Fire Resistance and Ultrasonic Testing of Rice Husk Ash Modified Foamed Concrete

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Foamed concrete (FC) is a relatively new construction material that has recently gained attention due to its unique properties, such as density and strength-to-weight ratio. This lightweight material makes it easy to form into different shapes and sizes. Its excellent thermal insulation makes it popular for building walls, roofs, and floors. This study investigates the fire resistance and ultrasonic testing of rice husk ash modified foamed concrete. The study adopted a design density of 1600 kg/m^3 and a 0.5% water-cement ratio. The concrete was cured in ambient conditions at 7,14, 28, 56, and 90 days. A cube specimen of 100 mm size was used to determine compressive strength, density, fire resistance, and ultrasonic pulse velocity (UPV). The control achieved the maximum compressive strength at 28 days, which achieved 15.85 N/mm^2. The fire resistance of FC is reduced as temperature increases. The strength of FC at an elevated temperature of 400^{0}C is minimally reduced. The results proved that the UPV was efficient in proving that the various samples of FC come from the same material (uniform and homogeneous structure) and are classified as good-quality concrete. The findings of this study show that FC with rice husk ash percentage up to 10% did not have a significant difference from the control concrete, while a higher percentage replacement level shows reduced strength. FC is recommended for application in structural lightweight insulating material. RHA is a good pozzolana and can reduce overburden on cement by reducing the quantity of cement used for FC production.
Keywords: Compressive Strength, Lightweight Concrete, Rice Husk Ash, Thermal Performance, Ultrasonic Pulse Velocity

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Introduction

Global warming is a phenomenon that is driving the world towards making drastic changes to mitigate its effects. Experimenting with and producing alternative fuels and recycling waste materials by producing new materials are measures to reduce greenhouse emissions. The construction industry is one of the largest contributors to global warming. Reducing dependency on cement is a primary focus for researchers. This has been translated to using several waste materials such as fly ash, silica fume, and rice husk ash as cement replacements. Designing and constructing energy-efficient buildings is another approach to reducing greenhouse emissions (Agboola *et al.,* 2024a). This is done using lightweight materials and incorporating waste into building construction materials (Al-Jabri *et al.,* 2005; Agboola *et al.,* 2024b). Concrete is one of the most versatile construction materials, offering potentially unlimited opportunities for developing diverse forms of construction, as its ingredients, namely cement, sand, aggregates, and water, are available all over the globe (Surendren, 2010). Concerning density, concrete can be classified into several types: lightweight, normal weight, and heavy concrete. Neville (2011) mentioned that a reduction in concrete density can be achieved by replacing some of the solid materials in the concrete.

Lightweight concrete has been used in industrial buildings as precast panels (Liu *et al.,* 2022; Hassanpour *et al.,* 2012). To achieve adequate features, researchers have used various components and additives within concrete mixtures (Kim *et al.,* 2012; Kim *et al.,* 2010; Mo *et al.,* 2017; Youm *et al.,* 2016). Lightweight concrete can be produced by different methods, e.g. by using only fine aggregate and introducing air voids into concrete structures with chemical admixtures and mechanical foaming (Othuman & Wang, 2011; Kan & Demirboğa, 2009). This type of concrete is known as aerated or foamed concrete. Foamed concrete consists of only a cement matrix (called a paste) or a cement and sand matrix (mortar) with homogeneous voids, which can be created by introducing small air bubbles. The introduction of air voids into concrete is carried out mechanically by foaming agents mixed with water. Foamed concrete is a lightweight material composed of cementitious mortar that is surrounded by disconnected bubbles (more than 50% by volume), which are a result of either physical or chemical processes during which either air is introduced into the mortar (un-foamed) mixture, or gas is formed within it (Tikalsky *et al.,* 2004). Because of the possibility of producing a wide range of densities (300-2000 kg/m^3), foamed concrete has the potential to fulfil the requirements and has now become widely used in the construction industry (Jones & McCarthy, 2005; Tarasov *et al.,* 2010). With foamed concrete, sustainability is enhanced as coarse aggregate is not required in its manufacturing, and there is the possibility of partially or fully replacing fine aggregate and cement with secondary material like fly ash and rice husk ash (Agboola *et al.,* 2023; Jones & McCarthy, 2006). Secondary or pozzolanic material from agricultural and industrial waste can be used as replacement material in the construction industry (Agboola *et al.,* 2022; Rahmat *et al.,* 2024; Ndahi *et al.,* 2024). Many factors influence the production of foamed concrete, such as the foam preparation system, foaming agent, the concrete mixture design, pozzolanic material, nature and aggregate type, and the procedure for mixing foam concrete (Agboola *et al.,* 2024b; Raj *et al.,* 2019; Gencel *et al.,* 2022). Pozzolanic materials have been added to reduce the cost, improve the workability of the mix, reduce the heat of hydration, and increase the long-term strength (Agboola *et al.,* 2023b; Dong *et al.,* 2020). Obtaining this uniformity in the structure of the FC ensures a balanced system that meets its main properties. Certain concrete parameters, including density, homogeneity, quality, durability, and depth of surface cracking, have been measured in recent decades using ultrasonic pulse velocity (UPV) (Lui *et al.,* 2018; Irrigaray *et al.,* 2016). It was used to evaluate the UPV and determine the nature and quality of foamed concrete. Nonetheless, the homogeneity of pore distribution in the FC's structure needs to be assessed to guarantee optimal performance.

