PERFORMANCE EVALUATION OF THE MECHANICAL PROPERTIES AND CHARACTERIZATION OF PALM KERNEL SHELL ASH-AUTOAERATED SANDCRETE BLOCKS

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Abstract

Palm kernel shell ash (PKSA) is the remain from burnt palm kernel shells and it has pozzolanic properties. This research investigates PKSA as partial replacement of cement in autoclave aerated sandcrete blocks (AASB) production in developing nations like Nigeria where housing is still under pressure from rapid urbanization. Sandcrete blocks is still the most popular walling material in building construction. With the increase in price of cement as the major issue, alternative partial replacement of cement with PKSA which Nigeria is the highest producer of palm fruit in Africa as the replacement. This research consists of two main parts. First, purchase commercially produced sandcrete blocks from local manufacturers. Secondly, production of AASB with PKSA, replacing 0%, 2.5%, 5%, 7.5%, and 10% of cement with PKSA and aluminium powder. Microstructural and mineralogy analysis with techniques like scanning electron microscopy (SEM), energy dispersive x-ray (EDX), and x-ray diffraction (XRD) were carried out. Mechanical tests were carried out to measure compressive strength and density after different curing times—7, 14, 21, and 28 days. The results show that the maximum strength from the commercially produced sandcrete blocks which was obtained at 28 days is 0.74N/mm2 while the maximum strength of AASB with PKSA was achieved at 28 days is 2.1553N/mm2. This clearly shows that AASB with PKSA has better strength. This demonstrate that the AASB's performance can be further optimized to meet or surpass the necessary standards, even though the compressive strength values of the laboratory-produced blocks were slightly below the British Standard's 2.5 N/mm² minimum requirement.

Keywords

Palm kernel shell ash (PKSA), autoclave aerated sandcrete block (AASB), Scanning electron microscopy (SEM), Energy dispersive x-ray (EDX), X-ray diffraction (XRD)

1. INTRODUCTION

Global demand for sustainable building materials has increased, especially in developing nations like Nigeria where the housing and infrastructure sectors are still under pressure from rapid urbanization. Because they are inexpensive and simple to make, sandcrete blocks continue to be the most popular walling material for building construction nationwide. However, low-quality raw materials, irregular production methods, and environmental issues related to cement use frequently compromise their strength and durability. The main binder in sandcrete blocks, ordinary Portland cement (OPC), is produced with a lot of energy and adds a lot of greenhouse gas emissions. Despite being the mainstay of contemporary construction, cement contributes significantly to global carbon dioxide emissions, making up between 7 and 8% of all anthropogenic CO_2 emissions (Andrew, 2018). The ability of PKSA to enhance the performance of concrete and mortar has been shown in recent studies by Adesanya and Raheem (2009). Blocks made in the unorganized sector usually don't meet the minimum compressive strength requirement of 2.5 N/mm² (BS, 2011).

However, Inadequate curing procedures, poor mix design, and inferior materials are frequently blamed for these mechanical performance issues (Raheem et al., 2010; Olusola and Umoh, 2012). Optimizing replacement levels, comprehending long-term behavior, and developing engineering guidelines for real-world applications all require a thorough understanding of mechanical and microstructural properties.

A promising pozzolanic material that can partially replace cement in concrete and sandcrete formulations is palm kernel shell ash (PKSA), a by-product of the palm oil industry. Nigeria produces a significant amount of palm kernel shells every year and is one of Africa's top producers of palm oil (Agwu, 2025). Reactive silica and alumina found in the ash produced from these shells, when processed appropriately, can contribute to the pozzolanic reaction with calcium hydroxide from cement hydration to create more calcium silicate hydrate (C-S-H) gels. Strength, durability, and permeability can all be improved by this reaction, which also helps to densify the cementitious matrix.

