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Transforming Sandcrete Blocks: Advancing Strength, Durability, and Performance for Sustainable Construction

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Abstract

To improve the strength, durability, and performance of sandcrete blocks which is a common building material in Nigeria, this study investigates strategies to optimise their use in sustainable construction practices. The effect of varying mix ratios and curing methods, as well as web thickness, on block strength are all thoroughly investigated through empirical experiments. With dimensions of 225 mm in height, 150 mm in width, and 35 mm in web thickness, the optimum mixture ratio is determined to be 1:12, exceeding conventional parameters and providing enhanced compressive strength, reduced water absorption, and adequate density. Notably, the optimal mix is paired with the water sprinkling curing method, which yields consistently greater compressive strengths when compared to alternative curing techniques. These developments highlight the potential for improved structural integrity as well as the benefits of sustainability that are enabled by reduced cement content and more efficient use of resources. Nigeria's expanding population has housing needs, and implementing these outcomes can greatly advance sustainable construction practices.

Keywords: Sandcrete blocks, sustainable construction, web thickness, compressive strength, durability, Optimal mix ratio.

Introduction

According to Easthope et al. (2020), housing is an essential human need that encompasses cultural, social, and economic aspects in addition to shelter. As such, it is a subject of scholarly inquiry and societal concern. The selection of building materials in various geographical locations is influenced by a multifaceted interaction between local resources, technological developments, and socio-economic considerations, as highlighted by Akpuokwe et al. (2024) and Huang et al. (2024). In Nigeria, a country characterised by rapid urbanisation and a growing population, sandcrete blocks have emerged as an ubiquitous building material and have been employed in a significant amount of residential structures (Aliu et al., 2022).

According to the Nigeria Industrial Standard NIS 978:2017, sandcrete blocks are standardised units made of cement, fine aggregates (primarily sand), and water that are extruded for use in walling applications (NIS, 2017). Onyia et al. (2022), also reiterated that the reason for the widespread adoption is their affordability and practicality, two aspects that are essential in addressing the country's burgeoning housing needs. But there have been concerns with the widespread use of sandcrete blocks, especially regarding their long-term durability and structural integrity (Marut et al., 2020).

Investigations conducted by Agbi et al. (2020), Akpokodje et al. (2020), Abubakar and Omotoriogun (2022), and other scholars have demonstrated that expediency has frequently taken precedence over quality in the production processes of sandcrete blocks in Nigeria, leading to variations in strength and susceptibility to environmental degradation. In the face of regulatory initiatives to enforce standards and specifications by organisations like the Standards Organisation of Nigeria (SON), gaps remain in ensuring the long-term durability and uniform performance of sandcrete block structures (Abubakar and Omotoriogun, 2022).

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Both academic inquiry and practical necessities highlight the importance of for a detailed understanding of the various factors impacting the performance of sandcrete blocks (Boateng et al., 2020; Agbi et al., 2020). Even though existing studies has offered information about the composition of materials, manufacturing processes, and regulatory frameworks (Di Maria et al., 2020; Jannat et al., 2020; Okonkwo and Onodagy, 2021; Onodagu et al., 2022), there is still a substantial absence of empirical studies investigating the effects of parameters, like web thickness, on block strength. A multidisciplinary strategy that incorporates material science, field research, and engineering concepts is required to close this gap.

In light of these imperatives, this study aims to improve our understanding of the behaviour of sandcrete blocks by conducting a thorough analysis of the impact of web thickness, curing methods and mix ratio on structural performance in order to obtain an optimum mix solution that adresss both sustainability and performance requirements. The objective of this study is to clarify the intricate relationships among material composition, geometric design, and mechanical qualities by integrating theoretical frameworks, empirical data, and practical observations. It aims to contribute to scholarly discourse as well as the practical advancement of Nigeria's housing infrastructure through critical synthesis and empirical research, fostering sustainability, resilience, and social well-being.

2.0 Literature Review

Sandcrete masonry materials are essential to the construction industry because they are affordable, durable, and adaptable for a wide range of uses (Ealefoh et al., 2024). The structural framework and load-bearing capacity of hollow blocks define them as a prominent category within this domain (Onyia et al., 2022). Hollow blocks can be roughly classified into two types according to American standard testing methods: hollow load-bearing blocks and hollow non-load-bearing blocks, commonly referred to as sandcrete blocks (ASTM C 20).

To guarantee structural integrity and performance, these blocks must adhere to the dimensional specifications set forth by regulatory organisations like the SON the Federal Ministry of Works and Housing in Nigeria or other prominent international standards (NIS, 2017). The geometric properties and functional qualities of various hollow and solid sandcrete block configurations are illustrated visually in Figures 1 to 3, describing their dimensions and configurations.