Concrete generally provides the best fire-resisting properties compared to other construction materials (Raut & Kodur, 2011; Khaliq *et al.,* 2013). These excellent fire-resisting characteristics are exhibited due to their low thermal conductivity, high heat capacity and slower strength degradation with temperature (Kodur *et al.,* 2019; Zhang *et al.,* 2014). Lightweight concrete has many advantages, which include excellent acoustic performance, workability, long life span due to termite and fire resistance, weatherproof and material savings (Upasiri *et al.,* 2020; Amran, 2020; Marunmale & Attar, 2014) and therefore can be utilized as a better construction material in low rise and multi-storey buildings. Laurent (2014) investigated the fire performance of foamed concrete under insulation criteria up to 900^0C temperature and concluded that foamed concrete has better fire performance characteristics compared to normal-weight concrete. Furthermore, studies on foamed concrete behaviour in the fire have yet to be available in different parametric fire situations. During fire exposure, structural elements will undergo high-temperature variation, which will induce internal stresses and variation of bonding in foamed concrete. Hence, post-fire load-bearing capacities need to be determined. This study, however, investigates the fire resistance and ultrasonic testing properties of rice husk ash foamed concrete.

Materials and Methods

Materials

Portland Cement (CEM 1) with grade 42.5R, whose production was in accordance with BS 12 (1996), was used as the main binder. Rice husk was obtained from a rice mill at Mudawal market in the Bauchi metropolis. River sand from the Yelwa River in the 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 might settle in a lightweight mix and lead to the collapse of the foam during mixing. A protein-based foaming agent was used for this project. The water used for this work is potable tap water. This is crucial when using a protein-based foaming agent because organic contamination can hurt the quality of the foam and the concrete produced.

Mix proportions

A mix proportion that will produce the target plastic density of 1600kg/m^3 (±50kg/m^3) was developed, with density being the design criterion in foamed concrete. To date, there is no standard method for designing foam concrete mixes. Therefore, to achieve the desired density and workability with the available local materials, trial mixes were carried out in this study. 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 (kg)	RHA (kg)			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

Methods

Dry density test

The concrete specimens were 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.

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

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

Curing of foamed concrete

The foamed concrete specimen was cast in the laboratory, demoulded after 24 hours, and cured in ambient conditions at 27^0 and 30^0C.

Compressive strength test

Compressive strength using a cube size of 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 foamed concrete was subject to a loading rate of 120KN/min. Three specimens for each curing age were tested for 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.

Fire resistance

This test was conducted according to the provisions of ASTM E119 (2000). Foamed concrete specimens were tested at 28 and 90 days. The concrete cube samples were then subjected to elevated temperatures of 200, 400, 600 and 800^0C for 2 hours at a heating rate of 10^0C/minute. 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.

