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Characteristics of a novel lightweight concrete

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Abstract

The growing need to reduce dead weight of structural elements to allow long spanning structures, has always been a key driver in the construction industry's quest to finding materials that can lead to such accomplishments. This paper is concerned with investigating the mechanical properties of a novel lightweight cementitious material made from a mix of sand, cement, water and admixture. It is environmentally friendly, requiring less cement consumption, self-levelling and free-flowing with potential for structural use in construction.

A rigorous experimental testing programme is carried to determine the mechanical properties of the material. Two sets of mixes of target densities 1810 and 1600 kg/m^3 were prepared and tested. The results showed that the admixture improved the properties of the material such as its compressive and flexural strengths. The material can be utilised as a structural member since it gained strength values above 20 MPa after 28 days.

Keywords: Compressive Strength, Elastic modulus, Tensile Strength, Cementitious Lightweight concrete.

1 Introduction

Previous research has shown that cement based materials, especially concrete, are the most widely used in construction in the world with more than 2 billion tonnes consumed yearly with a projection of 4 times its consumption in 1990 by the year 2050 (Crow, 2008). Concrete, despite its wide range of application, acceptance and excellent properties, has been criticised for its dead weight and high CO_2 emissions especially when constructing large structures on soils that are weak, thereby leading to the construction of very expensive foundations.

Lightweight cement-based materials such as foamed concretes were developed as a solution to reduce excessive dead weight that these materials impose on foundations. However, these materials have been limited to non-structural applications (void filling, partitioning, etc.).

Foamed concretes are cellular concretes, and according to Tikalsky et al. (2004), they are cementitious mortars containing a large amount of distinct air bubbles that occupy up to or more than 50% of its volume. Most foamed concretes result in low compressive strengths as they are designed to have low density ranges between 400 – 1600 kg/m^3 (Jones & McCarthy, 2005) and having between 10% - 70% air voids (Panesar, 2013) and as a result are neglected when designing structural members for construction. Therefore, in order to achieve lightweight members for structural applications, researchers have incorporated lightweight aggregates into the cement mortar to improve their engineering properties. Some of these lightweight aggregates includes scoria (Yasar et al., 2004), expanded clay (Bogas & Gomes, 2015), oil palm shell (Shafig et al., 2014) coconut shell (Rao et al., 2015), expanded shale (Li et al., 2011), demolition fines, china clay, crumb rubber (Jones et al., 2007) etc. Such aggregates require high energy for their production resulting from coal burning etc. (Shafig et al., 2014). Jones and McCarthy (2005) stated that some foamed concretes have the potential of being able to withstand structural loading if they can achieve a compressive strength of 25 MPa; and can be taken into consideration for structural application where they can be produced in an economical and sustainable manner. Shabaan et al. (2018a and 2018b) investigated the flexural behaviour of ferrocement beams with lightweight cores and different types of mesh reinforcement, where the cores were made of autoclaved aerated lightweight brick, extruded foam, and lightweight concrete cores. The authors concluded that ferrocement beams of lightweight cores maybe promising as an alternative to conventional beams especially for low cost residential buildings.

The proposed mix in this study is a highly workable lightweight cementitious material that uses a similar technique to that of foamed concretes, incorporating air cells in mortar and not containing coarse aggregates resulting in a free flowing and self-levelling mix in its fresh state. The key difference between this mix and that of foam concrete is the air bubbles are consistently distributed and of the same size, furthermore they do not break over time. The material uses up to 25% less cement than conventional concrete for its production and requires no coarse aggregates, therefore, it is a more environmentally friendly material that results in reduced carbon emission from the production of the cement and the quarrying of coarse aggregates.

1.1 The material

The mix is made up of sand, cement, water and a admixture forming a relatively consistent mix with billions of distinct air bubbles distributed within the mix. In its fresh state, the material is liquid form, free-flowing and self-levelling; in its hardened state, it is lightweight and preliminary cube tests showed good compressive strength values of the mix of up to and more than 20 MPa. Its liquid nature in its fresh states allows for pumping into moulds without the need for vibrating or tamping (Figure 1); this makes for reduced labour cost during construction.

(a)

(b)

Fig.1 The mix (a) freshly pumped into moulds (b) hardened state

Two features of the mix make it distinct from other cellular/foamed concretes; these are the mixing screw machine (Figure 2) and the admixture. The full concept of operation of the machine has been explained by Dan-Jumbo (2021), and a description of admixture in given in the section below.

Fig.2 Purpose-built machine used for the mixing

1.2 The admixture solution

The admixture is a taproduct made from waste materials. It is an organic surfactant mixed with water in specific proportions to form aqueous mix, mechanically introduced into the cement mortar simultaneously with compressed air to produce stable foam. The admixture is a liquid of dark brown colour, with a pungent smell and nontoxic in air. It has a pH value of 7 with a specific gravity of 1.05 g/ml at 20 ^{0}C. The solution is pumped into the machine at very slow rates (0.0608 to 0.235 l/min). It acts as a glue around surface area of the air bubbles, holds the bubbles in place throughout the rigorous mixing process and not allow them to coalesce or escape during the process.

Its composition by volume includes 2.5% sodium hydroxide, 2.5% hydrochloric acid, 3% ferrous sulphate and 92% organic waste material. The sodium hydroxide is added to the waste material to disinfect and kill the bacteria contained in waste material. The hydrochloric acid is then introduced in similar proportion to neutralize the mix to a pH of 7. Ferrous sulphates are brought into the solution to stabilize it, creating shear stress in the material and improving the surface tension in the material, making the solution a liquid superglue. The resulting surfactant is concentrated by 50%.

2 Material preparation

Two sets of mixes were prepared and tested; the first set of samples were designed using a target density of 1810 kg/m^3 and therefore designated with the code D1810, whereas, the second set of samples were designed using a target density of 1600 kg/m^3 and similarly designated with the code D1600. For most foamed concrete, it has been established that the engineering properties such as compressive strength etc. depends mainly upon the density of the material (Zulkarnain & Ramli, 2011; Nambiar & Ramamurthy, 2006; Ramamurthy et al., 2009). Therefore the D1810 mix was adopted because it is closest to the upper limit of density of 1850 kg/m^3 for a structural material to be classified as lightweight (the density ranged for lightweight concrete is 1440 to 1840 kg/m^3). The D1600 mix was considered for the test for comparison purposes and to investigate the effect of introducing more foam into the mix.

