STRENGTH DEVELOPMENT AND ELASTIC MODULUS OF ECO-BRICKS MASONRY

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Abstract

Several cities in Africa are faced with the problem of waste plastics disposal in the built environment, and at the same time, housing deficit is on the increase. In an attempt to solve both problems, eco-bricks are being produced from waste plastics for the construction of buildings to meet housing needs. However, the structural integrity of building components constructed of waste plastic materials are not sufficiently known, and there is no specific standard addressing the novel technology. This paper presents the experimental laboratory evaluation of the characteristic compressive strength and elastic modulus of eco-brick masonry as a debut towards the generation of data for the structural modelling of eco-brick masonry. Thirty eco-brick masonry prisms were built and subjected to quasi-static compressive loading until failure in accordance with BS EN 1052-1:1998 at 3 days, 7 days, 14 days and 28 days of laboratory ambience curing. The study found a compressive strength of 31.36 N/mm^2 and 2.21 N/mm^2 for eco-bricks and eco-bricks masonry, respectively. The failure of the masonry tested in compression was due to the development of tensile cracks parallel to the axis of loading. Although the elastic modulus was significantly low due to large deformation at ultimate load, the masonry indicated a high capacity to support load considerably, including post-peak loading. The study suggests that eco-brick masonry can substantially support load for single storey buildings commonly used in the construction of low-cost housing.

Keywords: Compressive strength; Eco-bricks; Masonry prisms; Plastic waste; Quasi-static compressive loading

Introduction

The world production of plastics continues to make phenomena progress. Lepoittevin and Roger (2011) reported that the worldwide production of plastic is approximately 14–60 million tons, while only 6.7 million tons are recycled annually (Kumar, et al., 2014). Thus over 7.3 million tons of plastic waste is generated annually (Geyer, et al., 2016). In Nigeria, PET is commonly used in packaging drinks and water known as bottled water. Once the water and drinks are consumed, the empty bottles are usually discarded indiscriminately and therefore constitute a colossal environmental nuisance. Discarded PET bottles, for instance, are common eye-sore on the streets; blocking drains and impeding the free flow of water channels and canals (Adewumi, 2006).

On the other hand, housing deficit continues to soar in developing countries despite the United Nations Committee on Economic, Social and Cultural Rights affirmation of the 1948 housing for all declaration in several of the committee general comments. The duty is on every country to implement the rights to housing for its citizens, irrespective of economic development, political situation, or social conditions (Bogumil, 2011). Despite the commitment of the government to the rights to housing declaration, there is a consistent rise in the number of homeless citizens let alone adequate housing (Crane & Joly, 2014). The increase in homelessness is a manifestation of housing deficit. In Nigeria, the World Bank Group approximated the housing deficit as 17 million housing units, for a population growing at approximately 2.6% annually (World Bank, 2019). This figure is expected to increase in the face of the current population estimated at approximately 200 million people but without a commensurate increase in decent shelters (World Bank, 2019).

Extensive research programmes are being conducted on the application of waste plastic in the production of construction materials to address both problems of housing deficit and plastic waste (Badejo et al., 2017; Edike et al., 2020; Ferrandiz-Mas, et al., 2014; Herki & Khatib, 2016; Jassim, 2017; Kim et al., 2019; Rai, et al., 2012; Thorneycroft, et al., 2018). Interestingly, eco-brick masonry is gradually becoming popular in the construction of low-cost housing in some regions of developing countries (see Figures. 1 and 2).

Fig. 1: Single storey building construction with eco-bricks

Fig. 2: Multistorey building construction building with eco-bricks

A number of residential buildings have been constructed using eco-bricks produced from recycled PET bottles that are filled with soil materials. The use of eco-bricks in construction of low-cost houses has recorded considerable progress in Yelwa, Kaduna State by way of application in the construction of bungalows, multistorey buildings, water reservoirs and underground tanks.

