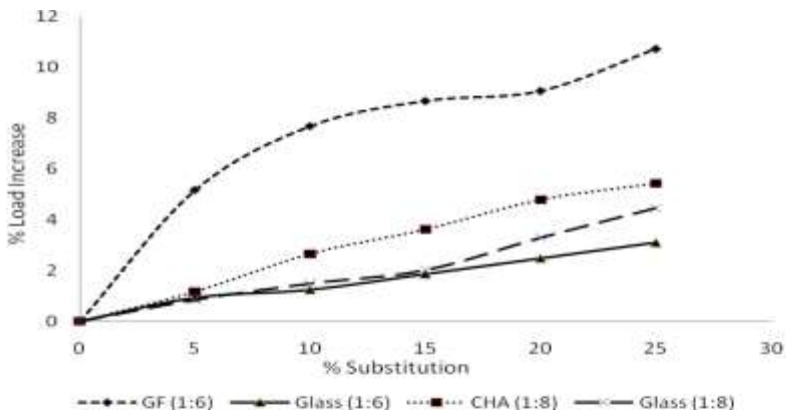

Figure 8: Percentage Increase in cooling load of building

It is observed that the cooling load increases steadily with percentage increase in admixture content. Blocks with granite-fines as admixture give the highest percentage increase in cooling load reaching as high as 10.4% at 25% substitution. Crushed-glass substituted blocks at the 1:6 mix ratio gives the lowest percentage increase at 3% at 25% substitution. Crushed glass is therefore the most preferred admixture from the thermal perspective, however availability, cost and other properties of concern must be considered in making an overall choice.

7. Conclusion

Results show that the substitution of sand or cement with admixtures has significant effects on the thermophysical properties of porous sandcrete blocks. As the percentage substitution of the admixtures increases with the thermal conductivity and the thermal diffusivity of the blocks while the specific heat capacity and the thermal effusivity decrease as the percentage substitution increases. It was observed that the inclusion of these admixtures have consequential effect on the cooling load of a building space.

The practical significance of this study is that the heat transfer characteristics of the sandcrete blocks presented will be of great value to building professionals engaged in the design and analysis of building structures. Also, designers would be able to properly size the cooling equipment necessary to provide a given level of thermal comfort over the annual climatic cycle.

Acknowledgement

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