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Full Length Research Paper

A study on the engineering properties of sandcrete blocks produced with rice husk ash blended cement

G. L. Oyekan[1]* and O. M. Kamiyo[2]

[1]Department of Civil and Environmental Engineering, University of Lagos, Nigeria.
[2]Department of Mechanical Engineering, University of Lagos, Nigeria.

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Sandcrete blocks have been in used in many nations of the world including Nigeria, playing a major role in the building industry. The material constituents, their mix, presence of admixtures and the manufacturing process are important factors that determine the properties of sandcrete blocks. This paper investigates the effects of a partial replacement of cement with rice husk ash (RHA) on some engineering properties of hollow sandcrete blocks with 1:6 cement-sand mix ratios. Single block size 225 x 225 x 450 mm, is produced with a vibrating machine. Results show that the addition of RHA produces blocks of lower density. Particularly, the density of the blocks decreases as the RHA content increases. The compressive strength of the block is also not enhanced. Results also reveal that the thermal and hygrothermal properties of the blocks are significantly affected.

Key words: Sandcrete blocks, rice husk ash, compressive strength, hygrothermal properties, thermal properties.

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, will be of great interest.

Over the past decade, the presence of mineral admixtures in construction materials has been observed to impart significant improvement on the strength, durability and workability of cementitious products (Mental, 1994; Falade, 1997; Oyekan, 2001). In areas prone to flood, hygrothermal properties of the buildings' construction materials are of importance. Also, energy requirements for residential and commercial buildings are known to be influenced by building design and by the materials used. In both temperate and tropical regions, thermal properties of building materials are of significant importance to the determination of the heating or cooling load within the building and hence the capacity of the mechanical equipment required in handling the load. This is necessary to provide a given level of thermal comfort within the building and over the annual climatic cycle. Substitution of any of these admixtures is aimed at enhancing at least one of the properties of the block. Rice husk is a residue 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, it's profitable use in an environmentally friendly manner, will be a great solution to what would otherwise be a pollutant. When burnt under controlled conditions, the rice husk ash (RHA) is highly pozzolanic and very suitable for use in lime-pozzolana mixes and for Portland cement replacement (Smith, 1984; Chandrasekhar et al., 2003; Yogenda et al., 1988; Anwar et al., 2000; Paya et al., 2000; Nair et al., 2006; Goncalves and Bergmann, 2007; Rodriguez et al., 2008). Effect of RHA blended cement on the strength and permeability properties of concrete has been investigated by Ganesan et al. (2008). On sandcrete block, Cisse and Laquerbe (2000)

*Corresponding author. E-mail: gloyekan@yahoo.com. Tel: +2348037140029.

observed that the mechanical resistance of sandcrete blocks obtained when unground ash is added increased in performance over the classic mortar blocks. Their studies on Senegalese RHA also revealed that the use of unground RHA enabled production of lightweight sandcrete block with insulating properties at a reduced cost. The ash pozzolanic reactivity was responsible for the enhanced strength obtained. Okpala (1993) partially substituted cement with RHA in the percentage range of 30–60% at intervals of 10% while considering the effect on some properties of the block.

His results revealed that a sandcrete mix of 1:6 (cement/sand ratio) required up to 40% cement replacement and a mix of 1:8 ratio required up to 30%, are adequate for sandcrete block production in Nigeria. However, it is worthy of note that due to the high cost of procuring the rice husk required for producing large number of blocks needed for an average-size building, and in the light of the diminishing agricultural activities in Nigeria, replacing cement with such high volume of RHA could be economically counterproductive for local sandcrete block manufacturers thereby defeating the main purpose of the substitution which is to reduce the unit cost of the block.

Also, the hygrothermal properties and some vital thermal properties are not considered in the investigation. Therefore, to encourage continual production and for better characterization of the sandcrete blocks, this paper investigates experimentally the effect of partially replacing cement with the Nigerian rice husk ash on some structural, thermal and hygrothermal properties of the blocks. The replacement is by volume and it is in the range of 5–20% at intervals of 5%.

MATERIALS AND METHODS

The material constituents, their mix, presence of admixtures and manufacturing process are important factors that determine the properties of sandcrete blocks. The materials used and method of manufacture employed in this investigation are thus presented.

Materials of the sandcrete blocks

The sandcrete blocks are made of sand, cement and water.

Sand

Sharp river quartzite sand that is free of clay, loam, dirt and any organic or chemical matter is used. It is sieved with the 3.35 mm zone of British standard (BS) test sieves. 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.

Cement

The cement used is the ordinary portland cement (OPC) from the West African Portland Cement Company, Ogun State, Nigeria with properties conforming to BS 12 (British Standards Institution, 1971).

Water

Fresh, colourless, odourless and tasteless potable water that is free from organic matter of any kind.

Rice husk ash

Rice husks used were collected from a threshing site at Ifo, Ogun State, Nigeria. Open field burning method is employed. The husks are burnt into ash and sifted in order to remove all particles that do not pass the 45 µm test sieve (British Standards Institution, 1997). Table 1 shows the result of the chemical analysis of the RHA and of the Portland cement. From the chemical analysis of RHA, the sum of SiO_2, Al_2O_3 and Fe_2O_3 is 79%. This satisfies the minimum percentage requirement for pozzolana when these constituents are added, which is 70% for ASTM C618 (American Society for Testing and Materials, 1978).The moisture content is less than 1.5% specified by BS 3892. It therefore implies that the RHA used in the present study is a good pozzolana since it meets the requirements of BS 3892 and ASTM C618 for pozzolana. The specific gravity of the RHA is 2.17 and its density is 2170 kg/m^3. The specific gravity value is almost the same as 2.15 obtained by Sampaio et al. (2003) but less than 2.36 reported by Cook et al. (1977) and higher than 1.54 obtained by Okpala (1993).These values indicate that the specific gravity of RHA is location and harvest-time dependent.