Studies have also shown that different types of materials can be used as infill material of waste PET bottles for the production of eco-bricks. Muyen et al. (2016) made eco-bricks with sand as infill material of 250ml to 2 litres upcycled PET bottles to determine the strength properties of plastic bottle bricks and their suitability as construction materials. The study reported a compressive strength of 8 N/mm^2 to 17.44 N/mm^2. Waste plastic bags have been used as infill material of 500ml waste PET bottles to produce eco-bricks (Taaffe et al., 2014). The compressive strength of the bottle bricks were between 2.55 N/mm^2 and 2.90 N/mm^2. Mokhtar et al., (2016) obtained higher compressive strengths of 27.39 and 38.34 N/mm^2 for 250 ml and

1.5 litres respectively, by using sand as infill material of recycled PET bottles. Rawat and Kansal, (2014) and Kim et al. (2019) also used soil materials as infill for the production of eco-bricks. The compressive strength of the bottle brick units reported in previous studies substantially satisfied the minimum requirement for use as a masonry unit (BS 5628 –1: 1998). However, the performance of masonry walls is influenced by several factors and not only the structural integrity of the masonry unit.

The characteristic compressive strength of masonry is an essential parameter in the structural modelling of masonry. The characteristic compressive strength of masonry walls is principally a function of the compressive strength of the masonry units and the mortar used to bond the units (EN 1996-1-1: 2005). BS 5628 -1: 1998 also acknowledged the influence of masonry mortar as a significant parameter for the determination of the characteristic strength of masonry. The importance of mortar has been revealed in Binda et al. (2008) study which obtained a compressive strength of 1.2 N/mm^2 for adobe masonry prisms constructed of adobe brick units of 1.1 N/mm^2 compressive strength. The compressive strength of the masonry is higher than the compressive strength of the adobe unit. Although the finding is contrary to the provisions of BS 5628 – 1 in which the compressive strength of masonry constructed of standard format bricks is not more than half of the compressive strength of the structural unit in all classes of mortar, the study clearly demonstrates the importance of mortar and the complexity alternative masonry materials present. Masonry wall has been described as a multiphase continuum comprising variations, discontinuities, cracks and interfaces depending on the variety of materials, bonding of the bricks, geometries, and the craftsmanship of masons (Croce et al., 2018; Kouris et al., 2020). These attributes present a large discrepancy on the mechanical properties of masonry structures built in-situ and create huge lacuna on the application of existing models in the computation of the compressive strength of masonries constructed of AMUs.

Besides, the elastic moduli are also needed for structural modelling of masonries. The current codes, however, do not include physically-based or theoretically-deduced estimates for elastic modulus. Instead, estimates of the elastic moduli of masonry walls are based on either prisms experiments or, on empirical formulas involving the prisms compressive strength which in turn is also given by an empirical formula. The commonly applied design methods for determination of elastic moduli of masonry are based on homogenised macro-mechanical properties of masonry using equivalent frame model of either shell or beam elements to describe the global behaviour of masonry structures (Kouris & Kappos, 2012; Penna et al., 2014; Kouris et al., 2014). However, the homogenised macro-mechanical models are being criticised of generating enormous inconsistencies in results and being far from accurate assumption (Kouris et al., 2020) due to the consideration of a perfectly homogeneous and isotropic material with a single adjustment of the elastic modulus for masonry.

To simulate the real nature of masonry materials during service, some studies (Greco. et al., 2020; Masi, et al., 2020; Petracca, et al., 2017; Prakash et al., 2020; Pulatsu, et al., 2016; Sarhosis & Lemos 2018) have proposed detailed discrete micro-models considering the exact arrangement of masonry units and mortar joints along with distinct properties and the component interfaces. However, due to the complexity of the micro-models, the use is only limited to local analysis and the models are neither feasible, nor applicable for the design of buildings (Lagomarsino, et al., 2013; Formisano et al., 2015; Maio et al., 2015) since the computational effort required is very high and exact units and mortars geometry is difficult to accurately define.