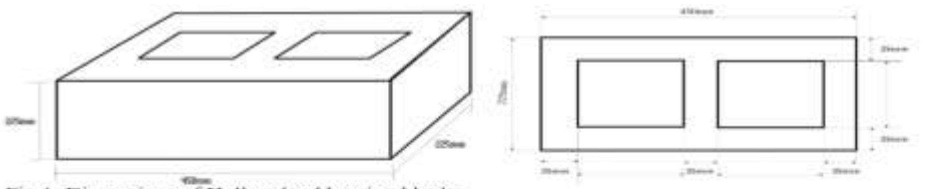

Fig 1: Dimensions of Hollow load bearing blocks

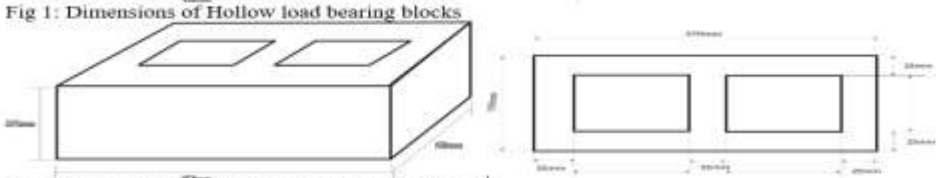

Fig 2: Dimension of hollow non-load bearing blocks

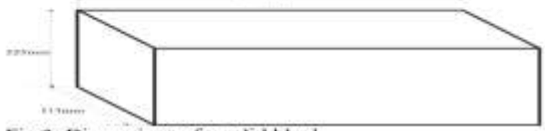

Fig 3: Dimensions of a solid block

The determination of the strength and durability requirements for sandcrete blocks have been subject to standards and guidelines set by national and international organisations (Osagie, 2023). For example, NIS (2004) required 3.45 N/mm2 of compressive strength for sandcrete hollow load bearing blocks, which is in line with B.S. 2028 standards. subsequent revisions and modifications, such as those outlined in the Proceedings of the Conference on Material Testing, Control, and Research and the Nigeria National Building Code, consider evolving industry standards and advances in technology. Standards for sandcrete blocks have been substantially improved by NIS (2017), which includes requirements for compressive strength and dimension specifications. A summary of these requirements is provided in Table 1, which also specifies the maximum compressive strengths and required dimensions for 28-day hollow load-bearing and non-load-bearing blocks.

Types of Blocks	**Dimension (mm)**				**Max. Compressive Strength at 28 days (MPa)**
	Length (L) mm	**Height (H) mm**	**Thickness (T) mm**	**Web thickness (w) mm**	
Hollow Load bearing	450	225	225	35	3.5 minimum
Hollow Non load bearing	450	225	150	25	1.5 minimum

Table 1: NIS (2017) Standards for Sandcrete Hollow blocks

Numerous studies have examined the properties, performance, and production methods of sandcrete blocks, adding to our understanding of their application in construction. Odeyemi et al. (2018) drew attention to the shortcomings in the sandcrete block production processes, pointing out that local techniques were not standardised, which frequently resulted in subpar strength and durability. An empirical study by Akpokodje et al. (2021) highlighted the necessity for stricter standards compliance by showcasing the variations in compressive strength of sandcrete blocks made in various locales. Additionally, Afolayan et al. (2017) investigated how various mix ratios and curing techniques affected the structural integrity of sandcrete blocks, offering vital information concerning how to optimise these parameters for improved performance. Oghenerukewve and Omotor (2024) additionally probed how the quality of the sand affected the blocks' compressive strength. In a separate study, Adese and Olajide (2021) examined the sustainability and environmental impact of the production of sandcrete blocks, arguing that eco-friendly materials and methods should be employed to reduce the carbon footprint. Their research emphasised how crucial it is to incorporate environmental factors into production procedures to meet global sustainability targets.

To improve their performance and obtain the most effective structural qualities, sandcrete block components and dimensions have been the subject of intensive research in the past. To increase the strength and durability of sandcrete blocks, researchers have examined the effects of changing the ratios of cement, sand, and water as well as incorporating supplementary constituents such as eggshell, pozzolans, fly ash, and rice husk ash (Anosike, 2017; Afolayan et al., 2017; Ibearugbulem et al., 2018; Ikeagwuani et al., 2020; Tijani et al., 2020; Sojobi et al., 2021; Wajid et al., 2021).

Moreover, the impact of different block dimensions on efficiency in construction and structural integrity has been investigated. In order to determine the best designs for load distribution and stress resistance, studies by Agunwamba et al. (2016) and Olagunju and Raheem (2021) examined the performance of sandcrete blocks with various cell configurations and overall dimensions. These studies demonstrated the potential of improving block dimensions to avoid material waste and increase load-bearing capacity. Alternative aggregates and binders have also been the subject of experimental research, which aims to replace or enhance conventional components. For instance, research investigating the use of quarry dust (Akorli et al., 2023) and lateritic soil (Awolusi et al., 2021) as partial substitutes for sand demonstrated that these substitutes could decrease the weight and increase the compressive strength of sandcrete blocks. The use of recycled sandcrete aggregates was also examined by Opeyemi et al. (2013), who showed that sustainable substitutes could preserve or even enhance the structural performance of sandcrete blocks.

The cumulative findings of these investigations highlight the significance of dimensional optimisation and material innovation in raising the quality and durability of sandcrete blocks. Researchers have advanced sustainable construction practices by identifying configurations that provide improved strength, durability, and cost-effectiveness by methodically altering the composition and dimensions. These initiatives support the overarching objective of enhancing building materials to satisfy the requirements of contemporary construction while reducing their negative effects on the environment and encouraging resource efficiency.

Even though numerous research has contributed to our understanding of the mechanical characteristics and performance of sandcrete blocks, there are still numerous opportunities for further optimisation, particularly in the areas of strength and durability. In order to improve structural performance and sustainability, previous research has shown the potential benefits associated with varying block dimensions, incorporating alternative materials, and changing component ratios. The standardised and consistent application of these findings in practice, however, still presents a challenge. Thus, the study plays an important role because it aims to close knowledge gaps and advance the development of more resilient and sustainable construction materials by conducting an experimental investigation into the effect of web thickness, curing methods and mix ratios on the strength of hollow sandcrete blocks. This study intends to obtain an optimum integration of mix, curing technique and dimension of sandcrete blocks to optimise performance and sustainability.

