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Mechanical, Durability and Fire Performance of Lightweight Foamed Concrete Incorporating Rice Husk Ash as Cement Substitute

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Foamed concrete is a relatively new building material; knowledge of the materials used in the production and the understanding of the reaction of such material will facilitate the design, performance, and behavioural prediction of such concrete products. This study investigated the mechanical, durability, and fire performance of lightweight foamed concrete incorporating rice husk ash as a cement substitute. The 0, 5 and 10% RHA replacement of cement in concrete has a dry density of 1685 kg/m^3, 1680 kg/m^3, and 1680 kg/m^3 respectively, at 28 days of curing time and a maximum compressive strength of 14.79 N/mm^2, 14.74 N/mm2, 14.69 N/mm^2, with maximum tensile strength of 1.59 N/mm^2, 1.55 N/mm^2, 1.54 N/mm^2 and maximum flexural strength of 2.46 N/mm^2, for 0, 5 and 10% respectively. The 28-day compressive strength result met standard requirements from either the ACI or BS standards. The compressive strength of foamed concrete is reduced when subjected to higher temperatures of 600 °C and 800 °C. The Ultrasonic pulse velocity increases as the percentage of pozzolana is reduced in foamed concrete. The model has been validated up-to 30% replacement of cement with RHA, and it can be concluded that the model is valid for foamed concrete produced with and without RHA. 10% rice husk ash was the optimal percentage for producing foamed concrete with rice husk ash. It was recommended that using foamed concrete with RHA for semi-structural and structural applications shows potential and encouraging results.

Keywords: Compressive strength, Durability Properties, Fire resistance, Foamed Concrete, Rice Husk Ash, Ultrasonic Pulse Velocity

Introduction

Concrete is a construction material composed mainly of aggregates (both coarse and fine), cement, and water. According to Neville (2010), concrete is any product or mass made with a cementing medium; generally, this medium is the product of a reaction between hydraulic cement and water. Concrete has many desirable properties and can be transformed and used in different forms (Agboola *et al.*, 2020). Concrete is a construction material widely used for its excellent properties, including workability, durability, satisfactory strength, and the easy availability of the raw materials used in its production (Mehta & Monteiro, 2006). However, conventional concrete has a high density, which makes it difficult to handle. Concrete has been produced by adding or replacing one or more of its main constituents with materials that tend to improve its properties, creating a new form of concrete with different, unique characteristics (Agboola *et al.*, 2024). One of these types is foamed concrete, which is generally produced by eliminating the use of coarse aggregate and introducing air bubbles, or by using lightweight aggregate.

Foamed concrete (FC) is a lightweight material composed of cementitious mortar surrounding disconnected bubbles (more than 50% by volume), which are produced as a result of either physical or chemical processes during which either air is introduced into the mortar (unfoamed) mixture, or gas is formed within it (Tikalsky *et al.*, 2004). These two basic methods of producing aeration in concrete have appropriate names for the end products: gas or foamed concrete. FC is manufactured either by adding to the mix an air-entraining agent (usually some form of hydrolysed protein or resin soap), which introduces air bubbles during mixing at high speed (mix-foam method) or, in some processes, by adding a stable pre-formed foam to the un-foamed mixture during mixing in an ordinary mixer (pre-formed foam method) (Neville, 2011). Pre-formed FC is made by adding pre-formed stable foam, prepared by aerating a foaming agent solution, to cement paste or cement mortar; this results in the concrete being lighter by incorporating small, enclosed air bubbles into the un-foamed mixture (Nambiar & Ramamurthy, 2006).

Concrete can also be classified into several types, such as lightweight, normal weight, and heavy concrete, in terms of its density. The density of the conventional concrete is 2200 to 2600 kg/m^3; this weight sometimes makes it uneasy to handle and an uneconomical structural material. Attempts have been made in the past to reduce the self-weight of concrete to increase its efficiency (Akshata & Dilip, 2018). According to Neville (2011), a reduction in concrete density can be achieved by replacing some of the solid materials with air voids in three possible locations: in the aggregate particles (lightweight aggregate concrete), in the cement paste (cellular concrete), and between the coarse aggregate particles by omitting fine aggregate (no-fines concrete). Lightweight concrete helps in the reduction of a structures dead load and increases the progress of the building. The weight of a building on the foundation is an important factor, in weak soil (Deifallaa *et al*., 2020). The practical density range of lightweight concrete is from about 300 kg/m^3 to 1850 kg/m^3. Moreover, ACI 213R-87 uses density to categorize lightweight concrete by application. The three categories are: low-density concrete with a density between 300 and 800 kg/m3 used for thermal insulation (non-structural purposes). Secondly, structural lightweight concrete, with a density of 1350 to 1900 kg/m^3 and a minimum compressive strength of 17 MPa, is used for structural purposes. Finally, moderate-strength concrete lies between the above two categories, with a compressive strength of 7-17 MPa (Neville, 2011).

FC can fulfil functional, economic and sustainable environmental requirements due to the method and material required in its production; and has the potential application of producing concrete with range of densities from (400-1600) kg/m3 and can meet up with a strength requirement of 25 Mpa (Jones & McCarthy, 2005; Tarasov *et al*., 2010; Nuruddeen *et al*., 2024). With FC, sustainability is enhanced because no coarse aggregate is required in its production, and it is possible to partially or fully replace fine aggregate with recycled or secondary materials (Jones & McCarthy, 2006; Agboola *et al*., 2024). The most obvious advantage of FC is its low density which results in reduction of dead load and substantially result to saving in cost, reduction of handling and transport costs, faster construction rates (reduction in manpower), good thermal insulation properties (giving energy conservation advantages, and thereby reducing operating costs, heating/air conditioning) and good acoustic properties (Nuruddeen *et al*., 2024). FC can be produced as precast elements (wall and ceiling panels), block production (sawed from large blocks or cast in specified moulds), and cast in situ (flooring systems, roof insulation, and wall fillings) for non-structural purposes; it can also be used for structural purposes.

However, foamed concrete poses challenges that affect its properties, such as cracking, shear, porosity, strength, and torsion (Deifallaa *et al*., 2019). According to Ramamurthy *et al*. (2009), foam concrete is perceived as weak, non-durable, and prone to high shrinkage. Also, the characteristics of its component materials, the cement paste and the voids, have a measurable effect on the properties and stability of the foamed concrete (Nambiar & Ramamurthy, 2007). Efforts have been made to improve the strength and stability of hardened materials by incorporating pozzolanic materials (Agboola *et al*., 2025). To condense this problem, sustainable materials need to be introduced into concrete production, such as rice husk ash as a cement replacement, which could aid in reducing energy consumption in cement production and cutting construction costs (Agboola, *et al*., 2025). Besides that, rice husk ash has a composition similar to that of concrete, containing calcium oxide, silicon oxide, aluminium oxide, and iron oxide (Khassaf *et al*., 2014). The most important single property of concrete is strength. This is because the primary aim of structural design is to ensure that structural elements can carry the loads imposed on them. Strength is also important because it is related to several other important properties that are more difficult to measure directly, and a simple strength test can give an indication of these properties (Peter & John, 2010). Based on the aforementioned challenges, researchers have, however, compared the strength and gel-space ratio strength in foamed concrete, which can be predicted using mathematical models (Nambiar & Ramamurthy, 2008). They found out that expressions derived from the strength model incorporating the fly ash model correlate well with the measured strength. However, incorporating rice husk ash could bring about a better strength-predicted model. To condense this problem, sustainable material needs to be introduced in production of concrete such as rice husk ash as cement replacement, which could aid reduction in the energy consumption in cement production and cut down construction cost (Khan et al., 2012; Nasreen, et al., 2023) Recent works by (Agboola *et al*., 2022a; Agboola *et al*., 2022b; Nagrale *et al*., 2012; Bui, 2001) have shown that rice husk ash up to 30% can be used to replace cement in the production of concrete. However, there is a need for a concerted effort to address the weaknesses of foamed concrete in terms of strength, stability, and quality by incorporating rice husk ash into the mix to assess its performance. The present study is concerned with the mechanical, durability, fire performance and numerical investigation of a 28-day compressive strength prediction model for water-cured foamed concrete containing rice husk ash as a partial replacement of cement.

Materials and Methods

Materials

Ordinary Portland Cement of grade 42.5R by Dangote is classified as CEM II. The percentage of clinker and gypsum in the cement is 95 - 100% and 0 – 5% respectively, whose production was in accordance with BS 12 (1996), was used as the main binder. The fineness of the cement obtained is 8%, which conforms to the requirement of BS 812 (1973) for ordinary Portland cement, which specifies a maximum residue of 10%. The finer cement aids early cement hydration, while the coarser cement slows its rate. The sieve analysis of cement is presented in Figure 1. Rice husk from which rice husk ash was produced was obtained from a rice mill at Mudawal market in Bauchi metropolis. The Specific gravity of rice husk ash was found to be 2.10. The sieve analysis of RHA is presented in Figure 2. River sand from the Yelwa River in Bauchi metropolis was used for this work. Fine aggregate passing through a 300-micron sieve size but retained on a 150-micron sieve aperture in accordance with BS 882 (1992). This is because coarser aggregate may settle in a lightweight mix, leading to foam collapse during mixing. A protein-based foaming agent was used for this project. The specific gravity of fine aggregate (Sand) was determined to be 2.65. The sieve analysis of fine aggregate is presented in Figure 3. Water used for this work is potable tap water conforming to BS EN 1008-2 (2002) for mixing concrete. This is crucial when using a protein-based foaming agent, as organic contamination can adversely affect the foam quality and the concrete produced. The foamed concrete produced was cured in water conditions.