In any case, both homogenised macro-mechanical models and the discrete micro-models are developed using masonry walls or prisms constructed of conventional materials. Thus, the models may not be fully adopted for the determination of the characteristic compressive strength and the elastic moduli of masonries constructed of alternative masonry units without a full-scale experimental campaign. Explicitly, there is no sufficient data or models for the estimation of the characteristic compressive strength and the elastic modulus of eco-brick masonry, which are essential parameters for the modelling of masonry walls. This paper presents the experimental laboratory evaluation of the characteristic compressive strength and elastic modulus of eco-brick masonry as a debut towards the generation of data for the structural modelling of eco-brick masonry. The experimental procedures and results generated with the quasi-static compressive loading of the masonry prisms and eco-bricks are discussed in the following sections.

2.0 **Experimental Programme**

2.1. Materials and masonry used in the investigation

Laterite soil material and waste PET bottles were used to produce the eco-bricks. The laterite was air-dried in the laboratory for a period of three months. The laterite soil material was used to fill the recycled waste PET bottles and compacted moderately to produce the eco-bricks. The PET bottles were 75 cl with uniform configuration. The eco-bricks were then used to build the masonry prisms.

2.1.1 Eco-bricks

75 cl waste PET bottles were gathered from waste bins and physically recycled for use as encapsulate for the eco-bricks. PET bottles were filled with the laterite and compacted moderately in three layers to avoid damaging the bottles. Each compaction layer involves 12 rounds of vibration on the floor with round displacement height not exceeding 150mm. Six eco-brick units were tested using uniaxial compressive load to determine the average compressive strength of the units. Detailed characteristics of the eco-bricks, such as compressive strength, specific strength, Poisson’s ratio and bulk density have been reported elsewhere (Edike et al., 2020).

2.1.2 Eco-brick masonry prism

Masonry prisms were used to determine the compressive strength and elastic modulus of the eco-brick masonry. The test prisms consisted of five courses of eco-bricks and six eco-bricks in a course which formed a 450 x 270 x 375 mm^3 eco-brick masonry prisms presented in Fig. 3.

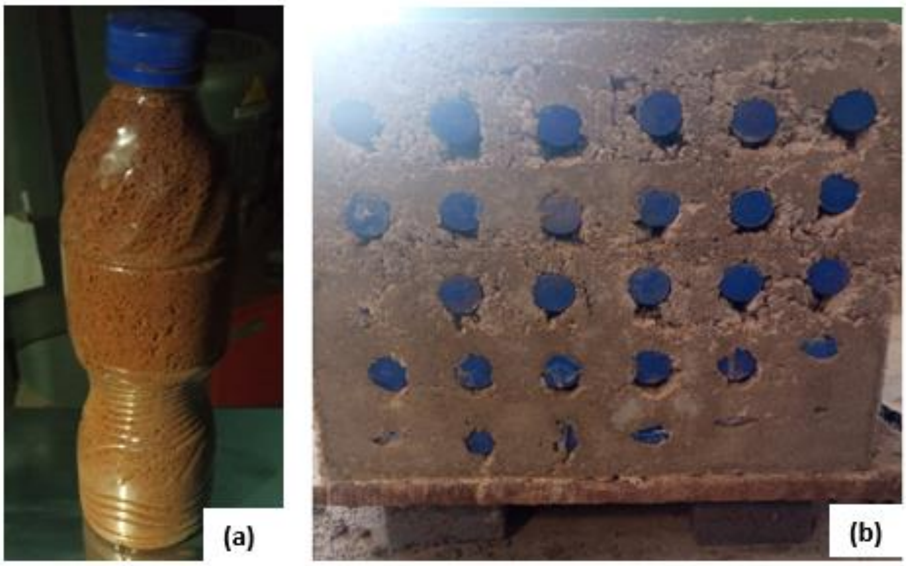

Fig. 3: (a) eco-brick made with 75 cl PET bottle (b) 450 x 270 x 375 mm^3 eco-brick masonry prism

The eco-brick units were bonded with mortar mix 1:5 cement: sand ratio with reference to mortar designation (iii) of BS 5628-2:1992. The construction of the masonry prisms was in accordance with BS EN 1052 – 1: 1998 and prisms were cured for 3 days, 7, 14, and 28 under laboratory ambience before the specimen were tested.