3.0 Materials and Methods

In accordance with BS 812 (BS-812-112, 1990), the quartering method was utilised to sample the aggregates employed in this investigation. By methodically reducing the sample size while preserving homogeneity, this approach guarantees a representative sample. Several steps were involved in the production of the 450 x 150 x 225 mm sandcrete blocks. For the first batching process, the necessary amounts for every test sample were precisely weighed. The ratios of cement to sand mix used were 1:12, 1:14, 1:16, and 1:20. All components, including the water, were mechanically mixed for one minute in a concrete mixer. The moulds were prepared for placement by cleaning them and applying oil to make block removal easier. To prevent air pockets and material segregation, the sandcrete was mechanically inserted into the moulds so that it could not fall freely from a height of more than one metre. Maximum density was ensured by mechanically achieving enough compaction, especially at the corners and joints of the mould. Several curing techniques, such as air curing, water sprinkling, and water submersion, were used over the course of 28 days to minimise rapid shrinkage and consequent cracking that may be caused by the evaporation of water during the cement setting process.

The six-inch hollow sandcrete blocks were made using a range of web thicknesses (20 mm, 25 mm, 30 mm, 35 mm, 40 mm, and 50 mm), cement-to-sand ratios, and curing techniques. The size distribution of the aggregate was ascertained by sieve analysis, in accordance with the protocols outlined in BS 812-103.1:1985. The testing equipment comprised trays, containers, a mechanical sieve shaker, a set of sieves, a vented oven, a balance accurate to 0.1 g, and a sample divider. For the analysis, a minimum of 500 g of material was prepared. The air-dried samples were mechanically shaken, and the sieves were stacked in descending order. To calculate the percentage of materials that passed and were retained, the weights of the materials retained on each sieve were recorded.

To determine the blocks' bulk density and water absorption capability, additional investigations were conducted. Based on BS 1377 (BSI, 1967), the water absorption capacity test determined how much water a block could absorb when submerged in room-temperature water. In accordance with BS 812-103.1:1985, the bulk density test measured the volume of 100 g of powder in a graduated cylinder following compaction. Finally, the compressive strength test was conducted using a continuous load applied to the blocks until failure, in compliance with B.S. 1881:1970. Three test cubes were used to calculate the average compressive strength, which allowed for a thorough evaluation of the blocks' structural integrity.

4.0 Results

4.1 Sieve Analysis

The sieve analysis results for the fine aggregate are illustrated in Figure 4. 93.36% of the aggregate, according to the analysis, passes through the 2.0 mm sieve; smaller percentages pass through finer sieves. The greatest material was retained (265 g, 21.06%) by the 0.425-mm sieve. There is a 0.99 fineness modulus. With D10, D30, and D60 values of 0.22 mm, 0.34 mm, and 0.49 mm, respectively, the coefficient of curvature (Cc) is 1.07 and the coefficient of uniformity (Cu) is 2.23. Based on the Unified Soil Classification System (USCS), these results suggest that the aggregate is well-graded.

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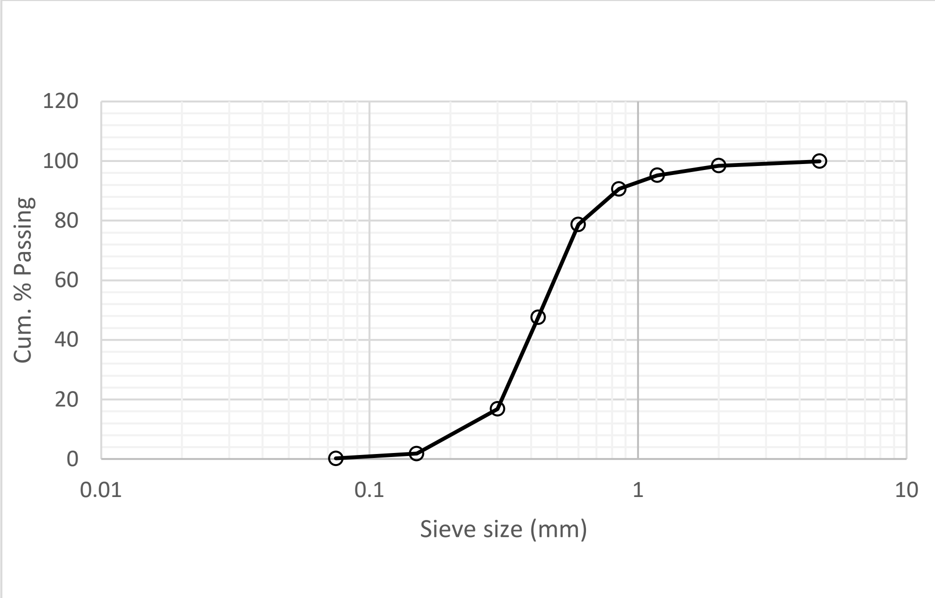
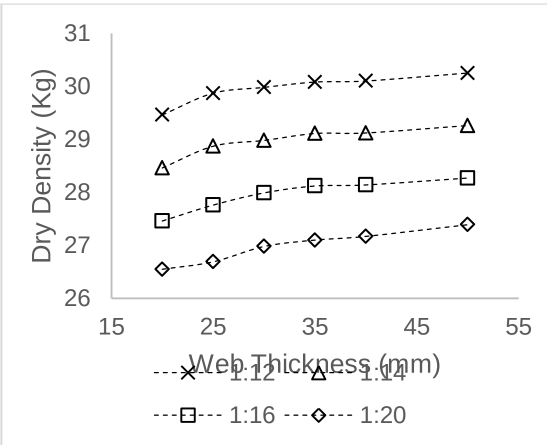


Fig 4: Particle size distribution

This sand satisfies the standards of BS 882:1992, which state that well-graded fine aggregate must have a curvature coefficient (Cc) between 1 and 3 and a uniformity coefficient (Cu) less than 6, demonstrating it is suitable for construction.

4.2 Bulk Density and Water Absorption Characteristics of Sandcrete Blocks at Various Mix Ratios and Web Thicknesses

As shown in Figures 4.1–4.3, the dry density, bulk density, and water absorption properties of sandcrete blocks were evaluated at various mix ratios and web thicknesses.