Grading of aggregates

The grading of an aggregate defines the properties of different sizes in the aggregate. This grading has a considerable effect on the workability and stability of the mix. Wet sieving analysis which is in accordance with BS 1377 (British Standards Institution, 1990) is used. The particle size distribution curve of the sand used in this study is shown in Figure 1.

Manufacture of sandcrete blocks

The blocks (all hollow) are manufactured with the use of a vibrating machine. The standard mix proportion of 1:6 cement-sand ratio; that is, one part by volume of cement to six parts by volume of coarse sand, is used in this investigation. The size of the block produced is 225 x 225 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. Four percentages of cement substitution with RHA (that is, 5, 10, 15 and 20%) by volume are used. A specific gravity of 2.17 for RHA in comparison with 3.14 for OPC implies that replacement of cement with RHA by weight would result in a much greater volume of the cementitious material in the mix. Consequently, the replacement of cement with RHA is by volume, as well as the batching of cement and sand.

In the manufacture of the blocks, hand mixing is employed and the materials are turned over a number of times until an even colour and consistency are attained. Water is added through a fire hose and it is further turned over to secure adhesion. It is then rammed into the machine moulds, compacted and smoothed off with a steel face tool. After removal from the machine moulds, the blocks are left on pallets under cover in separate rows, one block high and with a space between 2 blocks for the curing period. They are kept wet during this period by watering daily. The laboratory condition is 27 ± 2℃ dry-bulb temperatures, 50 ± 5% relative humidity. Testing for compressive strength is then carried out at ages 7, 14, 21 and 28 days. On the average, four specimens are tested at each age and each percentage replacement of cement with RHA.

Block units immersed in liquid absorb the liquid due to their porous nature. The volume, the rate and the dominant method of

Table 1. Chemical analysis of RHA and cement (OPC).

Parameter	Rice husk ash (%)	Cement (%)
Silica (SiO_2)	76.0	21.0
Aluminium oxide (Al_2O_3)	3.0	5.22
Ferrous oxide (Fe_2O_3)	Not detected	4.75
Calcium oxide (CaO)	6.0	64.73
Magnesium oxide (MgO)	1.3	2.01
Sodium oxide (Na_2O)	1:18	0.19
Potassium oxide (K_2O)	0.10	0.42
Barium oxide (BaO)	0.24	-
Lead oxide (PbO)	Not detected	-
Sulphite ($SO_3^{2-)}$	Not detected	1.48
Chloride	Not detected	-
Moisture	0.27	-
Ash	11.28	-

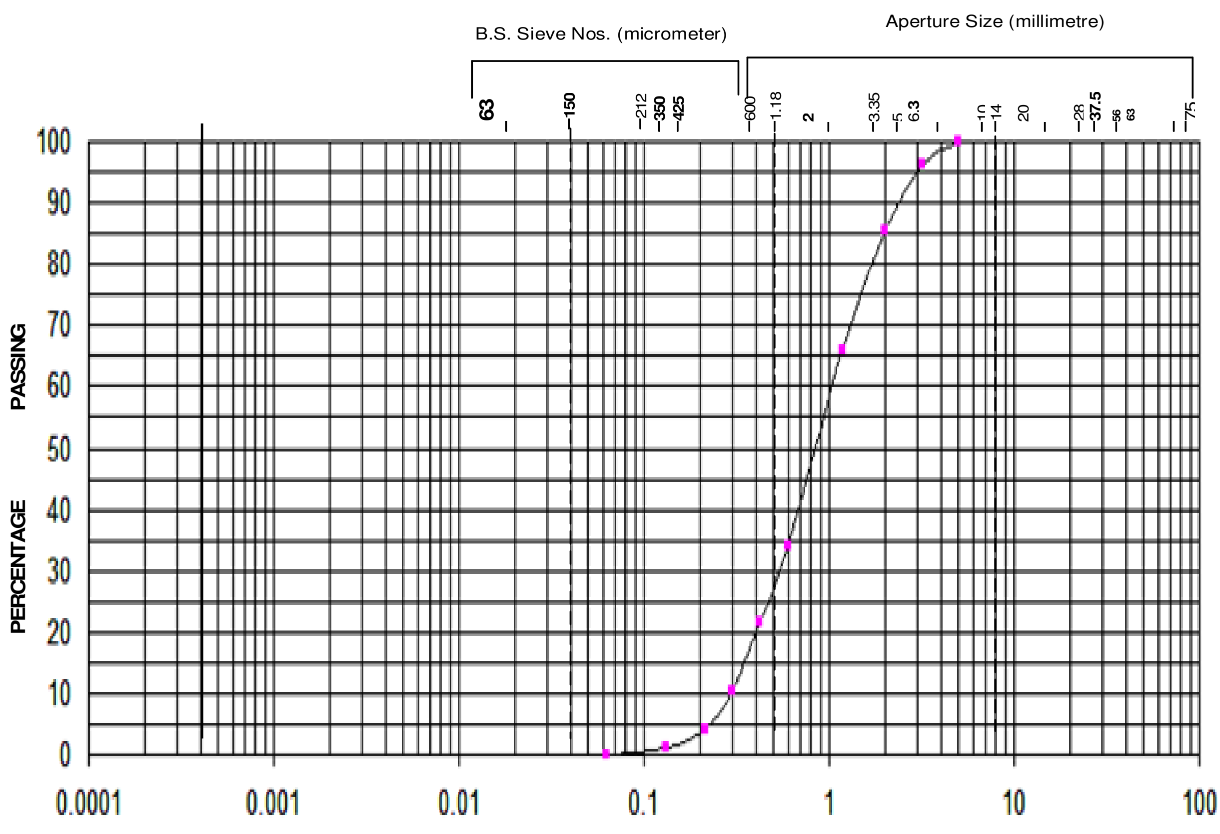


Figure 1. Particle size distribution curve of sand.

