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Pozzolanic Efficiency of Palm Kernel Shell Ash in Enhancing the Mechanical Properties of Autoclave Aerated Sandcrete Blocks

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KEYWORDS

Palm kernel shell ash (PKSA)
Autoclave aerated sandcrete block (AASB)
Scanning Electron Microscopy (SEM)
Energy dispersive x-ray (EDX)
X-ray diffraction (XRD)

ABSTRACT

This study evaluated the mechanical properties of palm kernel Shell Ash (PKSA) on sandcrete blocks. There is shortage of low and medium housing scheme in Nigeria. The research method was divided into two main parts. First, commercially used sandcrete blocks was collected, checking the performance and quality of blocks produced by local manufacturers. The second phase focused on creating autoclaved aerated sandcrete blocks using PKSA at replacement levels of 0%, 2.5%, 5%, 7.5%, and 10%. Moreover, our experimental program included microstructural analysis using Scanning Electron Microscopy (SEM), Energy Dispersive X-ray Spectroscopy (EDX), and X-Ray Diffraction (XRD). We also conducted mechanical tests, measuring compressive strength and density at different curing times (7, 14, 21, and 28 days) for all sandcrete blocks. At 28 days, the maximum strength measured from the commercial blocks was only approximately 0.74 N/mm2, while the maximum strength recorded at 7.5% replacement of PKSA at 28 days is 2.1553N/mm2. Even though the laboratory-produced blocks' compressive strength values were marginally below the British Standard's 2.5 N/mm² minimum requirement, the results show that the AASB's performance can be further optimized to meet or surpass the necessary standards.

11. INTRODUCTION

There has been a noticeable uptick in the demand for sustainable building materials, especially in developing nations such as Nigeria. Rapid urbanization is putting pressure on the housing and infrastructure sectors, making affordable solutions like sandcrete blocks more sought after.

Sandcrete blocks remain the go-to choice for wall construction across the country. But issues like low-quality raw materials, inconsistent production methods, and environmental concerns tied to cement use often compromise their strength and durability. The primary binding agent in these blocks, limestone Portland cement, is energy-intensive to produce and contributes significantly to greenhouse gas emissions. So, it's crucial—both academically and practically—to find alternative cement materials that can boost the quality of sandcrete blocks while also reducing their environmental impact.

One promising option is palm kernel shell ash (PKSA), a by-product of the palm oil industry that can partially replace cement in concrete and sandcrete mixes. Nigeria generates a large volume of palm kernel shells yearly and is one of Africa's leading palm oil producers. The ash from these shells contains reactive silica and alumina, which, if processed correctly, can react with calcium hydroxide from cement hydration to form more calcium silicate hydrate (C-S-H) gels.

In addition to aiding in the formation of extra calcium silicate hydrate (C-S-H), research by (Akande *et al.* 2021) shows that PKSA enhances the aeration process by regulating the distribution of pore sizes. This reaction can improve strength, durability, and permeability, while also densifying the cement matrix. In developing countries like Nigeria, the demand for affordable, eco-friendly building materials is even more pressing due to rapid urban growth and a rising population. Sandcrete blocks play a significant role in the local construction industry, often utilized for non-load-bearing walls in both residential and commercial buildings. According to (Oyetola *et al.* 2020), buildings constructed with aerated pozzolanic blocks experienced an indoor temperature decrease of up to 20% when compared to those constructed with dense concrete blocks. Their easy availability, low cost, and straightforward production have made them quite popular. However, concerns persist about the quality of sandcrete blocks, particularly those made in unregulated or informal settings. Most commercially available sandcrete blocks in Nigeria fail to meet the minimum compressive strength standards set by guidelines like BS EN 771-3 (2011) and NIS 587 (2020).

2. MATERIALS AND METHODS

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. The primary ingredients include BUA cement, clean drinking 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 Limestone Portland Cement

Limestone Portland Cement (LPC) serves as the main binding agent in this research. Known for its reliable fineness and high early strength, this LPC also works well with pozzolanic materials like palm kernel shell ash (PKSA). Its widespread use in construction across Nigeria and its compliance with relevant national and international standards were key factors in its 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 Limestone Portland Cement. These standards ensure that the cement achieves the strength, durability, and resistance to harmful expansion that are crucial for structural applications.

