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(RESEARCH ARTICLE)

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Production of geopolymer-based Sandcrete block using coal ash as partial replacement of OPC

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Abstract

This study investigated the production of Sandcrete blocks in Nigeria, focusing on the potential of coal ash as a partial replacement for Ordinary Portland Cement (OPC). With Nigeria facing significant housing deficits due to rapid population growth and economic challenges, the construction sector has shown modest growth, necessitating innovative approaches to building materials. Sandcrete blocks, a primary construction material in Nigeria, are traditionally made using OPC, whose production contributes significantly to greenhouse gas emissions. This research aims to compare the strength characteristics and benefits of Sandcrete blocks produced with coal ash, highlighting its eco-friendly properties and lower CO_2 emissions.

The study identifies various challenges within the block molding industry, including variability in raw materials, limited awareness of geopolymer-based alternatives, and the need for standardized production practices. Through laboratory experiments, including sieve analysis, dimension tests, and compressive strength assessments, the research seeks to establish optimal mix designs that enhance block quality while reducing costs. The findings underscore the importance of adopting sustainable materials in construction, contributing to environmental preservation and addressing the economic constraints faced by builders in Nigeria. Ultimately, this research provides insights into improving the Sandcrete block production process, promoting coal ash utilization, and enhancing the overall quality and affordability of construction materials in Nigeria.

Keywords: Coal Ash; Sandcrete Blocks; Ordinary Portland Cement (OPC); Geopolymer

1. Introduction

Population growth has led to increased demand for housing in developing countries worldwide (Nigeria). The rapid growth in population has caused a significant construction gap. The construction sector in Nigeria experienced growth of 4.8% in the first quarter of 2022 after faltering for around two years due to economic difficulties and the resulting effects of COVID19. From 2025 to 2028, the industry is expected to expand at an average annual growth rate (AAGR) of roughly 3% (Nigeria construction market report). This has also helped in the increased demand of building materials and the development and establishment of many construction industries. One of the key materials in the Nigeria building sector is the Sand Crete block, which is produced primarily from the mixture of sand, cement and water in different proportions which are then molded into different sizes using different sizes of molds (Abdullahi, 2006, Afolayan and Daramola, 2008, Ogunjiofor, et al, 2024)

In this study we will look into production of Sand Crete blocks using sand, water and a partial replacement of Ordinary Portland Cement (OPC) with coal ash as the cement.

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As we all know the production of Sand Crete blocks requires the use of OPC whose production involves the emission of CO2 into the atmosphere which causes global warming. The overall influence of ordinary Portland cement (OPC) production to the emission of greenhouse gases is projected to be over 1.35 billion tons per year, or almost 7% of the total amount of greenhouse gases released to the earth's atmosphere (Ogunjiofor, et al, 2023a).

It's crucial to prioritize sustainable building materials. Alternative building materials are developed by modifying or improving existing materials suitable for housing (Anigbogu,1999). According to (Mehta 2002), producing ecologically friendly concrete and lowering carbon dioxide emissions into the atmosphere can be accomplished with less energy and natural resource consumption. Industrial ecology is how he categorized these transient tasks.

According to (Anosike, 2011, Baiden and Tuuli, 2004, Anosike and Oyebade 2012), sandcrete technology, also known as block molding, is becoming a crucial component of infrastructure development in all countries. Nigeria's building industry relies heavily on block molding, making it one of its main industrial areas. Almost every local government area has a block production factory, whether small or large. Block production can be profitable with correct management. There are no established guidelines for producing blocks in Nigeria, leading to the emergence of numerous block molding firms to meet construction and infrastructure needs (Uzoamaka, 1977), (Oyekan and Kamiyo, 2008), (Ogunjiofor, et al, 2023b). In practice, average technical expertise, materials, tools, machinery and all necessary infrastructures are all that are required to start producing blocks either for private use or for commercial purpose. (Okoli et al,2008) argue that apart from manufacturers and entrepreneurs who are producing blocks strictly for business purposes, quite a number of contractors and clients are also making blocks for use on their projects.

Such contractors and clients employ block makers; provide them with all necessary materials and logistics to produce the block requirements of their building or infrastructural projects, with the sole aim of minimizing production cost and ensuring quality (Oluremi, 1990). Sandcrete blocks comprise of natural sand, water and binder. (Ogunjiofor and Ayodele, 2023) added that cement, as a binder, is the most expensive input in the production of sand Crete blocks. This has necessitated producers of sandcrete blocks to produce blocks with low OPC content that will be affordable to people and with much gain.

