Stress-strain characteristic of crumb-rubber masonry concrete prism column under compression

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ABSTRACT

This paper presents an experimental study into the stress-strain behaviour of an unreinforced and un-grouted crumb-rubber modified masonry hollow concrete block prism under uniaxial monotonic compressive loading conditions. The investigation was carried out on the reference and modified masonry prism samples with varying content of crumb-rubber from end-of-life tyres partially replacing coarse aggregate (granite) by volume at 0, 5, 10, 15, 20, and 25%. Based on the results obtained, the stress-strain curves have revealed a convergent strength level deformation under compression. Furthermore, the results indicated a linear increase in the stress of the reference prism column before fracture at the maximum stress with the stress-strain curve considered as a "sharp peak". It was also noticed that increasing the crumb-rubber content has a significant effect on the maximum stress and strain of the prism columns. This variation reached about 74% at maximum stress with crumb-rubber content up to 25%. The result also revealed an increase of 49% and 30% in lateral and vertical (strain) respectively at maximum stress to the reference prism column and crumb-rubber content up to 25%. Thus, the increase in the plastic strain translates into an increase in the toughness with a gradual failure and high-energy absorption capability.

Keywords: Concrete; Masonry; Crumb-Rubber; Specified Strength; Stress-Strain.

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ISSN No.: 2521-8263

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ABSTRACT

This paper presents an experimental study into the stress-strain behaviour of an unreinforced and un-grouted crumb-rubber modified masonry hollow concrete block prism under uniaxial monotonic compressive loading conditions. The investigation was carried out on the reference and modified masonry prism samples with varying content of crumb-rubber from end-of-life tyres partially replacing coarse aggregate (granite) by volume at 0, 5, 10, 15, 20, and 25%. Based on the results obtained, the stress-strain curves have revealed a convergent strength level deformation under compression. Furthermore, the results indicated a linear increase in the stress of the reference prism column before fracture at the maximum stress with the stress-strain curve considered as a "sharp peak". It was also noticed that increasing the crumb-rubber content has a significant effect on the maximum stress and strain of the prism columns. This variation reached about 74% at maximum stress with crumb-rubber content up to 25%. The result also revealed an increase of 49% and 30% in lateral and vertical (strain) respectively at maximum stress to the reference prism column and crumb-rubber content up to 25%. Thus, the increase in the plastic strain translates into an increase in the toughness with a gradual failure and high-energy absorption capability.

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1. INTRODUCTION

Masonry hollow concrete blocks are widely used in many parts of the world due to their numerous relative advantages such as low cost, lightweight, high bearing capacity, and efficiency in terms of energy and acoustic performance [22]. The brittle failure behavior of hollow concrete blocks masonry in compression necessitates the utilization of alternative materials such as post-consumer tyre particles to enable it to be more ductile and also produce more sustainable concrete blocks [11] Post-consumer tyres are always embattled with the problem of how to dispose of them. Discarded post-consumer tyre into landfills and open fields pile up and create large voids under the surface and on the surface of land as the case may be which leads to the trapping of gases such as methane. The trapped gases can ignite at any given opportunity leading to uncontrollable fire [4]; such as the recent experience reported by [2] in Sesena, Spain where an uncontrollable fire rage through a pile of millions of kilograms (millions number) of tyres unleashing and releasing a thick black cloud of toxic fumes into the air at the dumpsite covering 100,000 square meters. The blaze was said to have lasted for days before it was controlled as the fire continues to burn inside even though it has been extinguished from outside. Open-air combustion of waste tyre pollutes the air and poison the groundwater with the release of benzene and heavy metals that produce dioxins which are linked to various serious health problems [4] [21], revealed that every year around 9 billion kilograms of end-of-life tyres are discarded everywhere throughout the world, which was likewise evaluated to associate with one billion waste tyres generated annually [6] and [9] based on 2018 statistics with a 15% annual generation rate, it is estimated that around 37 million waste tyres exist in Nigeria [18]. One of the most common ways of disposing of waste tyres is through open field disposal and combustion [17]. With this quantity, the large stockpile of waste tyre poses both environmental and health risks to its population.

