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PERFORMANCE CHARACTERIZATION OF WASTE POLYETHYLENE TEREPHTHALATE MODIFIED MORTAR AND CONCRETE: A REVIEW

Uche Emmanuel Edike[1,2] and Koleola Tunwase Odusami[2]

[1]Department of Building Technology, College of Environmental Sciences, Bells University of Technology, Ota, Ogun State, Nigeria

[2]Department of Building, Faculty of Environmental Sciences, University of Lagos, Akoka, Lagos, Nigeria

ABSTRACT

Purpose: The aim of this paper is to present a state-of-the-art review of recent studies on performance properties of concrete and mortar production using waste plastic with a view to identifying areas of further improvement.

Design/methodology/approach: The method relies on literature review on application of plastics in concrete and mortar production. Papers employed for the study were majorly gathered from online repositories of Google Scholar, Elsevier and Taylor and Francis publishers.

Findings: The study found that waste plastics have been successfully incorporated into concrete and mortar production at various modes and levels of applications as aggregates, fibres, binding agent and as an encapsulate in eco-bricks production. Also, strength performance of plastic modified concrete and mortar are considerably reported in contemporary literature but studies on determination of life span of building components produced with waste plastics are currently not available.

Practical implication: The application of waste plastics as an alternative material for the production of concrete and mortar with special mix design would help reduce and partly prevent the environmental nuisance caused by plastic waste.

Originality/value: This paper contributes to the understanding of concrete and mortar production using plastic waste as an alternative material from a state-of-the-art-review perspective, to the knowledge on the modes and level of waste plastic application in concrete and mortar production, and to the identification of knowledge gap in contemporary studies.

Keywords: Compressive strength; plastic aggregates; plastic fibres; plastic waste; splitting tensile strength.

[1]euedike@bellsuniversity.edu.ng

1. INTRODUCTION

Concrete is one of the major building materials that are employed in several wet construction works due to its malleability and ability to acquire remarkable strength within a short period. It is usually produced with a mixture of binder, fine and coarse aggregates in the presence of calculated amount of water. A mixture of binder and fine aggregate in the presence of water without coarse aggregate is mortar which is often used in binding building components together. Concrete has been considerably employed in the production of building components such as slabs, beams, column, foundation bases and roofs while construction of masonry walls are often done with mortar. These building components and materials are in high demand as infrastructure remains a major indicator of nations prosperity. Consequently, the mining of virgin resources use in the production of construction materials is on the increase.

Mining of virgin resources for construction contributes to global warming as the emission of greenhouse gases such as carbon dioxide, hydro fluorocarbons, and methane into the atmosphere accompanies mining process (Sukontasukkul, Pongsopha, Chindaprasirt & Songpiriyakij, 2018). Also, environmental concerns arising from over-dredging of sand have been raised in some parts of the world and have led to restrictions on sand extraction in some cases (Thorneycroft, Orr, Savoikar & Ball, 2018). Such policies have direct economic impact on concrete production and have driven some studies in search of alternative materials.

On the other hand, the environmental challenges posed by the disposal of waste plastic are devastating. Discarded soft drinks and water bottles, for instance, are a common eye-sore on the streets; blocking drains and impeding the free flow of water channels and canals. Badejo, Adekunle, Adekoya, Ndambuki, Kupolati, Bada, and Omole (2017) remarked that plastic waste constitutes a major part of municipal solid waste in developing countries. The economic and environmental impacts of this plastic waste are increasing. Hence, the search for alternative means of waste plastic disposal has necessitated studies on potential applications of waste plastic in the construction industry.

To assess the potential of using waste plastic as an alternative construction material several studies are being conducted. Thorneycroft et al., (2018) investigated the performance of structural concrete with recycled plastic waste as a partial replacement for sand. Borg, Baldacchino and Ferrara (2016) studied the early age performance and mechanical characteristics of recycled PET fibre reinforced concrete. In another study, Foti (2011) investigated the preliminary analysis of concrete reinforced with waste bottles PET fibres. Taaffe, O'Sullivan, Rahman and Pakrashi (2014) examined the characterisation of Polyethylene Terephthalate (PET) bottle Eco-bricks. The study remarked that the cost of eco-brick in Central America is zero whereas the cost of a block averages out at roughly 75cent per block and there is a potential saving of approximately €1500 in construction of three-room building made of 8000 eco-bricks. The alternative materials are expected to offer structural, environmental and economic benefits.

On the contrary, Twumasi – Ampofo and Oppong (2017) reported that the cost of 10 m2 bottle bricks wall is approximately 640 Ghana cedi while similar wall made of sandcrete blocks cost 527.5 Ghana Cedi. Besides the controversies on the economic benefits of waste plastic application in production of building materials, the performance characterization of waste plastic modified construction materials has attracted several criticisms.

Against the backdrop, the current study presents a state-of-the-art review of performance characterization of waste plastic modified mortar and concrete. Also, direct application of waste plastic as binder and encapsulate for brick production is considered in the study.

2. Structural Characterization of Waste Pet Modified Brick

The structural characterization of mortar and concrete modified with waste plastic has been reported in several studies. However, literature on direct application of waste plastic in production of building components such as beams, slabs, masonry walls or units is scarce. Therefore, the review is more focused on the structural characteristics of concrete and mortar produced with waste plastic. The structural characteristics considered include compressive strength, flexural strength, splitting tensile and Poisson's ratio.

2.1. Compressive strength

Compressive strength is a distinctive value which denotes the amount of stress for units of construction under axial load. Compressive strength has been known to be influenced by several external factors such as loading rate, specimen size and shape, and specimen boundary conditions. Figure 1 represents the compressive strength behaviour of a typical brick unit during compression loading.