2.2 Experimental Procedure

Thirty eco-brick masonry prisms were tested in the Building Laboratory of the Nigeria Building and Road Research Institute (NBRRI), Ota, Nigeria under the application of quasi-static compressive load. After curing the prisms for 3 days, 7 days, 14 days and 28 days for mortar beds and joints to achieve considerable strength, the masonry prisms were tested for compressive strength as per BS EN 1052 – 1: 1998. The masonry prisms were placed on the UTM and instrumented with four position sensors for elastic modulus test, as indicated in Fig 4.

Fig. 4: Elastic modulus setup

The masonry prisms were subjected to quasi-static compression load at a rate of 0.05 MPa/s, beyond maximum load until major cracks had appeared and stopped automatically before the complete collapse of the masonry specimens. The vertical compression load and the longitudinal deformation were acquired using a computer controlled 2000 kN UTM and the four variable position sensors, respectively. Two position sensors were attached to each face of the masonry prism, as shown in Fig. 4. The elasticity Moduli of the six masonry prisms tested were computed using the expression in equation 1.

$$E_m = \frac{F_{m,max}}{3 \text{ x } \varepsilon_m \text{x } A_m} \quad (\text{N/mm}^2) \quad - \quad - \quad (1)$$

Where, E_m = modulus of elasticity of masonry; $F_{m,max}$ = mean of maximum compression strength of masonry; A_m = mean of areas of masonry; ε_m = mean strain of masonry.

3.0 Results and Discussion of Findings

3.1 Eco-bricks Results

The results of the test conducted on eco-brick units are presented in Table 1 and Fig 5. Table 1 shows the average compressive strength of eco-bricks and Fig. 5 displays the stress-time curve of the eco-brick units generated from the UTM. The average compressive strength of the eco-brick units was 31.36 N/mm^2. The compressive strength value exceeded the minimum 2.9 N/mm^2 compressive strength indicated in BS EN 771 – 3 and also surpassed the minimum requirement of 5 N/mm^2 recommended for external works by BS 3921 and EN 771-2:2011.

Table 1: Compressive strength of eco-brick units

Specimen ID	BBL1	BBL2	BBL3	BBL4	BBL5	BBL6	Average	COV
Compressive Strength (N/mm^2)	30.51	29.06	34.92	32.50	31.90	29.25	**31.36**	0.06