The poverty level amongst West African Countries and particularly Nigerian has made these blocks widely acceptable among the populace so as to minimize the cost of construction works. The improper use of these blocks leads to micro cracks on the walls after construction. The use of alternative cheaper local materials as stabilizer will greatly enhance the production of sandcrete blocks with the desired properties at low cost. It will also drastically reduce the cost of production and consequently the cost of construction works. A survey by raw materials research and development Council of Nigeria on available local building materials reveals that certain building materials deserve serious consideration as substitute for imported ones(El-Mahllawy, 2008; Ogunjiofor, 2020; Ogunjiofor, et al, 2023c). Few of these materials includes: cement / lime stabilized bricks /blocks, sundried (Adobe) soil blocks, burnt clay bricks/ blocks, cast in-situ walls, rice husk ash (RHA), mud and straw, lime and stonecrete blocks.

Some of the problems faced in construction today can be linked to this masonry unit, which is a major construction material. Poor quality of building materials is one of the factors responsible for the collapse of buildings. (Hornbostel, 1991) posit that it is therefore imperative to ensure that the production of blocks and bricks are not only standardized but regulated and adequately supervised to ensure quality. (Oyekan and Kamiyo, 2011) added that this comes with great challenge in Nigeria due to the large size of the block manufacturing industry coupled with the fact that most of those involved in block production are not registered and are inadequately trained.

Every industry has its own prospects and peculiar challenges which if identified and appropriately addressed will help bring about improvement for developmental purposes (Okpala, 1993), (Oyekan, 2001), (Rodriguez et al, 2008), (Umaru et al, 2012). Producing good quality blocks comes with quite a number of challenges and prospects. It is therefore important to identify these prospects and challenges with a view to improving and raising the standard of our block industry in Nigeria for the overall benefit of the construction industry.

The high and increasing cost of constituent materials of sandcrete blocks has contributed to the nonrealization 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. (Oyekan, 2001) argued that over the past decade, the presence of mineral admixtures in construction materials have been observed to impart significant improvement on the strength, durability and workability of cementitious products. The author added that in the areas prone to flood, hydrothermal properties of the building's construction materials are of importance (Ferone, et al, 2011; Agunwamba, et al, 2016; Oyekan and Kamiyo, 2008; Alejo, 2020; Odeyemi, et al 2015)

Also, energy requirements for residential and commercial buildings are known to be influenced by building design and by the materials used (Nair et al, 2006) posit that 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. However, (Obi et al, 2023) suggested that Jute fibre 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 is beneficial to adopt 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. 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) observed that the mechanical resistance of sandcrete blocks obtained when unground ash resulted to increase in performance over the classic mortar blocks. Their studies on Senegalese RHA also revealed that the use of ungrounded RHA enabled production of lightweight sandcrete block with insulating properties at a reduced cost. 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.

The experiment showed 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. Hence, as a result of 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 reducing 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.

2. Material and methods

2.1. Material

The following is a list of the material that was used for the experiment.

2.1.1. BINDER

The coal ash in Figure 1 which was used for this research work was obtained from Ezimo Coalfield in Enugu state. The OPC used (BUA Portland Limestone Cement) was gotten from Mr. Ezennaya's shop at Amamputu, Uli Anambra.

For the test the percentage replacement used for each the binders listed above are (30% of OPC and 70% of Coal ash).

Figure 1 Coal Ash

2.1.2. FINE AGGREGATE

The fine aggregate in Figure 2 which was used for this experiment was gotten form Nonso Block Industry, UmuomaUli, Anambra State.

Figure 2 Batching done for the OPC, Fine Aggregate and the Coal Ash (Note: The Coal Ash has already been mixed with the Calcium Chloride)

2.1.3. WATER

For the mixing of the mortar and the curing of the block samples, the water used for the experiment, for the hydration of the Sand Crete block samples was gotten from the Civil Engineering laboratory.

2.2. ALKALINE ACTIVATORS

Alkali activators are chemical compounds or mixtures used in activating the reaction between AluminoSilicate materials (such as fly ash, slag, or coal ash) and alkali sources (such as sodium hydroxide, NaOH) to form alkali-activated materials or geo polymers. These activators provide the necessary alkaline environment for the dissolution and subsequent polymerization of the AluminoSilicate precursors, resulting in the formation of a hardened material with desirable properties. In the case of alkali activators using NaOH (sodium hydroxide) and Na_2SiO_3 (sodium silicate), they work together to provide the necessary alkalinity and reactive species for the formation of alkali-activated materials. Sodium hydroxide (NaOH) is a strong base that provides the alkalinity required for the activation process. We got the alkali solutions from a Favorite Chemicals before head bridge Onitsha.