Waste tyres in form of chips, fibers, crumbs, and particles have been successfully incorporated into asphalt mix and used as a surface layer in a flexible pavement which is dated back to the 1980s; results reveals that the modified asphalt had better resistance to skidding, reduce fatigue cracking and prolong pavement life span compared to the conventional asphalt mix [([1]; [7]; [8], [13], [5] and [12])]. The application of waste tyre derived aggregate in Portland cement-based materials mixes such as structural concrete and blocks has been exploded in past years using chips, fines, shreds, slit, fibers, and crumb-rubber to replace fine aggregate. Results revealed that compressive strength decreased with an increase in rubber tyre particle content however structural concrete and blocks for both load-bearing and non-load bearing structures can be produced with partial replacement of rubber particles up to 15% [15, 120 and 10].

This present study is aimed at introducing crumb-rubber aggregate in various proportion as a partial replacement for coarse aggregate in masonry concrete mix and also investigate the unit weight specified compressive strength, and stress-strain characteristics of masonry hollow concrete blocks prism column constructed.

2. MATERIALS AND METHODOLOGY

2.1 Material

A general-purpose blended limestone Portland cement CEM II (42.5R MPa) with a specific gravity G of approximately 3.15 that conforms to BS EN 197-1:2000 was used in this work. The natural river quartzite sand smaller than 4.76mm but larger than 75µm with average bulk specific gravity (SSD) of 2.65 was used for both fine and medium-fine aggregate. It was graded with the appropriate zone of sieves according to BS EN 933-1:2012 to ensure that it conforms to BS EN 1260:2002+A1:2008 specification. Natural crushed (granite) with nominal maximum sizes of 9.52mm-10mm sourced from a local commercial quarry with average bulk specific gravity (SSD) of 2.66 was used. Tests were conducted on the coarse aggregate to ensure that it conforms to BS EN 1260:2002+A1:2008 specification. Crumb-rubber aggregate in Figure 1 was derived from post-consumer tyres and processed to a nominal maximum size of 4 - 9mm with average bulk specific gravity (SSD) of 1.14. The surface of the crumb-rubber was treated by soaking in a sodium hydroxide (NaOH) which enhances the hydrophilic properties of the rubber and increases the intermolecular interaction forces between rubber and calcium silicate hydrate (C-S-H) gel which enhances the strength of the composite matrix [14]. Ordinary tap water was used for all concrete mixes and curing.

2.2 Mix Design and Manufacture of Hollow Concrete Block Units

The mix design for the masonry hollow concrete block adopted was based on absolute volume method according to BS EN 206-1:2000, "Method of specifying concrete mixes", A mix ratio of 1:1.5:3 and water/cement ratio of 0.42 was adopted for all the concrete mixes due to the high strength above the required minimum standard of 30N/mm2. Water cement ratio (w/c) of 0.42 was taken as the optimum because of the moderate compacting factor of 0.84 (low) and high strength of 30.71N/mm^2 attached to it. General-purpose masonry mortar with a strength grade of 20N/mm2 was produced with a mix ratio of 1:3 (cement: sand) and a w/c ratio of 0.6. The masonry concrete blocks (hollow) with the size 450 x 225 x 225mm were produced to the requirements given in BS 771-3(2003) with the use of a vibrating machine. Six various percentages of coarse aggregate (granite) partially substituted with crumb-rubber at 0, 5, 10, 15, 20, and 25% by volume were used.

