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ORIGINAL ARTICLES

Structural behaviour of bamboo-reinforced foamed concrete slab containing polyvinyl wastes (PW) as partial replacement of fine aggregate

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KEYWORDS

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Abstract This paper reports the findings of experimental study to investigate the structural behaviour of bamboo-reinforced foamed concrete slab with polyvinyl waste as partial replacement of fine aggregates. The structural properties studied were: compressive strength, density, crack development pattern and propagation, failure pattern, load–deflection characteristics and the ultimate moment. Compressive strength and the density tests were also conducted using 150 × 150 × 150 cube specimens. The flexural behaviour was investigated by using 1300 × 500 × 100 mm slab specimens. The results showed that: (i) partial replacement of sand with polyvinyl waste (PW) improved the compressive strength of the foamed aerated concrete specimens, (ii) that slab specimens with polyvinyl waste as partial replacement sand exhibited shear bending failure, (iii) all the slab specimens with polyvinyl waste as partial replacement sand recorded lower values of deflection for the same loading, as the level of sand replacement with polyvinyl wastes increased, and (iv) increase in the amount of sand replaced with polyvinyl wastes resulted in improved bending performance of the slab specimens.

1. Introduction

Innovative structural and construction materials are believed to have the potential to curb the seeming overdependence on non-renewable materials like, sand, cement, etc. that are used globally for construction. This will definitely help to arrest the accompanying environmental degradation that accompanies extraction of non-renewable materials. Some innovative structural materials to date are obtained by partially replacing one of the major components of concrete with any of the many wastes (industrial, agricultural, construction, etc.) and non-waste materials. Some of the waste materials that have been used innovatively for structural concrete include: palm kernel fuel ash (Hussin and Abdullah, 2009), silica fume (Yilmaz, 2010) rice husk ash (Givi et al., 2010), fly ash

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(Wilson and Ding, 2007), pulverized bone (Falade et al., 2013a,b), etc. Other non-wastes materials that have been used innovatively for structural concrete, especially as alternatives to the traditional reinforcement include fibres (Ramaswamy, 2014), stainless steel clad black steel, microcomposite reinforcement, carbon fibre reinforced polymer (Hill et al., 2003), bamboo (Ikponmwosa et al., 2014a,b), etc. In the present study, the possibility of using polyvinyl waste (PW) as partial replacement of fine aggregates in the production of foamed aerated concrete slab is investigated. Polyvinyl are materials made from polymers of vinyl compounds, which are subsequently used to manufacture building materials (roofing sheets, windows, vinyl siding), consumer products, disposable packaging, and many every day products (Chej, 2004). According to Thornton (2002), annual generation of polyvinyl waste (PW) stands at about 12 million tones. He further concluded that these wastes pose a serious environmental threat because of the fact that they are difficult to dispose and recycle. Thus the aim of this work is to find out some structural properties of foamed aerated concrete slab, reinforced with bamboo, and containing polyvinyl wastes (PW) as partial replacement of fine aggregates. Ikponmwosa et al. (2014a) have previously studied beam specimens reinforced with bamboo. In the present work however, bamboo is being used as reinforcing material for slab specimens. The parameters investigated in the present work are: compressive strength, density, crack development pattern and propagation, failure pattern, load–deflection characteristics and the ultimate moment.

2. Materials and method

2.1. Materials and mix design

The materials used for these investigations are: cement, fine aggregates, water, polyvinyl wastes, foaming agent and bamboo.

2.1.1. Cement

The cement was Ordinary Portland cement produced to satisfy the requirements in BS 12 (1996) and NIS 444 (2003).

2.1.2. Fine aggregate

As fine aggregates river sand which was obtained from Ogun river basin in Nigeria was used. The sand was dried and sieved through sieve 2.36 mm and treated in accordance with BS 882 (1992).

2.1.3. Water

The water used for the experiment was potable tap water, free from any dissolved metal or ions that might inhibit the setting and hydration process of the foamed concrete. The water was also used to dilute the foaming agent for aeration process.