2.1 Material mix

The mix comprises four distinct constituents (sand, cement, water and the admixture solution) that are loaded into their respective compartments within the mixing machine. The cement used for this research is the high strength Portland Cement CEM 1 52.5 N conforming to BS EN 197-1 (2011). The fine aggregates are river sand finer than 2.36 mm, which are readily available in most part of the world for the construction industry. Normal potable tap water incorporated in the mix is introduced in two forms, the first being water for mixing both sand and cement in the mix with the water/cement ratio maintained at 0.73; the second being a solution water that is mixed with the admixture solution to form aqueous solution in a foam/water ratio of 0.26. In research carried out by Dan-Jumbo (2021), the optimum sand/cement ratio for the mix for maximum compressive strength was 4.78, maintained for both mixes used for this study.

The machine settings for the production of the materials used for the experiments are given in Table 1; the weight of the different constituent materials is given in Table 2. After mixing the fresh liquid mix is pumped through the hoses into the various moulds prepared for the various tests and allowed to set for 2 days; after which it was demoulded and allowed to cure in air at room temperature until their scheduled time of testing.

Table 1 Machine setting for different mixes

Constituent Material	**D1810**	**D1600**
Sand	111.09 kg/min	111.09 kg/min
Cement	28.58 kg/min	28.58 kg/min
Water	20.78 lit/min	20.78 lit/min
Catalyst	0.24 lit/min	0.27 lit/min
Solution water	0.89 lit/min	1.01 lit/min
Air flow	0.75 bar at 30 lit/min	0.75 bar at 35 lit/min

Table 2 Weight per cubic metre of constituent materials

	Cement (kg)	**Sand (kg)**	**Water (kg)**	**Catalyst Sol. (kg)**	**Solution Water (kg)**
D1810	261.00	1247.80	227.40	2.35	8.90
D1600	225.85	1080.64	186.22	2.70	13.57

2.2 Determining the density of the material

The measurement of the density of the material was carried out in accordance to procedures stipulated in the code BS EN 12390-7 (2009). Five samples each for both sets of mixes were examined for their densities after air curing for 7, 14, 28, 56 and 90 days. In each case, the concrete specimens were demoulded after 24 hours and kept in the water curing tank until the age of testing. The curing temperature of the water in the curing tank was maintained at 27-30°C.

2.3 *Compressive strength test*

A 2000 kN compressive strength machine was used for the testing of the 100 mm cube samples made from the material in accordance to the standard code BS EN 12390-3 (2011). The compressive strength of the samples was calculated as $f_c = F/A$, where F is the maximum load sustained by the sample and A is the loaded area of the sample. Five samples each for both mixes were tested after 7, 14, 28, 56 and 90 days; their average compressive strength was then recorded.

2.4 *Elastic modulus test*

Cylindrical shaped samples with a diameter of 150 mm and height of 300 mm were tested for elastic modulus in accordance to the standard code BS EN 12390-13 (2013). Prior the testing of the samples (about 24 hours), DEMEC buttons were placed 200 mm apart on 3 sides of the cylinder using the DEMEC gauge and are set 120^0 from each other. The load that corresponds to a third of the cylinder compressive strength for both mixes are determined and then divided into five steps. An initial preload of 8.8 kN is imposed on the sample, subjecting it to an initial stress of 0.5 MPa at which the initial strain gauge readings were recorded. This was also repeated for the five load steps, and the strains were calculated from the difference between the gauge readings for the specific load step and the initial strain gauge readings; after which the values are multiplied by a gauge factor of 0.403×10^{-2}.

2.5 *Tensile splitting strength test.*

A 5000 kN test machine was used in testing for the tensile splitting strength of the material samples made from both the D1810 and D1600 mixes in accordance to the code of practice BS

EN 12390-6 (2009). The tensile splitting strength values presented in this paper is the average result for minimum of 3 samples; the tensile splitting strength calculated from the equation;

$$f_{sp} = 2F/\pi dL \quad (1)$$

where f_{cs} is the tensile splitting strength, F is the failure load in N, d is the diameter of the specimen in mm and L is the length of the specimen in mm.

2.6 Flexural strength test

Mini-beam samples of sizes 100 mm × 100 mm × 500 mm were tested using a 150 kN test machine in accordance to the standard code BS EN 12390-5 (2009). The failure load is recorded and the flexural strength is calculated from the equation;

$$f_{tf} = FL/b_{fr}h_{fr}^2 \quad (2)$$

where f_{tf} is the flexural strength, F is the failure load in N, L is the distance between supports in mm, b_{fr} and h_{fr} are the width and height of the samples respectively in mm.

2.7 Four-Point loading test on reinforced beam members

Beams made from the material with dimensions 80 mm × 180 mm × 1.5 m reinforced with two 10 mm diameter steel bars and 8 mm diameter two-legged stirrups spaced at 80 mm centre to centre within the shear arm region of the beam as shown in Figure 3. The samples were tested after air curing for 56 days.

The failure load and deflection, as well as the strain gauge readings were read off and recorded. The mode of failure of the beam and crack patterns were also observed during the testing. The surface strain values were read from the DEMEC gauge that measures the change in the distances between DEMEC buttons glued to the face of the beam along the centre.

