*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

# *Maejo International Journal of Science and Technology*

**ISSN 1905-7873**
Available online at www.mijst.mju.ac.th

*Full Paper*

# Flexural performance of foam concrete containing pulverised bone as partial replacement of cement

**Funso Falade [1], Efe Ikponmwosa [1,*] and Christopher Fapohunda [2]**

[1] Department of Civil and Environmental Engineering, University of Lagos, Lagos, Nigeria
[2] Department of Building, Caleb University, Imota, Lagos, Nigeria

* Corresponding author, e-mail: efe_ewaen@yahoo.com

*Received: 27 March 2013 / Accepted: 27 January 2014/ Published: 29 January 2014*

---

**Abstract:** This paper presents the results of a study conducted to investigate the flexural behaviour of foam concrete containing pulverised bone as partial replacement of cement. A total of sixty reinforced beams (150×150×750 mm) were used to investigate the flexural behaviour of the specimens. For reinforcement of the beams, hot-rolled, deformed 10-mm-diameter bars with yield and ultimate stresses of 478.10 N/mm$^2$ and 710.81 N/mm$^2$ respectively were used. The cement constituent of the mix was partly replaced with up to 20% of pulverised bone. The flexural parameters investigated are crack formation and its pattern, failure mode, ultimate load, theoretical and experimental ultimate moments, deflection and stiffness. From the results of this investigation, it is concluded that the provision of the design standard in relation to shear and flexural design of beams can be considered as adequate for the design of reinforced foam concrete. It is further concluded that the stiffness is not affected by the inclusion of pulverised bone in the mix at up to 15% cement replacement level, and neither is the deflection pattern of the uncracked sections of the specimens affected by the inclusion of pulverised bone. The bending moments of the specimens, however, decreased with increase in pulverised bone.

**Keywords:** foam concrete, cement, pulverised bone, flexural strength

---

## INTRODUCTION

Foam concrete is a lightweight concrete that has proved suitable for lightly-loaded structural applications and as a weight-reducing measure in structures. It has also made possible the use of many industrial and agricultural waste products in its production with attendant environmental benefits [1-3]. A waste product suitable for use in foam concrete production, especially for low-cost construction, is pulverised bone obtained from cow bones generated from abattoirs [4]. Results of our previous investigation [4] conducted on paste and mortar have shown that pulverised bone is suitable as a partial replacement of cement because of its pozzolanic properties [5, 6]. Falade *et al.* [7] have demonstrated that using pulverised bone as a partial replacement of cement, at up to 20%

replacement level, in the production of foam concrete results in a lightweight concrete material with adequate strength (compressive and tensile) for structural applications in line with the recommendations for lightweight concrete [8, 9]. Furthermore, the use of pulverised bone was also found to be cost-effective when compared with normal concrete of comparable strength [10]. The objectives of the present study are to investigate into the flexural characteristic of foam concrete containing pulverised bone as a partial replacement of cement. The flexural parameters studied are crack formation and propagation, deflection, ultimate moment and stiffness.

## MATERIALS AND METHODS

### Materials

Ordinary Portland cement produced in accordance with British and Nigerian standards [11, 12] was used as the main binder. Cow bones from which pulverised bone was produced were obtained from Oko-Oba abattoir in Agege local government area of Lagos State. The bones were dried after they had been separated from all the muscles, flesh, tissues, intestines and fat. The dried bones were then pulverised with a grinder into powder and the fraction passing through BS sieve aperture opening of size 150 μm (0.15 mm) was packaged in bags and stored in a cool dry place. Sand from River Ogun at Ibafo town in Ogun State of Nigeria was used for this work. Particles passing through 3.35-mm sieve but retained on 0.150-mm sieve were used. Coarser aggregate might settle in a lightweight mix and lead to collapse of the foam during mixing. Lithofoam, a protein-based foaming agent supplied by Dr Lucas of West Germany, was used in this study. This is in line with the findings [13, 14] that protein-based foaming agents produce more stable, smaller and stronger bubble structure, resulting in foam concrete with higher strength when compared to foam concrete produced by other types of foaming agents. The dilution ratio for the surfactant was one part of surfactant to 25 parts of water. The water used was potable tap water. This is crucial when using a protein-based foaming agent because organic contamination can have an adverse effect on the quality of the foam, and hence of the concrete produced.