2.1.4. Polyvinyl wastes

The polyvinyl waste (PW) was obtained as waste material from a polyvinyl-based roofing sheet manufacturing company, Nigerite Limited, based in Ikeja, Nigeria. The waste was ground and packed in bags to be stored subsequently in a cool place.

2.1.5. Foaming agent

In order to aerate the mortar, a polyurethane foaming agent was used. It was obtained from Lagos in Nigeria.

2.1.6. Bamboo as reinforcement

The characteristics of bamboo used for these works were in accordance with the results of works done by Salau et al. (2012), and they include: (i) bamboos with at least three years old and showing a pronounced brown colour, (ii) bamboos without decay, fungus growth, or holes due to white ants, deformation with large diameter and straight long, (iii) bamboo having greater number of nodes. The selected bamboos were air dried for over 30 days (seasoning in air), and then sawn into strips size of $10 \times 10 \times 1200$ mm. In order to reduce water absorption and increase the bond with lightweight aerated concrete matrix, the bamboo strips were coated with bitumen. Wound around the bamboos is 1 mm diameter coir rope at a pitch of about 25 mm along the strip from end. The coir rope was also coated in hot bitumen after being wound round the bamboo strip. This gave a surface similar to a ribbed steel surface. The ribbed surface was expected to improve the bond considerably and the structural behaviour of the bamboo reinforced aerated concrete. Also, fine sands were sprinkled over the coats of bitumen with the aim of inducing roughness on its surface.

2.1.7. The mix design

Based on the equations suggested by Jones and McCarthy (2005), the following mix ratio: cement: sand ratio of 1:3, water: cement ratio of 0.5, and foaming agent: water ratio of 1:33 were used. The mix design was chosen for the target density for the foamed aerated concrete between 1600 and 1900 kg/m^3. All the measurements were by weight.

2.2. Experimental investigations

2.2.1. Density and compressive strength test

The density and compressive strength were performed in accordance with BS 12350: Part 6 (2000) and BS EN 12390-3 (2009). For the tests, $150 \times 150 \times 150$ mm cube specimens were used. This test was performed to confirm whether the targeted 28-day compressive strengths for both the normal weight and the foamed aerated concrete were achieved. The cubes were tested for their compressive strength at 7, 14, 21, and 28 day curing ages respectively. The strength characteristics of each cube were determined on 600 kN Avery Denison Universal Testing Machine at a loading rate of 120 kN/min. Three specimens were tested at each age and the values of the crushing load were averaged and used to evaluate the mean strength for each batch. The cubes were weighed on the Avery weighing machine prior to testing on the testing day, and the values recorded were used to compute the density of the specimens. A total number of 12 cube specimens were produced and tested.

2.2.2. Flexural test

Flexural tests were performed on foamed aerated concrete using $1300 \times 500 \times 100$ mm slab specimens. Before the commencement of concreting, the moulds were properly scraped and oiled to prevent adhesion of the concrete to the moulds.

The bamboo strips, 10 mm × 10 mm in section, were arranged inside the mould with a cover of 20 mm. The slab specimens were designed for bamboo reinforcement with the minimum area reinforcements of 0.24% *bh* (where *b* = width per m length, and *h* = total depth) as per BS 8110 (1997) by treating the bamboo strips as low yield reinforcement. The same bamboo strips of 10 × 10 mm section were used for both main and distribution. However, for the main bar, the spacing of the bamboo strips was at 150 mm, while the spacing of 250 mm was used for the distribution. The details of the bamboo strips reinforcement arrangement are shown in Figs. 1 and 2.

Binding wire was used to hold the bamboo together in the form of mesh. The tensile strength of the bamboo strips was 95 N/mm^2. Foamed aerated concrete was then cast in the specimens, air-cured and tested at 7, 14, 21, and 28 curing days. The sand fraction of the mix was replaced up to 30% at an interval of 5%. Experimental investigation included monitoring of cracks and measurement of central deflection for load increment of 5 kg/cm^2. Application of loads was gradual until failure occurs, and deflections at some intermediate load readings were also noted. The gradual application of the load was achieved with the use of a hydraulic jack and the deflection produced was recorded on the two dial gauges placed at the two critical points at the underside of the slab. The slab was simply supported with a span of 1300 mm. A fixed roller support is positioned at one end and a movable roller support at the other end. The concentrated central loading is spread by an I-section and rollers into line loads at one-third of the span to the right and left of the fixed and movable roller supports (Fig. 3).