The ability of PKSA to enhance the performance of concrete and mortar has been shown in recent studies (Adesanya and Raheem, 2009; Cheah and Ramli, 2011; Olusola and Umoh, 2012). However, the majority of the research that has already been done has mostly concentrated on mechanical characteristics like compressive strength, with little attention paid to the microstructural behavior of sandcrete blocks that contain PKSA. Optimizing replacement levels, comprehending long-term behavior, and developing engineering guidelines for real-world applications all require a thorough understanding of mechanical and microstructural properties.

The purpose of this study is to assess the mechanical and microstructural performance of sandcrete blocks that contain varying proportions of PKSA as a partial cement substitute. Apart from compressive strength, the morphological and compositional changes brought about by PKSA inclusion within the blocks was investigated using sophisticated analytical methods like Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDS), and X-Ray Diffraction (XRD).

2. MATERIALS AND METHOD

2.1 Materials

This study utilized a combination of traditional and supplementary cement materials to produce both commercial and lab-based sandcrete blocks. The chosen materials were selected for being easily accessible locally, structurally stable, suitable for autoclaving, and adhering to building regulations (Oyenuga and Shittu, 2018). The primary ingredients include BUA cement, portable water, palm kernel shell ash (PKSA) as a partial replacement for cement, stone dust as the fine aggregate, and aluminum powder to help aerate the mixture. Each of these materials influenced the mechanical and microstructural properties of the autoclaved aerated sandcrete blocks (AASBs) in unique ways. The following subsections will delve into their specific functions and descriptions.

2.1.1 Ordinary Portland Cement

Ordinary Portland Cement serves as the main binding agent in this research. Known for its reliable fineness and high early strength, this OPC also works well with pozzolanic materials like palm kernel shell ash (PKSA). The widespread use in construction across Nigeria and the compliance with relevant national and international standards were key factors for the selection. Notably, as shown in Figure 1 below, BUA Cement meets the Nigerian Industrial Standard (NIS) 444-1:2018 and ASTM C150 for Type I Ordinary Portland Cement. This standard ensures that the cement achieves the strength, durability, and resistance to harmful expansion that are crucial for structural applications.

Figure 1: Bua cement

2.1.2 Stone dust (fine aggregate)

ASTM C136 was used to check the physical properties of the stone dust as shown in Figure 2 below, focusing on things like particle size distribution, bulk density, and specific gravity. To keep our mix design consistent, the stone dust was sieved to remove any larger bits. A specific gravity test was carried out to evaluate the density of the material and see if it was suitable for making blocks. All the tests showed that the stone dust met the necessary grading standards for producing strong and structurally sound autoclaved aerated sandcrete blocks (AASBs).

Figure 2: Stone dust (Fine Aggregate)

2.1.3 Palm kernel shell ash (PKSA)

Palm Kernel Shell Ash (PKSA) was used as shown in Figure 3 below, to partially replace Ordinary Portland Cement (OPC) as supplementary cement material. The palm kernel shell ash (PKSA) was sourced from local palm oil processing plants, where they typically burn palm kernel shells under controlled conditions for fuel. To make sure everything burns completely and to reduce the chance of leftover carbon—which can interfere with the hydration process. In cement-based systems, close attention was placed on the combustion process. To enhance the reactivity and eliminate larger particles, the ash was filtered using a 75-micron sieve right after collecting it.

Figure 3: Palm Kernel Shell Ash (PKSA)

2.1.4 Aluminum powder

To achieve the lightweight and porous design of autoclaved aerated sandcrete blocks (AASBs), the aluminum powder as shown in Figure 4 below is mixed with the fine aggregate and binder as an aerating agent. This powder reacts with the mix's alkaline components, particularly calcium hydroxide [$Ca(OH)_2$], which releases hydrogen gas. As the gas bubbles expand and move throughout the mixture, they create small, evenly spaced voids. This controlled porosity is key because it helps lower the density of the blocks without significantly compromising the compressive strength, making them lighter and easier to handle. Plus, those air pockets