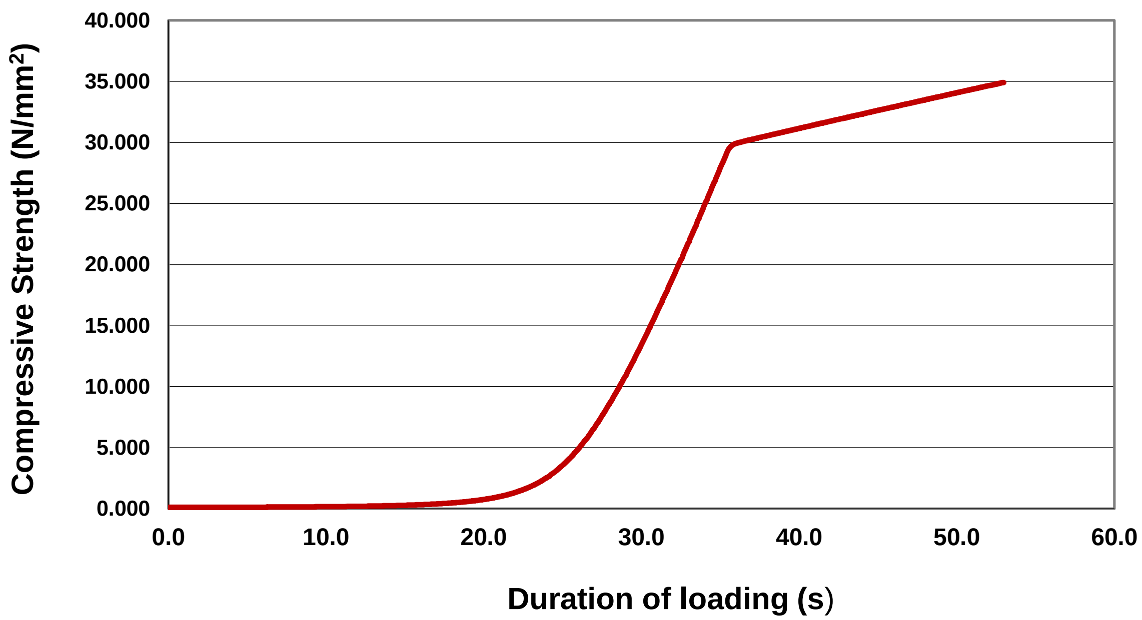

Fig. 5: Stress-time curve of the eco-brick units (BBL3)

3.2 Eco-brick Masonry

The results of the experimental tests conducted on eco-bricks masonry prisms are presented in Figure 6 and Tables 2. The figure shows the average compressive strength (f'_m) of the masonry prisms with different curing ages, while the elastic modulus (E_m) and the respective coefficient of variations (COV) are presented in Table 2. Six eco-brick masonry prisms were used to obtain the average compressive strength at each curing duration. The compressive strengths of the masonry prisms and the COV at 3 days, 7 days, 14 days and 28 days are respectively 1.06 N/mm^2 (COV, 0.43); 1.92 N/mm^2, (COV, 0.19); 219 N/mm^2, (COV, 0.09) and 2.21 N/mm^2, (COV, 0.09).

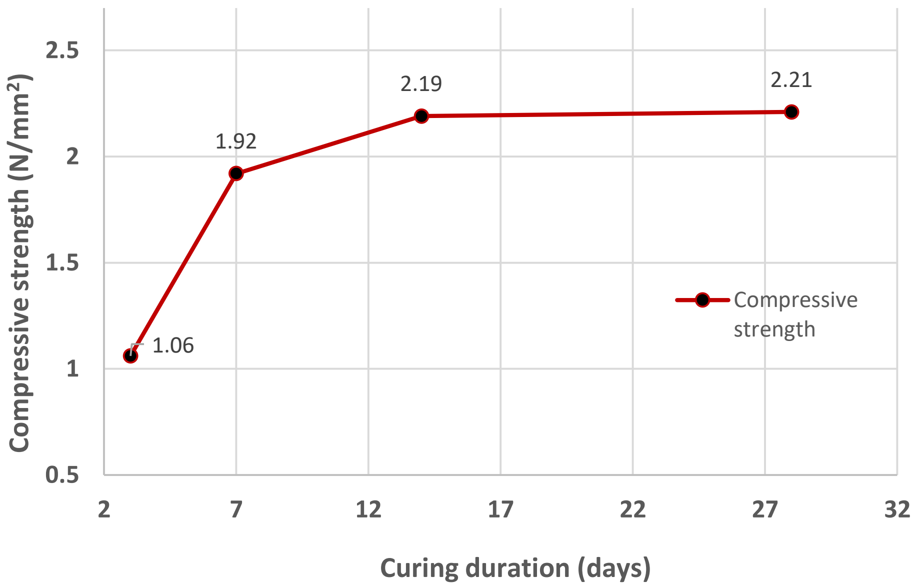

Fig. 6: Compressive strength of masonry prisms

The results indicated a steady increase in compressive strength with curing age. The masonry prisms under load developed tensile cracks which propagated as the load increased. At ultimate load, major failure modes include spalling of mortar paste and debonding of the eco-bricks (see Fig 7.) Post peak behaviour was dominated with debonding of eco-brick units and crushing of mortar paste without significant damage on the eco-brick units. The failure modes, particularly debonding, clearly demonstrated the weak bond between mortar paste and the eco-brick units in the masonry. The weak bond between mortar paste and the eco-brick units is attributed to the smooth surface of the PET bottles. The weak bond effect accounts for the wide margin between the compressive strength of the eco-brick units and the masonry prisms.