Ultrasonic pulse velocity (UPV) test

This method was based on ASTM C 597 (2016), which recorded the time the pulse travelled through the concrete specimen. Two transducers were placed on two parallel surfaces of the cube specimen. The portable ultrasonic non-destructive digital indicating tester (PUNDIT), consisting of a pulse generator, a pair of transducers (transmitter and receiver), an amplifier, a time measuring circuit, a time display unit, and connecting cables were used. In this test method, the traducer produces the ultrasonic pulse, which is in contact with one surface of the concrete member under the test. After traversing a known path length (L) in the concrete, the pulse of vibration is converted into an electrical signal by the second transducer held in contact with the other surface of the concrete member, and an electronic timing circuit enables the transit time (T) of the pulse to be measured. The pulse velocity (V) is calculated using Equation 2.

$$Velocity\left(\frac{m}{s}\right) = \frac{L}{T} \text{ - - - - - (2)}$$

Where L = distance between centres of transducers faces (m)

T = transit time (s)

Result and Discussion

Density of foamed concrete

Figure 1 presents the average density of foamed concrete 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. An increase in the content of rice husk ash resulted in a decrease in the dry density of foamed concrete at all the curing ages. At 7 days of curing age, there was a decrease in the dry density with an increase in the replacement of rice husk ash in the concrete mix. This trend was also observed for all curing ages. The density of foamed concrete samples varies from 1480 kg/m^3 to 1700 kg/m^3, increasing with increased curing periods. Concrete density of not more than 2160 kg/m^3 is considered lightweight concrete (Graybeal & Lwin, 2013). It can also be seen that the density of foamed concrete decreases with an increase in rice husk ash when used in the mix. This results from rice husk ash being lighter in weight than cement by about 32%. However, according to NRMCA (2015), this type of concrete density is classified under lightweight concrete. Therefore, other samples with pozzolanic material replacements were less dense than the control samples at all curing periods.

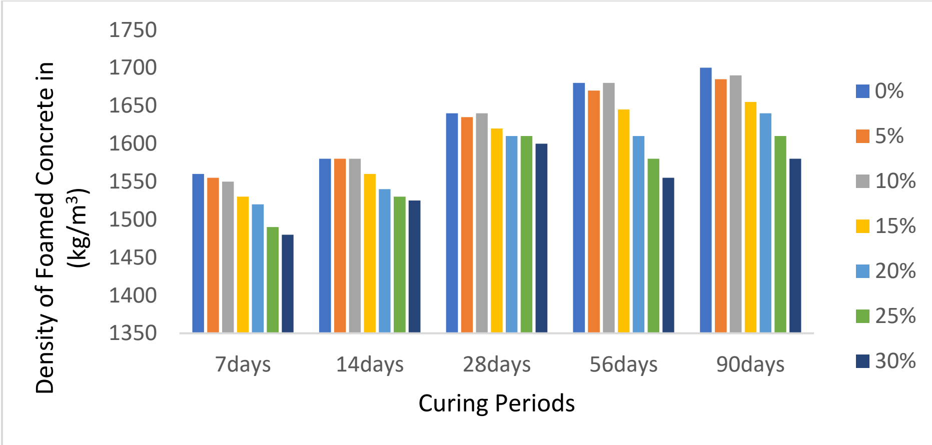

Figure 1: Density of Foamed Concrete

Compressive strength specimens cured in ambient condition

Figure 2 shows the compressive strengths of foamed concrete at different cement replacement levels of 0 to 30% with rice husk ash at 5% intervals and cured at 7, 14, 28, 56 and 90 days. The compressive strength at 28 days for 5, 10, 15, 20, 25 and 30% cement replacement include 15.85, 15.81, 15.79, 15.22, 13.13, 12.35 and 11.68 N/mm^2 respectively. This shows an increase in strength of 0.25%, 0.38%, 3.97%, 17.16%, 22.08% and 26.31% for 5, 10, 15, 20, 25 and 30% cement replacement, respectively, compared to control concrete. The results show no significant decrease in strength for foamed concrete with rice husk ash up to 10%. The same trend was observed for concrete at all curing ages.

The incorporation of a higher percentage of RHA in the mixture makes the RHA fill up the voids within the concrete mass, leading to a gradual decrease in the pozzolanic reaction and resulting in a reduction in the compressive strength of the foamed concrete, which is in agreement with (Narayanan *et al.*, 2014). Overall, except for 25% and 30% mixes, the results suggest that the remaining mixes are all suitable for use as lightweight concrete. RHA as cement replacement up to 15% can be used for the structural lightweight application since their densities did not exceed 2000 kg/m^3 and their 28-day compressive strengths are around 17 MPa (Neville, 2011; Kosmatka *et al.*, 2002) and exceed 15 MPa for (ACI 213, 2003).