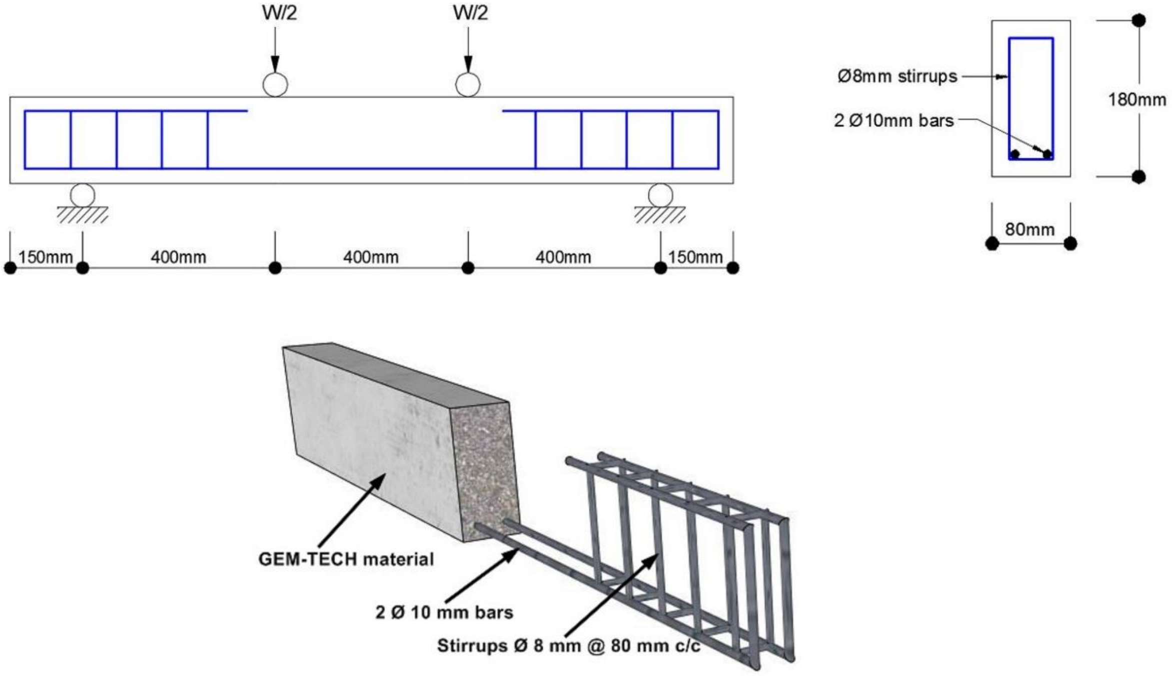


Fig.3 Sample beam dimension and loading arrangement

The apparatus for the testing and the arrangement of both DEMEC buttons and LVDT are shown in Figure 4.

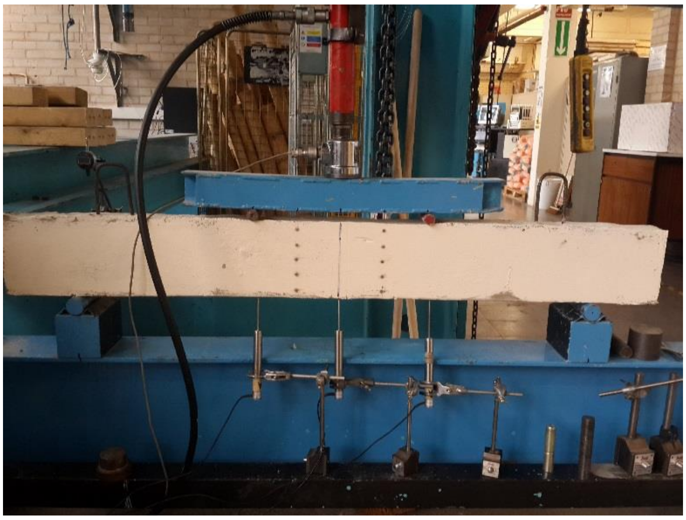


Fig.4 Experimental setup for 4-point loading of beams made from the novel material

3 Results and discussions

3.1 Density

The density of both mixes of the novel material after air curing for up to 90 days is shown in Figure 5. It shows that there is a decrease in density with age until after 28 days where there is no significant further decrease in the density. This results from loss of moisture to the atmosphere during hydration process. The material is almost liquid in its fresh state and a significant amount of water escapes to the atmosphere during the hydration process; it, therefore, was expected that even though the machine has been set to a specific design density, the dry density of the mix after 56 days maybe the target density ± 100 kg/m^3. Both mixes had the same aggregate to cement ratio of 4.78 and therefore the major determinant of the difference in density between both sets of mixes was the amount of aqueous foam introduced in the mix. The result showed that for 44% increase in the foam volume, there was a 6% decrease in the density of the mix after 56 days of curing in air. During the mixing process, compressive air pumped into the mix, simultaneously with the aqueous mix solution from the admixture, and is trapped inside the mortar forming many tiny discrete air voids in the mix and hence a corresponding reduction in weight of the mix.

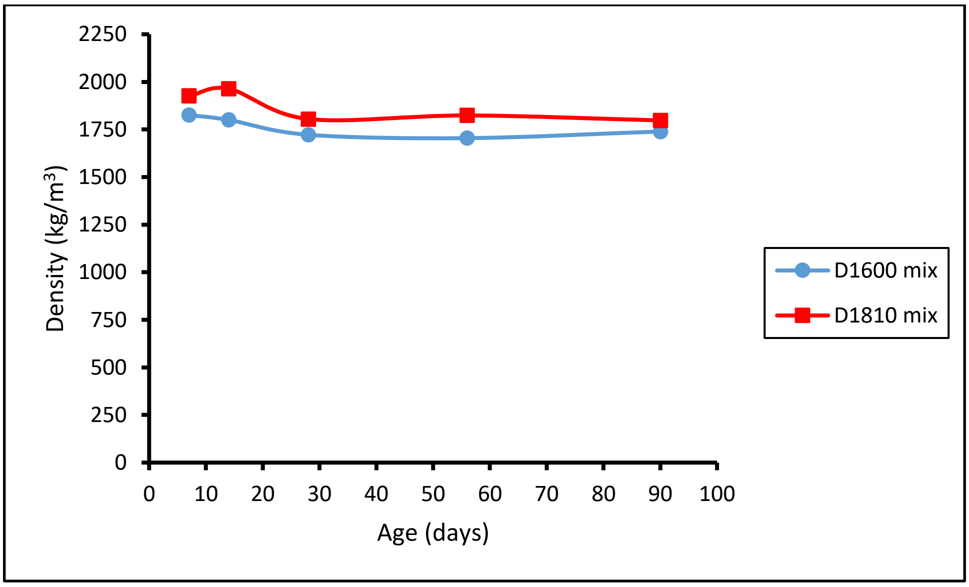


Fig.5 Plot of density vs. age of curing of the two mixes

3.2 Compressive strength

The development of compressive strength of the novel material with age after curing in air is plotted in Figure 6.