absorbing the liquid depends on the interstitial arrangement of the particles of the constituent materials at macro level. It is therefore necessary to investigate the effects of replacing cement with RHA on the hygrothermal properties of the block. Some of the properties are determined as follows:

Porosity

Presence of admixtures may increase, decrease or maintain the porosity of the main material depending on the aggregate sizes. When exposed to persistent flooding, a highly porous block could absorb much water, consequently become weakened and eventually fail. 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. Hence, porosity υ is obtained with the relation.

$$\upsilon = \frac{V_f}{V} x \, 100 \, \% \qquad \ldots\ldots(1)$$

Permeability

The term “permeability” is often loosely used to cover a number of different properties. In this paper, it is defined as the property of a porous medium which characterizes the ease with which a fluid will pass through it under atmospheric pressure. Darcy’s law for fluid flow in a permeable medium expresses permeability in terms of measurable quantities and states that the steady state rate of flow is directly proportional to the hydraulic gradient. Thus, for uni-axial penetration employed, permeability, K can be expressed as

$$K = \frac{\upsilon H^2}{2\,t\,h} \qquad \text{.......(2)}$$

Sorptivity

In using blocks 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. Many times, block work is used in the construction of channels for drainage. Blocks to be used for such purposes must have low sorptivity value. Sorptivity is a measure of the capacity of a porous medium to absorb liquid by capillarity. The absorption of water under capillary action is directly proportional to the square-root of time (Hall, 1989).

$$A'' = S\sqrt{t} \qquad \text{....... (3)}$$

Various test methods are used to determine hygrothermal properties of a material. However, in most cases, the test method chosen for a particular property is always the one appropriate to the predominant transport mechanism acting on the block. After evaluation of various methods, capillary rise method is employed in this investigation due to its simplicity and accuracy. Basically, a sample of sandcrete block is placed with one edge fully in contact with the water surface. Through that area, water is absorbed. The height of capillary rise is then measured at increasing time intervals. The fineness of the capillary pores in sandcrete blocks promotes absorption of water by capillary attraction; hence, a measure of the rate of absorption provides a useful indication of the pore structure. If water is absorbed rapidly, it shows that the pores are either large or straight; if the absorption rate is slow, then the pores are small or not easily accessible.

Thermal properties

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. In predicting the thermal performance of buildings, it is necessary to consider the dynamic effects of this variation. The thermal properties investigated in this study are:

Thermal conductivity (k)

Thermal conductivity is a measure of the quantity of heat that flows through a material per unit time. Thermal conductivity of most materials is found to change with the presence of impurities or admixtures. From the Fourier’s steady-state heat conduction equation, thermal conductivity is determined as

$$k = \frac{Q}{A}\frac{\Delta x}{\Delta T} \qquad \text{......... (4)}$$

Specific heat capacity (c)

It is a measure of the thermal storage capacity of the material. The specific heat capacity of a sandcrete block indicates the relative amount of heat energy the wall built with it is capable of storing per unit mass. Walls with high specific heat capacity can store more energy, have a larger thermal lag, and thus, generally be more effective for thermal storage and peak load shifting. This time lag effect contributes to shifting demand to off-peak periods and improves overall thermal efficiency. Specific heat capacity of the sandcrete block is determined from the classical heat capacity equation

$$c = \frac{Q}{m\,\theta} \qquad \text{..(5)}$$

Thermal diffusivity (α)

Thermal diffusivity is a measure of the material’s ability to undergo a temperature change. It describes the heat transfer capability of a material relative to its heat storage ability. Materials with a low thermal diffusivity have a slow rate of heat transfer relative to heat storage. Thermal diffusivity is obtained through the relation

$$\alpha = \frac{k}{\rho\,c} \qquad \text{...(6)}$$

Thermal effusivity (β)

Thermal effusivity represents 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 materials. Materials with high thermal effusivity cannot hold heat long enough because heat will quickly dissipate from its surface as soon as surrounding temperature drops. On the other hand, materials with low thermal effusivity (but with high thermal inertia) will hold heat much longer. Thermal effusivity is calculated as

$$\beta = \sqrt{k\rho c} \qquad \text{.....(7)}$$

RESULTS AND DISCUSSION

Necessary precautions were taken at every stage and for each procedure to minimize error as much as possible. The results are presented in graphical form in most cases.