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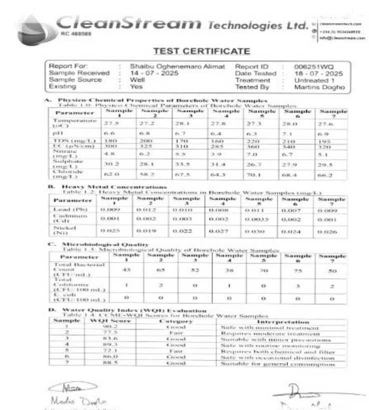
enhance the thermal insulation properties of the blocks, which is great for energy-efficient construction. Aluminum powder of 0.4% was carefully measured to ensure proper aeration without creating too many voids that could weaken the overall structure. The combination of PKSA and aluminum powder really boosts the structural integrity, workability, and sustainability of the AASBs produced in the lab.

Figure 4: Aluminium Powder

2.1.5 Water

Portable water was used for both mixing and curing as shown in the report below in Figure 5, ensuring it was free of any salts, organic materials, oils, or other contaminants that might disrupt the cement hydration or mess with the performance of the hardened blocks. The water quality was up to par with ASTM C1602 standards, which outline what mixing water should be like for making hydraulic cement concrete.

By using portable water, harmful compounds were kept from forming in the cement mix, which helped ensure more reliable results and consistent hydration. This was especially important for the pozzolanic reaction between calcium hydroxide and palm kernel shell ash (PKSA) that is crucial for the autoclaved aerated sandcrete blocks (AASBs) to gain strength and durability, all while maintaining a controlled chemical environment.



CleanStream Technologies Ltd.
RC 488588

TEST CERTIFICATE

Report For:	Shaibu Oghenemaro Alimat	Report ID	006251WQ
Sample Received	14 - 07 - 2025	Date Tested	18 - 07 - 2025
Sample Source	Well	Treatment	Untreated 1
Existing	Yes	Tested By	Martins Dogho

A. Physico-Chemical Properties of Borehole Water Samples

Table 1.0: Physico-Chemical Parameters of Borehole Water Samples

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Temperature (oC)	27.5	27.2	28.1	27.8	27.3	28.0	27.6
pH	6.6	6.8	6.7	6.4	6.3	7.1	6.9
TDS (mg/L)	180	200	170	160	220	210	195
EC (µS/cm)	300	325	310	285	360	340	320
Nitrate (mg/L)	4.8	6.2	5.5	3.9	7.0	6.7	5.1
Sulphate (mg/L)	30.2	28.1	33.5	31.4	26.7	27.9	29.5
Chloride (mg/L)	62.0	58.2	67.5	64.3	70.1	68.4	66.2

B. Heavy Metal Concentrations

Table 1.2: Heavy Metal Concentrations in Borehole Water Samples (mg/L)

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Lead (Pb)	0.009	0.012	0.010	0.008	0.011	0.007	0.009
Cadmium (Cd)	0.001	0.002	0.003	0.002	0.0035	0.002	0.001
Nickel (Ni)	0.025	0.019	0.022	0.027	0.030	0.024	0.026

C. Microbiological Quality

Table 1.3: Microbiological Quality of Borehole Water Samples

Parameter	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7
Total Bacterial Count (CFU/mL)	45	65	52	38	70	75	50
Total Coliforms (CFU/100 mL)	1	2	0	1	0	3	2
E. coli (CFU/100 mL)	0	0	0	0	0	0	0

D. Water Quality Index (WQI) Evaluation

Table 1.4: CCME-WQI Scores for Borehole Water Samples

Sample	WQI Score	Category	Interpretation
1	90.2	Good	Safe with minimal treatment
2	77.5	Fair	Requires moderate treatment
3	83.6	Good	Suitable with minor precautions
4	89.3	Good	Safe with routine monitoring
5	72.1	Fair	Requires both chemical and filter
6	86.0	Good	Safe with occasional disinfection
7	88.5	Good	Suitable for general consumption

Figure 5. Water

2.2 Methods

2.2.1 Sample collection and mix design

In this study, close look was taken at the two kinds of block samples to see how autoclaved aerated sandcrete blocks (AASBs) made in the laboratory stack up against those locally sourced for commercial use (Okonkwo et al., 2020). The first group included pre-made blocks that were sourced from four different block sellers in Auchi, Edo North. The locally sourced blocks were used as a benchmark for quality and performance since they represent the typical variations found in the local sandcrete block production. The second group consisted of autoclaved blocks that were created in a controlled lab environment.