Fig. 7: Failure modes of eco-brick masonry prism under load. (a) Tensile crack development and propagation (b) Mortar spalling failure (c) Debonding failure

The masonry prisms also demonstrated considerable resilience upon loading with curing duration. Figures 8 and 9 present the compressive strength and time curve generated from the UTM. In Figure 8, the ultimate stress obtained for the masonry prism at 3 days curing is 1.81 N/mm2 at 73.52 seconds of loading. At the 28 day of curing, the ultimate stress and duration of loading to failure increased to 2.05 N/mm^2 and 82.3 seconds, respectively. The results indicate the increase in resilience of the eco-brick masonry prisms with curing duration.

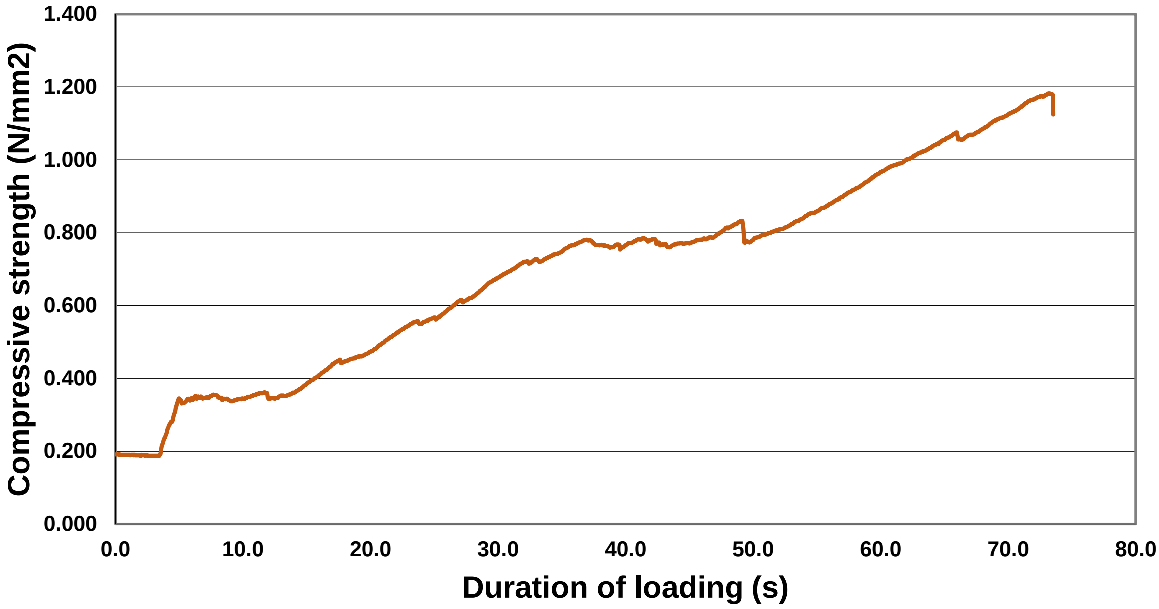

Fig 8: Compressive strength variation with the duration of loading at 3 days curing (BM_31)