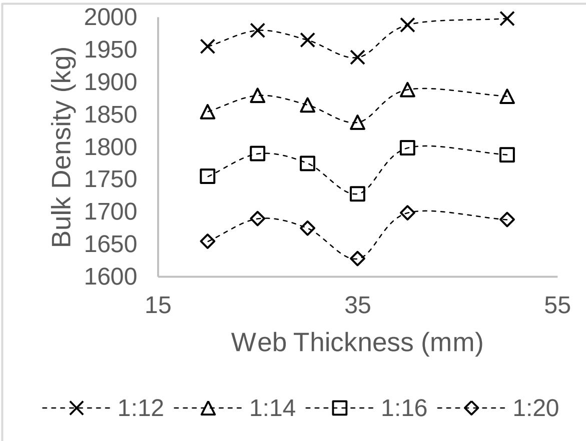


Fig 4.1: Dry Density (Kg)

Fig 4.2: Bulk Density (kg)

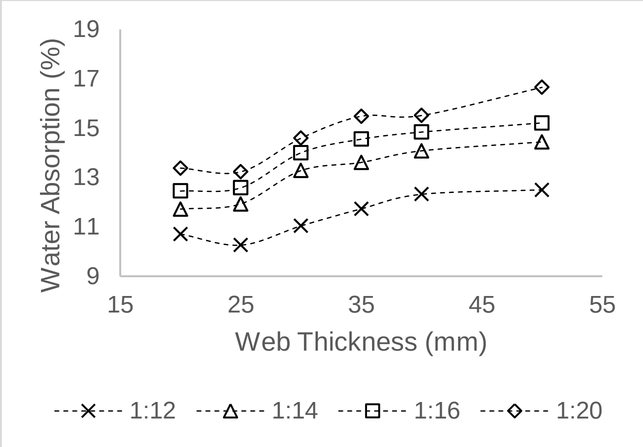


Fig 4.3: Water Absorption (%)

For all mix ratios, the dry density (Figure 4.1) and bulk density (Figure 4.2) increase with increasing web thickness. Greater water retention is indicated by the rise in water absorption (Figure 4.3) with thicker webs. For example, bulk density went up from 1954.67 kg/m^2 (20 mm web) to 1997.87 kg/m^2 (50 mm web) at a 1:12 mix ratio, and water absorption went up from 230.6 kg/m^2 to 271.55 kg/m^2.

As previously noted by Shakir et al. (2020), these findings suggest that although denser blocks have a higher load-bearing capacity, they also absorb more water, which may reduce their durability in damp environments. To provide adequate strength without sacrificing durability, sandcrete block performance must be optimised by striking a balance between density and water absorption (Ikegwuani et al., 2020).

4.3 Compressive Strength Test Analysis

The compressive strength analysis of sandcrete blocks reveals substantial variations based on mix ratios, web thickness, and curing methods as shown in figures 4.4 to 4.12.

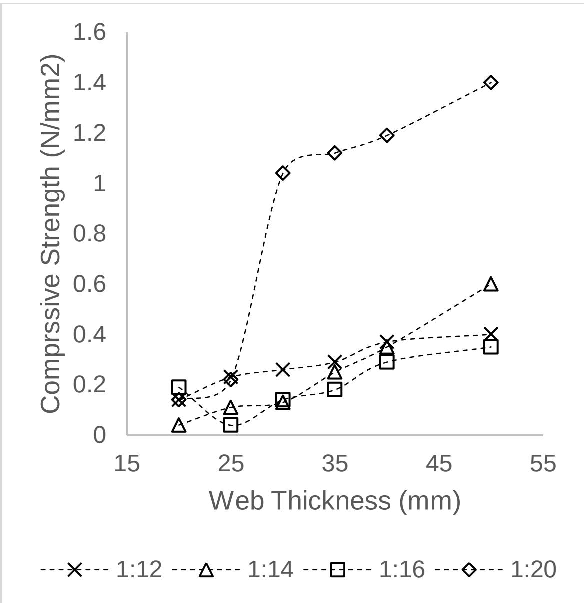


Fig 4.4: 7 days [Air Curing]

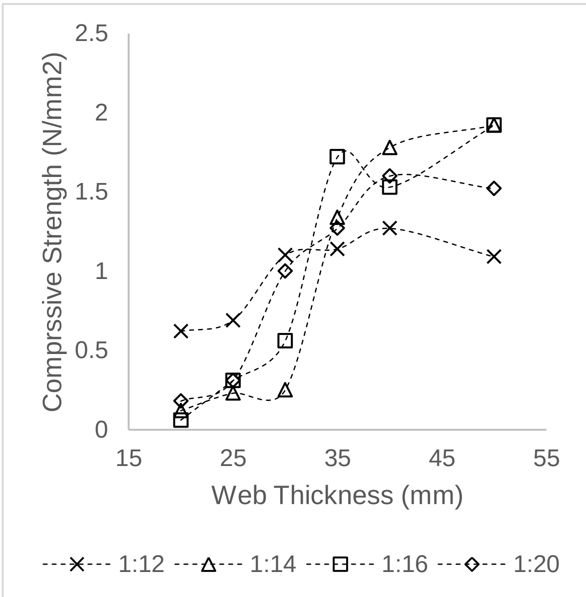


Fig 4.5: 14 days [Air Curing]

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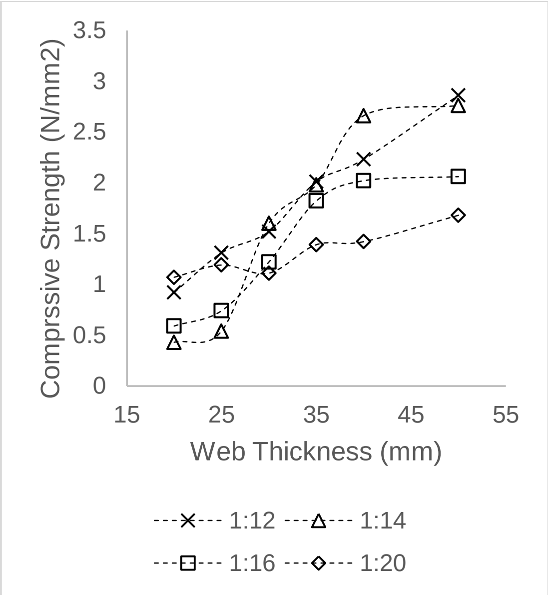