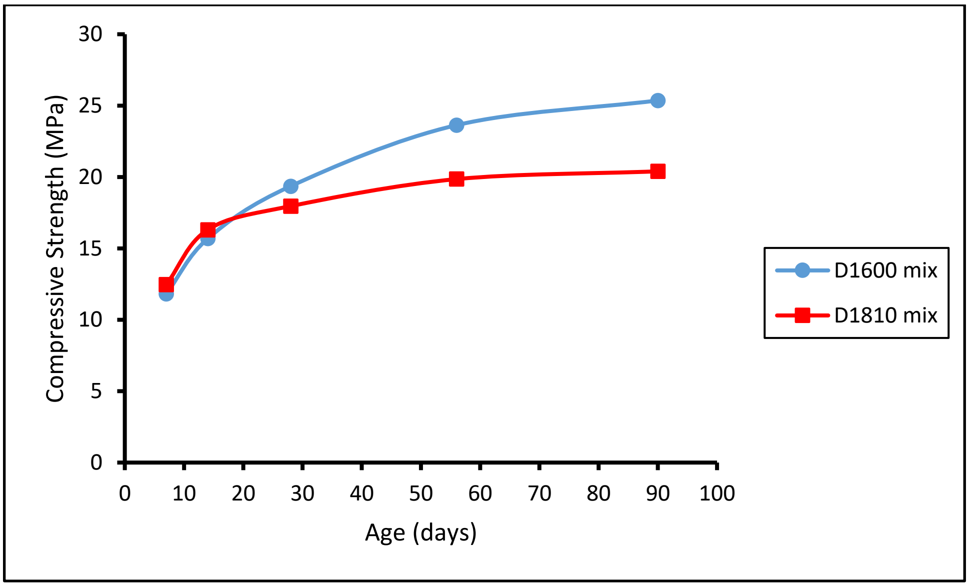


Fig.6 Development of strength with age

The compressive strength test shows that for both mixes, the compressive strength developed substantially with curing age. After curing in air for the 7 days, the D1810 mixes gained up to 50% of its 56 days compressive strength while the D1600 mixes surpassed that percentage by gaining up to 62% of its 56 days compressive strength value. The D1810 mixes gained compressive strength of 18 MPa and 20 MPa after 28 and 56 days respectively and similarly the D1600 mixes gained strength values of 20 MPa and 23 MPa after 28 and 56 days respectively. This trend differs from that of previous research on aerated cementitious materials (Kearsley & Wainwright, 2011; Bing et al., 2012; Nambiar & Ramamurthy, 2006), however, the novel material mixes produced with target density of 1600 kg/m^3 showed a higher compressive strength than the 1810 kg/m^3 mixes.

Increase for admixture introduced into the mix contributed to the strength development of the material. Unlike in the case of foam concrete, the air bubbles are non-collapsible with time, and contribute to the compressive strength. However, introducing more admixture beyond the optimum may lead to formation of larger air cells which may coalesce and result in a very light and weak structure or result in an unstable foam that will collapse and segregate due to settling of aggregates in the mix.

Both sets of mixes of the material, after 56 days, gained compressive strengths above 20 MPa which is the minimum compressive strength value for a material to be considered for structural application as established in the standard code BS 8500-1:2015 (2015). Based on the classification of lightweight concretes from the standard code BS EN 206: 2013 (2013), the D1810 mix falls into the category LC20/22 while the D1600 mix falls into the LC25/28 category.

3.3 Tensile splitting strength

The results, showing average tensile splitting strength of the material, from tensile splitting strength test conducted on 150 mm diameter cylinders after 28, 56 and 90 days are shown in Figure 7.