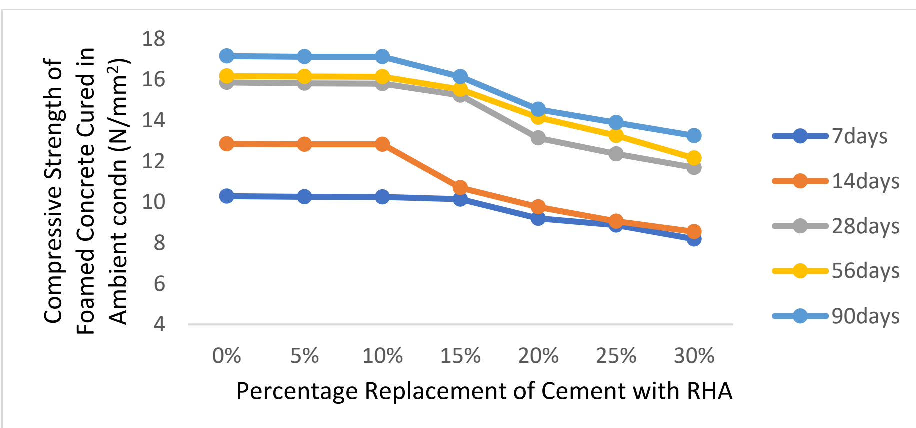

Figure 2: Compressive Strengths of Concrete at various curing periods

The relationship between the compressive strength developed at 7- and 28-days curing is presented in Table 2, which shows that the percentage of 28th-day strength developed on the 7th day by specimens with percentage replacement of rice husk ash at 0, 5, 10, 15, 20, 25 and 30% are 65%, 65%, 65%, 67%, 70%, 72% and 70% respectively.

Table 2: Relationship of the compressive strengths developed on the 7th and 28th days

% Replacement	f7 (N/mm^2)	f28 (N/mm^2)	f7/f28
0	10.28	15.85	0.65
5	10.25	15.81	0.65
10	10.24	15.79	0.65
15	10.13	15.22	0.67
20	9.19	13.13	0.70
25	8.86	12.35	0.72
30	8.18	11.68	0.70

Fire resistance of foamed concrete

Figures 3 and 4 illustrate the typical development of compressive strength for foamed concrete produced with rice husk ash thermally treated at 200, 400, 600 and 800ºC. It was observed that the compressive strength of concrete specimens with a percentage of rice husk ash increased at 5% and 10% rice husk ash with temperatures up to 400ºC and gradually declined from 600^0c up to 800^0C. From Figure 3, the result showed that, at 200^0C, the highest strength was observed with control foamed concrete with 13.22 N/mm^2, while 5 and 10% replacement with rice husk ash achieved 13.19 N/mm^2 and 13.15 N/mm^2, respectively. The lowest strength was at 30% RHA as cement replacement, which achieved a strength of 9.81 N/mm^2. The same trend was observed at 400^0C, 600^0C and 800^0C; as the temperature rose, the strength of foamed concrete declined. Also, as the percentage of RHA increases in the sample, the strength of the concrete decreases. However, up to 200^0C, foamed concrete maintains an average of 83% of its original unheated strength. However, at 400^0C, the strength reduces to 75%; at 600^0C, only 51% of the original strength was retained; and at 800^0C, only 27% of the original strength was retained at 28 days.

Figure 4, at 90 days of curing, showed that at 200^0C, the highest strength was observed with control foamed concrete with 14.24 N/mm^2, while 5 and 10% replacement with rice husk ash achieved 14.22 N/mm^2 and 14.25 N/mm^2, respectively. The lowest strength was at 30% RHA as cement replacement, which achieved a strength of 12.61 N/mm^2. The same trend was observed at 400^0C, 600^0C and 800^0C; as the temperature rose, the strength of foamed concrete declined. Also, as the percentage of RHA increases in the sample, the strength of the concrete decreases.

The minimal reduction in strength of 0% - 10% percentage rice husk ash concretes up to 400^0C may be due to the additional hydration of un-hydrated cement grains as a result of the steam effect under the condition of so-called internal autoclaving effect (Makinta *et al.,* 2021). This may be due to the reaction of the rice husk ash and the free lime, which produces more CSH and CAH and is deposited in the pore system. This phenomenon is attributed to a higher volume of CSH and CAH phases formed in the blended cement concrete on one hand and reduction in $Ca(OH)_2$ contents on the other hand relative to those developed in specimens with higher cement replacement as affirmed by (Bai *et al.,* 2021). A cement matrix with a higher volume of gel-like hydration products and lower crystal-like $Ca(OH)_2$ contents has improved fire resistance (Qu *et al.,* 2022). Mydin and Wang (2012) measured the mechanical properties of foamed concrete with various densities in elevated temperatures. All the tests were conducted by increasing the load while keeping the specimen at a constant, elevated temperature (100^0C, 200^0C, 300^0C, up to 600^0C), and it was found that the compressive strength of foamed concrete decreases with temperature.