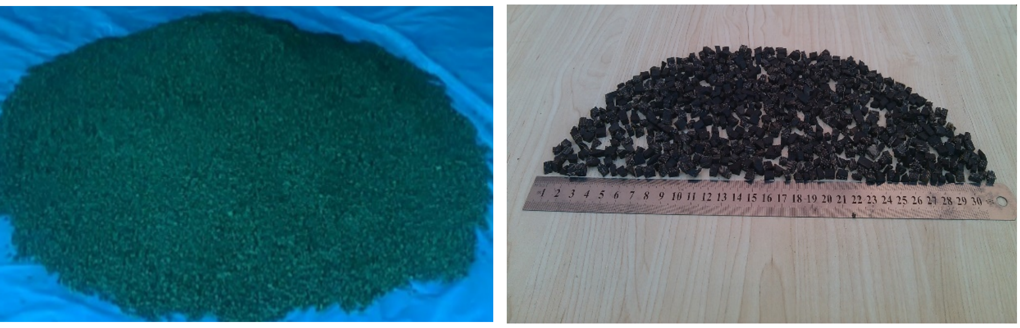

Figure 1: Crumb-Rubber Aggregate Used for Concrete Mix

Figure 2: Construction of Masonry Hollow Concrete Block Prism Column

2.3 Experimental Procedures

Tests were conducted to assess the workability of the freshly mixed concrete which includes compacting factor in accordance to BS EN 12350-4:2009 and unit weight in accordance to BS EN 12350-6:2009 while the yield was computed based on ASTM C138-09. The density and compressive strength of masonry hollow concrete block units were determined according to BS EN772 -13 (2000) and BS EN 772 -1:2000 respectively after twenty-eight (28) days of curing.

Masonry prism columns were constructed following ASTM C1314, wooden pallets of suitable sizes were prepared and used as a flat base upon which the masonry prism columns stand. A total of eighteen (18) masonry prism columns (230 x 720 x 230) mm were built as shown in Figure 2 in the same manner to investigate the effect of crumb-rubber on its properties. M20 general-purpose mortar with the mixture consisting of Portland cement (CEMII) and sand in a proportion of 1:3 by volume and water/cement ratio of 0.6 was used for the mix and kept constant for all mixes. All prism columns were covered with polythene and left for 24hrs to gain an initial set before being moved to storage. The constructed columns were cured with water through sprinkling twice per day for 28 days to achieve the desired bonding strength of the mortar.

2.4 Test Set-up, Instrumentation, and Measurement

The compressive strength of the un-grouted masonry prism column was tested following ASTM C1314 after curing for 28 days. A testing rig and lateral displacement gauges (dial gauge) were used for the test.

A schematic description of the setup can be seen in Figure 3. Displacement gauges (dial gauge) were set up on each prism column to record the strain values during compression. Loading was applied uniformly to the top and bottom of the specimen. The load increased steadily so that failure is reached after 15 min to 30 min from the commencement of loading. The compressive load (stress) at initial cracks and final cracks i.e., the ultimate load was observed. The net cross-sectional area of the masonry unit determined following ASTM C140 was used to calculate compressive strength for the un-grouted reduced-size prisms.

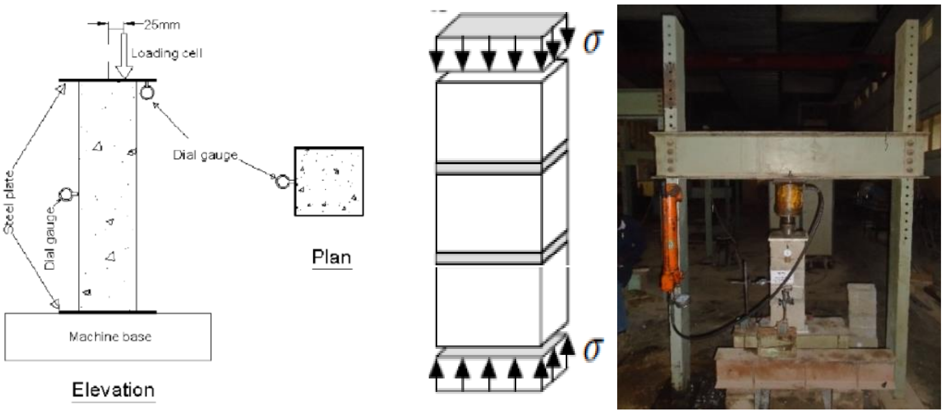

Figure 3: Schematic Description and Picture of Masonry Prism Column Test Set up

Equation 1 was used to determine the compressive strength of each prism column:

$$f_i = \frac{f_{imax}}{A_i} \qquad \text{Equation (1)}$$

Where f_i is the compressive strength of an individual masonry prism column specimen, (N/mm^2); f_{imax} is the maximum load reached on an individual masonry prism column specimen, (N); A_i is the loaded cross-section of an individual specimen, (mm^2). The specified compressive strength (f_m) was determined using Equation 2:

$$f_m = f \times 1.08 \ (N/mm^2) \qquad \text{Equation (2)}$$

Where: f = Compressive Strength (N/mm^2) and Correction factor = 1.08

3. RESULTS AND DISCUSSION

3.1 Compacting Factor, Yield, and Unit weight

The compacting factor (C.F) was observed to decrease significantly, reference masonry concrete mixes had a C.F of 0.84 (low workability) while the 25% rubberized mix had a C.F of 0.77 (very low workability) indicating an 8.3% reduction. Incorporation of crumb-rubber tyre aggregate decreased the unit weight of fresh concrete mix from 2,436Kg/m^3 to 2,191Kg/m^3 with crumb-rubber content up to 25% which indicates a 10.1% reduction.

3.2 Density

The density of control and rubberized masonry hollow concrete blocks samples indicates that the rubberized masonry hollow concrete blocks exhibited lower densities than the control mixes, also it can be deduced from the result that density reduces by 19%, with the reference concrete block units having an average net density of 2079 kg/m^3 while 25% modified masonry hollow concrete block units have an average of 1686 kg/m^3 which indicate a range of medium weight to normal weight.

3.3 Compressive Strength (f)

Compressive strength of rubberized masonry hollow concrete blocks results indicates a decrease in compressive strength with an increase in crumb-rubber content also a percentage loss of strength by 49% was observed with the reference units having a strength of 9.43N/mm^2 while 5, 10, 15, 20 and 25% crumb-rubber modified masonry concrete block units having a strength of 8.29N/mm^2, 7.20N/mm^2, 7.02N/mm^2, 6.61N/mm^2 and 4.84N/mm^2 respectively. [11] reported a non-linearly decrease in the compressive strength of masonry hollow concrete block unit. He also mentioned that increasing crumb-rubber replacement from 0 to 37% decreased the compressive strength by 77.5%. However, increasing rubber replace¬ment from 0 to 20% decreased the compressive strength by 48.3%.

3.4 Specified Compressive Strength (fm):

Specified compressive strength (fm) results of rubberized masonry hollow concrete block prism column shown in Figure 4 indicates a loss of strength by 74% with the reference prism column having a strength of 5.02N/mm^2 while 5, 10, 15, 20, and 25% rubberized masonry concrete block prism column have a strength of 4.72N/mm^2, 3.31N/mm^2, 3.23N/mm^2, 2.65N/mm^2 and 1.32N/mm^2 respectively. While conducting the compression test on the prism column, it was observed that the sides of prism columns were broken and several layers from the sides of the blocks were peeled off, which showed a larger deformation without complete disintegration and remained relatively intact after failure. The crumb-rubber aggregates were responsible for bridging the gap and keeping the broken parts together as one piece. This observation suggests a gradual change from brittle to more flexible behavior by using crumb-rubber aggregates. This may be attributed to the characteristics of crumb-rubber as it has great flexibility and the ability to stretch and rotate around its axes. Hence, rubber particles inside the mix seemed to act as springs causing a delay in widening the cracks [3]. This trend was more pronounced by increasing the content of crumb-rubber aggregate. [10] reported that using crumb-rubber generally reduced the compressive strengths of the investi¬gated un-grouted masonry prisms with ratios ranging from 31 to 71% proportional to the rubber content. The loss in strength can be attributed to factors which include: i) The large disparity between the Modulus of Elasticity (E) for rubber particles and the cement paste ii) The high Poisson ratio (v) for rubber particles, which may encourage premature cracking under load iii) Weak bonding characteristics in the ITZ between the cement paste and crumb-rubber particles [16]. .