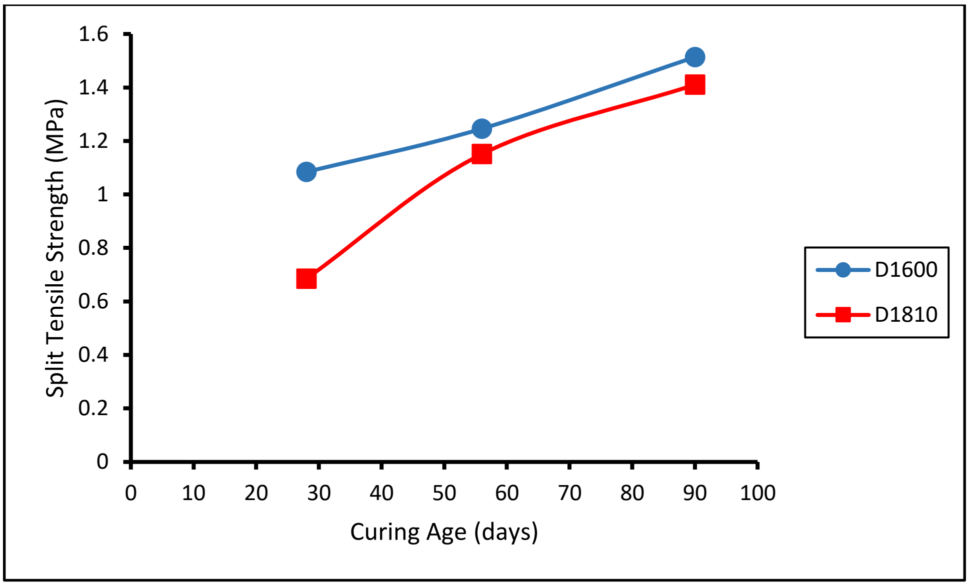


Fig.7 Tensile splitting strength development in the novel material

The tensile splitting strength of the material increased almost linearly with age after 28 days. Results showed that the D1600 mix developed greater tensile splitting strength than the D1810 mixes. This was expected as research has shown that tensile splitting strength of most cementitious materials would increase with increased compressive strength up to a compressive strength value of about 100 MPa, beyond which there is no further increase in the tensile splitting strength (Arioglu et al., 2006). According to Falade et al. (2013), the bonding between the particles of the cementitious material contributes immensely to the tensile splitting strength of the material. The D1600 mix has a greater foam volume per cubic metre of the mix than the D1810 mix and therefore a better bonding between the constituents of the mix resulting from the gluing action of the admixture. The gluing action of the admixture around the surface area of the air cells may have improved the compressive strength of the mix, however, the air cells have no resistance to shear, as coarse aggregates would have resisted in normal weight concrete. This means that the material would have lesser tensile splitting strength than conventional concrete of similar strength class. The higher tensile splitting strength of conventional concrete is also a result of the interlocking capabilities of the coarse aggregate present in them which resists shearing (Brady et al., 2001; Bogas & Gomes, 2014). Sand, on the other hand, offers less resistance interlock capacities compared to coarse aggregates. This can be seen from a plot of the tensile splitting strength versus compressive strength (f_{tsp}/f_c) of the material after 28 days of curing compared to that of conventional concretes established by Oluokun (1991) and the design code CEB-FIP MC 90 (1993) shown in Figure 8.

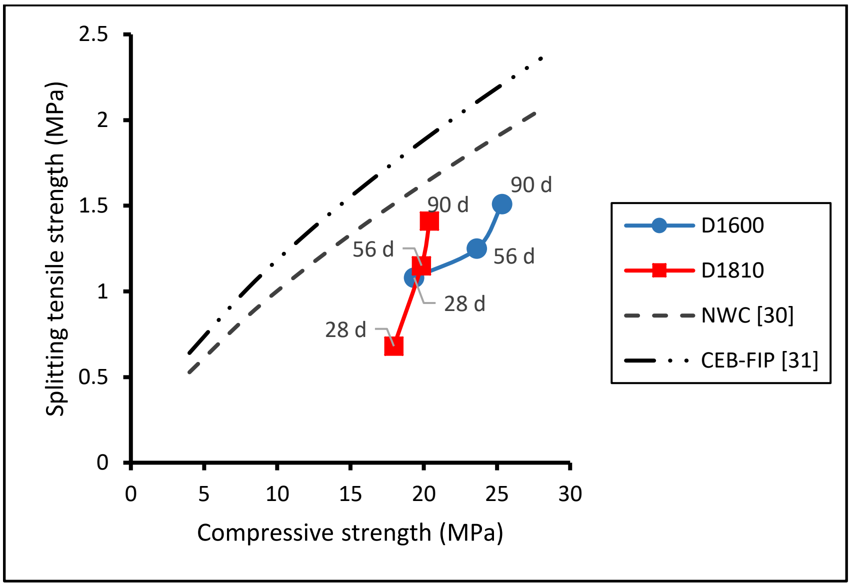


Fig.8 Comparing the f_{tsp}/f_c ratio of the novel material with that of conventional concretes obtained from the literature

Test results show that, on the average, the novel material will develop about 6% of its compressive strength value which is lower than the 10 – 15% range of values obtained from similar investigations on lightweight aggregate concretes and conventional concretes (Arioglu et al., 2006; Falade et al., 2013). Additionally, the age of curing of the material has a very insignificant effect on the f_{tsp}/f_c ratio.

3.4 Flexural Strength

The four-point flexural tests on 100 × 100 × 500 mm beams were carried out to give a measure of the flexural strength of both mixes of the material. There was a significant development in the flexural strength of the material with age as seen in Figure 9.