2.2.1. Preparation of the alkali activators

To prepare alkali activators using sodium hydroxide (NaOH) (Figure 3) and sodium silicate (Na_2SiO_3), the following procedures were observed.

Sodium Hydroxide (NaOH)

- We measured the desired quantity of NaOH needed, using the proper mix ratio for Na_2SiO_3:
- NaOH of 2:2.5.
- Add the measured amount of NaOH into a container or mixing vessel.
- Stir well with 1kg of water.
- Continue stirring until the NaOH pellet dissolves completely in water.
- Allow the solution to rest for about 24hrs to ensure complete dissolution and reaction

Figure 3 Sodium Hydroxide pellet

Sodium Silicate (Na_2SiO_3)

Using the mix ratio for Na_2SiO_3:NaOH of 2:2.5, we then measured the weight of Na_2SiO_3 (Figure 4) needed and then we mixed it with the NaOH after its left for 24 hours, then it is stirred well and then added to our cement and fine aggregate mix.

Figure 4 Sodium Silicate

2.2.2. Calcium oxide (CaO)

CaO (calcium oxide), also known as quicklime, plays a crucial role in cement production. It is one of the main components of cement and contributes to several important aspects of cement properties and performance. CaO in Figure 5 plays a vital role in the chemical reactions, binding, hardening, strength development, and durability of cement. It is an essential component that contributes to the performance and properties of sandcrete blocks. From our study and research, we found out coal ash had a very low quantity of CaO and will need 30% - 67% of CaO. Lime was gotten from a chemical vendor at Plateau State.

Figure 5 Calcium oxide

2.2.3. Calcium chloride (CaCl)

Calcium chloride as seen in Figure 6 is sometimes used in cement production or as an additive to cement to achieve specific effects. The use of CaCl in cement is not as common or widespread as other additives or admixtures. Its application is typically limited to specific situations where accelerated setting, cold weather performance, or early strength development is desired. Proper dosage and careful consideration of potential drawbacks are essential when utilizing CaCl in concrete mixes. Calcium chloride was also gotten from Favorite Chemicals before head bridge Onitsha.

Figure 6 Calcium chloride

2.3. Preliminary Test

2.3.1. Sieve Analysis

This test was carried out to determine the particle size distribution of each granular materials we used (Coal Ash and Fine Aggregate).

Equipment Used

- Gauging trowel
- Weighing balance
- Brush and scoop
- Drying oven
- Sieve shaker

Procedures Used in Carrying the Sieve Analysis Test for The Coal Ash and Fine Aggregate

- An oven dried sample of weight 1kg was poured into the top sieve as in Figure 7 which has the largest screen opening.
- Each of the sieve is stacked such that the one below has smaller openings than the one above, and then at the bottom is the pan.
- The samples were accurately weighed before they were poured into the shaker.
- After the shaking is done, the weight of the remaining samples left in each sieve is recorded and calculated.

Figure 7 Sieve analysis

2.4. Test on hardened sandcrete block

2.4.1. Compressive Strength of Sandcrete Block Test and Procedures

The compressive strength test gives us an idea of all the characteristics of the Sand Crete block. With the help of this test, we can check whether there was a proper mix of the binder and fine aggregate. Compressive strength is the ability of a material or structure to carry the loads on its surface without any crack or deflection. A material under compression tends to reduce its size, while in tension, size elongates.

The compressive strength of Sandcrete block depends on many factors such as water-cement ratio, cement strength, type of fine aggregate, and quality control during the production of block.

The blocks are repeatedly cured consecutively for about 4-6 days before use for better bonding.

Mathematical equations

Formula for compressive strength test as in equation 1 is given as

$$F = \frac{P}{A} \quad , \ldots\ldots\ldots\ldots\ldots.. \quad (1)$$

Where;

- F = The compressive strength (MPa)
- P = Maximum Load (or Load Until Failure) to the Material (N)
- A = A cross-section of the area of the material resisting the load (mm^2)

2.5. Calculation of materials

2.5.1. Finding the self-weight of each material used in one mold of the spacemen;

Mix ratio = 1:6

Size of mold = 450×127×225mm

Percentage replacements in the binders;

OPC = 30%, Coal Ash = 70%

Find the mass of each sample from density equation in equation 2 given below.

$$Density = \frac{Mass}{Volume} \qquad \dots\dots\dots \; (2)$$

Density =2178.03 kg/m^3 mass =?