### Mix Proportions

From available literature [15-17], foam concrete of structural value can be produced at densities between 1200-1900 kg/m$^3$. The density being the design criterion in foamed concrete, a mix proportion that produces the target plastic density of 1600 kg/m$^3$ (±100 kg/m$^3$) was then developed. To achieve the desired design density and workability, trial mixes were carried out. The following mix design parameters were adopted: (i) a binder (cement and pulverised bone)/sand ratio of 1: 3, (ii) a water/binder ratio of 0.5, and (iii) a foaming agent dilution of 1:25. The mix constituent proportions are shown in Table 1.

### Reinforced Concrete Beam Details and Instrumentation

In order to assess the flexural behaviour of the foam concrete, reinforced foam concrete beams were designed in accordance with British Standard [18], the current code of practice in use in Nigeria. Details of the beam are shown in Figure 1.

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

**Table 1.** Mix constituent proportions for foam concrete mixes

| PB* | Binder (kg) | | Sand | Water for base | Foam concentration | |
|---|---|---|---|---|---|---|
| | Cement | PB* | (kg) | mix (kg) | Mixing water (kg) | Foam agent (g) |
| 0% | 25.00 | 0.00 | 75 | 12.50 | 4.688 | 187.5 |
| 5% | 23.75 | 1.25 | 75 | 12.50 | 4.688 | 187.5 |
| 10% | 22.50 | 2.50 | 75 | 12.50 | 4.688 | 187.5 |
| 15% | 21.25 | 3.75 | 75 | 12.50 | 4.688 | 187.5 |
| 20% | 20.00 | 5.00 | 75 | 12.50 | 4.688 | 187.5 |