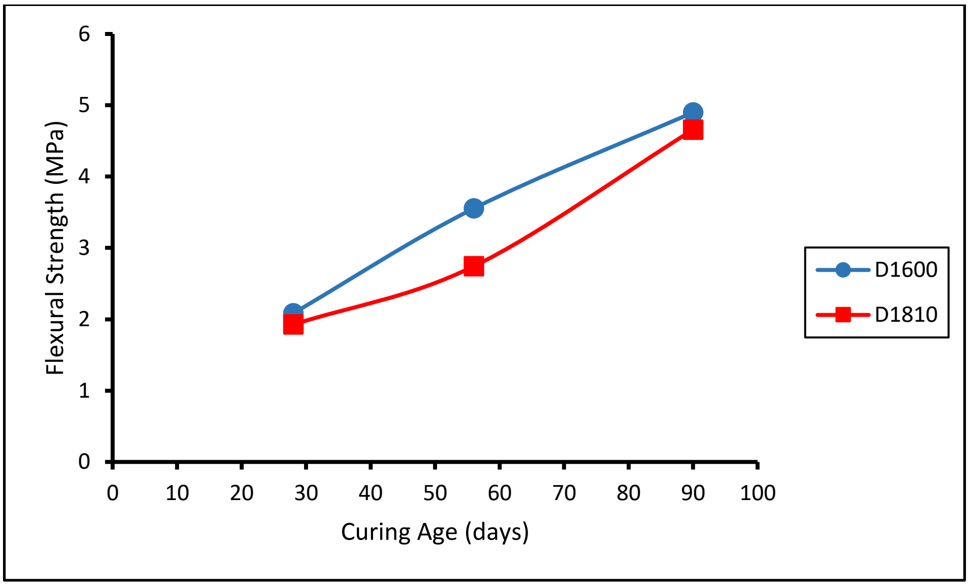


Fig.9 Plot of flexural strength vs. age of curing

Both the D1600 and D1810 mixes gained flexural strengths of 2 MPa and above by 28 days. Just like the observations from the tensile splitting test, the D1600 mixes resisted flexural loads better than the D1810 mixes. After 56 days, the D1600 mixes gained an average of 3.6 MPa of flexural strength whereas the D1810 could develop an average of 2.8 MPa. Observation during the test showed that the failure pattern was slightly brittle as the crack propagation was almost straight through the centre of the beam. Previous research (Tan et al., 2013; Ikponmwosa et al., 2014) suggested that crack formation and propagation is one of the factors that affecting the flexural strength of cementitious materials. There are good bonding results in improved shear capacity between the sand particles and the cement paste (Jones & McCarthy, 2005). A stronger bond between the particles of the mix would resist the propagation of cracks and that is why the D1600 mix had shown greater flexural strength. The sand/cement ratio for both mixes are the same but the D1600 mix contains more volume of the admixture solution that had improved the bonding of the constituent materials better than that of the D1810 mix. However, comparing the flexural strength of the current material to that of conventional concrete of similar strength class, the material showed lower flexural strength value. The additional resistance to propagation of cracks offered by the coarse gravel in the conventional concrete has been compromised in the material. The flexural strength to compressive strength plot for different curing ages was compared with established relationship from literature for normal weight concrete (Oluokun, 1991) and high strength concrete (Shah & Ahmad, 1985) given by the formulae (3) and (4), respectively:

$$f_r = 0.438(f_c)^{2/3} \tag{3}$$

and

$$f_r = 0.46(f_c)^{2/3} \tag{4}$$

The plot in Figure 10 shows that at early ages the flexural strength of the material is lower than that of conventional concretes of similar strength class; however, at later ages there is further development in the flexural strength of the material even though there is very little development in the compressive strength. This trend was the same for both sets of mixes. At later ages, the material develops a better than flexural strength to compressive strength ratio than conventional concretes. There is a further stiffening of the bond between the cement paste and sand resulting from hydration of cement and the action of the admixture. The f_r/f_c ratio for mixes of the material, from the results of the tests, ranges between 0.1-0.23, with the upper range observed at later ages.

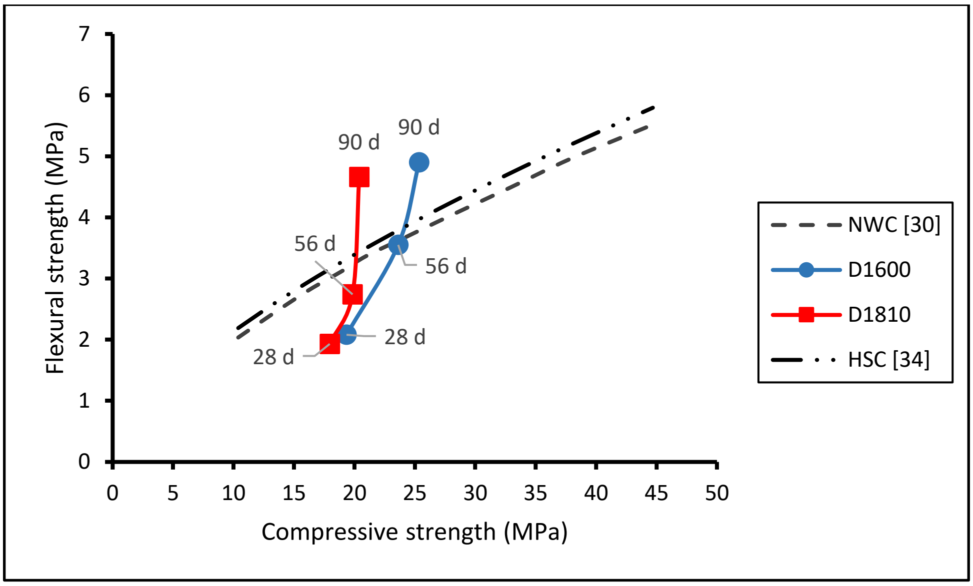


Fig.10 Comparing the f_r/f_c ratio of the material to that of conventional concrete from literature

3.5 Elastic modulus

The development of elastic modulus of both mixes of the material after 28, 56 and 90 days curing period from test is plotted (Figure 11).