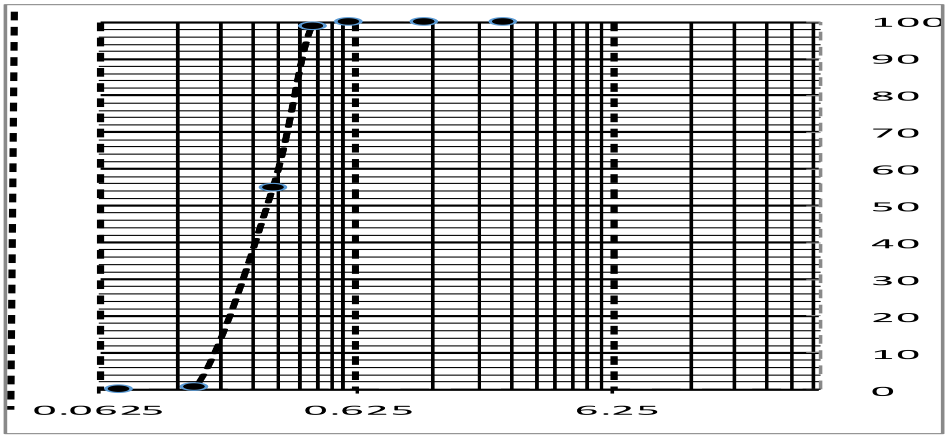

Figure 1: Sieve Analysis of Cement

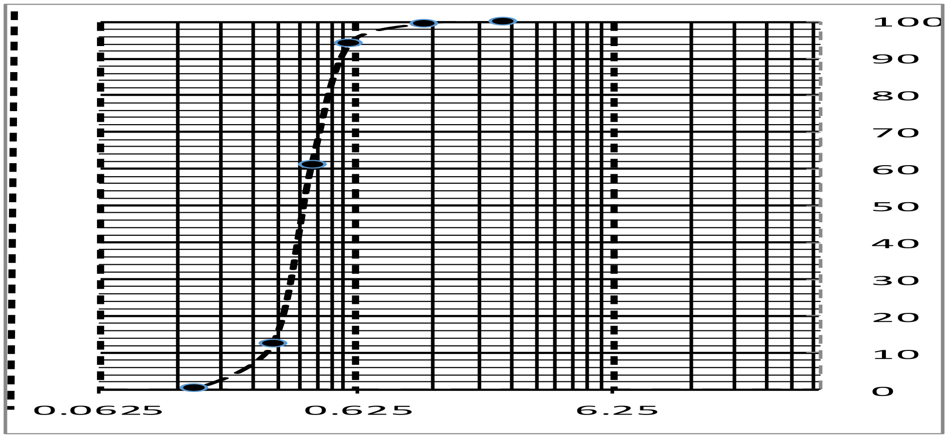

Figure 2: Sieve Analysis Graph Showing Rice Husk Ash

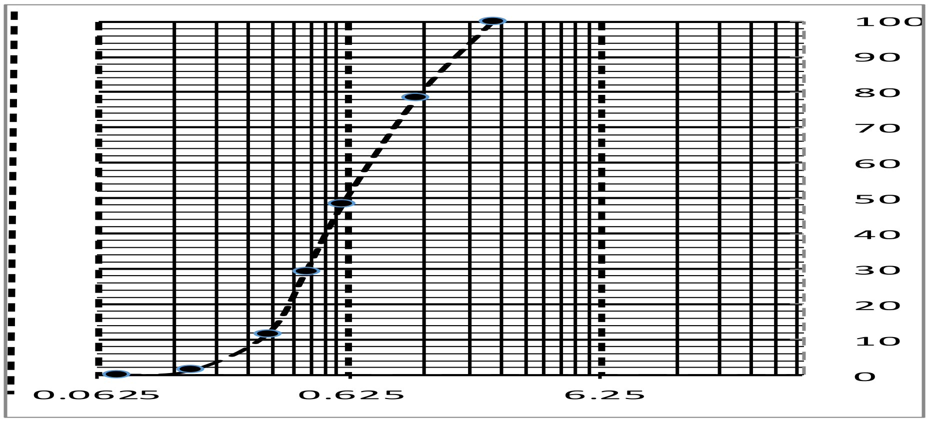

Figure 3: Sieve Analysis Graph Showing Well Graded Fine Aggregate

Mix proportioning and experimental design

A mixed proportion that will produce the target plastic density of 1600kg/m3 (±50kg/m^3) was developed; the density being the design criterion in foamed concrete. Foamed concrete with high density leads to stability of the concrete mix (Agboola *et al*, 2026). The concrete was cured in water. To date, there is no standard method for the mix design of foam concrete. To achieve workability and density with the available local materials, trial mixes were prepared using the absolute volume method. From the preliminary work, 0.8 ml of the chemical foaming agent was diluted in 45 g of water to produce 1 L of foam with a density of 45 kg/m^3. The mixed constituent proportions for the foamed concrete are presented in Table 1.

Table 1: Mix Constituents Proportions for the Foam Concrete Mixes

Mix Constituents Proportions for the Foam Concrete Mixes in kg/m^3

%RHA	Binder(kg/m^3)		Sand (kg/m^3)	Water for Base Mix (kg/m^3)	Foam Concentration	
	Cement	RHA*			Mixing Water (kg/m^3)	Foam (g/m^3)
0%	500.00	0.00	850.00	250.00	12.78	227.20
5%	475.00	25.00	850.00	250.00	12.6	224.00
10%	450.00	50.00	850.00	250.00	12.42	220.80
15%	425.00	75.00	850.00	250.00	12.24	217.60
20%	400.00	100.00	850.00	250.00	12.02	213.60
25%	375	125	850.00	250.00	11.84	210.4
30%	350	150	850.00	250.00	11.7	208

Fresh properties test

Wet density test

The wet density of foamed concrete was determined in accordance with BS EN 12350-6 (2000) by weighing a fresh sample in a container of known volume and weight for each batch before casting in a mould. The density was then calculated by dividing the difference between the weight of the concrete-filled container and the weight of the empty container by the container's volume.

Marsh cone test

The flowability of foamed concrete can be assessed from the efflux time of a liter sample through a modified Marsh cone. Marsh cone is a workability test used for specification and quality control of cement pastes and grouts. It is developed from V-funnel equipment used to test the flowability of high-flow concrete (Roussel & Le Roy, 2005). The marsh cone was modified in terms of opening diameter and efflux volume. The diameter of the funnel top is 152mm, and the extreme bottom is 12.7mm; the volume of efflux is 1 litre (Roussel & Le Roy, 2005). The procedure is as follows:

1. A Marsh cone is attached to a stand. The dimensions of the modified Marsh cone were measured.
2. After closing the nozzle, the cone was filled with 1.5 litres of sample, and the time required for foamed concrete to flow through the constricted orifice and fill a 1-litre container was measured. The flow time and behaviour are recorded and presented.

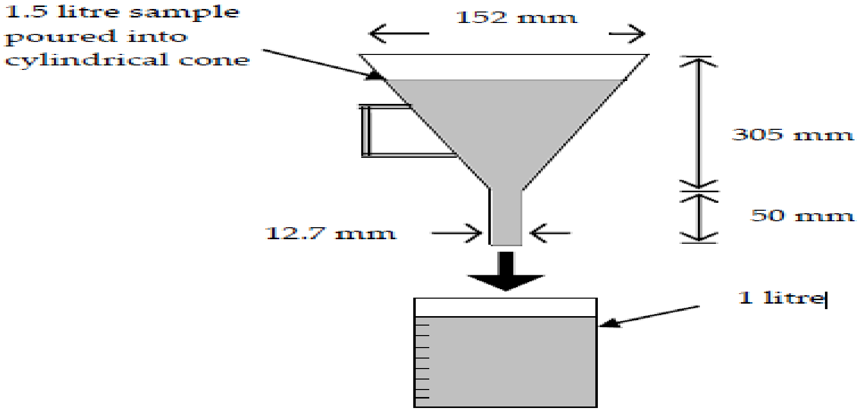

Figure 4: Dimensions of modified Marsh cone

Spread test

The workability of foamed concrete was evaluated through spread measurement in accordance with ASTM-230 (2003). The truncated cone mould was placed on a metal plate, filled with paste, and lifted in accordance with BS 1881-116 (2000). The flow diameter indicates the workability of the mix.

Figure 5: Spread Diameter Test of Foamed Concrete

Hardened properties test

Dry density test

The concrete specimens were cured and weighed using the weighing balance to determine the mass of the samples in accordance with BS EN 12390-7 (2009). The density of the concrete specimen was calculated using Equation 1.