Volume = 0.45×0.127×0.225 = 0.01286m^3

∴ Mass = 2178.03 x 0.01286 = 28.01m^3

ii. To find the weight of each material using the mix ratio

Sum of mix ratio = 1 + 6 = 7

$$Fine\ aggregate = \frac{6}{7} \times 28.01 = 24.01kg$$

$$Binder\ (OPC\ \&\ Coalash) = \frac{1}{7} \times 28.01 = 4.00kg$$

$$OPC = \frac{30}{100} \times 4 = 1.2kg$$

$$Coal\ Ash = \frac{70}{100} \times 4 = 2.8kg$$

2.5.2. Water to cement ratio

Adopting a water-cement ratio of 0.5 as stated in equation 3, we have

$$Weight\ of\ water\ = \frac{w}{4}\ = 0.5 \qquad \dots\dots \; (3)$$

2.5.3. To Find the Quantity of Alkaline Activators

Sodium hydroxide (NaOH) and sodium silicate (na$_2$sio$_3$). which was used at a ratio of 2:2.5 for Na_2SiO_3 and NaOH respectfully.

Calculation for NaOH

For every mole of sodium hydroxide, we are to use 40g weight of NaOH mixed with 1 liter of water. But for our tests it is advised we use between 8mols to 16mols ratio of NaOH

Note: for any mole of NaOH mix it must be dissolved using 1 liter of H_2O. For this practical we used 10mols of NaOH mixed with 1 liter of water and then left for 24 hours before use, after which the weight was taken and the mix ratio of 2:2.5 was used to get the corresponding values of Na_2SiO_3 which was mixed directly with the coal ash.

- 1mol (NaOH) = 40g

- 10mols = 10 x 40 = 400 = 0.4kg
- Water used = 1 liter = 1kg
- Total weight of NaOH used = 1.4kg

After getting the NaOH mix, we then use the ratio 2:2.5 to find the Na_2SiO_3 weight. Na_2SiO_3: NaOH = 2:2.5

First to find the general weight

Sum of mix ratio = 2 + 2.5 = 4.5

$$\frac{2}{4.5} \times x = 1.4kg$$

x = 3.15kg

To get the self-weight of Na_2SiO_3

$$\frac{2.5}{4.5} \times 3.15 = 1.75kg$$

2.5.4. To find the quantity of Calcium Oxide (CaO) and Calcium Chloride ($CaCl_2$) used for each spaceman

Calcium Oxide (CaO)
It was recommended we use 30% weight of the binder to get the quantity of CaO for the experiment

Therefore, to get the 30% 0f CaO

Weight of the binder = 4.00 kg

30% of 4.00 kg gives

$$\frac{30}{100} \times 4 = 1.2kg$$

Weight of CaO used = 1.2kg

Calcium Chloride (CaCl2)
The weight of $CaCl_2$ used was 2% of the weight of the binder (Coal ash)

Weight of the coal ash = 4 kg

2% of 6.96 kg gives

$$\frac{2}{100} \times 4 = 0.08kg$$

Weight of $CaCl_2$ used = 0.08kg

Note: to mix the CaO and $CaCl_2$ with coal ash, CaO was mixed with dry coal ash properly for about 3 – 5mins. While $CaCl_2$ was added last after all chemical and materials have been mixed properly.

2.6. Production process of geopolymer-based sandcrete

2.6.1. Blocks

Using a 1:6 mix ratio of fine aggregate and a partial replacement of the binders (i.e. coal ash and OPC), the required amounts of fine aggregate, Coal Ash, OPC and the chemicals were weighed according to Table 3.2.

Following adequate mixing, the alkaline activator (sodium hydroxide) was in the water and allowed to sit for 24 hours. The resulting measurement was obtained using the computation that was requested. After the dry mortar and the alkaline activators were well mixed, and a small amount of water was added according to the water to cement ratio. Afterward, the mold was greased in other to facilitate the easy removal of the mix, following the proper mixing of the mortar. The sandcrete mix is carefully placed into the mold and firmly compacted to eliminate air pockets, and by carefully demolding, the spacemen were then cured by sprinkling water on the spacemen twice a day for four consecutive days.