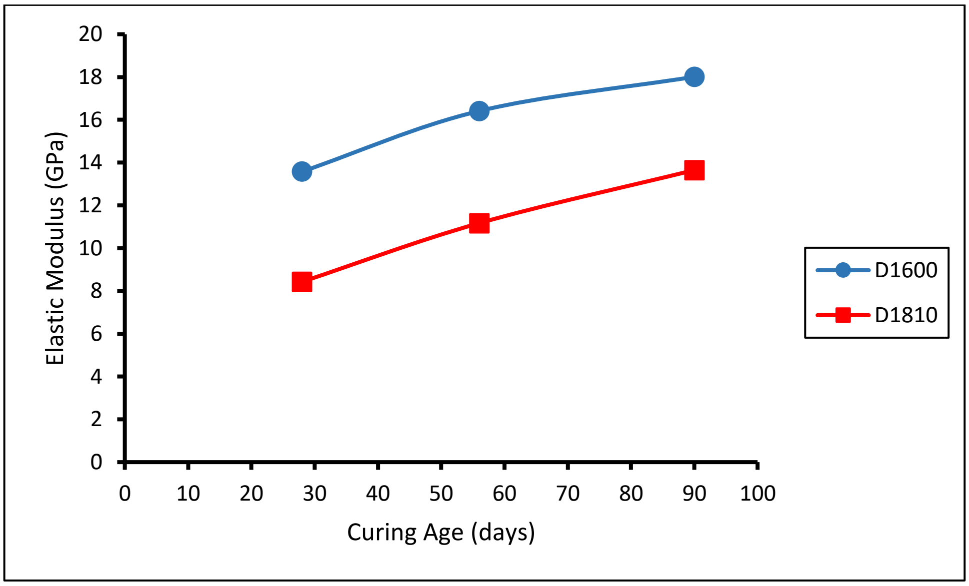


Fig.11 Development of elastic modulus with *age*

Results from test show that there is an improvement in the elastic modulus of the material with time. Previous studies on the mechanical properties of cementitious materials established that elastic modulus of cementitious materials like concrete is a function of their compressive strength; a higher compressive strength corresponding to higher modulus of elasticity (Shah & Ahmad, 1985; BS EN 1992-1-1, 2015; Amran et al., 2015). The D1600 mixes attained a higher elastic modulus values than the D1810 mixes even though the later had higher density values. As explained in the previous sections, the higher volume of admixture in the D1600 mix improved the bonding between the constituent materials therefore holding the air pores in place and resisting crack propagation better than the D1810 mixes. Since the D1600 mixes showed higher resistance to compressive loading, a higher modulus of elasticity was also expected. At 28 days, the material from the two mixes developed up to 90% of its 56 days elastic modulus values. Brady et al. (2001) found that the elastic modulus of foamed concretes is between 1 – 12 GPa for density range of 400 – 1600 kg/m^3.The D1600 mixes exceeds this upper limit of 12 GPa to attain an average value of 16.5 GPa after 56 days. This implies that the material deflects less than other foamed concretes under similar loading conditions.

The E/f_c ratio for the material was compared with that of normal weight concrete (BS EN 1992-1-1, 2015) and sand foamed concretes (Jones & McCarthy, 2005) given by the equations $E = 22(f_c/10)^{0.3}$ and $E = 0.42f_c^{1.18}$ respectively as shown in Figure 12.

The modulus of elasticity of the material mixes was lower than that of conventional concrete of similar strength class. This is a typical feature of foamed concretes; however, the D1600 mixes gained elastic modulus values up to 62% of that of normal weight concrete predicted by established models as shown in Figure 12 for similar strength class while the D1810 gained an average of 45% of the value of elastic modulus of normal weight concrete of similar strength class. This implies that, like other foamed concretes, the material deflects more than conventional concretes of similar strength class under the same flexural loading. This is due to loss of stiffness resulting from the absence of coarse aggregates in the mix.

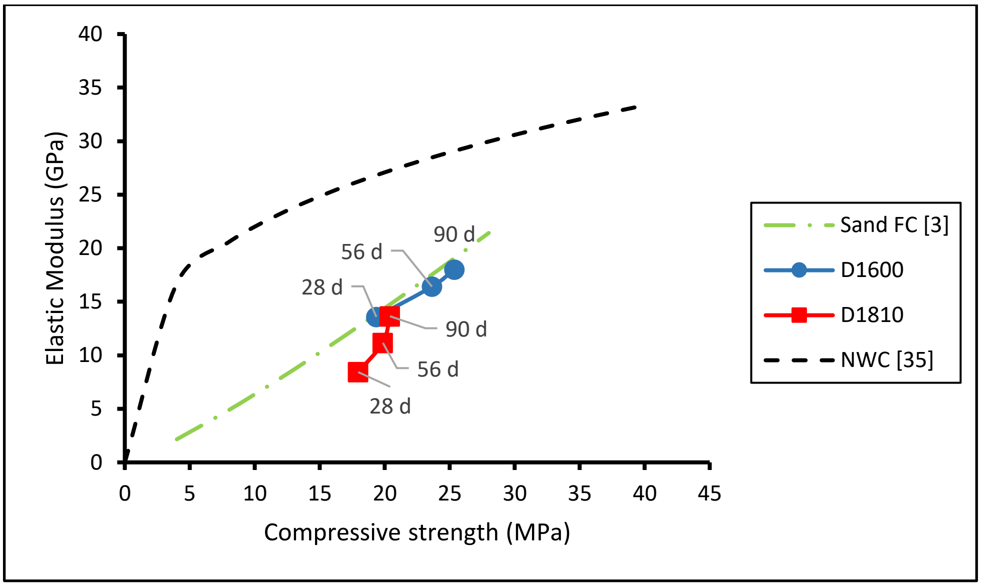


Fig.12 Comparing the E/f_c ratio of the material with conventional concretes and sand foamed concrete

3.6 *Performance of reinforced beam*

The load-deflection curves for 5 reinforced beam members of dimension 80 × 180 × 1500 mm were plotted against that of analytical (theoretical) estimates from calculation using established formulas for determining the performance of reinforced concrete subjected to flexural loading. Three beams from the D1810 mix were compared to plots derived from analytical calculations for reinforced concrete of class C20/25 (Figure 13a) while the two beams from the D1600 mix was compared to reinforced concrete class C25/30 (Figure 13b).

The theoretical relationship is given by;

$$\delta = 23Wa^3/48EI_{tr} \qquad (5)$$

where a is shear arm from the loading arrangement which represents the horizontal distance between one support and the one of the points of application of the load, W the applied load, E the modulus of elasticity and I_{tr} the second moment of area of transformed section (Megson, 2014) given by;

$$I_{tr} = \frac{by^3}{3} + nA_s(d-y)^2 \quad (6)$$

where b is the width of the beam, n is the modular ratio, d is the effective depth of beam, A_s is the cross sectional area of the steel reinforcement and y is the depth of the beam from its neutral axis given by:

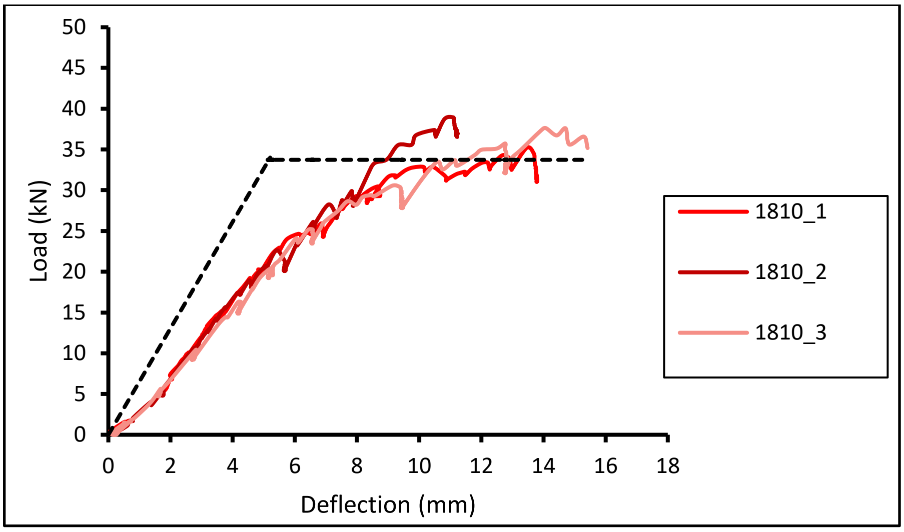
$$y = \frac{nA_s}{b}\left(\sqrt{1+\frac{2bd}{nA_s}} - 1\right) \quad (7)$$