2.2.2 Mix design for autoclaved blocks

For the mix design of the autoclaved aerated sandcrete blocks, water-to-cement ratio of 0.4% and a cement-to-stone dust ratio of 1:6. Palm Kernel Shell Ash (PKSA) was also incorporated as a partial replacement for cement, at different weight percentages: 0%, 2.5%, 5.0%, 7.5%, and 10%. To help create pores during autoclaving, aluminum powder was added along with the PKSA to act as an aerating agent. The aim of this mix was to enhance the blocks' mechanical properties and boost their compressive strength.

2.2.3 Mixing and casting

Once the materials were all set, dry mixing took place. In a clean mixing container, the right quantities of BUA cement, stone dust, and PKSA was combined, then mixed together for five minutes for uniform distribution of the powder reinforcement with the molten aluminium matrix, leading to more homogeneous metal matrix composite (MMC) with improved mechanical properties and reduced particle agglomeration. The aim here was to achieve consistent blend before water was added to the aluminium powder.

Next up was the wet mixing phase, which kicked off after everything was well mixed. 0.4% of aluminum powder was taken, dissolved in clean water, and then slowly added to the dry mix. To make sure the aluminum powder spread out evenly and to keep the mixture aerated, the aluminium powder was stirred for another five minutes for sufficient uniform distribution. After that, freshly mixed concoction was poured into standard molds measuring 450 x 225 x 225 mm. At this stage, the aluminum powder reacted with the mix's alkaline components, releasing hydrogen gas that caused the slurry to expand, creating porous structure in aerated blocks. The mixture settles in the mold and sets properly.

2.2.4 Autoclaving process (laboratory produced AASB)

The molded blocks went through a high-pressure steam curing process as part of making autoclaved aerated sandcrete blocks (AASB) in the laboratory as shown in Figure 6 below. This treatment lasted about eight to twelve hours and took place at temperatures of from 180°C and pressures of 9 bars (Mohei et al., 2022). The goal here was to speed up hydration and promote the rapid formation of calcium silicate hydrate (C-S-H), which is key for the strength development of cement-based materials.

Figure 6: Autoclave Machine

2.2.5 Testing method

A series of tests was carried out to check the mechanical, microstructural, and physical properties of the autoclaved aerated sandcrete blocks (AASBs) that was made in the laboratory, along with the blocks from local manufacturers that was collected from the local manufacturers. This test was carefully carried out to show the blocks' internal structure, how they handle hydration, what materials they are made of, and how strong they are under pressure. Some of the techniques used included specific gravity measurements, sieve analysis, compressive strength tests, and microstructural evaluations with X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), and scanning electron microscopy (SEM). To make sure our results were accurate, reliable, and comparable, British Standards were followed throughout the testing process (Agwu, 2025).

X-Ray Fluorescence (XRF) analysis was also carried out to get a better understanding of the chemical composition of the PKSA. The key objective was to identify the ratios of several important oxides, such as calcium oxide (CaO 0.49%), ferric oxide (Fe_2O_3 8.11%), aluminum oxide (Al_2O_3 18.22%), silicon dioxide (SiO_2 58.50%), titanium dioxide (TiO_2 1.61%), phosphorus pentoxide (P_2O_5 0.16%), potassium oxide (K_2O 2.50%), manganese (II) oxide (MnO 0.08), magnesium oxide (MgO 0.92%), sodium oxide (Na_2O 1.10%) and (LOI 8.10%).