Each slab was whitewashed with emulsion paint and allowed to dry before the application of the loads. This was done so as to facilitate the registration of cracks. The locations of the dial gauges, supports and load spreaders are then marked with a black marker to ensure an easy setup. After taking the dial gauge readings as a result of the forces from the initial loads, the load from the hydraulic jack is then applied in increments of 5 kg/cm^2 until failure. For each increment,

(a) Bamboo (b) Arrangement of Bamboo in Slab Mould

Figure 1 Arrangement of bamboo splits prior to placement and in slab mould.

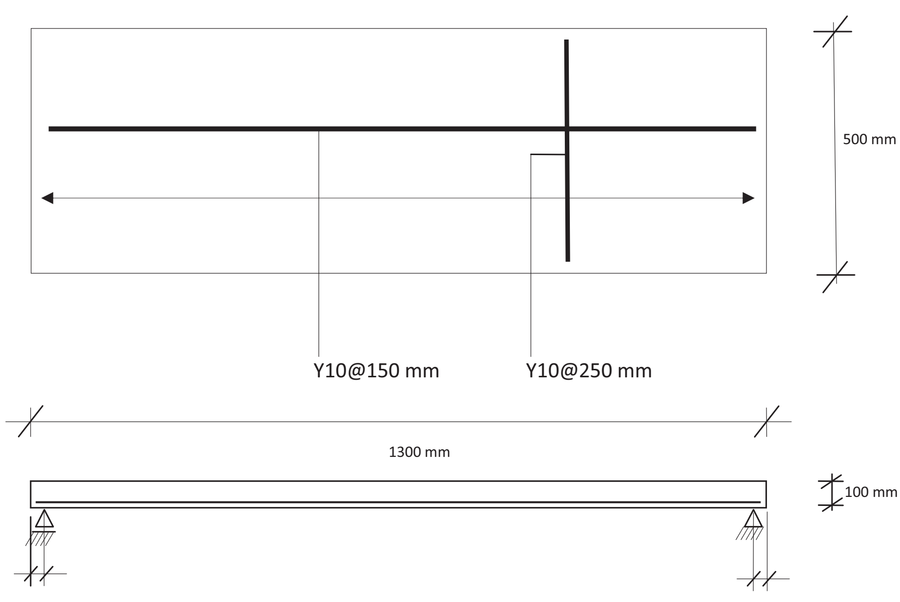


Figure 2 Typical reinforcement details for the slab specimens.

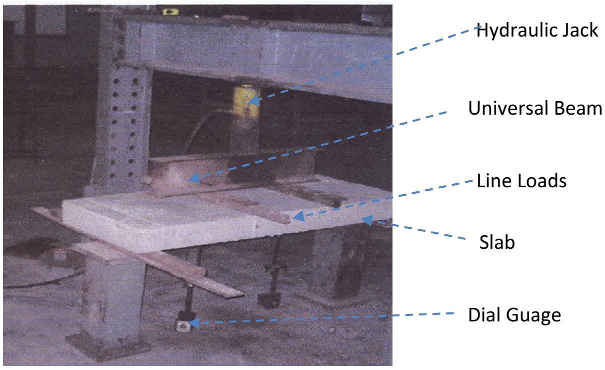


Figure 3 Testing arrangement for the slab.

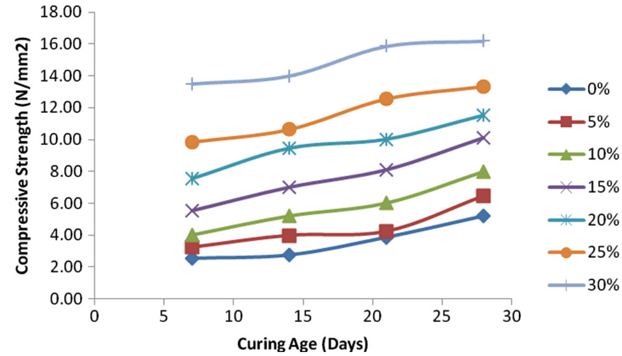


Figure 4 Effect of curing age on the compressive strength on the foamed aerated concrete with PW as partial replacement of sand.