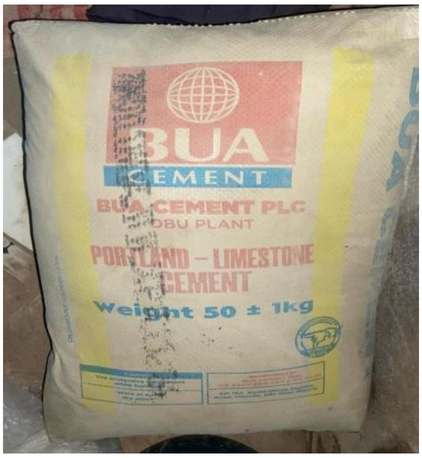


Figure 1. Bua Cement Sample

2.1.2 Stone Dust (Fine Aggregate)

The stone dust was sourced in uzairue, used ASTM C136 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, we sieved the stone dust to remove any larger bits. We also ran a specific gravity test to evaluate the density of the material and see if it was suitable for making blocks. All these 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)

We used Palm Kernel Shell Ash (PKSA) as shown in Figure 3 below, to partially replace Limestone Portland Cement (LPC) as a supplementary cement material. This ash is 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, we kept a close eye on the combustion process. To enhance its reactivity and eliminate larger particles, we filtered the ash using a 75-micron sieve right after collecting it. We also carried out X-Ray Fluorescence (XRF) analysis 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), ferric oxide (FeO_3), aluminum oxide (AlO_3), and silicon dioxide (SiO_2).

Figure 3. Palm Kernel Shell Ash (PKSA)

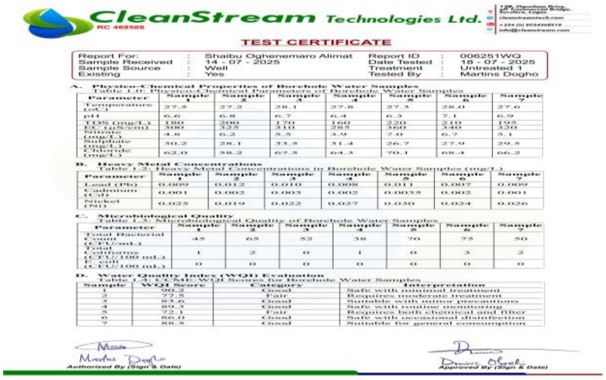
2.1.4 Aluminum Powder

To achieve the lightweight and porous design of autoclaved aerated sandcrete blocks (AASBs), the aluminium powder was mixed as shown in Figure 4 below, into the ingredients 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 their compressive strength, making them lighter and easier to handle. Plus, those air pockets enhance the thermal insulation properties of the blocks, which is great for energy-efficient construction. We took care to measure the aluminium powder precisely to ensure proper aeration without creating too many voids that could weaken the overall structure. The combination of PKSA and aluminium 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 from Edo State University, Iyamho as shown in Figure 5 below was used for both mixing and curing, 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 standard-quality water, we kept harmful compounds from forming in the cement mix, which helped ensure more reliable results and consistent hydration.



CleanStream Technologies Ltd.
RC 488588

TEST CERTIFICATE

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

Martins Dogho
Authorized By (Sign & Date)

Approved By (Sign & Date)

Figure 5. Water

2.2 Methods

2.2.1 Experimental Design

In this study, two types of block samples were compared to see how lab-made autoclaved aerated sandcrete blocks (AASBs) measure up against commercially produced ones. For the first group, pre-made blocks from four different sellers in Auchi was collected, Edo North. These blocks served as our quality and performance benchmark because they reflect the usual variations seen in local sandcrete block production. The second group was made up of autoclaved blocks that we created in a controlled lab setting.

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, cement-to-stone dust ratio of 1:6 and aluminium powder of 0.4% was used. Palm Kernel Shell Ash (PKSA) as a partial replacement for cement, trying out different weight percentages: 0%, 2.5%, 5.0%, 7.5%, and 10% was incorporated. The choice of percentage for palm kernel shell ash (PKSA) used for this project is gotten from the design of experiment (DOE) carried out on minitab.

To help create pores during autoclaving, we added aluminum powder 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

Following the preparation of materials, dry mixing was conducted. A clean mixing container was utilized to combine precise quantities of BUA cement, stone dust, and PKSA, with the mixture being agitated for approximately five minutes. The aim here was to achieve a consistent blend before we added water and other ingredients.

Next up was the wet mixing phase, which kicked off after everything was well mixed. We took a specific amount of aluminum powder, dissolved it in clean water, and then slowly added it to the dry mix. To make sure the aluminum powder spread out evenly and to keep the mixture aerated, we kept stirring it for another five minutes. After that, we poured the freshly mixed concoction 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 that porous structure we see in aerated blocks. We then let the mixture settle in the mold so it could start to set properly.