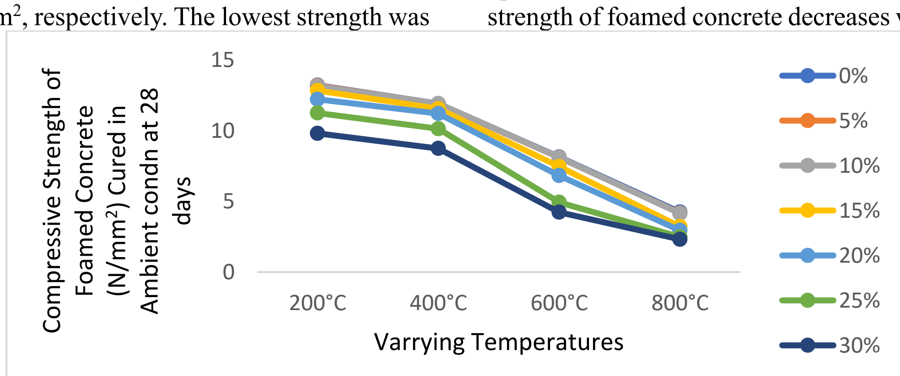

Figure 3: Fire Resistance of Foamed Concrete Cured at 28 days

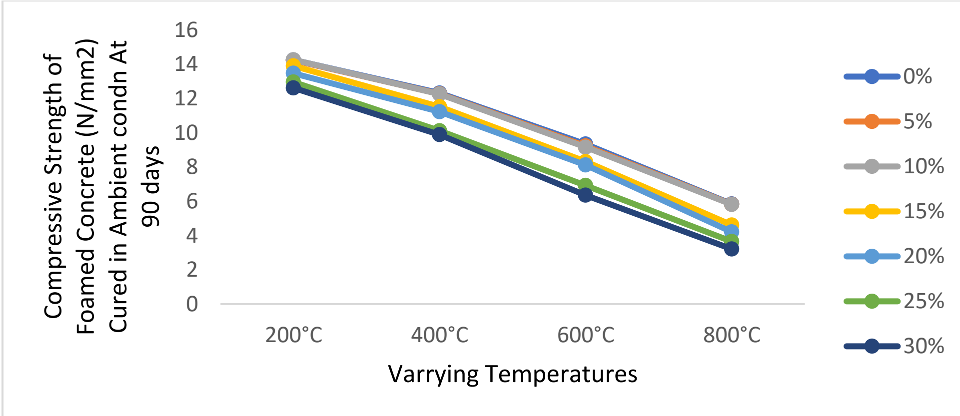

Figure 4: Fire Resistance of Foamed Concrete Cured at 90 days

Ultrasonic pulse velocity test for foamed concrete

The ultrasonic pulse velocity (UPV) values for all mixes are shown in Figure 5. UPV test is used to assess the uniformity and relative quality of concrete, to indicate the presence of voids and cracks, and to estimate the depth of cracks (ASTM C597, 2009). The UPV values of all concrete mixes produced with rice husk ash as partial cement replacement are close to the UPV values of control foamed concrete at all ages. Foamed concrete at 7 days has a UPV within the range of 3.06 to 3.29 m/s; at 28 days, foamed concrete has a UPV within the range of 3.14 – 3.76 m/s, while at 90 days, foamed concrete has a UPV of 3.34 – 3.75 m/s. According to (ACI 228 2013; Pedreros *et al.,* 2020; Quiñones-Bolaños *et al.,* 2021), UPV of 3.00 m/s is considered of good quality, and greater than 4.5 m/s is considered of excellent quality, while below 3.0 m/s is considered of low, poor and questionable quality. Concrete of excellent quality possesses uniformity in internal voids, while concrete of good quality attains good uniformity due to concrete placement and the minimal presence of cracks. The UPV values at the age of testing showed that all the mixes attained the minimum required value specified for good-quality concrete. In addition, UPV values showed an increase of 11.75% at 90 days compared to the 7-day average values.