* PB = Pulverised bone

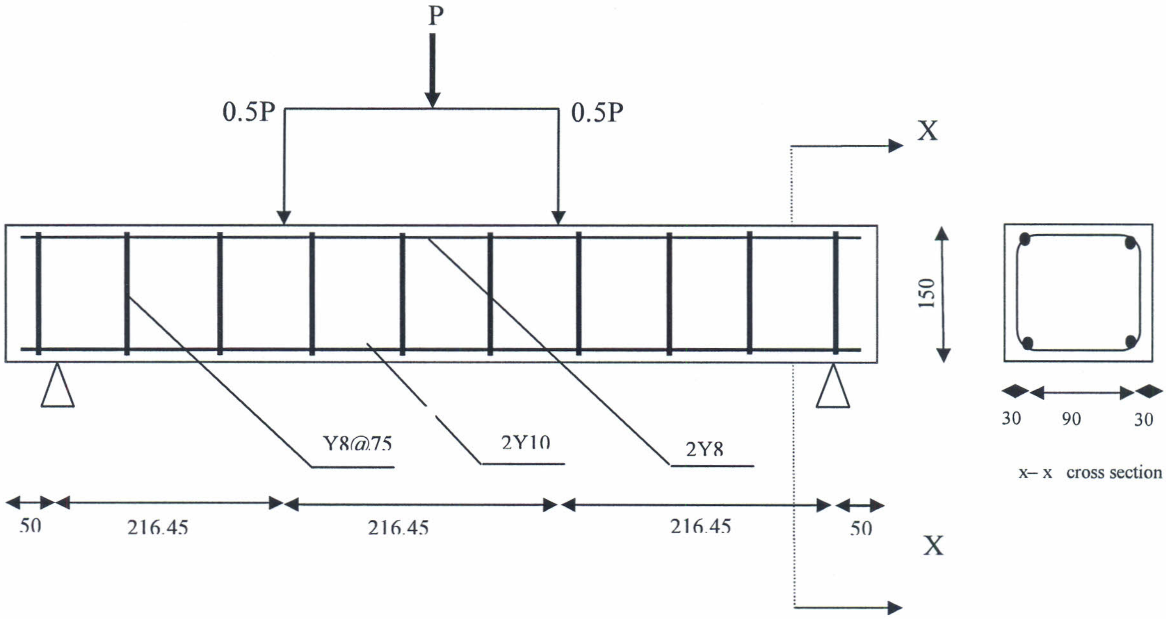



**Figure 1.** Details of reinforced foam concrete beam and loading arrangement. All dimensions are in millimetres. High yield steel is indicated by Y and the number following Y represents the diameter. The number before Y indicates the number of either tension or compression reinforcements while the symbol @ represents the spacing of links. The applied load is represented by P. Line X-X indicates the point of cross-section.

The beams (150×150×750 mm) were reinforced with minimum area of reinforcement (0.13% bh, b = breadth of beam, h = depth of beam) in accordance with British Standard [18]. The reinforcement for the beams consisted of two 10-mm-diameter hot-rolled, deformed bars with yield and ultimate stresses of 478.10 N/mm$^2$ and 710.81 N/mm$^2$ respectively. For shear reinforcement, 8-mm-diameter hot-rolled, deformed bars with yield and ultimate stresses of 475.42 N/mm$^2$ and 666.90 N/mm$^2$ respectively were used. The cover was 30 mm while the spacing for shear reinforcement was 75 mm to satisfy the requirement of British Standard [18], limiting the spacing for shear reinforcement to a value less than 0.75 of the effective depth (0.75 x 107 = 80.75 mm).

The replacement of cement with pulverised bone in the beams was varied from 0 to 20% at 5% increment (based on preliminary findings). Beams without pulverised bone served as control. Beam specimens were produced and tested under the third point loading (Figure 2) in accordance with British Standard [19]. A dial gauge was placed under the beam at the mid-span to measure the deflection at regular interval of loading. The load at which the first visible crack was noticed was recorded; so was the load at which failure occurred. The test was terminated when a little increase in load led to a very large deflection. A total number of 60 beams were cast and tested at 28-day curing age [20].

**Figure 2.** Testing arrangement of beam specimens

## RESULTS AND DISCUSSION

### Crack Formation, Its Pattern and Failure Mode

For all the beams, both with and without pulverised bone, the typical crack patterns formation is shown in Figure 3. The crack usually started at the support followed by a tiny one adjacent to it. These cracks gradually widened, so that at failure another crack parallel to the previous one developed as well as a tiny vertical one at the centre.

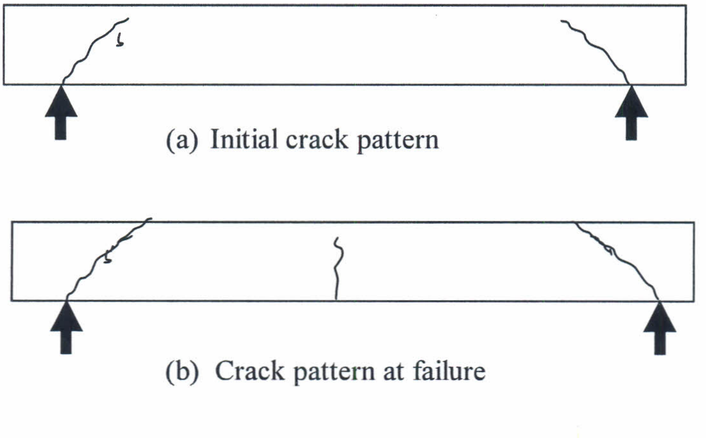



**Figure 3.** Crack development of beams

The angle of inclination of the cracks to the horizontal varied between 41.8-49° as the percentage of cement replacement with pulverised bone increased (Table 2), the average being 44.95°. In the design of links for beams with normal concrete, it is assumed [18] that the diagonal crack is generated at an angle of 45° to the tension reinforcement (i.e. to the horizontal) for normal concrete.