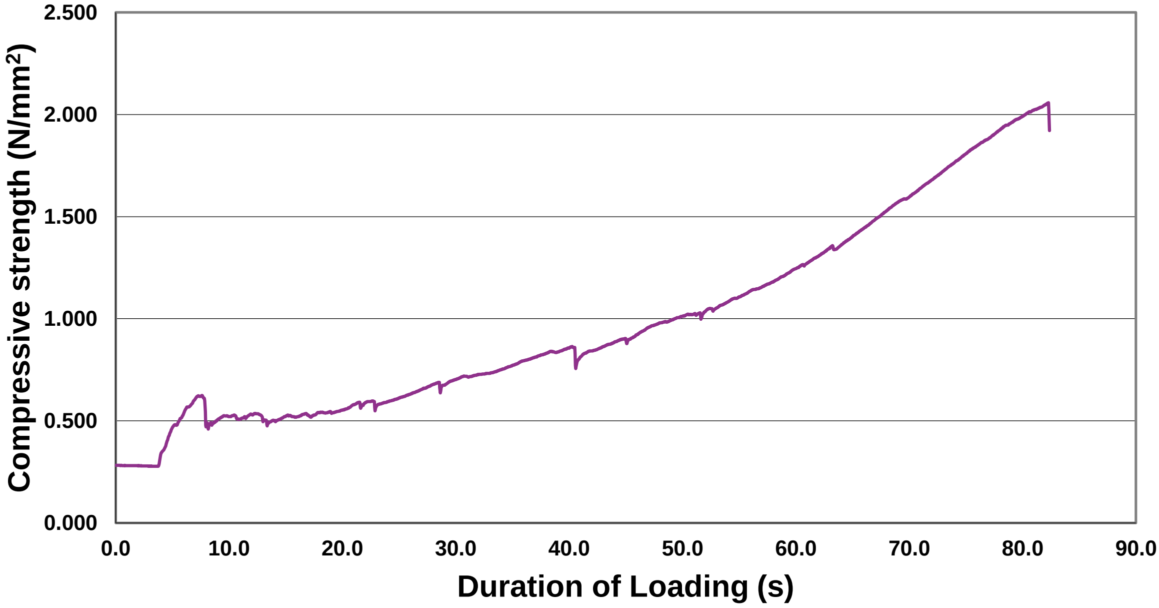

Fig. 9: Compressive strength variation with the duration of loading at 28 days curing (BM_83)

Table 2: Elasticity Modulus of eco-brick masonry prisms

Specimen ID	BMe1	BMe2	BMe3	BMe4	BMe5	BMe6	Average	COV

Elastic modulus (N/mm^2)	105	125	90	170	180	110	**130**	0.26

The elasticity moduli of the eco-brick masonry prisms shown in Table 3 were determined using equation 1 as per the provision of BS EN 1052 -1: 1998. The average modulus of elasticity is 130 N/mm^2. The value is comparatively low with respect to the compressive strength and the provisions of EN 1996-1-1:2005 for conventional masonry units where the minimum elastic modulus is 1000. Low modulus of elasticity appears to be common among alternative masonry units. Oliveira et al., (2007 as cited in Binda et al., 2008) also reported a low elastic modulus (630 N/mm^2) for adobe masonry. The low modulus of elasticity obtained in the current study is attributable to the mode of failure resulting in large deformation and enormous strain exhibited by the masonry under load.

4.0 Conclusion

In this paper, the effect of curing age on the compressive strength of eco-brick masonry prisms is investigated. Also, the elastic modulus of eco-brick masonry prisms is presented. From the findings of the study, the following conclusions can be drawn.

1. The compressive strength of eco-brick units (31.36 N/mm^2) exceeded the minimum 2.9 N/mm^2 compressive strength indicated in BS EN 771 – 3 and also surpassed the minimum requirement of 5 N/mm^2 recommended for external works by BS 3921 and EN 771-2:2011. This suggests that eco-bricks can be used as masonry units.
2. The study found a steady increase in compressive strength with curing age of eco-brick masonry prisms reaching 2.21 N/mm^2 at 28 days.
3. Failure of eco-bricks masonry prisms under load was principally tensile cracks, spalling of mortar, debonding of eco-brick units and crushing of mortar occasioned by the weak bond between mortar and the smooth PET bottles interface.

4. The ultimate load of the eco-bricks masonry prisms were attained without significant damage on the eco-brick units. This presents the capacity to recycle the eco-bricks for another structure after the present life span.
5. The elastic modulus of the eco-brick masonry prisms was substantially low due to large deformation. However, the masonry indicated a high capacity to support load considerably, including post-peak loading.
6. The study suggests that eco-brick masonry can considerably support load for single storey buildings commonly used in the construction of low-cost housing.

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