Fig 4.6: 28 days [Air Curing]

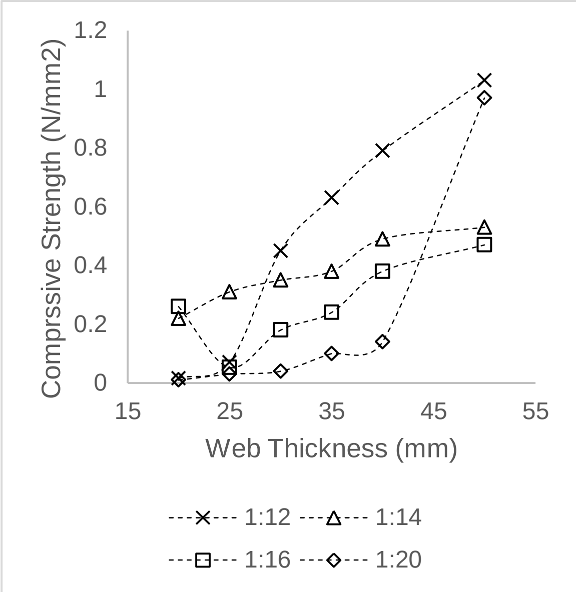

Fig 4.7: 7 days [Water Sprinkling Curing]

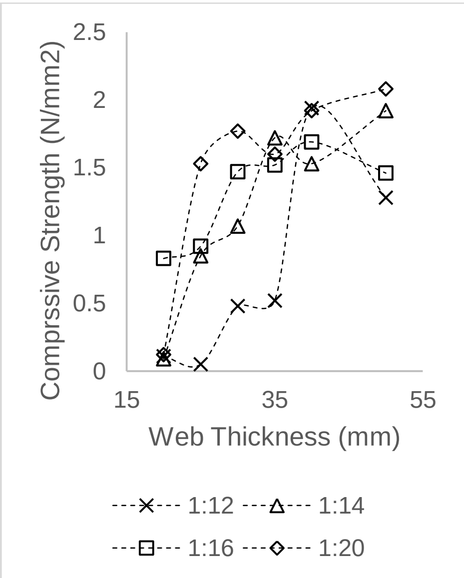

Fig 4.8: 14 days [Water Sprinkling Curing]

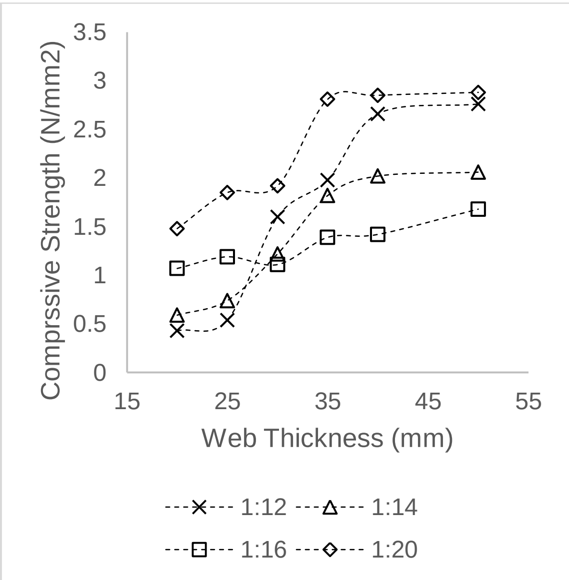

Fig 4.9: 28 days [Water Sprinkling Curing]

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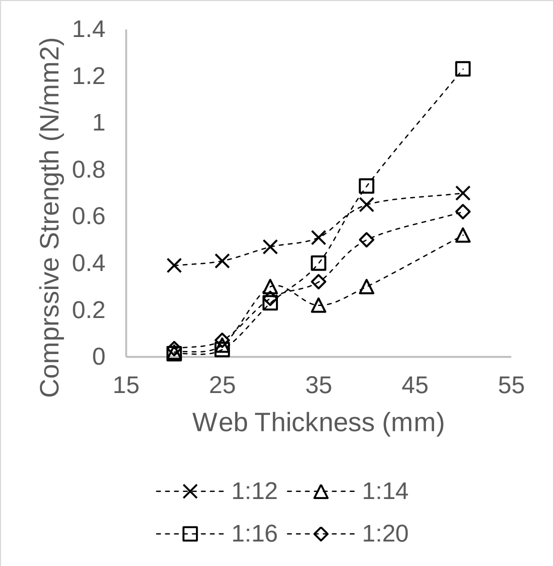

Fig 4.10: 7 days [Submerged Curing]

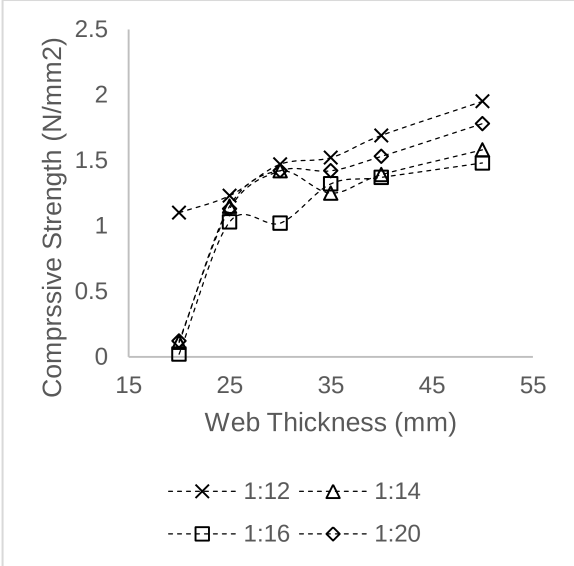

Fig 4.11: 14 days [Submerged Curing]