2.2.6 Compressive strength test

Both the sandcrete blocks collected from the different locations in Auchi and the ones made in the laboratory were tested for compressive strength to determine their load bearing capacity. This was to see if the blocks were suitable for structural use, following the guidelines set out in (BS, 2011). To do this, a universal testing machine (UTM) was used as shown in Figure 7 below, gradually applying pressure on each block until the block broke. The maximum weight the block could support was recorded, measured in kilonewtons (kN), then calculated the compressive strength by dividing that number by the area of the block's cross-section. The blocks' dimensions were measured carefully for consistency and adjusted where necessary if there were any size discrepancies.

For the blocks from the laboratory, compressive strength tests were conducted at different intervals—7, 14, 21, and 28 days—to see how their strength developed over time. The curing age mentioned by the suppliers was followed for testing the field-collected blocks. Lastly, all the results were compared against the minimum compressive strength requirement of 2.5 N/mm² for non-load-bearing sandcrete blocks as specified in BS EN 771-3:2011+A1:2015.

Figure 7: Universal Testing Machine

2.2.7 Microstructural analysis (SEM, EDX, and XRD Studies)

A close look was taken at the block samples using scanning electron microscopy (SEM) as shown in Figure 8 below to get a better understanding of their surface structure and microstructure. The SEM images revealed details like porosity, particle shape, bond structure, and how compact the matrix is. This analysis was really important for showing how gel forms and crystallizes, especially when this comes to the distribution of hydration products and how well the PKSA particles integrate with the cement matrix. Energy Dispersive X-ray Spectroscopy (EDX) alongside SEM, to get some useful quantitative and qualitative insights into the elemental makeup of certain micro-areas within the samples. Attention was paid to calcium (Ca), silicon (Si), and aluminum (Al) — key players in cement hydration and pozzolanic reactions. The ratios and concentrations of the elements showed much on how hydrated the samples were and how effective PKSA can be as an additional cementitious material.

Figure 8: Scanning Electron Microscope (SEM)

3. RESULTS AND DISCUSSION

3.1 Strength Analysis Compressive

The results showed the outcomes from testing the mechanical properties and microstructure of sandcrete blocks that have been partially replaced with aluminum powder and palm kernel shell ash (PKSA). Specifically, focus was on how different levels of substitution (0%, 2.5%, 5%, 7.5%, and 10%) affected the development of compressive strength and the microstructural traits of autoclaved aerated sandcrete blocks. Attention was paid on the results from the compressive strength tests conducted on several types of blocks with curing intervals at 7, 14, 21, and 28-days.

The compressive strengths of 5-Inch Solid Blocks are shown in Table 1 below. The highest value recorded was 0.74 N/mm² from Location 4 after 28 days, which is still just 30% of what was needed for the minimum strength. The ongoing underperformance could be due to a few reasons, one being that manufacturers have intentionally lowered the cement content to cut down on production costs.

Table1: Compressive Strength of 5-Inch Blocks

Day	Location 1	Location 2	Location 3	Location 4
7	0.2676 N/mm^2	0.6493 N/mm^2	0.5658 N/mm^2	0.6849 N/mm^2
14	0.2613 N/mm^2	0.6009 N/mm^2	0.5813 N/mm^2	0.7071 N/mm2
21	0.2338 N/mm^2	0.6271 N/mm^2	0.6142 N/mm^2	0.7142 N/mm^2
28	0.2573 N/mm^2	0.6410 N/mm^2	0.6280 N/mm^2	0.7413 N/mm^2

As shown in Table 2 below, the compressive strength of 6-Inch Hollow Blocks is still significantly below the minimum of 2.5 N/mm² specified for non-load-bearing blocks (BS, 2011). After 28 days, the highest strength measured at Location 4 was just 0.1801 N/mm², which is under 8% of what is typically needed.