$\boldsymbol{D} = \frac{\boldsymbol{M}}{\boldsymbol{V}}$ ………… (1)

Where D is the density of the concrete specimen in kg/m^3

M = mass of the specimen in kg

V = Volume of the specimen in m^3

Compressive strength test

Compressive strength of cubes measuring 100 x 100 x 100 mm was investigated at 7, 14, 28, 56, and 90 days in accordance with BS EN 12390-3 (2009). The specimens were tested at saturation (immediately after removal from the curing tank). Three specimens at each curing age were tested to failure by crushing. The average of the three specimens was then taken and divided by the area of the specimens to obtain the compressive strength.

Split tensile strength test

The split tensile test was carried out on kenaf fibre-reinforced foamed concrete in accordance with BS EN 12390-6 (2009). The cylindrical specimens of size 100 x 200 mm. The splitting tensile strength (Ts) is calculated in Equation 2 as follows:

$\mathrm{Ts} = \frac{2\mathrm{F}}{\pi \times \mathrm{L} \times \mathrm{d}}$ ……… (2)

Where: F is the maximum load in (KN), L is the length of specimen in (mm), d is the diameter of specimen in (mm), The split tensile strength is expressed to the nearest 0.05 MPa.

Flexural strength test

The flexural strength or modulus of rupture of kenaf fibre-reinforced foamed concrete was determined using a simple unreinforced beam subjected to a point load. The beam specimens were produced, prepared, and tested in accordance with BS EN 12390-5 (2009). The test specimens were 100 x 100 x 500 mm beams and were tested under single-point loading. The flexural strength (Mr) is calculated in Equation 3 as:

$\mathrm{Mr} = \frac{\mathrm{PL}}{bd^2}$ …… (3)

Where: b = measured width in “mm” of the specimen, d = measured depth in “mm” of the specimen, L = length in “mm” of the span on which the specimen was supported, P = maximum load in “kg” applied to the specimen

Durability tests

Water absorption test

The foamed concrete samples (cubes) at the determined curing age were placed in the electronic oven to oven-dry at 1050 °C for 72 hours. The samples were removed from the oven and allowed to cool at room temperature, then weighed to determine the initial weights (W_1). The final weights were determined after immersing the concrete samples in the curing medium for 30 minutes, then drying them on a cloth and reweighing them (W_2). The values obtained were recorded and the results calculated to assess the rate of absorption of the concrete specimens in accordance with BS 1881-122 (1983). The equation below was used to compute the absorption capacity for the specimens, which is given as:

WA = $\frac{W2 - W1}{W2}\ x\ 100\%$ ……… (4)

Sorptivity test

The sorptivity was determined by measuring capillary rise absorption on reasonably homogeneous material. Water was used as the test fluid. The cube was cast and cured under ambient conditions, and tests were carried out at 28, 56, and 90 days. After drying the specimen in an oven at a temperature of 100 + 10 °C, it is placed in water with the level not more than 5 mm above the base of the specimen, and the flow from the peripheral surface is prevented by sealing it with a non-absorbing sealant using an Abro Sealant or (Silicon Sealant) as a coating. The quantity of water absorbed over 10, 20, and 30 minutes was measured by weighing the specimen on a digital balance. Surface water on the specimen was wiped off with a dampened tissue, and each weighing operation was completed within 30 seconds. Sorptivity (S) is a material property that characterizes the tendency of a porous material to absorb and transmit water by capillary action. The cumulative water absorption per unit area of the inflow surface increases as the square root of elapsed time (t). The results were calculated using the equation 5:

$$S = \frac{I}{t1/2} \text{...........} \quad (5)$$

Where, S = sorptivity in mm
T = elapsed time in minutes
I = Δw/Ad
Δw = change in weight = $W_2 - W_1$
W_1 = Oven dry weight of cubes in grams
W_2 = weight of cube after successive minutes' capillary suction in grams
A = surface area of the specimen through which water penetrated
d = density of water

Fire resistance

This test was conducted according to the provisions of (ASTM E119-2000). The concrete cube samples were then heated to 200, 400, 600, and 800 °C at a heating rate of 100 °C/min for 2 hours. After exposure to elevated temperatures, the concrete samples were allowed to cool down naturally to room temperature and then subjected to a compressive strength test. Table 2 presents the standard test methods used to conduct the various tests.

Table 2: Tests description and specification

Test Description	Specification
Wet Density of Concrete	BS EN 12350-6 (2000)
Dry Density of Concrete	BS EN 12390-7 (2009)
Compressive Strength	BS EN 12390-3 (2009)
Split Tensile Strength	BS EN 12390-6 (2009).
Flexural Strength test	BS EN 12390-5 (2009)
Water Absorption	BS 1881 (1983)
Fire Resistance	ASTM E119 (2000)

Strength-predicting model

An expression relating the porosity and the compressive strength of foamed concrete with cement paste was developed by Hoff (1972). A simple model in which foamed concrete is composed of air, evaporable water, non-evaporable water, and cement. By applying the successive approximation principle and the Bisection Technique of numerical analysis **(**Agboola *et al*., 2025; Abdulazeez *et al*., 2025; Murthy, 2007; Scheid, 1989**)**, the principles of the model assumptions for compressive strength at no pores (f_0) and empirical contact (n) were determined to be 94.51 N/mm^2 and 3.60 respectively (principle underlying the process method is contained in Appendix). Using equation 6 and values of model constants found through the principle of approximation, the equation becomes:

$$\text{fc} = 94.51 \left(\frac{dc(1+0.20\rho b+K_{SBV})}{(1+\text{Kws})(1+K_{SBW})\rho b \Upsilon w} \right)^{3.60} \qquad (6)$$

where:
$d_C =$ the fresh weight of the foamed concrete
$f_C =$ compressive strength at 28 days
$PB =$ the binder′s specific gravity
$K_{SBV} =$ the volume ratio of sand to binder
$K_{WS} =$ the weight to solid ratio
$K_{SBW} =$ the weight − based ratio of sand to binder

Results and Discussion

Marsh cone test for foamed concrete

Table 3 shows the Marsh cone time for different mixes. The flow time for a 0.5 w/c ratio shows a clear drop at all cement replacement levels, except at 30% RHA. From the findings, the foamed concrete has increased flow time at lower w/c ratios because the finer cements require more water for flowability. RHA, which has higher fineness, also requires more water to flow through it due to its higher volume in the mix. The ideal flow time for application is between 1 minute and 3 minutes (Amran *et al*., 2020; Chen *et al*., 2021). This assumes that mixes taking more than 3 minutes to flow out were too slow, whilst mixes taking less than 1 minute suggest the mix was too wet. In this study, the 0.5 w/c ratios that fall within this 'acceptable' range. These were empirical values, and values within this range were assumed to be flowable; when RHA was high, a higher water-cement ratio was required. This is due to the high fineness, which requires more water to achieve flowability. However, RHA increases flowability when it is replaced with cement at lower percentages (5% to 15%), thereby improving flowability. Higher RHA demand requires more water in the mix.

Table 3: Marsh cone time for 1600 kg/m^3 in minutes

% Replacement of Cement	Density 1600 (kg/m^3) at 0.5 W/C ratio
0	1.49
5	1.44
10	1.51
15	2.36
20	3.13
25	Very sticky
30	Very sticky

Effect rice husk ash on spread diameter of foamed concrete

Table 4 presents the spread test results for foamed concrete with varying RHA cement replacement. The spread diameters for the control (0% replacement of cement) and 5, 10, 15, 20, 25, and 30% RHA at a 0.5 water-cement ratio are 450, 450, 450, 425, 400, 375, and 320 mm, respectively. This observation can be attributed to differences in particle size distribution, sand specific gravity, and the percentage of supplementary cementitious material in the mix. The differences in sand properties, rice husk ash, water-cement ratio, and foam agent in the concrete mix affect the spreadability of the foamed concrete. Also, the increased surface area of fine aggregates and the cohesive properties of the aggregates affect the mix. Consequently, the higher the percentage of supplementary materials added to the mix, the more water is required to achieve good spreadability.

Table 4: Spread Test of Foamed Concrete in mm

% Replacement Cement	Density 1600 (kg/m^3) Spread Dimeter/water-cement ratio of 0.5
0	450
5	450
10	450
15	425
20	400
25	375
30	320

Wet density of foamed concrete produced with Rice Husk Ash

The wet density values for foamed concrete are presented in Table 5. The plastic density ranged from 1589 to 1649 kg/m^3, with a small deviation from the target density of 1600 kg/m^3.

Table 5: Average Wet Density of foamed concrete in (kg/m^3)

% Replacement of cement	Actual Plastic Density (kg/m^3)
0	1641
5	1635
10	1635
15	1627
20	1614
25	1604
30	1589

Dry density of foamed concrete

A significant increase in the density of water-cured specimens was observed, which agreed with Neville (2012). The density of foamed concrete cured with water is higher than that of foamed concrete cured with other methods. This is in agreement with Yahaya *et al.* (2015), who state that foamed concrete with adequate distribution of moisture within the concrete increases in density. Figure 6 presents the average density of foamed concrete samples produced with rice husk ash at 0%, 5%, 10%, 15%, 20%, 25% and 30% and weighed at 7, 14, 28, 56, and 90 curing days. The density of foamed concrete samples ranges from 1530 kg/m^3 to 1720 kg/m^3 and increases with increasing curing period.