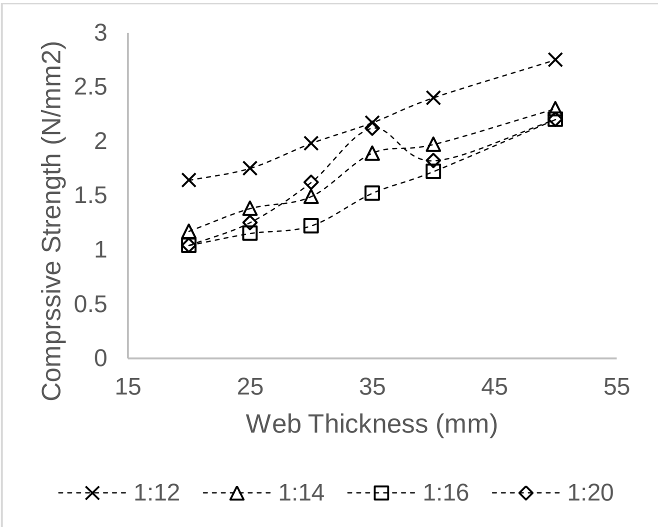

Fig 4.12: 28 days [Submerged Curing]

Significant variations in compressive strength can be observed across sandcrete blocks depending on mix ratios, web thickness, and curing techniques. Compressive strength increased steadily with curing time and web thickness for the 1:12 mix ratio with air curing, reaching a peak value of 2.86 N/mm^2 at 50 mm of web thickness after 28 days. In comparison to lower mix ratios such as 1:14 and 1:16, which demonstrated maximum compressive strengths of 2.76 N/mm^2 and 2.06 N/mm^2, respectively, this suggests robust structural performance. All mix ratios saw a general increase in compressive strength with water sprinkling curing; however, the 1:12 ratio once again showed superior results, reaching up to 2.88 N/mm^2 at 50 mm of web thickness. Submerged curing is noteworthy for producing high compressive strengths of up to 2.75 N/mm^2, particularly for the 1:12 mix. These results highlight the 1:12 mix ratio's highest performance, especially with thicker webs and the right curing, confirming that it is suitable for making durable sandcrete blocks. The 1:12 mix's greater compressive strength and conformance to density and water absorption standards demonstrate its potential for innovative and sustainable construction methods, providing a cost-effective and sustainable substitute for conventional mix ratios.

4.4 Impact of Different Curing Methods on Compressive Strength

The impact of curing methods on the compressive strength of sandcrete blocks is substantial, as demonstrated by the data across various mix ratios illustrated in Figures 4.13 to 4.16.

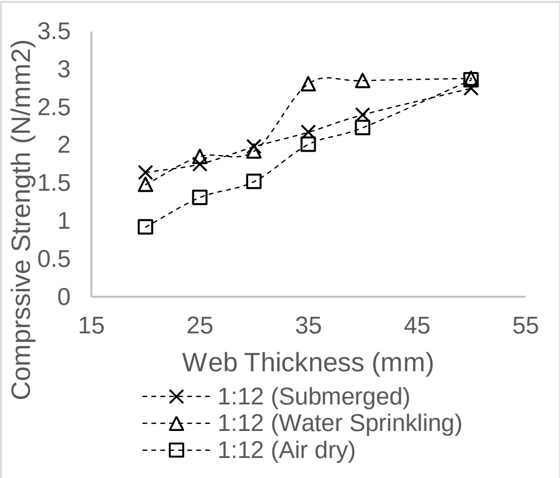

Fig 4.13: Mix Ratio 1:12 [C:S]

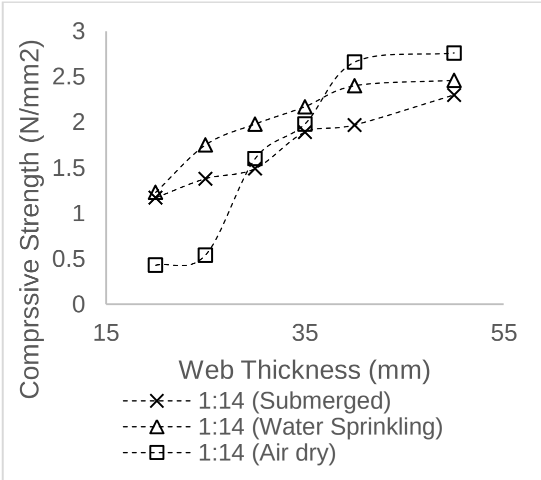

Fig 4.14: Mix Ratio 1:14 [C:S]

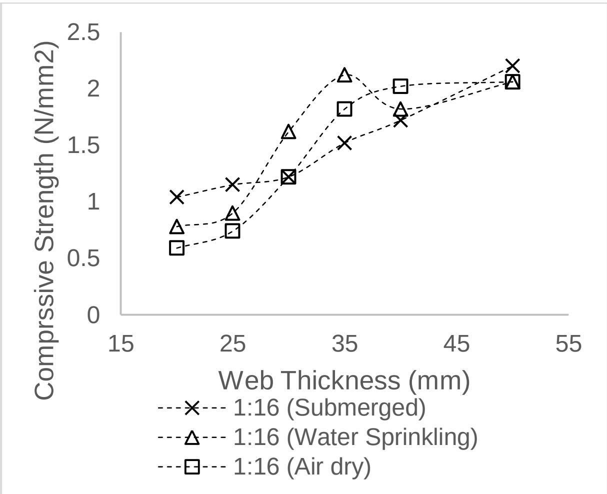

Fig 4.15: Mix Ratio 1:16 [C:S]