**Table 2.** Angle of inclination of the cracks to the horizontal

| % PB* | Angle (degree) of crack from horizontal | Deviation from 45° | % Deviation |
|---|---|---|---|
| 0 | 41.80 ± 0.20 | - 3.20 | - 7.11 |
| 5 | 42.00 ± 0.90 | - 3.00 | - 6.67 |
| 10 | 43.95 ± 0.22 | - 1.05 | - 2.23 |
| 15 | 46.97 ± 1.26 | +1.97 | + 4.38 |
| 20 | 49.00 ± 0.78 | +4.00 | + 8.89 |

* Pulverised bone

From the above values of angle of inclination in Table 2, the numerical variation was less than 10%. Thus, the equations developed for the calculation of area of shear reinforcement for beams of normal concrete (equation 1), according to British Standard [18], can be considered valid for reinforced foam concrete beam with and without pulverised bone. These equations, on the basis of shear stress value, are given as [18]:

$$\left.\begin{array}{lll} A_{sc} = \dfrac{0.4s_v b}{0.95 f_{yv}} \text{ or nominal links} & & (\text{for } v < 0.5v_c) \\[2ex] A_{sc} \geq \dfrac{0.4s_v b}{0.95 f_{yv}} & & (\text{for } 0.5v_c < v\ (v_c + 0.4) \\[2ex] A_{sc} = \dfrac{0.4s_v b(v+v_c)}{0.95 f_{yv}} & & (\text{for } v_c + 0.4 < v < 0.8\sqrt{f_{cu}} \text{ or } 5\text{N/mm2}) \end{array}\right\} \quad (1)$$

where:

| | |
|---|---|
| $A_{sc}$ | = area of shear reinforcement |
| $s_v$ | = spacing of shear reinforcement |
| $f_{yv}$ | = characteristic strength of shear reinforcement |
| b | = breath of the beam section |
| v | = shear stress due to ultimate loads |
| $v_c$ | = shear resistance of the concrete |

The failure mode for all the specimens irrespective of the content of the pulverised bone was in the form of inclined cracks that developed at the edge of the support, extending to the direction of the loading point as the load was increased, thus resulting in the splitting of the beam. This can be seen in Figure 3. This mode of failure is described as the diagonal tension failure [2].

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

**Effect of Pulverised Bone on Failure Load and Failure Moment**

The theoretical bending moment was calculated for each of the beam specimens from equation (2), derived by assuming the idealisation of rectangular stress block and using an average stress of 0.67 $f_{cu}$ (N/mm$^2$) over 0.9 time of the neutral axis depth, i.e. the stress block contained in British Standard [18] as suggested by Regan and Arasteh [21]:

$$M_u = 0.156 f_{cu} b d^2 \quad \text{..........} \qquad (2)$$

where:

$f_{cu}$ = compressive strength of specimen for each cement replacement level with pulverised bone (N/mm$^2$)
b = width of beam specimen (mm)
d = effective depth (mm)

The experimental bending moment ($M_{EXP}$) was calculated by using the equation for the structural form that is compatible with the third point loading configuration as shown in Figure 4.

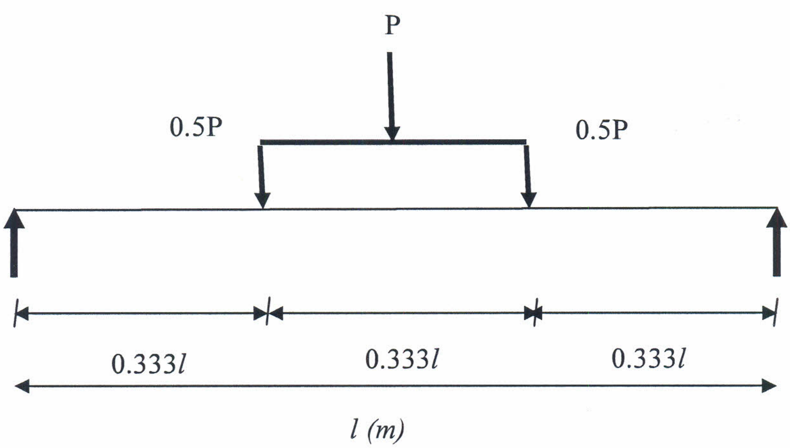



**Figure 4.** Structural configuration for third point loading (P = applied load, *l* = span of beam)

The bending moment equation [22] is:

$$M = 0.167Pl \quad \text{..........} \qquad (3)$$

where:

M = maximum bending moment
P = failure load (KN)
L = span of beam specimen (m)

The failure load, the theoretical ultimate moment ($M_{BS}$) and the experimental ultimate moment ($M_{EXP}$) computed from equations (2) and (3) are shown in Table 3. It is noted, however, that in computing $M_{EXP}$, the service load was obtained by dividing the load at the first visible crack by 1.6. This presupposes that flexural failure by the load has already occurred at the first visible crack, and this load was thus used to calculate the experimental ultimate moment. From the Table, the following observations can be made.

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

**Table 3.** Comparison between experimental and theoretical bending moments

| % PB | Load at first crack (KN) | Failure load (KN) | % Decrease in failure load | Service load (KN) | Theoretical (BS 8110) design moment (KN.m), $M_{BS}$ | Experimental ultimate moment (KN.m), $M_{EXP}$ | $\frac{M_{EXP}}{M_{BS}}$ |
|---|---|---|---|---|---|---|---|
| 0% | 75.00 ± 0.50 | 92.50 ± 0.96 | - | 46.88 | 4.13 | 4.40 | 1.07 |
| 5% | 70.00 ± 1.50 | 87.50 ± 1.32 | 5.4 | 43.75 | 3.88 | 4.10 | 1.06 |
| 10% | 70.00 ± 0.87 | 85.00 ± 1.31 | 8.1 | 43.75 | 3.75 | 4.10 | 1.09 |
| 15% | 65.00 ± 0.50 | 80.00 ± 0.87 | 13.5 | 40.63 | 3.55 | 3.81 | 1.07 |
| 20% | 62.50 ± 0.50 | 72.50 ± 0.87 | 21.6 | 39.06 | 3.48 | 3.66 | 1.05 |

* PB = pulverised bone

*Effect of pulverised bone on failure load*

It is observed from Table 3 that the failure load decreases with increasing pulverised bone content. The load at which the first crack occurred follows the same trend. This can be attributed to a lowering of density with increase in pulverised bone content as a result of lower specific gravity of pulverised bone (2.22) in relation to that of cement (2.92). On average the cracking load is about 82% of the failure load (81.1%, 80.0%, 82.4%, 81.3% and 86.2% for 0%, 5%, 10%, 15% and 20% respectively of cement replacement with pulverised bone).

*Effect of pulverised bone on ultimate moment*

The effects of pulverised bone on the flexural strength can be seen in Table 3. The bending moments (both theoretical and experimental) decrease with increasing pulverised bone content, probably as a result of reduced density [7], with consequent reduction in compressive strength. The bending moments are calculated on the assumption that failure takes place at the onset of the first visible crack. The values of the experimental bending moments are consistently higher than those of the theoretical ones calculated using equation (2), although the difference can be considered insignificant (generally less than 10%), considering the fact that aerated concrete is a variable material. Thus equation (2) developed on the basis of rectangular stress idealisation can be considered to be valid for foam concrete with and without pulverised bone.

**Effect of Reinforcement on Failure Load**

The failure loads for the beam specimens are shown in Table 4. It can be seen that the addition of reinforcement significantly improves the flexural performance of the foam concrete at all replacement levels. The failure loads for reinforced beam specimens are multiples of those of unreinforced specimens. This is an indication that the inclusion of reinforcement inhibits the propagation of cracks in foam concrete and thus enhances its bending resistance.