Effect of RHA substitution on compressive strength

Figures 2a and b show the variation of compressive

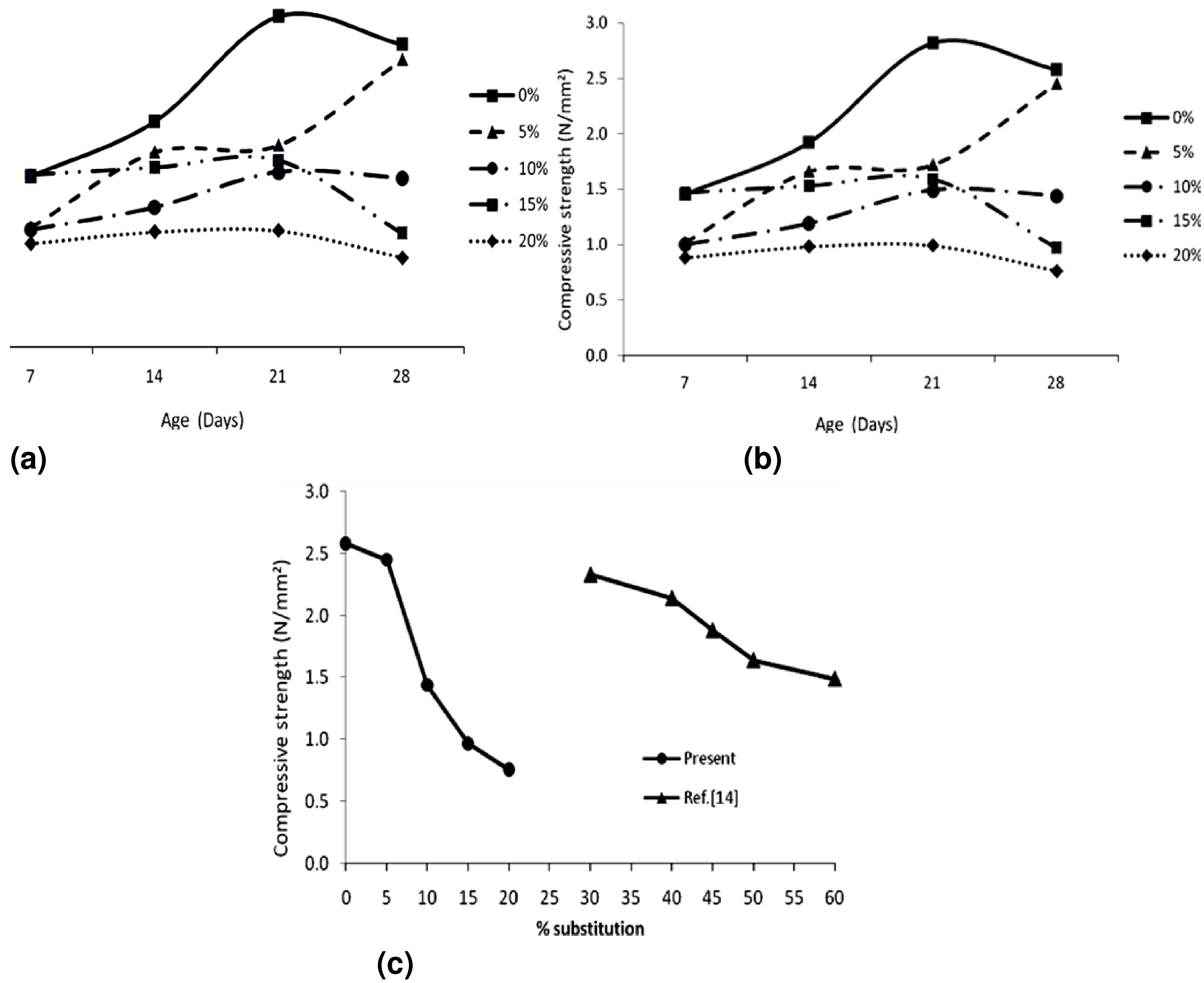


Figure 2. Plot of compressive strength against (a) percentage RHA substitution; (b) age of sandcrete blocks; (c) percentage RHA substitution.

strength with percentage RHA content for the mix proportion used. The graphs show that the blocks decrease in strength as the RHA percentage content in the mix increases. It shows that RHA does not appreciably enhance the compressive strength of the conventional sandcrete block. The reduction in strength could be attributed to the fact that the partial replacement of cement with the RHA caused a reduction in the quantity of cement in the mix available for the hydration process and hence a reduction in the formation of the stable strength- producing cementitious compounds. The difference in the chemical composition of RHA and of cement it replaced is also a major factor. As shown in Table 1, the major constituent of RHA is silica (SiO_2) while that of cement is quicklime (CaO). On mixing with water, the silica produced in solution reacts with calcium to produce calcium fly ash (C_3H) which is further hydrated in the reaction with water to produce tobermorite (CSH) gel. The formation of CSH gel is responsible for slower rate of hydration of cement which commences after about 14 days and extends up to about 150 days after which the fly ash particles would almost be completely disintegrated.

Figure 2c shows the plot of the compressive strength against percentage RHA substitution for the 0-20% range considered in the present study and the plot for the 30-60% range investigated by Okpala (2003) for the 28-day-old blocks. Rather than the gradual decrease in the compressive strength observed in Okpala (1993), the decrease is sharp in the present study. At 20% RHA substitution, the compressive strength has reduced drastically to 29.5% in the strength of the control block. But in Okpala (1993), at 60% RHA substitution, the strength is just 39% of that of the control block. This means that the strength of the blocks produced with RHA used by Okpala within the 5-20% range would be higher