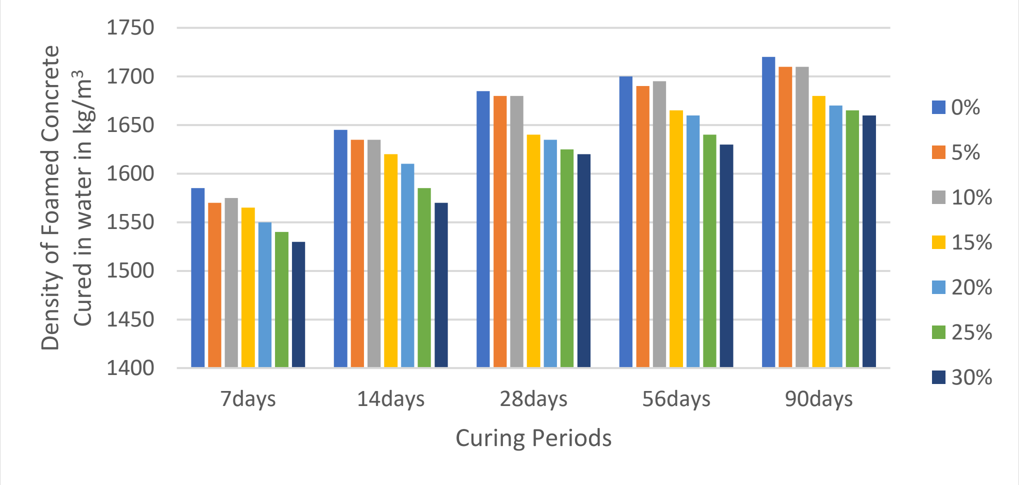

Figure 61: Density of Foamed Concrete

Compressive strength of concrete

Figure 7 shows the compressive strengths of concrete with rice husk ash as a cement replacement at curing periods of 7, 14, 28, 56, and 90 days, with RHA at 0, 5, 10, 15, 20, 25, and 30 % as cement replacement. The result shows that the control concrete has the highest strength at 7 days, with a 0.97% increase in strength beyond 5 and 10% RHA as cement replacement in concrete, respectively. The compressive strength increased with increasing curing period for all concrete specimens and decreased with increasing pozzolana proportion. At 28 days, the 0% control concrete achieved compressive strength 0.34% higher than 5% RHA concrete, 0.68% higher than 10% RHA concrete, 2.77% higher than 15% RHA concrete, and 17.38% higher than 20% RHA concrete. 25% and 30% RHA replacements of cement yield lower results than other replacement levels. This could be due to high SCM in the mix and to a higher number of pores, which result in lower strength. At 28 days of curing age, the average strength of foam concrete without rice husk ash was found 87% of the required strength for structural lightweight concrete, which is 17 MPa (Neville, 2011). On the other hand, the foam concrete mixes containing 5%, 10%, and 15% RHA achieved 86.7%, 86.4% and 84.6% of the strength classification for structural light-weight concrete. 0 % control concrete is the optimal level of cement replacement.

The addition of pozzolana into the concrete mix in an optimal quantity reduces the interparticle spaces between the fine aggregate's particles, which improves the strength of the concrete. The fine aggregate size and SCM distribution contribute to reducing the size and quantity of entrained air pores in the concrete structure. This is in agreement with Gambhir (2013) and Kearsley (2001), who found that the compressive strength of concrete increases with a reduction in porosity.

The adequate water content and high pozzolanic reactivity were the main factors in accelerating the hydration of rice husk ash in concrete. Water is required to facilitate the hydration of the pozzolanic material with the $Ca(OH)_2$ produced by OPC. In another study, Praveenkumar and Sankarasubramanian (2018) suggested that an optimal water-cement ratio in the concrete mix and an extended curing time would reduce the pore width, thereby enhancing its strength. The use of additives greatly improves compressive strength development at all test ages. Overall, except for mixes with 25% and 30%, the results suggest that the remaining mixes are all potentially suitable for use as a lightweight concrete for semi-structural or structural purposes since their densities did not exceed 2000 kg/m^3 and their 28-day compressive strengths are around 17 MPa (Kosmatka *et al.*, 2002; Neville, 2011).

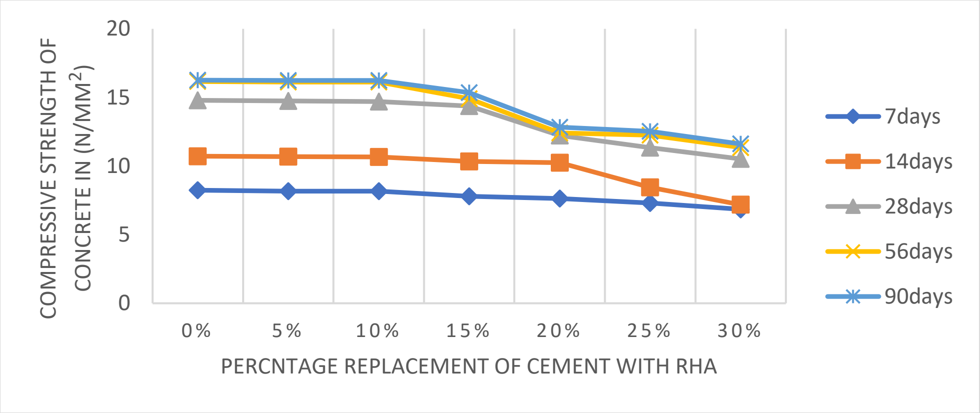

Figure 7: Compressive Strengths of Concrete at various curing periods

The relationship between the compressive strength developed at 7- and 28-days curing are presented in Table 6, which shows the percentage of 28th day strength developed at 7th day by specimens with percentage replacement of rice husk ash at 0, 5%, 10%, 15%, 20%, 25% and 30% are 54%, 55%, 56%, 54%, 62%, 65% and 65 % respectively.

Table 61: Relationship of the compressive strengths developed at 7th and 28th days curing

% Replacement	f7 (N/mm^2)	f28 (N/mm^2)	f7/f28
0	8.24	14.79	0.54
5	8.16	14.74	0.55
10	8.16	14.69	0.56
15	7.79	14.38	0.54
20	7.63	12.22	0.62
25	7.31	11.33	0.65
30	6.85	10.52	0.65

Split tensile strength of concrete

Figure 8 shows the split tensile strengths of cylindrical specimens with rice husk ash at different cement replacement levels and curing periods of 7, 28, 56, and 90 days. The result shows that the split tensile strength at different curing periods increases with increasing percentage of supplementary cementitious materials. The split tensile strengths of the cylindrical specimens cured for 7 days with 0, 5, 10, 15, 20, 25, and 30% rice husk ash are 1.38, 1.36, 1.36, 1.29, 1.27, 1.24, and 1.23 N/mm2, respectively. The split tensile strength at 28 days curing age include are 1.59, 1.55, 1.54, 1.49, 1.42, 1.35, and 1.26 N/mm2 respectively, the split tensile strength at 56 days curing is, 2.11, 1.96, 1.99, 1.55, 1.55, 1.41, and 1.31 N/mm2 respectively, while at 90 days curing period the tensile strength is 2.51, 2.48, 2.46, 2.05, 1.86, 1.52, and 1.35 N/mm2 respectively. From the findings of this research 0% shows increase in strength beyond all other replacement levels in all curing period, 0% control concrete shows an increase of 2.52% as against 5% RHA concrete, 3.14% increase in strength as against 10%, 6.30% increase in strength beyond 15%, 10.69% increase in strength beyond 20%, 15.09% increase in strength beyond 25% and 20.75% increase in strength beyond 30% RHA concrete. The structural properties of concrete, such as shear resistance, bond strength, and resistance to cracking, depend on the tensile strength; the higher the tensile strength, the better the structural properties (Babu, 2008; Hilal *et al*., 2015). This finding shows that proper, adequate curing of foamed concrete in the early days after production is important, as in conventional concrete, as stated by Gambhir (2013).