The horizontal line from the plot denoting the failure load of beam obtained by equating moment of resistance of a rectangular concrete beam section to the maximum moment from the loading arrangement as given in equation (8) (Punmia & Jain, 1992);

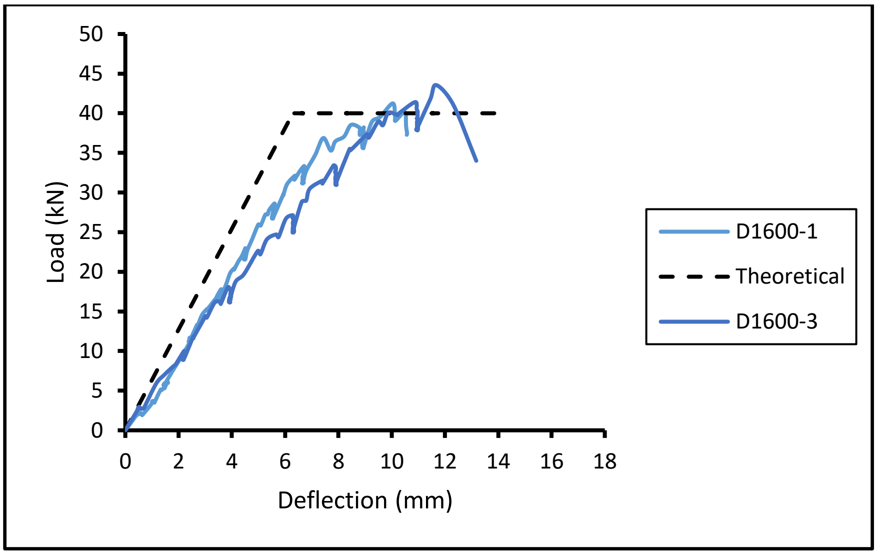
Moment of resistance = $0.156 f_c bd^2 = 0.65 f_y A_s d$ (8)

$$\therefore W_{max} = 0.312 f_c\, bd^2/a \quad (9)$$

The failure load predicted from equation (6) for both C20/25 and C25/30 concretes where 33.3 kN and 40 kN respectively. It was observed from the test that the material of both mixes, under flexural loading of reinforced beam, could withstand loads up to and slightly above the theoretical failure load for reinforced concrete of similar strength class. However, the deflection was up to 60% more than that in the counterpart conventional concrete, this is because of the higher elastic modulus.



(a)



(b)

Fig.13 Load deflection plot

The first notable crack for both the D1810 and D1600 beams was at loads of 10 kN and 12 kN respectively. Observation from test showed that, upon incremental application of flexural loads, there were more diagonal cracks within the shear arm of the beam than vertical flexural cracks within the middle third of the beam and at failure, there is local crushing at load and support points (Figure 14).

This observation implies that, since the material is more prone to crushing or shear compression failure rather than flexure, it may best suited for members that are not exposed to concentrated loads or punching.

(a)

(b)
Fig.14 Failure of the beams under flexural loading

4 Conclusion

This study has explored some engineering properties of the novel lightweight material including properties such as its compressive strength, flexural strength, tensile splitting strength, elastic modulus and the behaviour of the material under structural loading. Results discussed in this paper therefore suggests the following;

- The material can be used for structural applications as it can develop compressive strength values above 20 MPa for densities of at least 1600 kg/m^3. The D1600 and D1810 mixes can therefore be classified as LC25/28 and LC20/22 strength class respectively according to the standard code (BS EN206, 2013) classification of lightweight cementitious materials.
- The constituent material composition shows that this strength class was achieved using about 85 kg less amount of cement per cubic metre of the material compared to conventional concretes of similar strength class. This implies that the material constitutes less carbon emission compared to other cementitious construction materials.
- The foam volume introduced into the mix is the major factor that determines the density of the mix. Result from this paper showed that 6% decrease (about 150 kg/m^3) in density was achieved by increasing the aqueous foam volume of the admixture solution by 44% (5 kg/m^3).
- The admixture improves the bonding between the cement paste and the sand particles and acts as a glue around the surface area of the air cells thereby holding the cells in place. Thus, engineering properties such as compressive strength, tensile splitting strength, flexural strength, and elastic modulus were improved.
- The material has lesser resistance to crack propagation compared to conventional concrete of similar strength class resulting from loss of interlock capability offered by the presence of coarse gravel in concrete and thus has lower values for tensile splitting strength and elastic modulus than its counterpart conventional concrete.

- Reinforced beam member made from the material subjected to flexural load would resist up to and more than failure load predicted by analytical calculations for conventional concrete of similar strength class even though the deflection is more because of the lesser modulus of elasticity. The material is more likely to fail by shear compression than flexure because of its relatively low resistance to crack propagation resulting from loss of interlock capability from absence of coarse gravel and the presence of air pores.

Deductions from investigating the engineering properties of reveals that, it may be best suited for members that are not exposed to high stress concentrations or punching. Results show that the material performs best under flexural loading and, as such, can be effectively utilised as reinforced beam members and slab members that are subjected to flexural loading with a much more uniformly distributed load over the member.

More research is needed to investigate the bond action between steel reinforcement bars and the material to fully understand the composite action of the structural member. Structural testing under dynamic loading will also be beneficial to establish the resistance of structural elements to dynamic loading.

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Data value statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. Some or all data, models, or code generated or used during the study are proprietary or confidential in nature and may only be provided with restrictions.

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