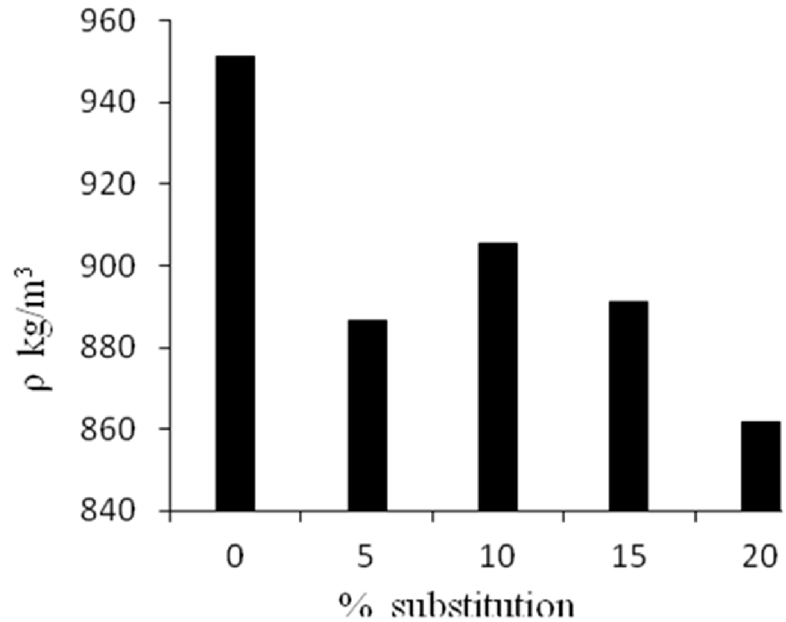


Figure 3. Plot of density against percentage RHA substitution.

than that obtained in the present study. This may be due to differences in the physical properties of the RHA used. These properties depend on the source location, harvest time, rice husks processing and burning procedure used. The differences in block size and block manufacturing process could also be some of the possible reasons.

Effect on density

The plot of density variation with the percentage increase in the RHA substitution after 28 days is shown in Figure 3. The plot indicates decrease in density with percentage increase in RHA substitution. Other data indicate that the density decreases with curing age. This means that partially substituting cement with RHA produces lighter sandcrete blocks.

Effect on porosity

The variation of porosity with percentage substitution of the RHA is presented in Figure 4. The results show that all the blocks with the admixture are more porous than that of the control (0%). Figure 4 shows a gradual increase in the value of porosity when only 5% RHA is added. But further addition of the admixture rapidly increases the porosity value. This increase in porosity may be as a result of trapped air bubbles that are interconnected. It can be concluded that sandcrete blocks with RHA blended cement is more porous, absorbs more liquid and hence could fail faster than those without admixture. This makes such type of block not suitable for areas prone to flood or with year-round rainfall like Niger Delta areas.

Effect on permeability

Figure 5 shows the variation of permeability with the percentage increase in RHA content. It is observed that partially replacing cement with RHA increases the permeability of the sandcrete block. The value of the permeability steadily increases with percentage increase in RHA content. The value is almost doubled for every 5% addition of RHA. This means that the inclusion of the admixture opens up the block in a way that encourages upflow of fluid. This rapid flow of water indicates that the pores are either large or straight.

Effect on sorptivity

It is observed in Figure 6a that the value of sorptivity of the sandcrete blocks gradually increases with the percentage content of RHA. This implies that blocks made with cement partially replaced with RHA are not suitable for drainage channels construction but could be useful for partitioning of building spaces. The results of the present study were compared with the experimental data of Sampaio et al. (2003) on sandcrete blocks produced with Portuguese RHA (Figure 6b). The plot shows that while the sorptivity value of the blocks produced with cement and blended with Nigerian RHA increases, that of the blocks produced with the Portuguese RHA blended cement decreases as the

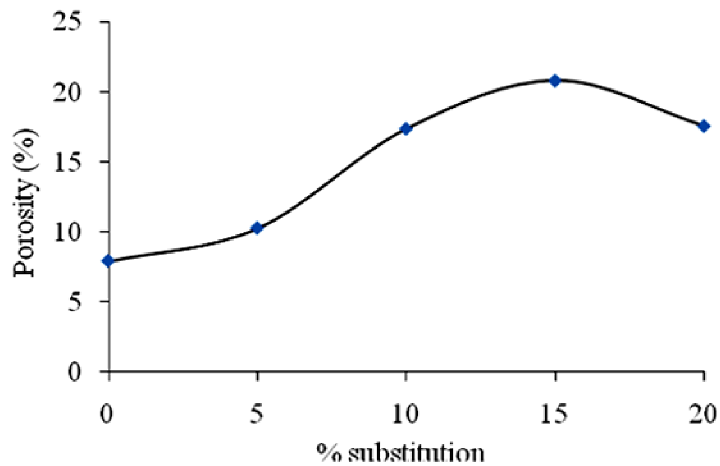


Figure 4. Plot of porosity against percentage RHA substitution.

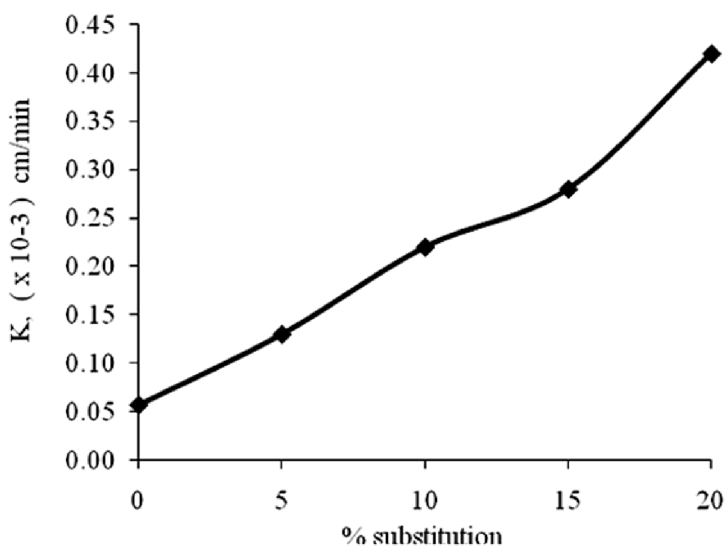


Figure 5. Plot of permeability against percentage RHA substitution.