2.2.4 Autoclaving Process (Lab-Produced AASB)

The molded blocks underwent a high-pressure steam curing process during the production of autoclaved aerated sandcrete blocks (AASB) in the laboratory in the autoclave machine as shown in Figure 6 below. The treatment duration ranged from eight to twelve hours, conducted at temperatures between 180°C and pressures of 9 bars. The objective was to enhance hydration rates and facilitate the swift formation of calcium silicate hydrate (C-S-H), which is essential for the strength development of cement-based materials.

Figure 6. Autoclave Machine

2.2.5 Testing Method

A series of tests were conducted to evaluate the mechanical, microstructural, and physical properties of the autoclaved aerated sandcrete blocks (AASBs) produced in the laboratory, as well as those obtained from the field. These tests were selected meticulously to analyze the internal structure of the blocks. structure, hydration management, material composition, and pressure resistance. The techniques employed comprised specific gravity measurements, sieve analysis, compressive strength tests, and microstructural evaluations utilizing X-ray diffraction (XRD), energy dispersive X-ray spectroscopy (EDX), and scanning electron microscopy (SEM). British Standards application was adhered to during the testing process to ensure the accuracy, reliability, and comparability of our results.

2.2.6 Compressive strength test

Sandcrete blocks we made in the lab and the ones we gathered from the field. This was done in accordance with BS EN 772-1:2011 to determine whether they were appropriate for structural use. We accomplished this by applying pressure to each block gradually until it broke using a universal testing machine (UTM) as shown in Figure 7 below. The compressive strength was determined by dividing the maximum weight it could support, expressed in kilonewtons (kN), by the area of the block's cross-section. To ensure consistency, we took careful measurements of the blocks' sizes and made the required adjustments if there were any differences. Strength tests were conducted on the lab blocks at intervals of 7, 14, 21, and 28 days to assess the development of their strength over time. The curing age specified by the suppliers was adhered to for the testing of the field-collected blocks. Finally, we evaluated all results in relation to the minimum compressive strength standard of 2.5 N/mm^2 for non-load-bearing sandcrete blocks, as outlined in BS EN 771-3:2011+A1:2015.

Figure 7. Universal Testing Machine

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

Block samples was examined with scanning electron microscopy (SEM) as shown in Figure 8 below, to enhance our understanding of their surface structure and microstructure. The SEM images provided insights into porosity, particle morphology, bonding structure, and matrix compactness. This analysis is significant for demonstrating the formation and crystallization of gel, particularly regarding the distribution of hydration products and the integration of PKSA particles within the cement matrix.

Additionally, the application of Energy Dispersive X-ray Spectroscopy (EDX) in conjunction with SEM provided valuable quantitative and qualitative insights into the elemental composition of specific micro-areas within the samples. We focused on calcium (Ca), silicon (Si), and aluminum (Al), which are essential components in cement hydration and pozzolanic reactions.

Figure 8. Scanning Electron Microscope (SEM)

3. RESULT AND DISCUSSION

In this study, a close look was taken at 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, focused was placed on the different levels of substitution—0%, 2.5%, 5%, 7.5%, and 10%—affect the development of compressive strength and the microstructural traits of autoclaved aerated sandcrete blocks (AASB).

3.1 Strength Analysis Compressive

In this section, we'll take a look at the results from the compressive strength tests conducted on several types of blocks:

i. 5-inch solid blocks sourced from field sites, including Auchi and nearby areas.
ii. 6-inch and 9-inch hollow blocks from the same location
iii. 9-inch solid blocks created in a lab using aluminum powder and PKSA.

Each test was carried out with curing intervals at 7, 14, 21, and 28-day.

Table 1: Compressive Strength of 5-Inch Solid Blocks (N/mm²)

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/mm^2
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/mm2	0.7413 N/mm^2

Interpretation:
Looking at table 1 above, the highest value recorded was 0.74 N/mm² from Location 4 after 28 days, which is still just 30% of what we need for the minimum strength. This 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.

Table 2: Compressive Strength of 6-Inch Hollow Blocks (N/mm²)

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	0.1526N/mm^2	0.1801 N/mm^2

Interpretation:
Looking at table 2 above, the strength values are still significantly below the minimum of 2.5 N/mm² that BS EN 771-3:2011+A1:2015 specifies for non-load-bearing blocks. After 28 days, the highest strength measured at Location 4 was just 0.1801 N/mm², which is under 8% of what's typically needed.

Table 3: Compressive Strength of 9-Inch Hollow Blocks (N/mm²)

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

Interpretation:
According to the data in table 3 above, the strength values 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. It's interesting to note that the 9-inch hollow blocks consistently fell short compared to the 6-inch versions, despite having a larger cross-sectional area.