2.7. Equipment Used for Production of Sandcrete Blocks

- Gauging trowel
- Shovel
- Weighing balance
- Three separate containers for mixing each of the required chemicals
- Block mold (Figure 8)

Figure 8 Block mould

2.8. Quantity of material used

Table 1 Quantity of material used for one spaceman

Materials	Quantity Used
Fine aggregate	24.01
OPC	1.2
Coal Ash	2.8
NaOH	1.4
Na_2SiO_3	1.75
CaO	1.2
$CaCl_2$	0.08

Figure 9 Processing of the sodium hydroxide

Figure 10 Slump test

3. Results and discussion

Here we'll outline the results, analysis and interpretation of the data's obtained from the practical. The data are listed in tabular form in accordance to specific value, readings and calculation gotten from the test results.

3.1. Sieve analysis

The sieve analysis was conducted for the Fine Aggregate and the Coal Ash used. Table 2 and Table 3 below shows the result of the sieve analysis test for Fine Aggregate and Coal Ash respectively.

Table 2 Sieve analysis test result for 1.5kg of the fine aggregates used

Sieve No.	Weight retained (kg)	% Retained on sieve	Cumulative % retained	% Finer
8	0.05	3.33	3.33	96.67
10	0.05	3.33	6.66	93.34
12	0.15	10.00	16.66	83.34
20	0.45	30.00	46.66	53.34
30	0.26	17.33	63.99	36.01
40	0.34	22.67	86.66	13.36
80	0.15	10.00	96.66	3.34
Pan	0.05	3.33	99.99	0.01

The Sieve Analysis was conducted on a 1.5kg soil sample to determine the particle size distribution of the fine aggregate. The weight retained on each sieve was recorded. The sieve sizes used were 8, 10, 12, 20, 30, 40, 80, and pan. The mass retained on each sieve was as follows: 0.05kg, 0.05kg, 0.15kg, 0.45, 0.26kg, 0.34kg, 0.15kg and 0.05kg respectively. The weight of each sieve was assumed to be 0.40kg.

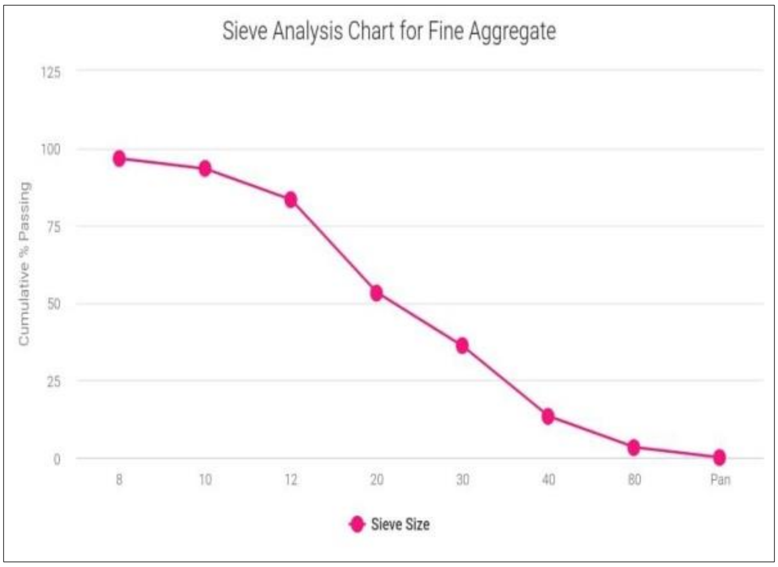

Figure 11 Sieve analysis chart for fine aggregate

The curve in Figure 11 shows a gradual decrease, indicating a well-graded fine aggregate distribution. This grading is crucial for ensuring adequate compaction, which also aided to the sandcrete blocks strength and durability.

Table 3 Sieve analysis test result for 1kg of Coal Ash

Sieve No.	Weight retained (kg)	% Retained on sieve	Cumulative % retained	% Finer
8	0	0	0	100
10	0	0	0	100
12	0	0	0	100
20	0	0	0	100
30	0.40	40	40	60
40	0.45	45	85	15
80	0.10	10	95	5
Pan	0.05	5	100	0

This Sieve Analysis was conducted on a 1kg soil sample to determine the particle size distribution of the fine aggregate. The weight retained on each sieve was recorded. The sieve sizes used were 8, 10, 12, 20, 30, 40, 80, and pan. The mass retained on each sieve was as follows: 0kg, 0kg, 0kg, 0kg, 0.40kg, 0.45kg, 0.10kg and 0.05kg respectively. The weight of each sieve was assumed to be 0.40kg