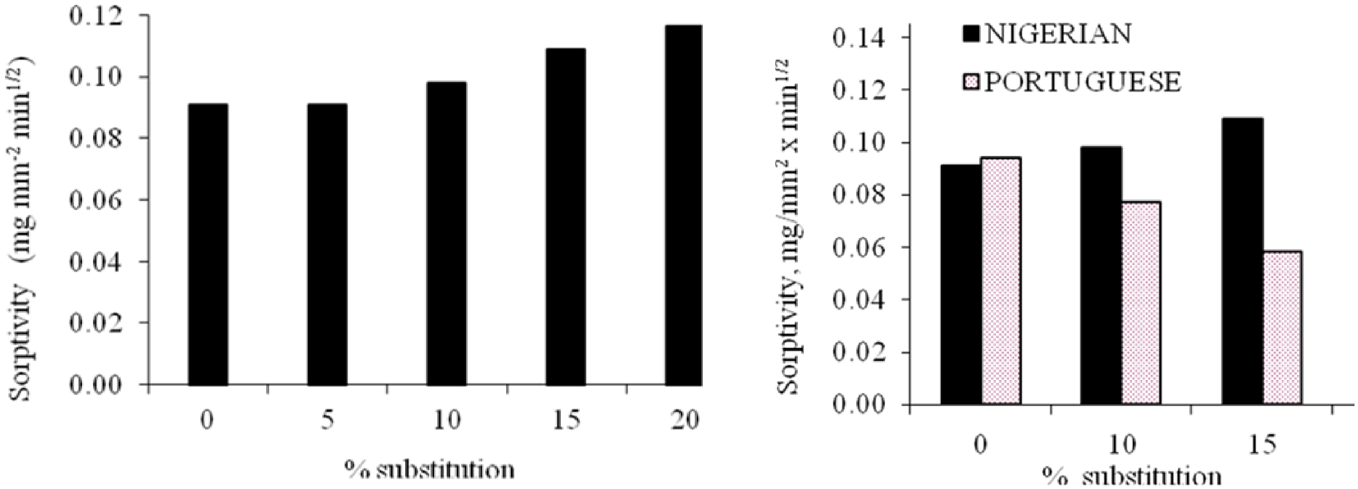
percentage RHA content increases. The implication of this is that the substitution of cement with the Nigerian RHA forms a material structure that encourages liquid absorption as the RHA content increases whereas the blocks produced with the cement partially replaced with the Portuguese RHA forms a more compact structure that reduces absorption of liquid.

Effect of temperature change on the hygrothermal properties

As the temperature of the block increased above the room temperature, it was observed that the block absorbed water at a faster rate. This means that the higher the temperature around a building, the greater the rate of liquid absorption.