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As shown in Table 3 below, the **c**ompressive Strength of 9-Inch Hollow Blocks remained on the lower side, with the highest strength recorded at Location 4 after 28 days being just 0.1379 N/mm². This is significantly below the British Standard requirement of 2.5 N/mm² for non-load-bearing blocks, coming in at less than 6% of that benchmark. Interestingly, note that the 9-inch hollow blocks consistently fell short compared to the 6-inch versions, despite having a larger cross-sectional area.

Table 2: Compressive strength of 6-inch blocks

Curing Age	Location 1	Location 2	Location 3	Location 4
7 Days	0.0738 N/mm^2	0.1307 N/mm^2	0.1274 N/mm^2	0.1751 N/mm^2
14 Days	0.0761 N/mm^2	0.1431 N/mm^2	0.1508 N/mm^2	0.1710 N/mm^2
21 Days	0.0649 N/mm^2	0.1496 N/mm^2	0.1419 N/mm^2	0.1745 N/mm^2
28 Days	0.0812 N/mm^2	0.1606 N/mm^2	0.1526 N/mm^2	0.1801 N/mm^2

Table 3: Compressive strength of 9-inch hollow block

Curing Age	Location 1	Location 2	Location 3	Location 4
7 Days	0.0604 N/mm^2	0.1049 N/mm^2	0.1146 N/mm^2	0.1268 N/mm^2
14 Days	0.0654 N/mm^2	0.1110 N/mm^2	0.1163 N/mm^2	0.1327 N/mm^2
21 Days	0.0717 N/mm^2	0.1161 N/mm^2	0.1185 N/mm^2	0.1363 N/mm^2
28 Days	0.0739 N/mm^2	0.1205 N/mm^2	0.1235 N/mm^2	0.1379 N/mm^2

Table 4 summarizes the compressive strength data of 9-inch AASB with PKSA. The findings show that compressive strength increased steadily with PKSA replacement up to 7.5%, after which there was a slight dip. After 28 days, the mix with 7.5% PKSA achieved the highest compressive strength at 2.1553 N/mm², which is an improvement compared to the control group's strength of 2.0352 N/mm². This trend aligns with what was expected from the pozzolanic activity of PKSA, since the boost in strength likely comes from the extra calcium silicate hydrate (C-S-H) gels that help strengthen the block matrix, peaking at that 7.5% replacement level.

The data show that compressive strength increased steadily with PKSA up to 7.5%, after which the compressive strength started to dip slightly. After 28 days, the block with 7.5% PKSA had the best compressive strength at 2.1553 N/mm², which is better than the control strength of 2.0352 N/mm². This aligns with what was expected, the PKSA has enhanced the strength by forming extra calcium silicate hydrate (C-S-H) gels that help reinforce the block matrix, explaining why 7.5% was the sweet spot. A similar result that was reported, showed strength gained from pozzolanic materials usually peak at an optimal replacement level before further increases start to impair performance (Adewuyi and Adegoke, 2008)..

Table 4: Compressive Strength of 9-Inch AASB with PKSA

Replacement (%)	7 Days	14 Days	21 Days	28 Days
0%	2.0111 N/mm^2	2.0144 N/mm^2	2.0201 N/mm^2	2.0352 N/mm^2
2.5%	2.0257 N/mm^2	2.0518 N/mm^2	2.0531 N/mm^2	2.0634 N/mm^2
5%	2.0680 N/mm^2	2.0950 N/mm^2	2.1136 N/mm^2	2.1406 N/mm^2
7.5%	2.1110 N/mm^2	2.1320 N/mm^2	2.1446 N/mm^2	2.1553 N/mm^2
10%	1.9880 N/mm^2	1.9949 N/mm^2	2.0097 N/mm^2	2.0160 N/mm^2

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3.2 Effect of Aluminum Powder and Aeration Process

When aluminum powder is mixed in, the aluminium powder reacts to form gas bubbles during the autoclaving process, which leads to evenly distributed pores throughout the block. The way aluminum powder interacts with PKSA at lower replacement rates helps to optimize this aeration, resulting in smaller, nicely-formed pores instead of larger, interconnected ones that could compromise the block's strength. The best compressive strength observed was at 7.5% PKSA replacement, suggesting that this was the point where the balance between compaction and aeration worked out the best. Figure 9 below shows a comparison of the compressive strength of both locally manufactured sandcrete blocks and AASBs.