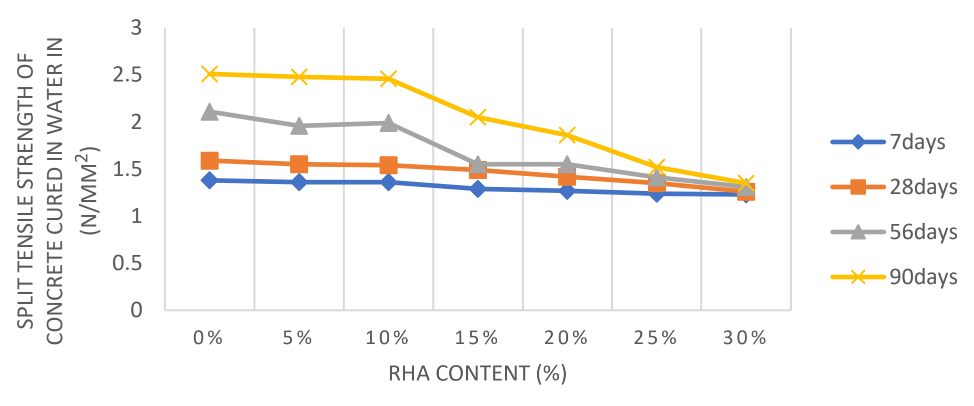

Figure 8: Split Strengths of Concrete at various curing periods

Relationship of split tensile and compressive strength of foamed concrete
Figure 9 shows the relationship between tensile strength and compressive strength of specimens cured in water. The result shows that the tensile strength increases with increasing compressive strength of foamed concrete. The regression line of the relationship is an exponential function, which can be expressed as.

$Ft = 0.0539Fcu^{1.2}$ ……. 7
Also, the ratios of tensile to compressive strength for the specimens indicate that tensile strength is approximately 10-12% of compressive strength. According to Kosmatka and Kerkhof (2002), the tensile-to-compressive strength ratio is between 8% and 12%. However, specimens with water curing fall within this range.

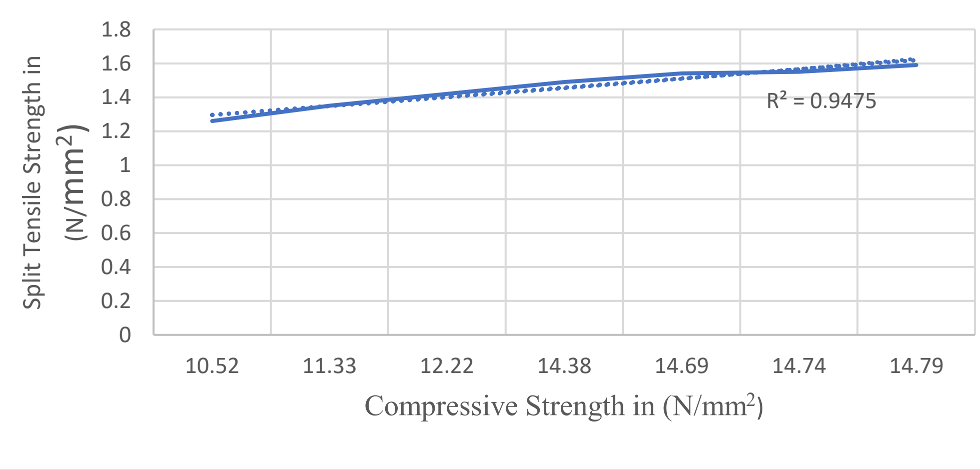

Figure 92: Relationship of split tensile to compressive strength at 28th days

Modulus of rupture of specimens cured
Figure 10 shows the results of the modulus of rupture of the unreinforced beam specimen produced with RHA as a partial replacement of cement cured in water. The modulus of rupture of specimens with 0, 5, 10, 15, 20, 25, and 30 % RHA concrete at a 7-day curing period is 2.28, 2.27, 2.27, 2.22, 2.15, 1.95, and 1.75 N/mm^2, respectively. The flexural strengths at 28 days are 2.46, 2.46, 2.46, 2.25, 2.21, 2.14, and 1.87 N/mm^2, respectively. The flexural strength at a 56-day curing period is 2.57, 2.55, 2.55, 2.48, 2.41, 2.21, and 1.92 N/mm^2, respectively. The flexural strengths at 90 days of curing are 2.62, 2.55, 2.58, 2.51, 2.48, 2.24, and 2.12 N/mm^2, respectively. The findings of this study revealed that the modulus of rupture of the specimens increases with increasing curing period. Thus, the modulus of rupture of the specimens at 28 days with 0% control concrete has same strength as 5% and 10% RHA concrete and shows in increase in strength of 8.54% beyond 15% RHA concrete, 10.16% increase in strength beyond 20%, 13.01% increase in strength beyond 25% RHA concrete and 23.98% increase in strength beyond 30% RHA concrete. The reduction in the modulus of rupture with higher cement replacement compared to the control may be due to weakening, leading to a weaker bond between the paste and the sand grains. The moduli

of rupture obtained in the study were high compared to the value of 1.00N/mm2 obtained by Brady *et al*. (2001) for foamed concrete of the same density.

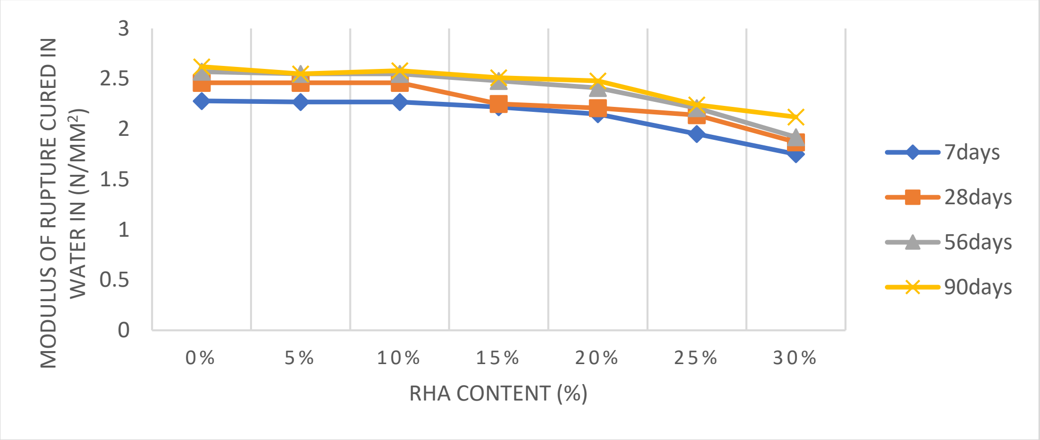

Figure 10: Modulus of Rupture of Concrete at various curing periods

Relationship of modulus of rupture and compressive strength of foamed concrete

Figure 11 shows the relationship between modulus of rupture (flexural strength) and compressive strength of specimens cured in water. The result shows that the flexural strength increases with increasing compressive strength of foamed concrete. The regression line of the relationship is an exponential function, which can be expressed as.

$Fr= 1.8843Fcu^{0.10}$ …… 8

Also, the ratios of tensile to compressive strength for the specimens indicate that tensile strength is approximately 16-19% of compressive strength. These values are higher than the values from the study of Arthur *et al*. (2010) who state that the modulus of rupture of light weight concrete is between 10 - 12 % of the compressive strength. Therefore, foamed concrete develops greater flexural strengths than other light weight concrete. The result of this study is close to the finding of NRMCA (2000) who stated that the ratio of flexural strength to compressive is about 10 – 20%.

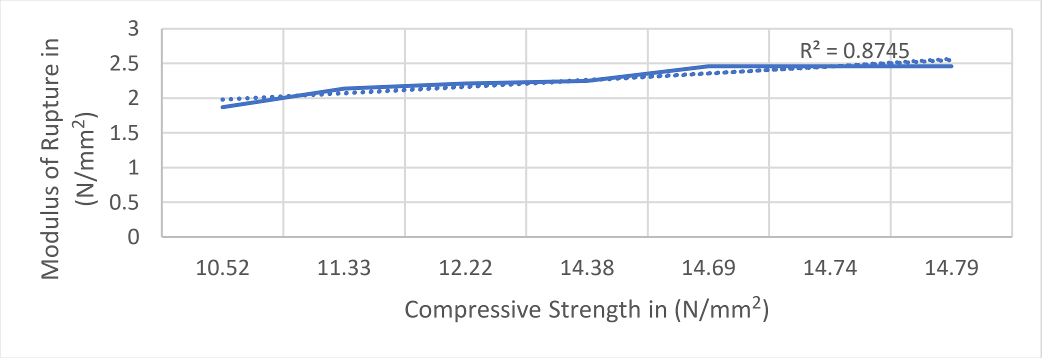

Figure 11: Relationship of Modulus of Rupture strength to compressive strength at 28th days

Result of ultrasonic pulse velocity test of foamed concrete

The ultrasonic pulse velocity (UPV) values for all mixes are shown in Figure 12. The UPV values of all concrete mixes produced with rice husk ash as a partial cement replacement are quite close to those of the control concrete at all ages. Foamed concrete at 7 days has a UPV within the range of 3.01 to 3.47 m/s; at 28 days, it has a UPV within the range of 3.35 – 3.90 m/s; and at 90 days, it has a UPV of 3.59 – 4.08 m/s. The UPV values at the time of testing showed that all the mixes met the minimum required value for good-quality concrete. In addition, the trend of UPV values showed an increase of 14.95% at 90 days compared to the 7-day average.