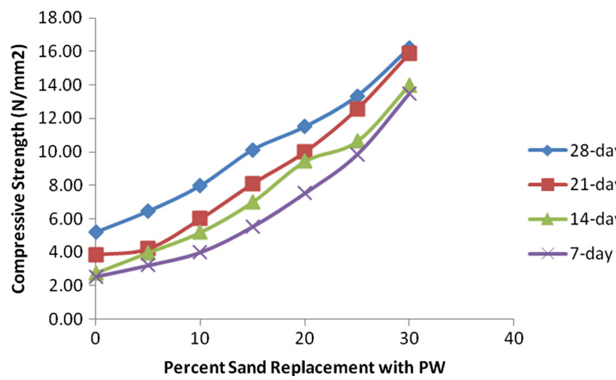


Figure 5 Effect of partial replacement of sand with polyvinyl waste (PW) on the compressive strength on the foamed aerated concrete.

the deflection, initial and propagation of cracks were monitored and were recorded. For this investigation, eighty-four (84) numbers of 1300 × 500 × 100 mm slab specimens were produced and tested.

3. Results and discussions

3.1. Density and compressive strength

The results of the density for the foamed concrete used in this investigation are shown in Table 1. The standard deviations are in parenthesis.

The densities of the foamed aerated concrete specimens ranged between 1454.82 and 1999.11 kg/m^3. These values fell within the range of densities targeted for this work, which is necessary if the results of this investigation are to be considered as valid for foamed aerated concrete. It can however be noticed from Table 1 that the density of all the specimens increased with curing age at the replacement level of sand with polyvinyl waste (PW). From Table 1, it is particularly noticed that the density increased with the increase in the percent of sand replaced with PW. It can thus be inferred that the PW has a densifying effect on the matrix of the material, and this densification increased as the percent of its replacement with sand increased. The results of the compressive strength tests on the cube specimens are shown in Figs. 4 and 5. From Fig. 4, it can be seen the compressive strength increased with curing ages. This increase can be attributed to continuous hydration of cement which made it possible for the development of the strength-forming C-S-H gel.

Continuous hydration also means that sufficient water is available to maintain the hydration process without which the process will stop, leading to loss in strength development (Neville, 2003). Further, from Fig. 5, it can be particularly noted that the compressive strength increased with increase in the sand replacement with PW at all the curing ages. Relative to the control, all the specimens developed higher compressive strength, and it increased as the content of PW increased. This can be explained by the fact the PW used has some fine-grained particles. The chemical properties of the PW (Appendix A) are suggestive of pozzolanic characteristics (with a combined silica, alumina and ferrite content of above 51.45%). The presence of CaO in substantial quantity (30.11%) also suggests reactivity potential to produce C-S-H gel.

Table 1 The density of the specimens.

% PW in mix	Curing age (days)			
	7	14	21	28
0	1454.82 ± 12.01	1483.70 ± 9.67	1531.88 ± 12.67	1568.89 ± 10.09
5	1538.23 ± 12.01	1567.67 ± 10.11	1586.45 ± 12. 67	1601.23 ± 11.19
10	1587.89 ± 15.12	1591.11 ± 10.11	1598.01 ± 10.34	1613.23 ± 11.23
15	1601.34 ± 14.67	1598.23 ± 12.12	1611.12 ± 11.21	1678.56 ± 11.23
20	1665.19 ± 13.33	1674.07 ± 11.11	1689.26 ± 11.21	1703.70 ± 10.09
25	1724.44 ± 12.56	1765.56 ± 11.11	1961.48 ± 11.21	1992.59 ± 10.23
30	1857.78 ± 12.45	1920.00 ± 10.11	1988.15 ± 11.21	1999.11 ± 12.11

Thus the presence of fine grain PW in the mix gave room for the PW to participate in the hydration process to yield extra strength for the foamed aerated concrete. The increase in the compressive strength increased with the increase in the sand replacement with PW.