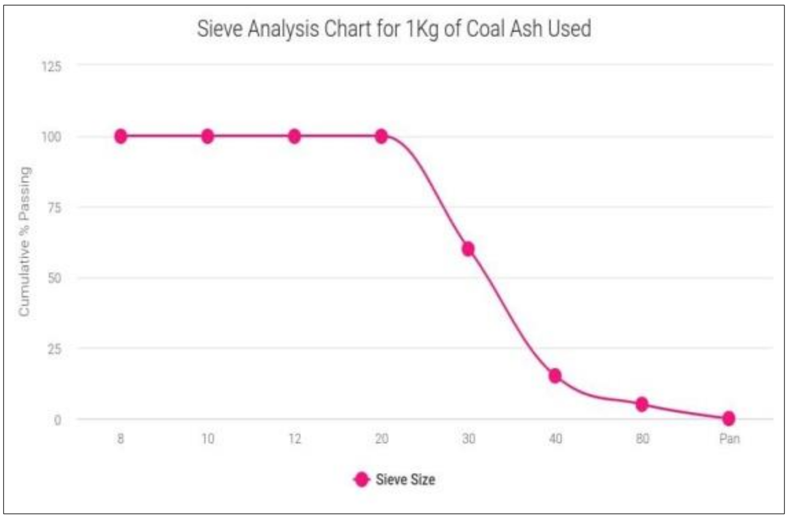

Figure 12 Sieve analysis chart for 1kg coal ash used

3.2. Slump test

Table 4 Table of slump test value

Mix No	Height of cone	Height of Slump Concrete	Slump value	Type of Slump
1	300mm	300mm	0	Zero Slump

From Table 4 above, it shows that the test was carried out to determine the workability of

Geopolymer-Based Sandcrete Block Produced Using Coal Ash as a partial replacement for OPC. The results obtained were well presented in Table 4. The slump test result showed that the mortar was workable for a sandcrete block.

3.3. Compressive strength test

Table 5 Final Compressive Strength Test Results after calculation

MIX NO.	Weight (kg)		Crushing load (KN)		TEST RESULTS (N\mm^2)	
	7th DAY	14th DAY	7th DAY	14th DAY	7th DAY	14th DAY
1	20.613	21.50	18 0.9	191.8	3.165	3.356
2	20.614	21.56	158.3	174.5	2.770	3.053
3	20.618	21.60	86.9	177.6	1.520	3.108

From Table 5 which has shown the compressive strength test of Geopolymer-Based Sandcrete Block Produced Using Coal Ash as a partial replacement for OPC for 7th and 14th day. After demoulding of the sandcrete block samples, it was left to cured by sprinkling water on the spacemen twice a day for four consecutive days. After the curing period the compressive strength test were conducted for day 7 and 14. The result shows that the average compressive strength our coal ash concrete for 28days ranged from 1.52 – 3.412 N/mm^2.

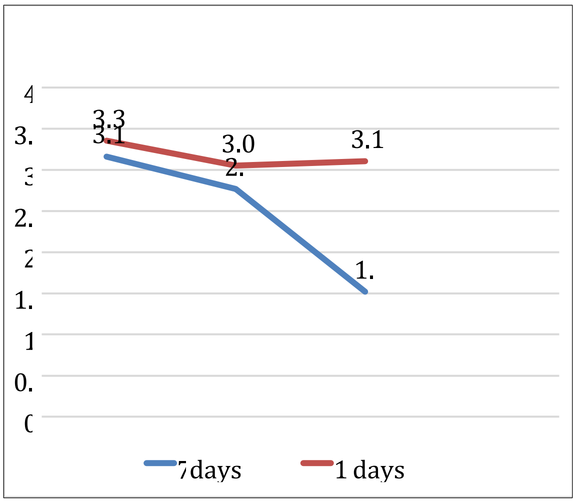

Figure 13 A line chart representation of compressive test result

3.4. Recommendation

After the whole practical, observation and test, Geopolymer-Based Sandcrete Block Production Using Coal Ash as a partial replacement for OPC at 70% & 30% respectively, showed a tremendous result. The results proved that production of sandcrete blocks using coal ash as partial replacement for OPC, is of same strength or slightly above that produced with just OPC.

4. Conclusion

The sieve analysis showed that the fine aggregate used for the sandcrete mix was well-graded. It also showed that the coal ash used was sieved to a well finer state, which aided to the proper mixing and molding of the block samples.

The reason for the slump test was to ensure that the water to cement ratio used for the sandcrete block production was to standard.

This result proves that sandcrete blocks can be produced using coal ash as a partial replacement for OPC, which in turn is better than blocks produced with just OPC.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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