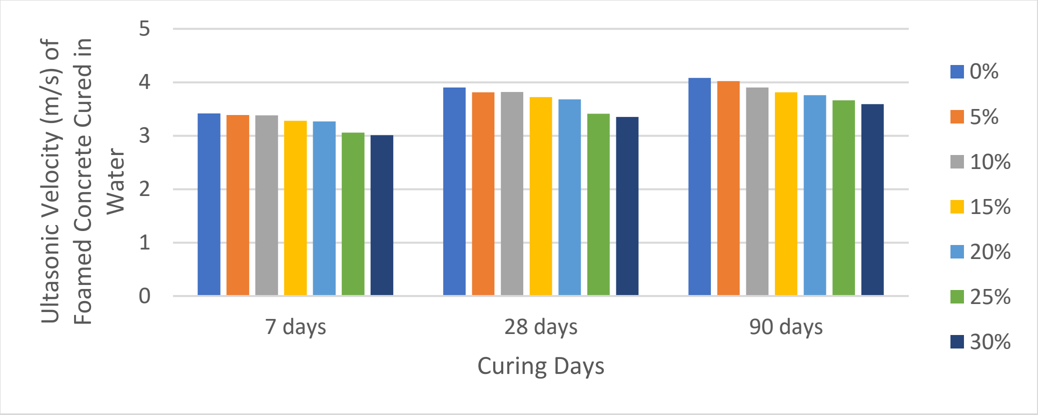

Figure 12: Average Ultrasonic Pulse Velocity of foamed Concrete

Fire resistance of foamed concrete of specimens

Figures 13 and 14 illustrate the typical development of compressive strength for foamed concrete produced with rice husk ash thermally treated at 200, 400, 600, and 800 °C. Exposure to elevated temperatures led to progressive strength degradation across all mixes. Specimens retained substantial compressive strength up to 400 °C, beyond which significant deterioration occurred, particularly at 600 °C and 800 °C. Strength loss at elevated temperatures is attributed to dehydration of hydration products, microcracking, and pore coalescence. Mixes containing up to 10% RHA demonstrated thermal resistance comparable to that of the control concrete, indicating that moderate RHA incorporation does not adversely affect fire performance. At higher replacement levels, increased porosity accelerated thermal degradation, reducing residual strength. This finding is similar to that of Mydin *et al*. (2024), who reported that foamed concrete exposed to elevated temperatures results in decreases in compressive, tensile, and modulus of elasticity strengths.

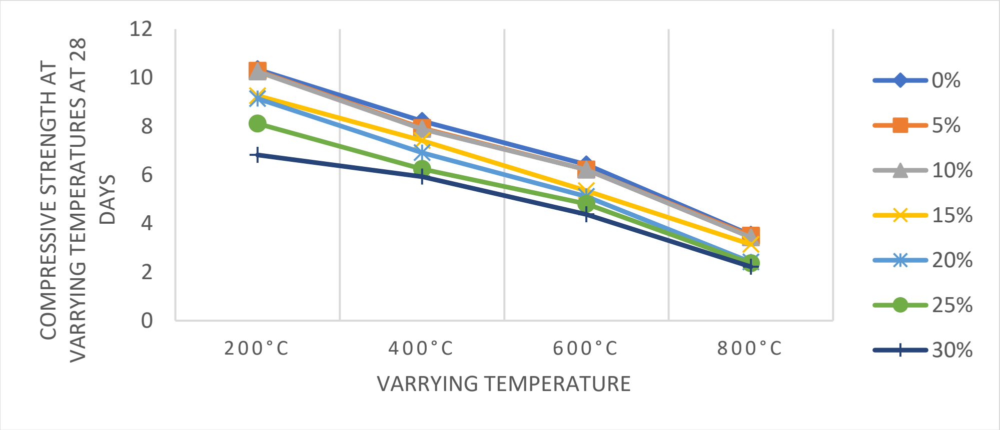

Figure 13: Residual compressive strength of foamed concrete incorporating varying rice husk ash contents after exposure to elevated temperatures (200–800 °C) at 28 days curing

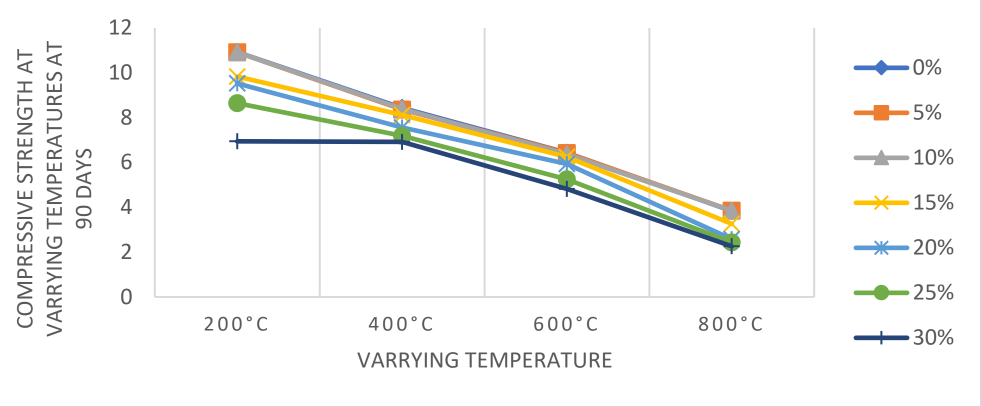

Figure 14: Residual compressive strength of foamed concrete incorporating varying rice husk ash contents after exposure to elevated temperatures (200–800 °C) at 90 days curing

Average water absorption test of foamed concrete

Figure 15 presents the water absorption test of foamed concrete cured in water and tested at 28, 56, and 90 days' hydration periods. For cubes cured in water at 28 days, the 30% cement replacement absorbed more curing agent than the control concrete and other replacement levels, while the 0% cement replacement absorbed less than all replacement levels. Concrete samples with 0% replacement absorbed 1.94%, while 5%, 10%, 15%, 20%, 25%, 30%, cement replacement with rice husk ash absorbed 2.06%, 2.25%, 2.50%, 2.64%, 2.79%, and 2.99%, respectively, at 28 days. Concrete samples with 0% replacement absorbed 2.43%, while 5%, 10%, 15%, 20%, 25%, 30% cement replacement with rice husk ash absorbed 2.57%, 2.74%, 2.80%, 3.14%, 3.32%, and 3.38%, respectively, at 56 days. Concrete samples with 0% replacement absorbed 2.72%, while 5%, 10%, 15%, 20%, 25%, 30% cement replacement with rice husk ash absorbed 2.84%, 2.99%, 3.12%, 3.34%, 3.76%, and 4.12%, respectively, at 90 days.

The result shows that cement replacement percentages with 30% rice husk ash absorbed a larger amount of curing agent than the control and all other cement replacement levels, which can be attributed to the capillary suction effect. Water absorption is affected by the concrete mixture proportions, the interconnected pore network, the duration of curing, the type, age, or degree of hydration, the existence of microcracks, and the entrained air content (Şahmaran & Li, 2009). The water absorption capacity varies from 1.94% to 2.99% at 28 days, 2.43% to 3.38% at 56 days, and 2.72% to 4.12% at 90 days, for 0% to 30% cement replacement with RHA. This is a measure of its ability to withstand water-based deterioration agents in the service environment. Concrete with a water absorption capacity of less than 10 is considered good (Neville, 2003). The NIS 87 (2004) requires a water absorption capacity of less than 12 for materials to be used for blocks, both load-bearing and non-load-bearing, in addition to a compressive strength of 3.45N/mm2 or above. However, low water absorption from this study will increase C-S-H reaction, enhance durability, limit shrinkage and cracking, and maintain good thermal insulation properties in foamed concrete.

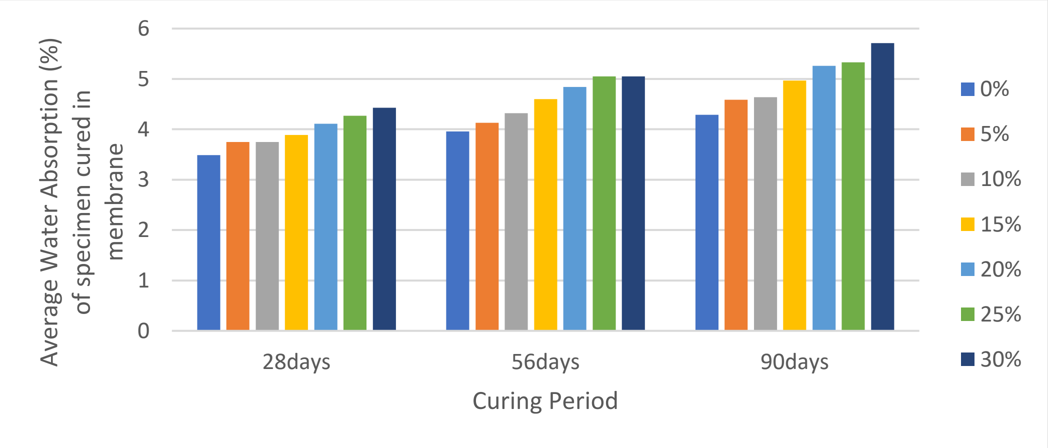

Figure 15: Water absorption test of foamed concrete

Sorptivity of foamed concrete

Figures 16 to 18 present plots of sorptivity versus rice husk ash replacement levels (0% to 30%) at 10 to 30 minutes for foamed concrete cured at 28, 56, and 90 days. The control foamed concrete has a value of 8.7 x 10-8 mm/min$^{0.5}$, 5% has a value of 8.8 x 10-8 mm/min$^{0.5}$, while 30% cement replacement has a value of 12.73 x 10-8 mm/min$^{0.5}$ at 28 days, and it shows a linear trend graphically. The control foamed concrete has a value of 10.6 x 10-8 mm/min$^{0.5}$, 5% has a value of 10.7 x 10-8 mm/min$^{0.5}$, while 30% cement replacement has a value of 13.8 x 10-8 mm/min$^{0.5}$ at 56 days, while at 90 days, control concrete has a value of 11.1 x 10-8 mm/min$^{0.5}$, 5% has a value of 11.53 x 10-8 mm/min$^{0.5}$, while 30% cement replacement has a value of 14.5 x 10-8 mm/min$^{0.5}$.The sorptivity increased with increasing rice husk ash content in concrete; the control concrete had the lowest sorptivity, while the 30% cement replacement level had the highest. A linear trend was also observed at 56 days and 90 days of curing. The linear trend was due to the relatively uniform pore structure and capillary suction behavior of foamed concrete.