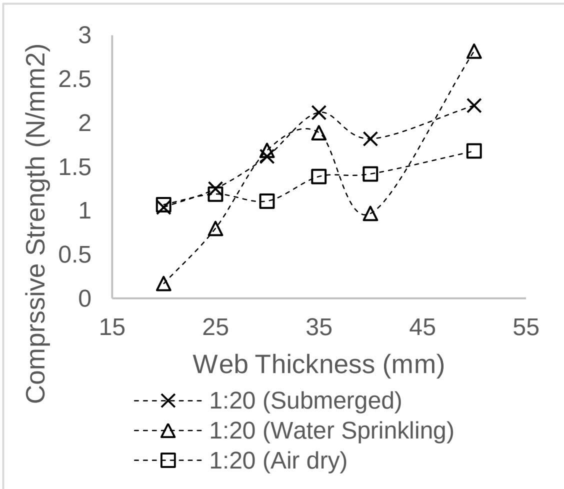

Fig 4.16: Mix Ratio 1:20 [C:S]

The lowest compressive strengths were typically obtained using air curing, notwithstanding the simplicity of the method. For instance, after 28 days of air curing, the 1:12 mix ratio produced a maximum compressive strength of 2.86 N/mm^2 at a 50 mm web thickness. Higher compressive strengths were consistently obtained by water sprinkling curing; the same mix ratio peaked at 2.88 N/mm2, demonstrating the benefits of steady moisture availability. While submerged curing in terms of compressive strength performed relatively well, water sprinkling curing was still superior, with blocks made with a 1:12 mix ratio reaching 2.75 N/mm^2 for submerged curing. Submerged curing and water sprinkling both performed better than air curing at different mix ratios, although water sprinkling was superior. The superior outcomes from water sprinkling can be ascribed to its capacity to sustain ideal moisture levels for hydration without the risk of cementitious material leaching, which can happen during submerged curing. Thus, the best way to maximise the compressive strength and structural integrity of sandcrete blocks is to use water sprinkling curing.

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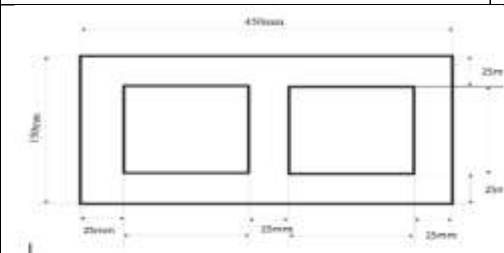
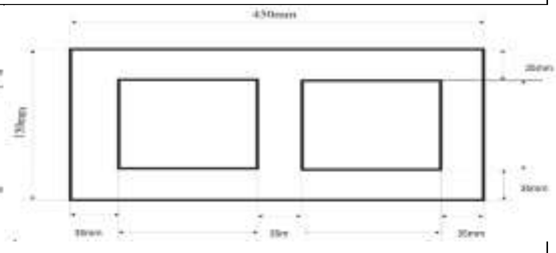
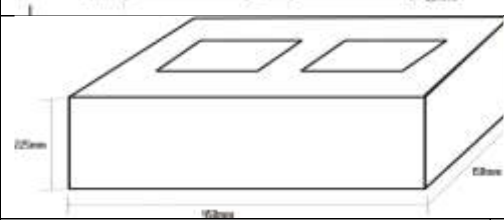
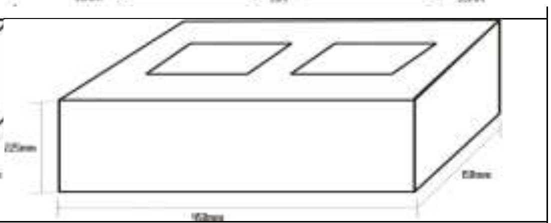
This study has demonstrated substantial advances in sustainability and innovation by identifying a considerable upgrade in the mix ratio, dimensions, and curing procedures for making sandcrete blocks, as shown by the data shown in Table 4.1.

Table 4.1: Identification of optimum block dimensions.

	Compressive Strength; NIS 27:2007 – min. 2.5N/mm².												Water Absorption				Density			
Curing Method	Air curing				Sprinkling				Submerged				NIS 27:2007 – max. 12%				NIS 27:2007 – min. 1920kg/m³			
C:S ratio	1:12	1:14	1:16	1:20	1:12	1:14	1:16	1:20	1:12	1:14	1:16	1:20	1:12	1:14	1:16	1:20	1:12	1:14	1:16	1:20
20mm	0.92	0.43	0.59	1.07	1.48	1.23	0.78	0.17	1.64	1.17	1.04	1.04	10.71	11.72	12.45	13.38	1954.67	1854.41	1754.31	1654.27
25mm	1.31	0.54	0.74	1.19	1.85	1.75	0.90	0.8	1.75	1.38	1.15	1.25	10.26	11.93	12.58	13.23	1979.54	1879.23	1789.32	1689.29
30mm	1.52	1.6	1.22	1.11	1.92	1.98	1.62	1.69	1.98	1.49	1.22	1.62	11.04	13.28	14	14.59	1964.49	1864.54	1774.48	1674.38
35mm	2.01	1.98	1.82	1.39	2.81	2.17	2.12	1.89	2.17	1.89	1.52	2.12	11.73	13.61	14.55	15.48	1937.88	1837.76	1727.54	1627.49
40mm	2.23	2.66	2.02	1.42	2.85	2.4	1.82	0.97	2.4	1.97	1.72	1.82	12.32	14.08	14.84	15.51	1988.06	1888.26	1798.34	1698.29
50mm	2.86	2.76	2.06	1.68	2.88	2.46	2.06	2.82	2.75	2.30	2.20	2.20	12.5	14.44	15.21	16.65	1997.87	1877.83	1787.79	1687.68

Sandcrete blocks typically follow a mix ratio of 1:8 (cement to sand) and have dimensions of 225 mm for height, 150 mm for width, and 25 mm for web thickness, which satisfies the NIS 27:2007 minimum requirements for non-load bearing walls. This study suggests that an ideal mix ratio of 1:12 (cement to sand) with dimensions of 225 mm for height, 150 mm for breadth, and 35 mm for web thickness far exceeds these requirements. The specifics are provided in Table 4.2.