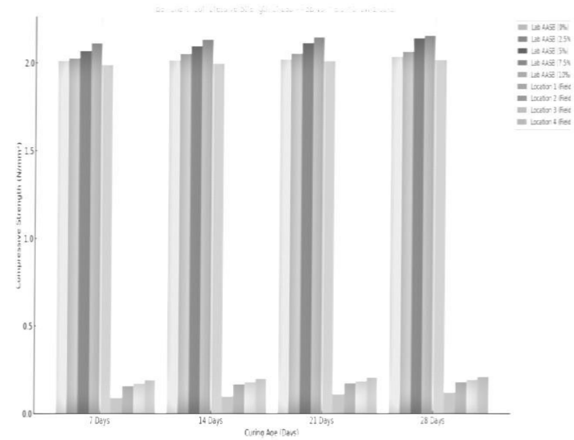

Figure 9: Bar Chart Showing Compressive Strength of AASB (Laboratory-Produced) vs Field Hollow Blocks

The auchi SEM image as shown in Figure 10 below has a highly porous and irregular matrix with weak hydration product and sand grain bonding. The gel structure showed obvious cracks, microvoids, and generally lack of cohesiveness. This look suggests inadequate pozzolanic or cementitious reaction and uncontrolled hydration. Poor compaction during block formation is reflected in the disconnected microstructure, which is probably caused by low cement content and insufficient water-to-cement ratios, which are typical in artisanal block manufacturing.

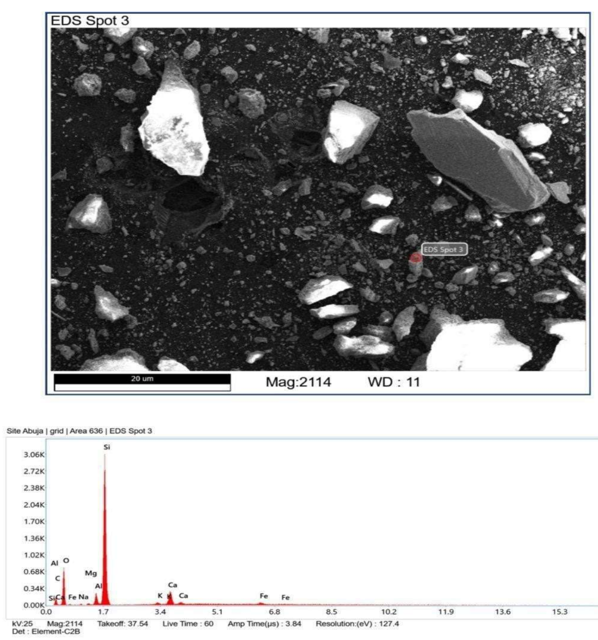

Figure 10: SEM Image of Auchi Field Block

4. CONCLUSION

In this study, the mechanical properties of autoclaved aerated sandcrete blocks (AASB) that had aluminum powder and palm kernel shell ash (PKSA) mixed in. The results were pretty clear: when the use of lower to moderate amounts of PKSA, the compressive strength was boosted and microstructure of the blocks. Up to a 7.5% replacement level, the blocks made in the laboratory with PKSA and aluminum powder showed a solid strength increase, but when the replacement level went beyond 7.5%, the strength actually began to drop off. This consistent rise in strength is due to an effective pozzolanic reaction happening between the silica-heavy PKSA and the calcium hydroxide released when cement hydrates.

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