The result agrees with Sabir *et al.* (1998), who tested the sorptivity of mortar containing ground bricks (10, 20, and 30% replacement for cement). However, the graph shows that the sorptivity of the foamed concrete specimens is linear over 10-30 min. In another study, Islam (2012) observed a non-linear trend across three concrete mixes: without additives, with an air-entraining agent, and with a superplasticizer. They proposed that this phenomenon referred to the new hydration of cement, which occurred when the specimen was placed in water and increased the effective grain size, thereby tending to block the micro-pores. Accordingly, water movement through concrete is hindered. Other trends in sorptivity were also reported by Huang *et al*. (2023), Lu *et al*. (2020), and Jennings and Tennis (1994), in which cumulative water absorption was found to follow a curve with time raised to the square root.

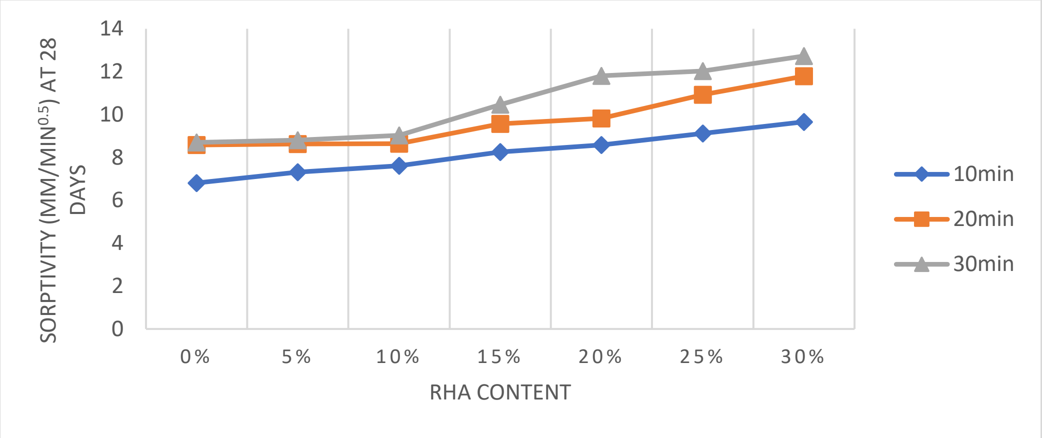

Figure 16: Sorptivity Test of Foamed Concrete at 28 days

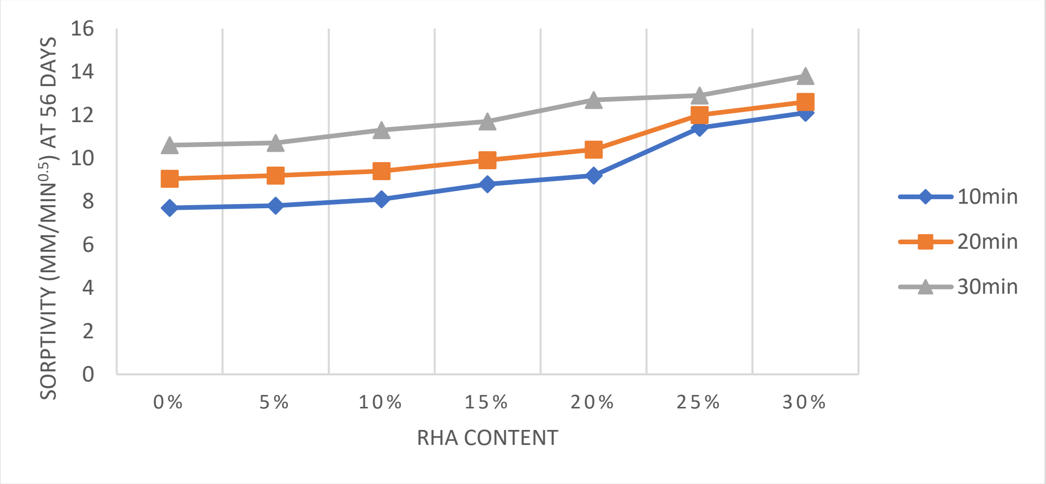

Figure 17: Sorptivity Test of Foamed Concrete at 56 days

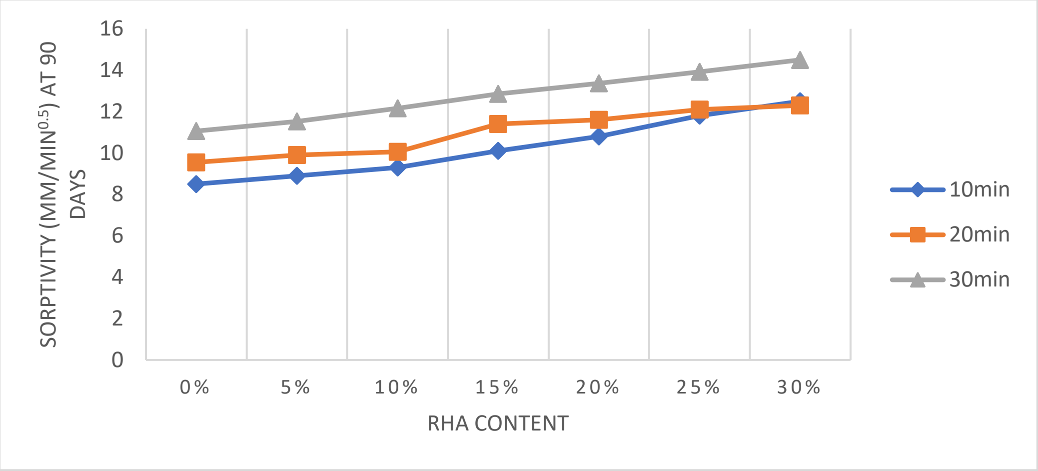

Figure 18: Sorptivity Test of Foamed Concrete at 90 days

Validation of the strength prediction model

To validate the derived strength-predicting mathematical model, the compressive strengths obtained using equation 6, accounting for the physical properties in the Appendices, are compared with those from cube tests at all levels of cement replacement with rice husk ash. These results are presented in Table 7 and the Appendix.

From Table 7, it can be seen that the compressive strengths obtained from the model equation correlated well with the experimental compressive strengths across all levels of cement replacement with rice husk ash. When expressed as a percentage of model strength, the differences between the predicted and experimentally observed strengths across all replacement levels range from 0% (for the control) to -6.73% (for 15% replacement of cement). The highest difference - 6.73% occurred at 15% replacement level. The overall average difference is -0.24%. An average of less than 15% is considered acceptable for laboratory-produced foamed aerated concrete (Agboola *et al*., 2025; Ikponmwosa *et al*., 2013; Rao, 2011).

Also, from statistical analysis, the mean is 13.24N/mm^2, and the standard deviation is 0.24. A lower standard deviation indicates that the data cluster around the average. In addition, the statistically significant test at significance levels of 1%, 5%, and 10% showed that the difference is not significant, as the confidence values fall outside the critical regions, indicating that there is no reason to reject the result of the model at the level of confidence of 1%, 5%, and 10%. Thus, the strength-predicting equation 6 can be considered valid for foamed concrete with and without rice husk ash as a cement replacement, provided the replacement level does not exceed 30%, and the density is within the same range of 1600 kg/m^3, under the same curing conditions.

Table 72: Comparison of the Model and Experimental Compressive Strengths

% Replacement	Experimental (N/mm^2)	Model(N/mm^2)	% Difference
0%	14.79	14.79	0.00
5%	14.74	14.58	-1.08
10%	14.69	14.00	-4.89
15%	14.38	13.47	-6.73
20%	12.22	12.43	1.71
25%	11.33	11.77	3.78
30%	10.52	11.14	5.54
Average	13.24	13.17	-0.24

The curves for the experimental and predicted strength are shown in Figure 19. It can be observed that the predicted and experimental strengths are the same for the control (0% replacement). At 5% to 15% replacement, the experimental strength is higher than the model strength. At replacement levels of 20% or higher, the experimental strengths are lower than the model strengths.