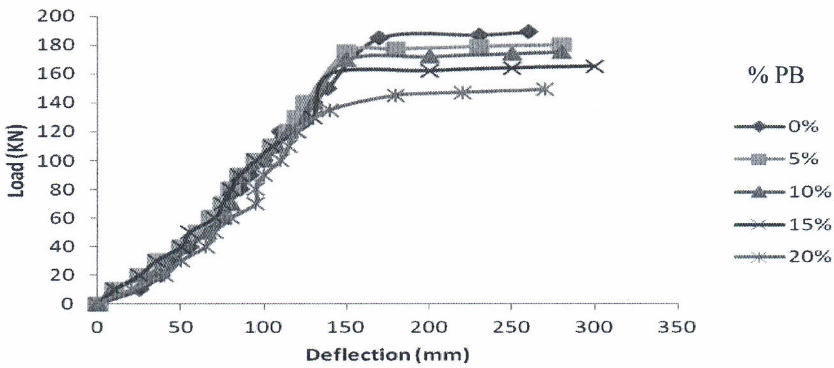
**Effect of Pulverised Bone on Load Deflection**

The mid-span load-deflection curves for the foam concrete with and without pulverised bone are presented in Figure 5. The curves are characterised by three distinctly different segments separated by three significant events that took place during the process of loading until failure. Using the 0% replacement (Figure 5b) as representative, these regions are AB, BC and CD. In the

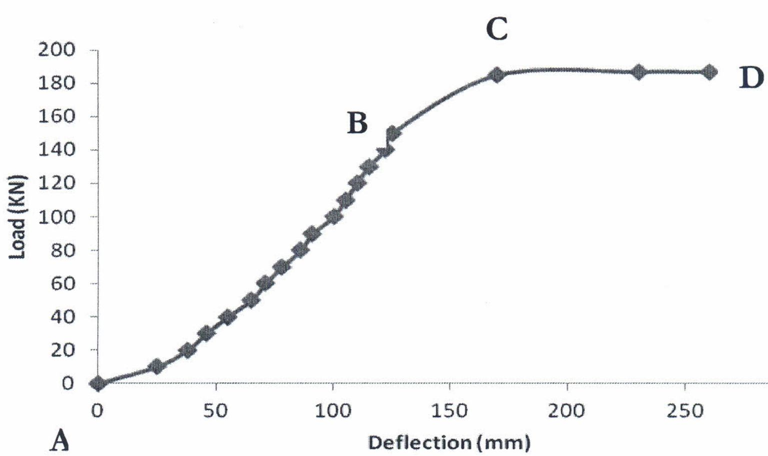
**Table 4.** Effect of reinforcement on failure load

| % PB* | Failure load (KN) of beam without reinforcement, $P_{WOR}$ | Failure load (KN) of beam with reinforcement, $P_{WR}$ | $P_{WR}/ P_{WOR}$ |
|---|---|---|---|
| 0% | 15.0 ± 1.80 | 92.50 ± 1.96 | 6.17 |
| 5% | 15.0 ± 0.87 | 87.50 ± 1.32 | 5.83 |
| 10% | 12.5 ± 1.32 | 85.00 ± 1.31 | 6.80 |
| 15% | 12.5 ± 0.00 | 80.00 ± 0.87 | 6.80 |
| 20% | 10.0 ± 0.50 | 72.50 ± 0.87 | 7.25 |

* PB = pulverised bone




(a) Load deflection for all cement replacements with pulverised bone




(b) Load deflection for 0% replacement of cement with pulverised bone

**Figure 5.** Load-deflection curves for foam concrete

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

first region (AB), deflection can be considered to be directly proportional to the applied load until the first visible crack appears. This region terminates at the load at which the first visible crack occurs. The relationship between load and deflection of the material can be described as linear in this region. The second region (BC) represents that between the load at first crack and the load at failure. A relatively larger deflection results from load increase until complete failure. Also, the cracks become wider and the load deflection cannot be considered to be linear. The last is the failure region (CD) where sustained load results in a large deflection.

Table 5 compares the cracking load to the failure load for all the mixes. The cracking load decreases with increasing pulverised bone content. This can be attributed to a decrease in density and consequent decrease in compressive strength. The failure load also follows the same trend. The cracking load is 82% of the failure load on the average. The effect of pulverised bone on the deflection is presented in Table 6. It can be seen that the deflection at first crack of the foam concrete with 5-20% pulverised bone in relation to the control (0%) does not differ significantly. In other words, the addition of pulverised bone has no effect on the specimens up to initial cracking, although the same cannot be said of the behaviour after the appearance of first crack and at failure. At failure, the final deflection of the foam concrete with 15-20% pulverised bone becomes significant in relation to the control.