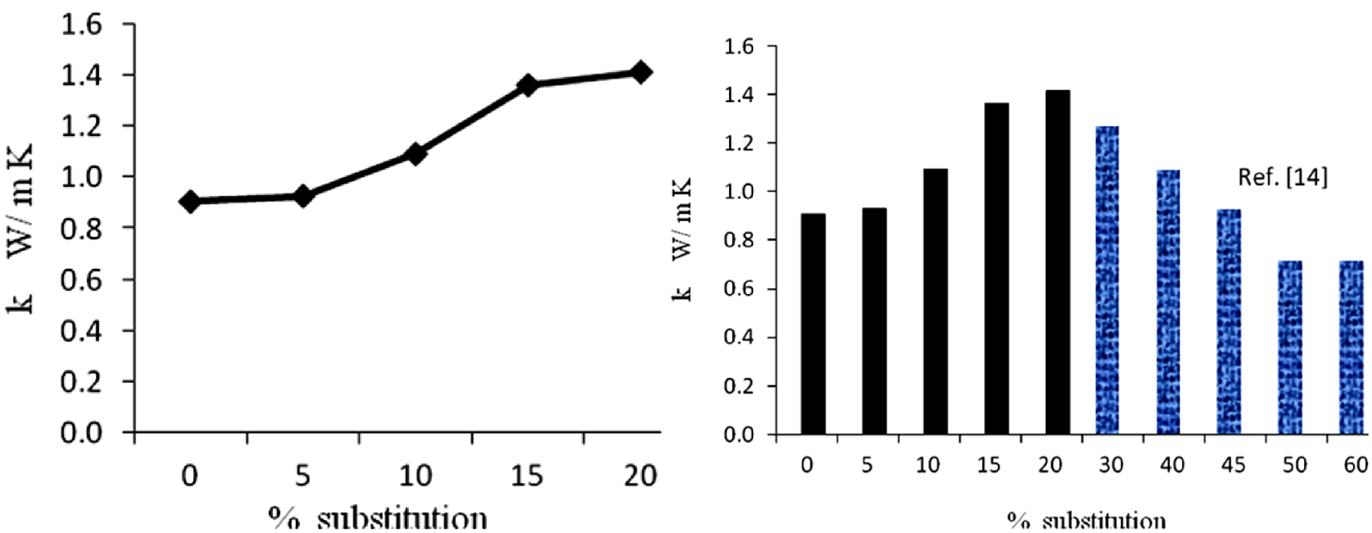
Effect on thermal conductivity

The thermal conductivity of the sandcrete blocks is determined using the Guarded Hot Plate Box conforming to the requirements of ASTM C177 (American Society for Testing and Materials, 2004). The effect of the substitution of RHA on the thermal conductivity of the sandcrete blocks is presented in Figure 7a. The value of the thermal conductivity increases with the percentage RHA content. The higher k value obtained when cement was partially substituted with RHA may be as a result of the products of reaction of RHA with cement in the mix during the hydration process. The products that tend to increase the k value of the block despite its increased porosity are subject to further investigation. For a hot climate, higher thermal conductivity block is undesirable for construction as it increases the cooling/heating load



(a) (b)

Figure 6. Plot of sorptivity against (a) percentage RHA substitution;(b) percentage RHA substitution for Nigeria and Portugal.



(a) (b)

Figure 7. Plot of thermal conductivity against percentage RHA substitution for (a) 0-20; (b) 0-60.

in the building space.

The plot of the 0-20% RHA substituted range investigated in this study and the 30-60% range of Okpala (1993) in Figure 7b, shows an interesting variation. The value of the thermal conductivity is found to increase with percentage RHA substitution up to a maximum at 20% (or possibly 25%) and then decreases thereafter as the percentage RHA increases. The initial increase in k value with increase in the percentage RHA content may be as a result of higher k values of the products of reaction between RHA and cement. However, as more RHA is added to the mix and the quantity of cement reduces, the inert nature of the excess RHA probably caused the thermal conductivity to reduce. The complex structure of the block material may be a contributing factor. Also, being a non-metallic solid, heat is transferred via lattice vibrations which is characterised by much variability.

Effect on specific heat capacity

The determination of the specific heat capacity of the sandcrete blocks is carried out using the adiabatic calorimetric technique. The plot of the specific heat capacity against percentage RHA substitution in Figure 8, indicates that all the blocks with the admixture have slightly lower values (except the 5% block) than that of the control block; hence, lower heat energy storing capacity and lower thermal mass. In tropical environment, these blocks will lose heat gained during the day faster, thereby

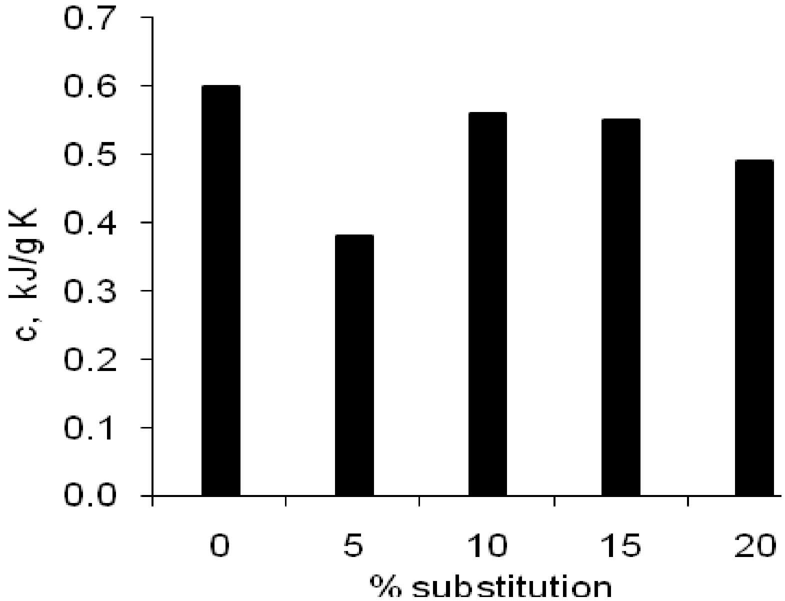


Figure 8. Plot of specific heat capacity against percentage RHA substitution.

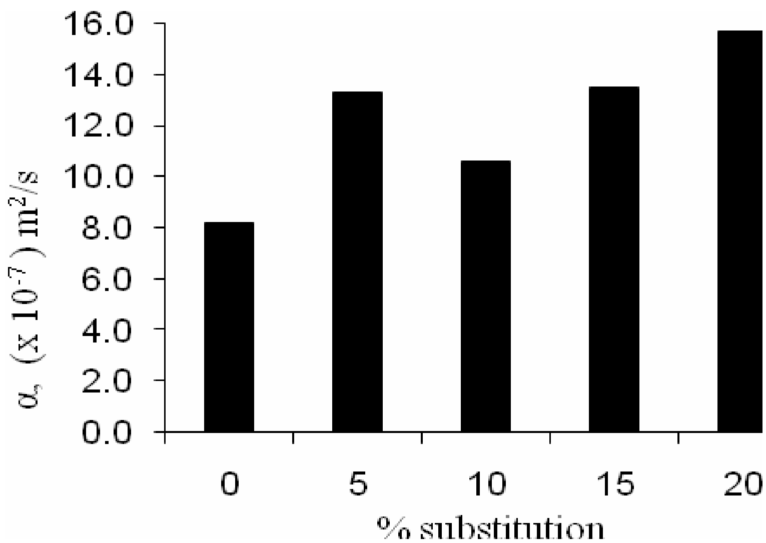


Figure 9. Plot of thermal diffusivity against percentage RHA substitution.

making the building space comfortable for early sleep.