3.5 Stress-Strain Behavior of Crumb-Rubber Masonry Concrete Block Prism Column

The stress-strain relationship of crumb-rubber masonry hollow concrete block prism column can be seen in Figure 5. The behavior indicates a convergent strength level and deformation criterion under compression loads for these concrete mixes. There was a linear increase in the stress of the reference and modified masonry hollow concrete block prism columns until reaching the maximum stress before releasing the energy by fracture. The stress-strain curves, in this case, are "sharp peaks" therefore the stress-strain relationships were considered to be quasi-linear. Furthermore, it can be noticed that increasing the crumb-rubber content has a significant effect on the maximum stress and strain of the masonry prism column. Nevertheless, a remarkable variation in the stress and deformation was observed between the reference mix and the modified mixes. This variation reached about 74% at the maximum stress with crumb-rubber content up to 25% as shown in Figure 5. The modified prism columns also revealed an increase in lateral and vertical (axial) strain up to 49% and 30% respectively at the maximum stress for the reference prism columns and crumb-rubber content up to 25%. This increase in the plastic strain translates into an increase in the toughness with a gradual failure and high-energy absorption capability [19]. The displacement-load relationship of the modified masonry

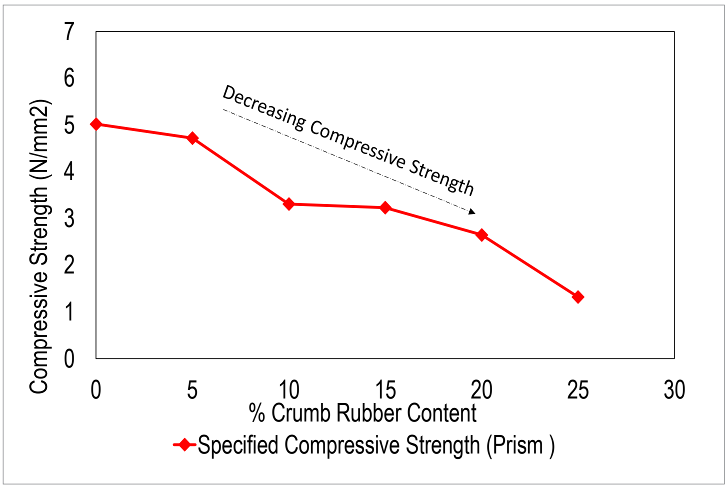

Figure 4: Specified Compressive Strength of Rubberized Masonry Hollow Concrete Block Prism Column Against % CR Content