**Table 5.** Comparison between cracking and failure loads

| % PB* | Cracking load (KN) | Failure load (KN) | % Cracking load in relation to failure load |
|---|---|---|---|
| 0% | 75.00 ± 0.00 | 92.50 ± 0.00 | 81.1 |
| 5% | 70.00 ± 5.00 | 87.50 ± 5.00 | 80.0 |
| 10% | 70.00 ± 5.00 | 85.00 ± 5.00 | 82.4 |
| 15% | 65.00 ± 0.00 | 80.00 ± 0.00 | 81.3 |
| 20% | 62.50 ± 0.00 | 72.50 ± 0.00 | 86.2 |

* PB = pulverised bone

**Table 6.** Effect of pulverised bone on deflection of foam concrete

| % PB* | Deflection at crack (mm) | % Difference from control | Deflection at failure (mm) | % Difference from control |
|---|---|---|---|---|
| 0 | 125 ± 0.00 | - | 260 ± 5.00 | - |
| 5 | 125 ± 5.00 | 0 | 280 ± 0.00 | 7.7 |
| 10 | 130 ± 5.00 | 4 | 280 ± 5.00 | 7.7 |
| 15 | 130 ± 0.00 | 4 | 300 ± 5.00 | 15.4 |
| 20 | 135 ± 0.00 | 8 | 300 ± 0.00 | 15.4 |

* PB = Pulverised bone

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

**Stiffness**

Sin [23] reported that the gradient of the load-deflection curve is an indication of beam stiffness. The stiffness computed from load-deflection curves in Figure 5 is shown in Table 7. Prior to cracking, the stiffness values are not affected significantly by the inclusion of pulverised bone up to 15% replacement, the difference being less than 10%. It only becomes significant at 20% replacement. However, after cracking, the stiffness is affected by inclusion of pulverised bone at all replacement levels. The loss of stiffness after cracking is a consequence of the reduction in cross-sectional area of the concrete. The stiffness of the control is not affected by cracking.

**Table 7.** Stiffness of foam concrete beam specimens

| % PB * | Pre-crack stiffness | % Variation from control | Post-crack stiffness | % Variation from control |
|---|---|---|---|---|
| 0% | 1.09 ± 0.00 | -- | 1.09 ± 0.01 | -- |
| 5% | 1.12 ± 0.01 | + 2.75 | 1.40 ± 0.02 | 28.40 |
| 10% | 1.08 ± 0.00 | - 0.91 | 1.50 ± 0.04 | 37.62 |
| 15% | 1.00 ± 0.00 | - 8.25 | 1.50 ± 0.02 | 37.62 |
| 20% | 0.89 ± 0.02 | - 18.35 | 2.00 ± 0.05 | 83.50 |

* PB = Pulverised bone

## CONCLUSIONS

From the results of this investigation, the followings conclusions can be made:

1) The equation developed for the calculation of shear reinforcement for beams in normal concrete can be considered valid for reinforced foam concrete beam with and without pulverised bone.
2) Increase in pulverised bone does not have an effect on crack formation and propagation, and neither does it have any effect on the mode of failure.
3) Deflection of beam specimens increases as the quantity of pulverised bone in the mix increases.
4) Increase in the dosage of pulverised bone brings about the reduction in bending moment.
5) Equation (2), developed on the basis of rectangular stress idealisation for normal concrete, can be considered to be valid for foam concrete with and without pulverised bone.
6) The stiffness of foam concrete is not affected by the inclusion of pulverised bone up to 15% replacement level.
7) The use of reinforcement significantly improves the flexural performance of foam concrete.

## ACKNOWLEDGEMENTS

We appreciate the Management of the University of Lagos providing a substantial fund for this research as well as creating a conducive environment for the execution of the work at the Structures and Concrete Laboratories in the Civil and Environmental Engineering Department.