3.2. Crack and failure patterns

The summary of the failure pattern is presented in Table 2. The single span middle point loading configuration was used to investigate the flexural characteristics of the slab specimens. In this arrangement, the middle third of the span is expected to be in pure bending under loading, so that the middle span developed maximum bending moment and zero shear force. Varying bending moment and maximum shear force will be experienced by other sections. This condition produces the largest strains in the middle third and thus expected to display the first crack.

The specimens did behave this way. The control specimens (0% PW) failed in diagonal tension. This is manifested by the development of crack at the support (under side of the slab specimens) along the whole width of the slab specimens, and propagated diagonally in the direction of the applied load. The failure was very brittle. However, for all other specimens having polyvinyl waste (PW) as partial replacement of sand, failure was a combination of bending moments and shear forces. The crack began at a distance from the support at the tension zone across the width of the slab, and grows vertically into the slab specimens' cross section (Fig. 6) as the load was increased before final failure.

All the specimens failed due to the extension of the crack into the compression zone. Astill and Martin (1981) and Arya (2004) described this mode of failure as shear bending failure. The crack widened as the loading was increased. Also it was observed that the distance "x" from the support from which the crack propagates decreased as the percentage replacement of sand in the mix with PW was increased. This might be due to increased bending resistance at higher replacement levels resultant from improved compressive strengths (Figs. 4 and 5). Though the specimens still exhibited brittle failure, but less abruptly with increase in the level of partial replacement of sand with polyvinyl wastes.

Table 2 Summary of failure mode of slab specimens.

% PW in mix	Failure mode
Control (0)	Diagonal tension failure and brittle
5	Combination of bending and shear
10	Combination of bending and shear
15	Combination of bending and shear
20	Combination of bending and shear
25	Combination of bending and shear
30	Combination of bending and shear

3.3. Deflection and failure loads

The load–deflection curves of the slab specimens at all the replacement levels of sand with polyvinyl wastes (PW) at the curing ages considered are shown in Figs. 7–10.

It can be observed in Figs. 7–10 for all the curing ages that the pre-cracking stage where the curves are expected to be linear are clearly absent, suggesting the inelastic behaviour of the material. The fact that stress–strain relationship of bamboo is non-linear (Rahman et al., 2011; Sevalia et al., 2013) may have contributed to the non-linear behaviour of the specimens.

At all the replacement levels, the load-carrying ability of the slab specimens increased with increase in sand replacement with polyvinyl waste (PW) at all the curing ages.

The failure load increased with the increase in sand replacement with PW at all the curing ages. This may due to the fact that the compressive strength of the specimens has been found to be improved upon by the addition of polyvinyl waste in the mix because of its pozzolanic traits.

For the same load, the values of deflection reduced as the percent of sand replaced with polyvinyl waste in the mix

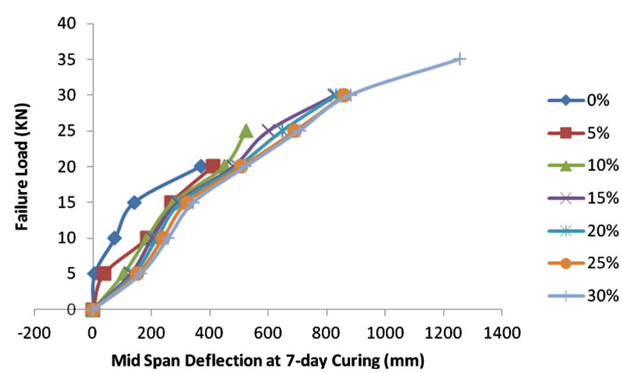
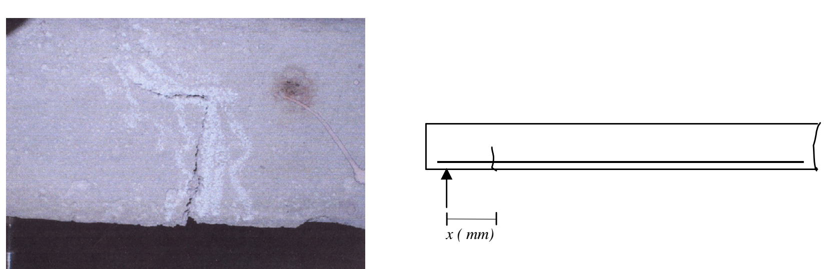


Figure 7 Load–deflection curve for slab specimens at 7-day curing.