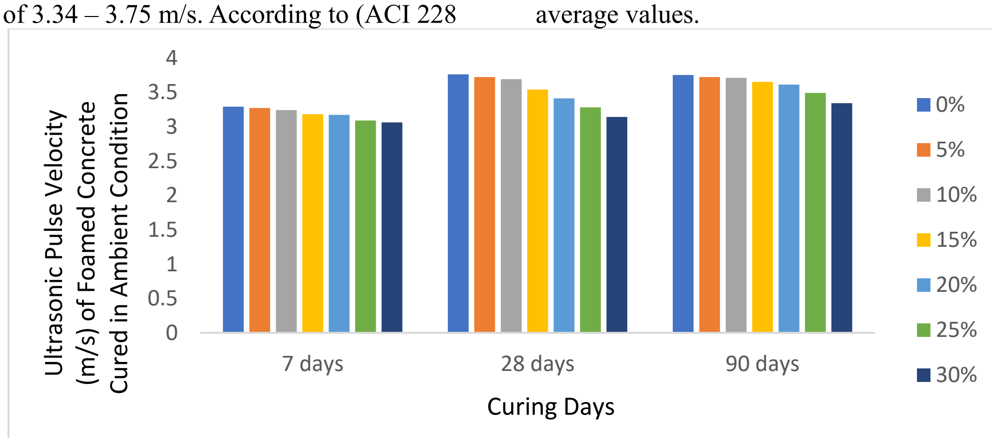

Figure 5: Average Ultrasonic Pulse Velocity of foamed Concrete

Relationship of compressive strength and ultrasonic pulse velocity test for foamed concrete

An empirical equation based on regression analysis from Figure 6 is proposed to evaluate the compressive strength (fcu) based on the UPV values for foamed concrete cured in Ambient Condition.

$$fcu = 0.13\,(UPV)^{1.7}$$

Where fcu = Compressive strength (N/mm^2); UPV= UPV value (m/s)

Also, from the figure, it can be seen that the compressive strength of foamed concrete correlates well with the ultrasonic pulse velocity, with a value close to unity, which shows a strong correlation.

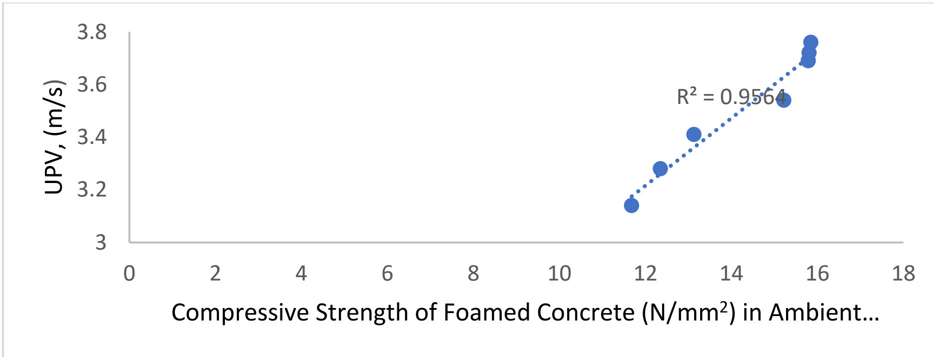

Figure 6: Relationship of Compressive Strength and UPV of foamed Concrete

Conclusion

This study uses fire resistance and ultrasonic testing of rice husk ash foamed concrete. The 28-day compressive strength of 15.85 N/mm^2, 15.81 N/mm^2, 15.85 N/mm^2, 15.79 N/mm^2, and 15.22 N/mm^2, obtained for foamed concrete at 0, 5, 10, 15 and 20% RHA as cement replacement in this study at the designed density of 1600 kg/m^3 meets the minimum strength requirement as structural lightweight of 15 N/mm^2 as per (ACI 213R). Foamed concrete produced with rice husk ash at 5 and 10% can produce structural lightweight concrete. 0% - 10% RHA in foamed concrete resists fire better. Also, foamed concrete could resist temperatures up to 400, with less deformation. The fire resistance of foamed concrete depends not only on the density but also on the manufacturing process, foam amount, percentage of pozzolana, nature of material and presence of admixture. The use of ultrasonic pulse velocity in the analysis of the foamed concrete specimens proved effective in proving each sample's homogeneity. The pulse velocity depends on the percentage of pozzolana in the concrete; the greater the amount of RHA, the lower the UPV. All concrete produced is classified as of good quality foamed concrete. The investigation should focus on developing local foaming agents and foam generators. Further investigation is needed to develop compatible chemical admixtures that will improve the capacity of foamed concrete.

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