Table 4.2: NIS 27:2007 standard and optimised characteristics in this study

	NIS 27:2007	**This study**
Laying face		
h x w		

Improvements in sustainability and innovation have resulted from the investigation's identification of significant enhancements in the mix ratio and dimensions for producing sandcrete blocks. Sandcrete blocks have traditionally been made with a 1:8 cement to sand mix ratio, measuring 225 mm in height, 150 mm in width, and 25 mm in web thickness. This conventional configuration satisfies the NIS 27:2007 basic requirements, which state that there must be a minimum density of 1920 kg/m³, a maximum water absorption rate of 12%, and a minimum compressive strength of 2.5 N/mm². However, our research indicates that a 1:12 cement to sand mix ratio with dimensions of 225 mm in height, 150 mm in width, and 35 mm in web thickness surpasses these requirements.

The optimised mix ratio and dimensions result in a compressive strength that is higher than the recommended minimum at 2.81 N/mm². To ensure structural integrity and standards compliance, the water absorption rate is further lowered to a maximum of 11.73%, which is below the maximum allowable limit, and the density is maintained at a minimum of 1937.88 kg/m³. These outcomes demonstrate substantial enhancements in the performance attributes of sandcrete blocks.

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From a sustainability standpoint, the new mix ratio is quite beneficial. The amount of cement used is reduced by lowering the cement content from a 1:8 to a 1:12 ratio. Reducing the amount of cement used instantly lowers the carbon footprint of the construction process because cement production is a major source of CO2 emissions (Ni et al., 2022). Moreover, by attaining superior structural performance with less material waste, the optimum mix ratio and web thickness assure effective resource utilisation. This is in line with sustainable construction strategies, which minimise the quantity of resources consumed while maximising the longevity and durability of the construction materials (Tian et al., 2024).

Ingeniously, the new sandcrete blocks' higher compressive strength and lower rate of water absorption indicate enhanced longevity and durability. This will increase the blocks' long-term sustainability by reducing the need for periodic maintenance and replacements. Not to mention, this new mix ratio has significant economic benefits.

Considering only cement and sand, this study also examined the expenses associated with manufacturing sandcrete blocks using the conventional 1:8 mix and the ideal 1:12 mix in order to rationalise the new mix ratio and dimensions economically. With a capacity of 0.00084375 m^3, the 1:8 mix block costs ₦322 per block (₦252 for cement and ₦70 for sand) since it contains 1.4 kg of cement and 11.2 kg of sand. On the other hand, the 1:12 mix block, which has a volume of 0.00118125 m^3, costs ₦320.8 per block (₦216 for cement and ₦100.8 for sand) since it comprises 1.2 kg of cement and 14.4 kg of sand. The 1:12 blend offers better compressive strength (2.81 N/mm^2), lower water absorption (11.73%), and a suitable density (1937.88 kg/m^3), which improves the blocks' durability and minimises long-term maintenance and replacement costs. This is despite the somewhat higher cost of sand. Additionally, by lessening the impact on the environment, the decreased cement content promotes sustainability. In addition to the fact that constructing blocks with the ideal 1:8 mix ratio costs a little more compared to the conventional 1:12 ratio, there are substantial long-term financial benefits due to lower maintenance and replacement expenses of associated with the optimal mix. Thus, the new optimal mix ratio is a worthwhile investment since it provides a balance of enhanced performance, sustainability benefits, and long-term economic savings.

Conclusion

By improving the structural properties of sandcrete blocks, this study has significantly improved our understanding of their behaviour. By examining the impact of web thickness on block strength and experimenting with different mix ratios and curing techniques, this study demonstrated that a mix ratio of 1:12 is optimal with dimensions of 225 mm in height, 150 mm in width, and 35 mm in web thickness. This mix ratio exceeds conventional requirements and provides enhanced compressive strength, decreased water absorption, and adequate density. These outcomes highlight the sustainability benefits associated with lowering cement content and optimising resource utilisation, in addition to demonstrating notable improvements in sandcrete block performance. The revised ideal mix ratio offers better performance, durability, and long-term cost reductions while delivering a balanced investment from an economic and environmental perspective. By incorporating these discoveries into building methods, Nigeria's housing infrastructure might become far more resilient, sustainable, and efficient moving forward, advancing sustainable development goals and societal well-being.

Remarks

The pioneering study "Transforming Sandcrete Blocks: Advancing Strength, Durability, and Performance for Sustainable Construction" provides a compelling blueprint for transforming the production and utilisation of sandcrete blocks in construction processes. Through a thorough examination of crucial factors like mix ratios, dimensions, web thicknesses, and curing techniques, the study not only demonstrates critical areas that require improvement but also proposes innovative approaches to maximise block performance. The study surpasses the current norms in compressive strength, reduced water absorption, and enhanced durability by introducing a new mix ratio of 1:12 and corresponding dimensions. It also promotes sustainability by minimising cement usage and long-term maintenance costs. The recommendations of this study provide policymakers, researchers, and stakeholders in the construction industry a transformative opportunity to adopt more resilient,

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sustainable, and economically viable construction practices, therefore enhancing environmental stewardship and societal well-being.

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