Effect on thermal diffusivity

In a manner slightly consistent with the thermal conductivity variation, Figure 9 shows that the values of the thermal diffusivity of all the blocks is higher than that of the control. The reducing values of both density and the specific heat capacity with RHA content caused the thermal diffusivity value to increase with the percentage RHA substitution. In effect, sandcrete blocks made with RHA-blended cement will undergo a faster temperature change or allow more rapid heat flow through them than those without the admixture.

Effect on thermal effusivity

The thermal effusivity value in Figure 10 fluctuates as the percentage RHA content increases. The β values of most of the blocks containing RHA are more than those of the control block. The β value of the 15% RHA block, which is the largest, is 17.5% more than that of the control block. In practical terms, the higher thermal effusivity of the blocks made with RHA-blended cement increases its ability to conduct heat away from the building space faster thereby reducing the air-conditioning load, and

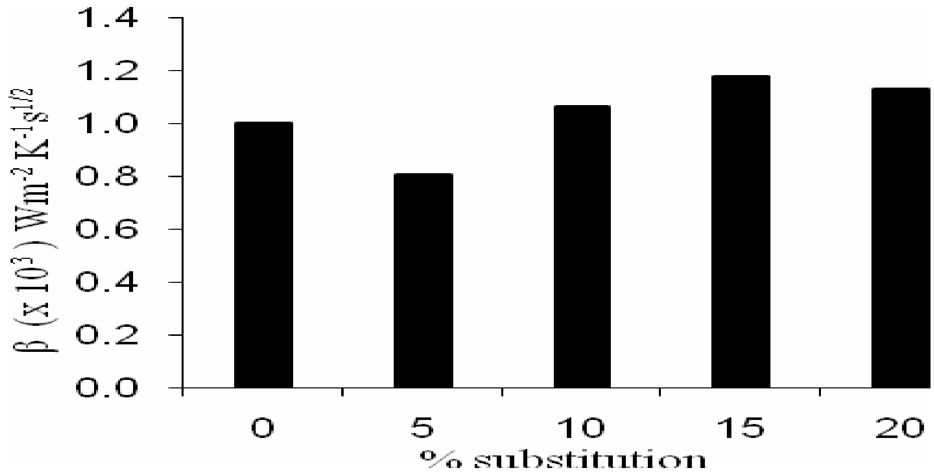


Figure 10. Plot of thermal effusivity against percentage RHA substitution.

consequently increasing the period of thermal comfort.

It is worthy of note that, despite much effort in minimizing possible areas of errors, the observed thermal test results may have some influences which might likely be caused by two factors: differences in heat transfer pathways and differences in sample homogeneity. There may be inhomogeneous intrasample effects, contact resistance effects and differences in the heat transfer process through the sample which could affect the test results. Though the particle sizes of RHA and OPC are the same, for a given volume of sample, changes in the particle size distribution of both materials in the mix with sand may lead to changes in the number of particle-particle and particle-gas interfaces as well as the interstitial voids and the volume of those voids. A wider variety of heat transfer pathways are available to the penetrating heat wave through a sample with broader particle size distribution. This also could, by extension, be applied to the hygrothermal properties due to the phenomenon of flowing water's 'path of least resistance'. Nevertheless, since the test results agree to some extent with the internationally-accepted standard values available in the literature, it would appear that these factors did not have any significant effects.

Conclusions

The main conclusions derived from this investigation are as follows:

1. As the percentage RHA content in the mix increases, the compressive strength of the sandcrete block decreases. Hence, RHA does not enhance the compressive strength of the conventional sandcrete block with 1:6 cement-sand mix.
2. The addition of RHA into the cement-sand matrix produces sandcrete blocks of lighter weight. The density of the blocks decreases as the percentage RHA content in the mix increases.
3. A sandcrete block with RHA-blended cement is more porous than a pure sand-cement block. Its permeability increases with RHA content and ambient temperature.
4. The products of the reaction between the rice husk ash and the ordinary Portland cement tend to initially slightly increase the thermal conductivity of the block. However, as the percentage RHA content increases beyond 20%, the thermal conductivity reduces with increasing RHA content.
5. The sandcrete blocks made with RHA-blended cement have lower heat storage capacity and lower thermal mass than those without the admixture.
6. Due to the increasing values of thermal diffusivity with increasing RHA content, blocks containing RHA tend to undergo faster temperature change as heat flows through them more rapidly.
7. The increased thermal effusivity of the sandcrete block with RHA content is an advantage over pure sandcrete block as it improves its ability to conduct heat away from the building space faster thereby reducing the air-conditioning load and hence increasing the period of human thermal comfort.

The practical significance of this study is that the strength, liquid-absorption and heat transfer characteristics of the sandcrete 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. Consequently, 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.

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Abbreviations: BS, British standard; **OPC,** ordinary Portland cement; **RHA,** rice husk ash; **A,** area of material perpendicular to heat flow (m^2); **A″,** cumulative infiltration; **c,** specific heat capacity (J/g K); **H,** height of liquid rise after time t (m); **h,** hydraulic head (m); **k,** thermal conductivity (W/m K); **K,** permeability (cm/min); m, mass of the sample (kg); **P,** percentage substitution of admixture (%); **Q,** heat flux (W); **S,** sorptivity ($m/s^{½}$); **ΔT,** temperature change (K); **T,** time taken for liquid to rise (s); **V,** volume of material sample (m^3); **V_f,** volume of water absorbed (m^3); **Δx,** sample thickness (m); **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); **υ,** porosity of the material (%).

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