(a) The Specimen at Failure

(b) Schematic representation of Specimens at the failure

Figure 6 Schematic representation of failure modes of slab specimens containing polyvinyl waste (PW) as partial replacement of sand.

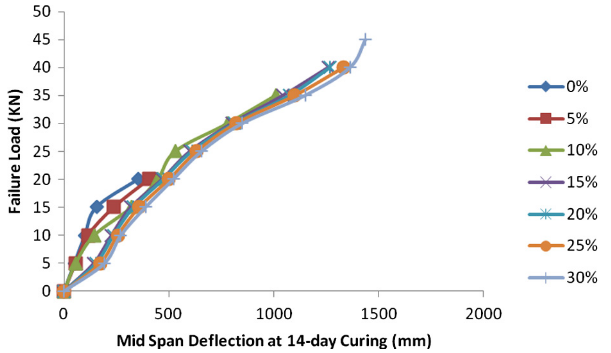


Figure 8 Load–deflection curve for slab specimens at 14-day curing.

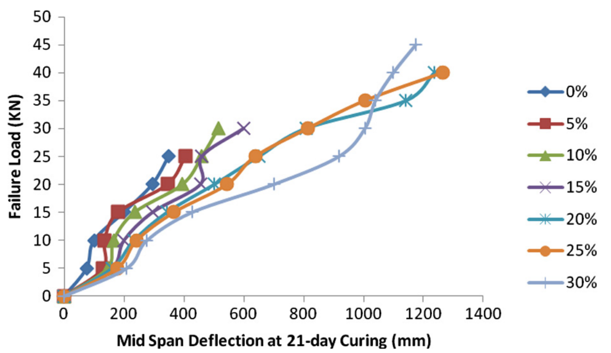


Figure 9 Load–deflection curve for slab specimens at 21-day curing.

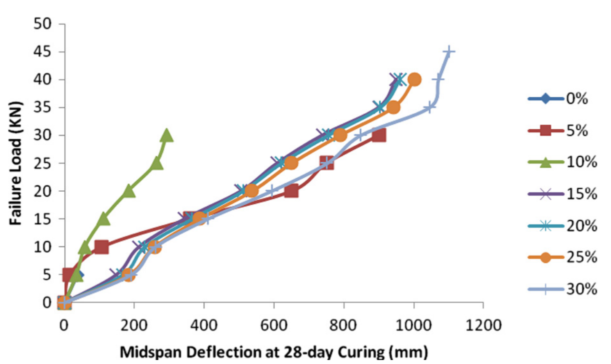


Figure 10 Load–deflection curve for slab specimens at 28-day curing.

increased at all the curing ages. For example, at 10% sand replacement with polyvinyl waste, the deflections at 20KN were 480, 467, 455, and 405 mm respectively at 7-, 14-, 21-, 28-day curing ages. The same pattern was exhibited at all the other replacement levels. The reason for improved deflection characteristics can be explained from the expression for calculating the deflection in which the denominator is the term *EI* (the flexural rigidity) of the material. According to Nageim et al. (2010), increase in the value of the flexural rigidity means a decrease in deflection. While the geometrical properties *I* remaining constant in this study, the value of *E* cannot be said to be constant, as it usually varies with materials (Nageim et al., 2010). It is probable that the Modulus of Elasticity *E* of the material increases with the increase in the sand replacement with PW. This increase in *E* resulted in higher values for *EI*, the denominator of the deflection equation, with subsequent reduction in the deflection. Another way of explaining this is to infer that the increase in percent of sand replacement with PW made the material progressively stiffer, leading to greater resistance to bending, and subsequently a smaller deflection.