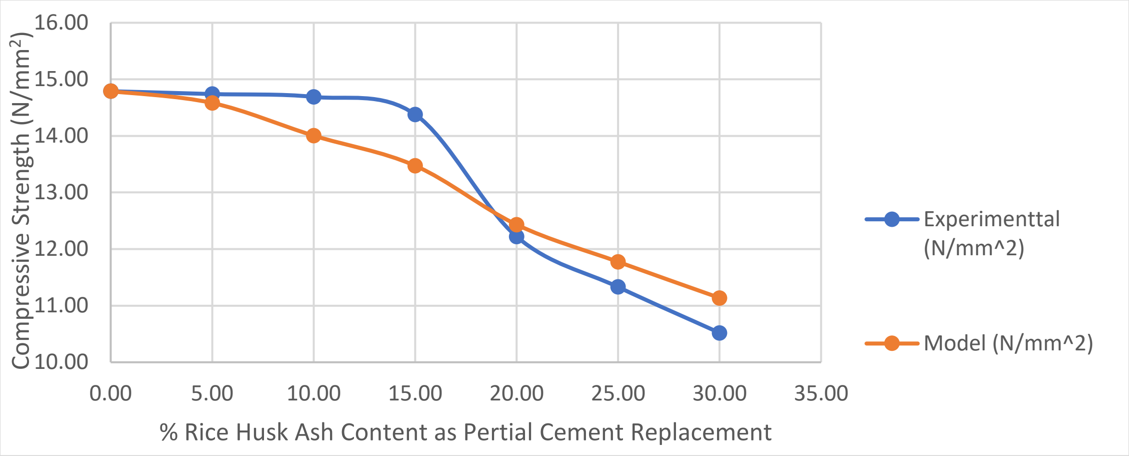

Figure 19: Variation of Experimental and Model Strengths of FC with Rice Husk Ash

The relationship between the experimental and predicted compressive strength values is shown in the scatter plot in Figure 20.

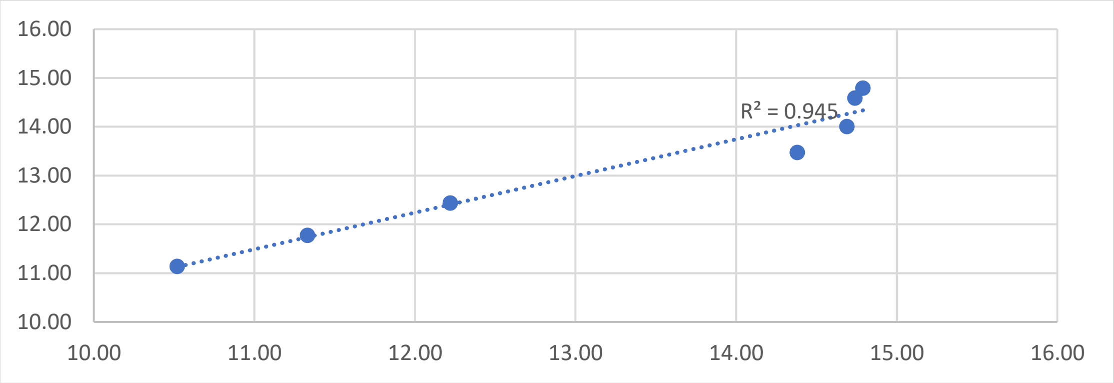

Figure 20: Relationship between the Experimental and Predicted Strength Values

A correlation coefficient of 0.945 indicates a strong, positive linear relationship between the model strength and the experimental strength. Using the statistical line of best fit, this relationship can be expressed through a linear regression equation of the form:

fcue= Af$_{cum}$ + B (8)

where:

fcue= experimentally observed compressive strength

fcum= compressive strength obtained from the mathematical model

A and B = regression coefficients representing the slope and intercepts respectively of a plot of experimental strength against model compressive strength.

By determining these coefficients through regression analysis, equation 22 becomes:

fcue= 3.22 fcum - 0.75 (9)

where:

fcue= experimentally observed compressive strength

fcum= compressive strength obtained from the mathematical model

Conclusion

The density of foam concrete increases with age. The 28-day compressive strength of control concrete with 14.79N/mm^2, 5% with 14.72N/mm^2, and 10% with 14.69N/mm^2, obtained for foamed concrete in this study at the designed density of 1600kg/m^3, were around the minimum strength requirement for classification as a structural lightweight of 15N/mm^2 as per (ACI 213R). The 28-day split tensile strength of control foamed concrete for water-cured concrete was 1.59N/mm^2, respectively, and meets the ASTM specification for lightweight concrete. The 28-day flexural strength of foamed concrete was2.46N/mm^2, respectively, and meets the ASTM specification for lightweight concrete. The sorptivity of foamed concrete increases slightly with curing age and increases further with a higher percentage of rice husk ash as a partial cement replacement. The void in the foamed concrete mix also affects the specimen's sorption capacity. The density of foamed concrete affects its sorption performance. Rice husk ash significantly affects the properties of foamed concrete. As the pozzolana content increases, the density of foamed concrete decreases, resulting in lighter specimens. Rice husk ash tends to create more voids in concrete, which increases water absorption.

The ultrasonic pulse velocity decreases with an increase in the percentage of rice husk ash present in the foamed concrete specimen. The UPV value of the specimen is directly proportional to its unit weight, and this affects the strength quality of the concrete produced.

The study simulated and validated a mathematical model for predicting the 28-day compressive strength of foamed concrete with and without rice husk ash. The model has been validated up to 30% partial replacement of cement with rice husk ash. The model predicts the 28-day compressive strength of freshly mixed concrete as it hardens and could be used as an effective quality-control measure on construction sites.

All the tested foamed concrete specimens exhibited brittle failure at all temperature levels, failing soon after reaching their peak strength. For the foamed concrete, the end portions of the failed specimens exhibited a ‘double cone pattern’ at the top and bottom at 400 °C, and when exposed to 600 °C, the specimens failed in an irregular pattern.

The optimal replacement level for rice husk ash was 10%, which is consistent with previous research on compressive and flexural strength. With 10% rice husk ash as a cement replacement, the integrity of concrete is not affected, as there is little significant impact on concrete absorptive properties and therefore no significant effect on durability. RHA will help reduce the volume of industrial waste and reduce the amount of cement used in concrete production.

Research recommends further investigation into the effect of pozzolana and admixture on the absorptive properties of foamed concrete. A proper magnification technique must be employed to examine the microstructure of the mixes, from the fresh to the hardened state, to determine the pozzolanic and cement matrix contributions to the functional performance of foamed concrete. Further investigation on the effect of lightweight aggregate sizes and proportions on the mechanical properties of foamed concrete, and investigations to improve the tensile properties of foamed concrete with varying forms of natural and synthetic fibres.

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Appendices

Table A1: Effect of Rice Husk Ash on Physical Properties and Setting times of Ordinary Portland Cement mortar

Table A1: Effect of Rice Husk Ash (RHA) on Physical Properties and Setting times of Ordinary Portland Cement mortar

%RHA*	SG	W/C Ratio for SC	Setting Times	
			Initial	Final
0%	3.10	0.50	61	114
5%	3.05	0.50	68	128
10%	3.04	0.50	72	149
15%	3.02	0.50	89	184
20%	3.02	0.50	101	211
25%	3.01	0.50	121	232
30%	3	0.50	148	258

Table A2: Repeatability of 1600 kg/m^3 **wet Density Foamed Concrete**

RHA	**Wet Density**
0%	**1641**
5%	**1635**
10%	**1635**
15%	**1627**
20%	**1614**
25%	**1604**
30%	**1589**

Table A3: Development of Strength-Predicting Model

%RHA*	kSBW	kSBV	kws(T)	pB	Dc	A	B	P= A/B	fc (N/mm^2)
0%	1.7	2.02	0.194652	3.10	1641	5973.2400	9999.236	0.5974	14.79
5%	1.7	1.97	0.194519	3.05	1635	5853.3000	9836.860	0.5950	14.74
10%	1.7	1.92	0.194385	3.04	1635	5768.2800	9803.514	0.5884	14.69
15%	1.7	1.88	0.194252	3.02	1627	5668.4680	9737.930	0.5821	14.38
20%	1.7	1.83	0.194089	3.02	1614	5542.4760	9736.601	0.5692	12.22
25%	1.7	1.79	0.193956	3.01	1604	5440.7680	9703.277	0.5607	11.33
30%	1.7	1.76	0.193852	3	1589	5339.0400	9670.200	0.5521	10.52

RHA = Rice Husk Ash
kSBW = Sand Binder weight ratio
kSBV = Sand Binder Ratio by Volume
Kws = Water Solid Ratio by weight
pB = Specific Gravity of Binder
Dc = Fresh Density of Foamed Concrete
P = Porosity
A=dc(I+0.20pB +kSBV)
B=(I+kws,)(1+ kSBW)PBYW