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

**REFERENCES**


1. E. K. Nambiar and K. Ramamurthy, "Models for strength prediction of foam concrete", *Mater. Struct.*, **2008**, *41*, 247-254.
2. U. J. Alengaran, M. Z. Jumaat and H. Mahmud, "Structural behaviour of reinforced palm kernel shell foamed concrete beams", in "Challenges, Opportunities, and Solutions in Structural Engineering and Construction" (Ed. N. Ghafoori), CRC Press, Boca Raton, **2009**, Ch.41.
3. M. W. Hussin and K. Abdullah, "Properties of palm oil fuel ash cement based aerated concrete panel subjected to different curing regimes", *Malaysia J. Civil Eng.*, **2009**, *21*, 17-31.
4. F. Falade, E. Ikponmwosa and C. Fapohunda, "Potential of pulverized bone as a pozzolanic material", *Int. J. Sci. Eng. Res.*, **2012**, *3*, 15-20.
5. R. L. Day, "Pozzolans for use in low-cost housing", Report to the International Development Centre, Ottawa Canada, **1990**.
6. M. S. Shetty, "Concrete Technology: Theory and Practice", Multicolour Edn., S. Chand and Company Ltd, New Delhi, **2009**, pp.45-50.
7. F. Falade, E. Ikponmwosa and C. Fapohunda, "A study on the compressive and tensile strength of foamed concrete containing pulverized bone as a partial replacement of cement", *Univ. Pakistan J. Eng. Appl. Sci.*, **2013**, *13*, 82-93.
8. ACI Committee 213, "Guide for Structural Lightweight Aggregate Concrete", American Concrete Institute, Farmington Hills (MI), **2003**.
9. RILEM, "Functional Classification of Lightweight Concrete: Recommendations LC2", 2nd Edn., RILEM Publications, Bagneux, **1978**.
10. F. Falade, E. Ikponmwosa and C. Fapohunda, "Low-cost construction through the use of pulverized bone foam concrete (PB-FAC)", *Civil Environ. Res.*, **2013**, *3*, 107-113.
11. BS 12, "Specifications for Portland Cement", British Standards Institution, London, **1996**.
12. NIS 444, "Standard for Cement", Standard Organisation of Nigeria, Lagos, **2003**.
13. D. Aldridge, "Foamed concrete for highways bridge works', One-day Awareness Seminar on Foamed Concrete: Properties, Applications and Potential, **2000,** University of Dundee, Scotland, pp.33-41.
14. G. McGovem, "Manufacture and supply of ready-mix foamed concrete", One-day Awareness Seminar on Foamed Concrete: Properties, Applications and Potential, **2000**, University of Dundee, Scotland, pp.12-25.
15. K. C. Brady, G. R. A. Watts and M. R. Jones, "Specifications for Foamed Concrete–The Use of Foamed Concrete as Backfill", TRL Ltd., Wokingham, **2001**, pp.2-10.
16. M. R. Jones and A. McCarthy, "Preliminary views on the potential of foamed concrete as a structural material", *Magaz. Concrete Res.*, **2005,** *57*, 21-31.
17. Litebuilt, "Lightweight, foamed or cellular concrete technology", http://www.litebuilt.com (Accessed: January 2011).
18. BS 8110, "Structural Use of Concrete – Part 1: Code of Practice for Design and Construction", British Standards Institution, London, **1997**.
19. BS EN 12390 – 5, "Testing Hardened Concrete: Flexural Strength of Test Specimens", British Standards Institution, London, **2009**.
20. J. K. Wright and J. G. MacGregor, "Reinforced Concrete: Mechanics and Design", 5th Edn., Pearson Education International, Upper Saddle River (NJ), **2009**, pp.61-72.
21. P. E. Regan and A. R. Arasteh, "Lightweight aggregate foamed concrete", *Struct. Eng.*, **1990**, *68*, 168-173.

*Maejo Int. J. Sci. Technol.* **2014**, *8*(01), 20-31

22. Constructional Steel Research, "Steel Designers Manual", 4th Edition, ELBS and Granada Publishing, London, **1982**, p.35.
23. L. H. Sin. "Structural response of LWC beams in flexure", *PhD Thesis*, **2007,** National University, Singapore.