3.4. Ultimate bending moments of the slab specimens

For the structural and loading configurations for a two-point loading arrangement used for this investigation shown in Fig. 11, the Davison and Owens (2005) gave the ultimate mid span bending moment (experimental) as:

$$M_{\max} = \frac{Pl}{3}. \tag{1}$$

where P = failure load (KN) and l = span of the slab (m). Also the BS 8110 (1997) gave an expression for theoretical ultimate moments of resistance as:

$$M_u = 0.156 f_{cu} b d^2 \tag{2}$$

where M_u = ultimate moment of resistance (N mm), f_{cu} = 28-day compressive strength (N/mm^2), b = the width of the section (mm), and d = the effective depth of the section (mm).

Eq. (2) suggests that the ultimate moment of resistance depends on the properties of the concrete materials and geometry of the beam. The values of the bending moments using Eqs. (1) and (2) for the slab specimens at all the replacement levels of sand with polyvinyl wastes are shown in Fig. 12.

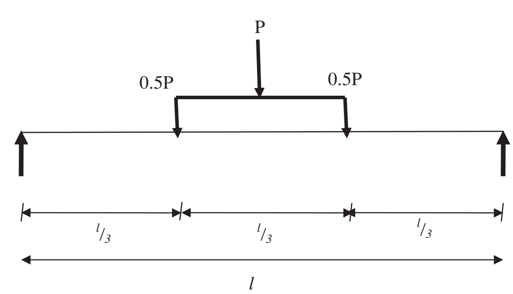


Figure 11 Structural configuration for third point loading.

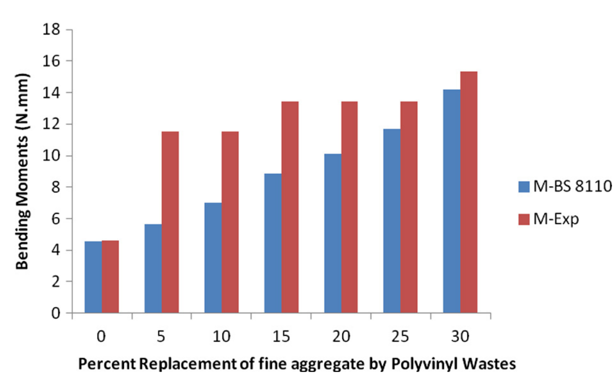


Figure 12 Comparison of theoretical and experimental moments.

From Fig. 12, it can be observed that the experimental moments are consistently higher than the theoretical moments (BS 8110) at all the replacement levels of sand with polyvinyl waste. The higher bending moments obtained experimentally is to be expected. This is because Eq. (1) used for its computation depends on the failure loads. The failure load in turn is a function of the resistance provided both by the concrete materials and the bamboo reinforcement. This is unlike BS 8110 equation in which the contribution of bamboo reinforcement to the values of the bending moment was not part of the parameters of the equation. The bending response of the slab specimens improved as the percentage of sand replaced with polyvinyl wastes increased.

4. Conclusions

From the results of this investigation, the following conclusions are made:

(1) The use of polyvinyl waste as partial replacement of sand improved the compressive strength of specimens, and this improved development of compressive strength increased with the increase in the content of sand replaced with PW.
(2) All the slab specimens with polyvinyl waste as partial replacement sand developed exhibited shear bending failure as against diagonal shear for the control slab specimens.
(3) All the slab specimens with polyvinyl waste as partial replacement sand recorded lower values of deflection for the same loading, as the level of sand replacement with polyvinyl wastes increased. Higher percentage of polyvinyl wastes resulted in higher failure loads.
(4) Increase in the percent replacement of sand with polyvinyl wastes resulted in improved bending performance of the slab specimens.

Appendix A

Chemical properties of polyvinyl waste.

	Compound	Cement	Polyvinyl waste
1	SiO_2	20.34	21.64
2	CaO	63.45	30.11
3	Al_2O_3	6.10	29.86
4	MgO_2	2.13	2.41
5	K_2O	0.38	0.28
6	Na_2O	0.27	0.13
7	Fe_2O_3	2.27	0.05
8	SO_3	1.21	–

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