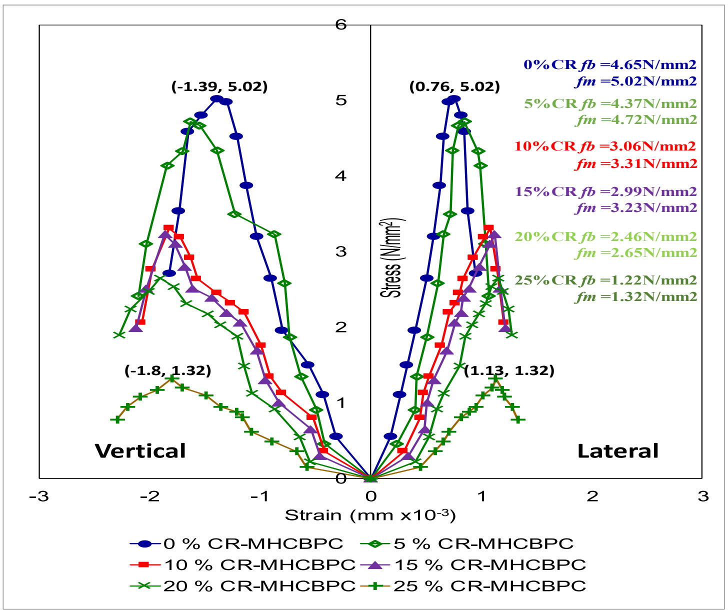

Figure 5: Stress-Strain Relationship for Masonry Concrete Prism Column

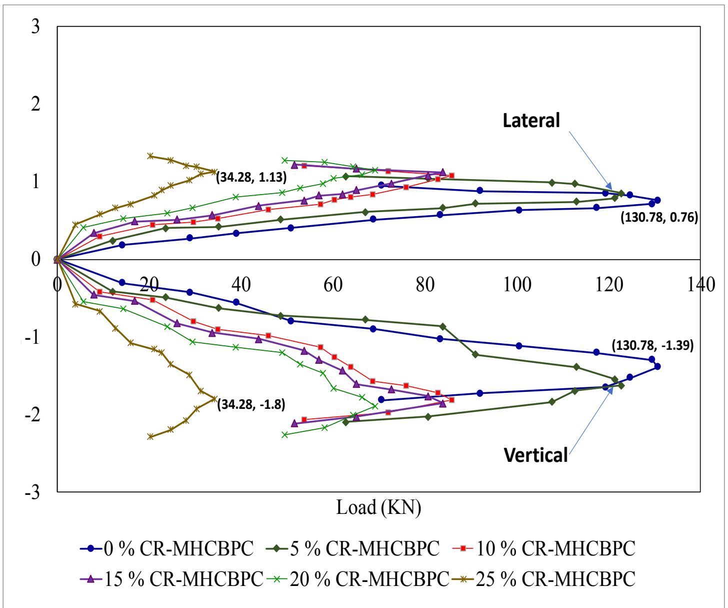

Figure 6: Displacement-Load Relationship for Concrete Prism Column

concrete block prism columns as shown in Figure 6 revealed that the maximum axial loads at failure were 130.78kN for the reference prism column implying a corresponding vertical (axial) displacement of 0.00139 and lateral displacement of 0.00076. while the 5, 10, 15, 20, and 25% modified prism columns recorded maximum axial loads of 122.89kN, 85.89kN, 84.02kN, 69.13kN, and 34.28kN respectively

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with a corresponding ultimate displacement of 0.00180 for vertical and 0.00113 for lateral respectively with 25% crumb-rubber replacement which indicates a percentage loss in the vertical strain of 22.8% and lateral strain of 38.7%. It can also be observed that the displacement-load relationships were quasi-linear..

4. CONCLUSIONS

i. The compacting factor (C.F) of masonry concrete was observed to decrease significantly by 8.3%, the yield of fresh concrete mix increased slightly by 10.2%, and the density of masonry hollow concrete block unit reduced by 19% with 25% crumb-rubber content.

ii. Compressive strength of 9.43N/mm^2 was obtained for the reference mixes while the compressive strength of rubberized masonry hollow concrete block with 25% crumb-rubber content is 4.84N/mm^2 indicating a loss of strength by 49%. Despite the strength reduction, load-bearing rubberized masonry hollow concrete blocks can be produced with 15% crumb-rubber content which is above the minimum (7N/mm^2) requirement specified in BS EN 771-3. Also, Non-load bearing rubberized masonry hollow concrete blocks with strength above the minimum (>3N/mm^2) specified in BS EN 771-3 can be produced with crumb-rubber content ranging from 16% to 25% which makes the material viable for building applications.

iii. Specified compressive strength (fm) of masonry concrete block prism column decreased in strength with increase in crumb-rubber content, a percentage loss of strength by 74% was recorded with the reference prism column having a strength of 5.02N/mm^2 while 5, 10, 15, 20 and 25% crumb-rubber modified masonry concrete block prism column recorded strength of 4.72N/mm^2, 3.31N/mm^2, 3.23N/mm^2, 2.65N/mm^2 and 1.32N/mm^2 respectively.

iv. The stress-strain relationship of crumb-rubber masonry concrete block prism column shows a quasi-linear relationship with an increase in the crumb-rubber content which has a significant effect on the maximum stress and maximum strain. **CB**

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