Table 4: Compressive Strength of Laboratory Produced 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	2.0160N/mm^2

Compressive Strength 9-Inch AASB with PKSA (N/mm^2)

Interpretation:

Compressive Strength Progression with PKSA Replacement

Looking at table 4 above, we can see the compressive strength data for the autoclaved aerated sandcrete blocks (AASB) that were made in a lab with various amounts of aluminum powder and palm kernel shell ash (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 we expect 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.

Mechanism behind strength improvement

The pozzolanic reaction is primarily responsible for the strength increase that was noted. To create additional C-S-H gels, the reactive silica (SiO_2) in the PKSA reacts with calcium hydroxide ($Ca(OH)_2$) released during cement hydration. The observed strength increase is caused by these secondary gels, which also improve the matrix density. Additionally, the finely ground PKSA particles' micro-filling effect enables them to fill in tiny spaces in the cementitious structure, decreasing porosity and boosting compactness. At the 7.5% replacement level, where the ratio of cement to PKSA is optimized to support both hydration and matrix packing, this effect is especially advantageous and most noticeable.

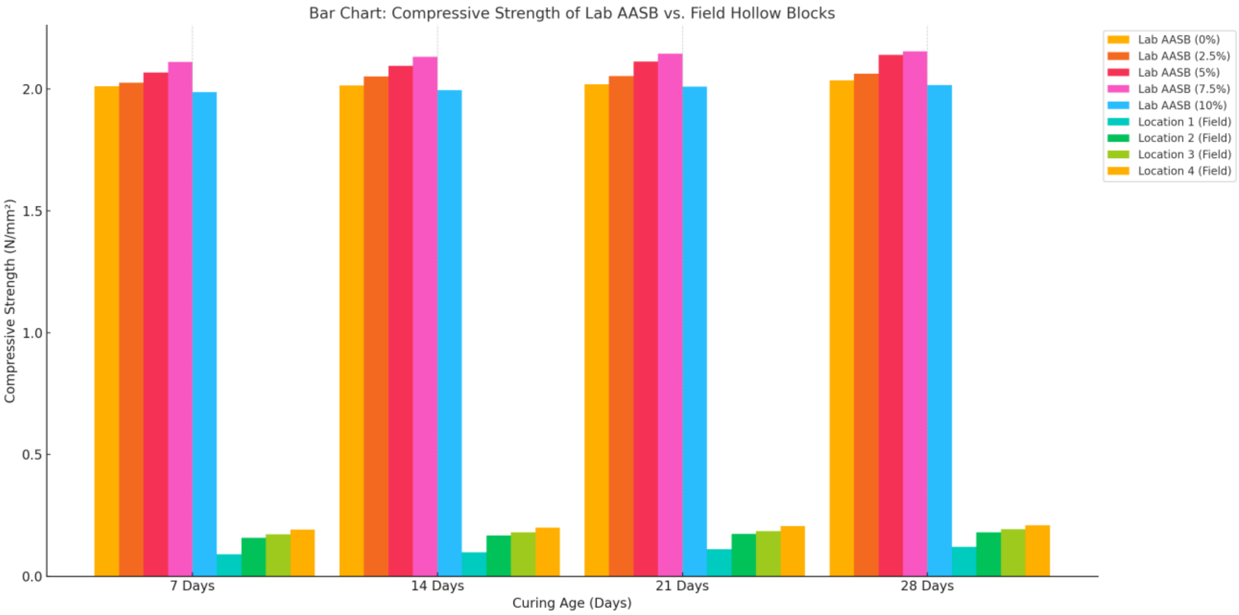


Figure 9. Bar Chart Showing Compressive Strength of AASB (Laboratory-Produced) vs Field Hollow Blocks

Effect of Aluminium Powder and Aeration Process

When aluminium powder is mixed in, it reacts to form gas bubbles during the autoclaving process, which leads to evenly distributed pores throughout the block. It looks like the way aluminium 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 we observed was at a 7.5% PKSA replacement, suggesting that this was the point where the balance between compaction and aeration worked out the best.

4. CONCLUSION

In this study, we took a close look at 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 we used lower to moderate amounts of PKSA, it really boosted the compressive strength and microstructure of the blocks. Up to a 7.5% replacement level, the blocks made in the lab with PKSA and aluminum powder showed a solid strength increase, but if we went beyond that, 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. Figure 9 above, shows the compressive of both laboratory AASB and the locally sourced sandcrete blocks.

Abbreviations

AASB	Autoclave Aerated Sandcrete Block
EDX	Energy Dispersive X-ray
LPC	Limestone Portland Cement
PKSA	Palm Kernel Shell Ash
SEM	Scanning Electron Microscopy
XRD	X-Ray Diffraction

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