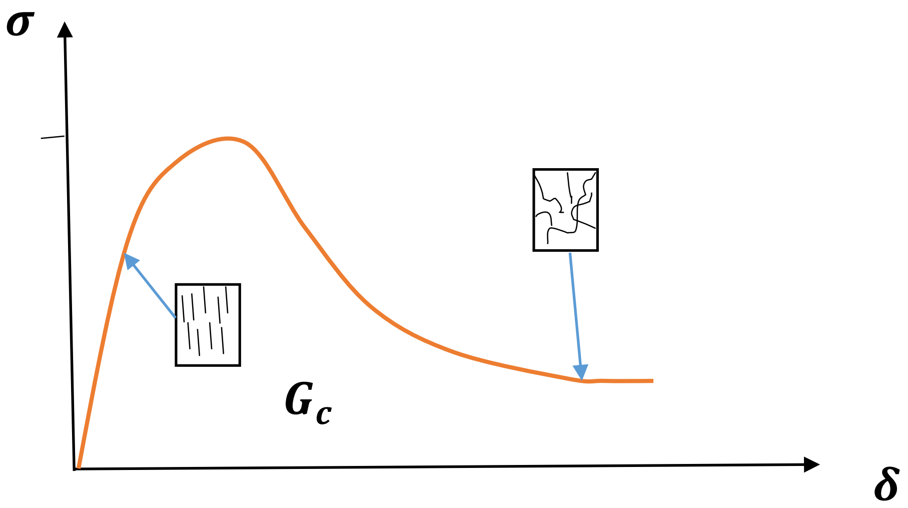


Figure 1: Typical behaviour of brick unit under compressive loading
Source: Koltsida (2017)

In Figure 1, the compressive behaviour starts with a linear elastic part up until the first micro-cracks appear. The hardening commences at this moment, which means that the stiffness of the material starts to decrease as the load increases. Mokhtar *et al.* (2016) investigate the application of plastic bottle as a wall structure for green house and conclude that compressive strength of 250ml and 1.5L plastic bottles filled with sand is 38.34 N/mm2 and 27.39 N/mm2 respectively, while a maximum stress of 8.58 N/mm2 was recorded for clay brick. It can be deduced from the study that the larger the waste plastic bottle the less the compressive strength. Similar study reports a compressive strength of 1.4 kPa (0.0014 N/mm2) and 25 kPa (0.025N/mm2) for bottle bricks filled with water and sand respectively (Oyinlola *et al*. 2018). Kim, Wisniewski, Baker and Oyinlola (2019) investigate the behaviour of sand-filled plastic bottled clay panels for sustainable homes and found a horizontal row of 6 sand filled bottle bricks yielding at approximately 298.05kN. The study reported continues increase compression resistance of the bottle bricks beyond the failure of the PET bottle, thus the test was stopped at 300kN.

Again, for the use of waste PET as an encapsulate, Taaffe *et al*. (2014) observe a linear relationship between the weight of a brick and the compressive strength of PET waste bottle eco-bricks filled with waste plastic. The study concludes that compaction/packing ratio is the main variable that affects the strength of eco-bricks. A maximum compressive strength of 2960 kN/m2 (2.96 MPa or 2.96 N/mm2) was recorded at a maximum mass of 260g. The maximum compressive strength of 2.96 N/mm2 achieved in the experiment falls short of the minimum 5 N/mm2 recommended for external building works in BS 3921 1985. Hence, the PET waste bottle eco-brick manufactured using plastic infill materials cannot be recommended for building works unless further improvement is made on the compressive strength to meet the minimum requirement standard.

The compressive strength of plastic aggregate (PA) concrete or mortar depends on many parameters such as the w/c, RPA, and the types and shapes of waste plastic (Gu & Ozbakkaloglu, 2016). The study notes that the use of PAs with a low elastic modulus (e.g. EPA and EVA aggregates) result in substantial reduction in the compressive strength of concrete than those result from the use of PAs with a high elastic modulus (e.g. PET aggregates).

Previous studies on recycled plastic concrete have shown that the compressive strength of PA concrete with the same w/c decreases with increasing recycled plastic aggregate, RPA (Thorneycroft, et al., 2018; Akinyele & Ajede, 2018; Ferrandiz-Mas, Bond, Garcia-Alcocel & Cheeseman 2014; Saikia & de Brito, 2014). Similarly, Ge, Sun, Zhang, Gao and Li (2013) report decrease in compressive strength of mortar with increasing PET RPA content at the same w/c. The low compressive strength of concrete and mortar containing PAs has been attributed in some studies to the elastic modulus of PAs being lower than that of natural CA or FA; the low bond strength between the surface of the PA and cement paste; the restrained cement hydration reaction near the surface of PA resulting from the hydrophobic nature of PA; high air content and porosity of PA concrete; and the possible deterioration of PET aggregates exposed to the concrete pore fluid (an alkaline environment).

Wang and Meyer (2012) report the compressive strengths of mortar prepared with 10, 20, and 50% fine high-impact polystyrene (HIPS) FA decreased almost linearly with the increase in the substitution level, and the reduction in the strengths of the mortar were 12%, 22%, and 49%, respectively, at 28 days curing age. In addition, Thorneycroft et al., (2018); Saikia and de Brito (2014) present that different shape and size distribution of waste PET aggregates resulted in different compressive strengths of concrete with the same substitution levels of PAs. The effect of size, with smaller particle size of PA similar to size of sand being substituted at 10% yielded higher compressive strength than PA (2 – 4mm) of larger sizes was reported in Thorneycroft, et al., (2018) at equal volume of sand replacement. Figure 2 shows the graph of percentage change in compressive strength with plastic aggregate sizes.

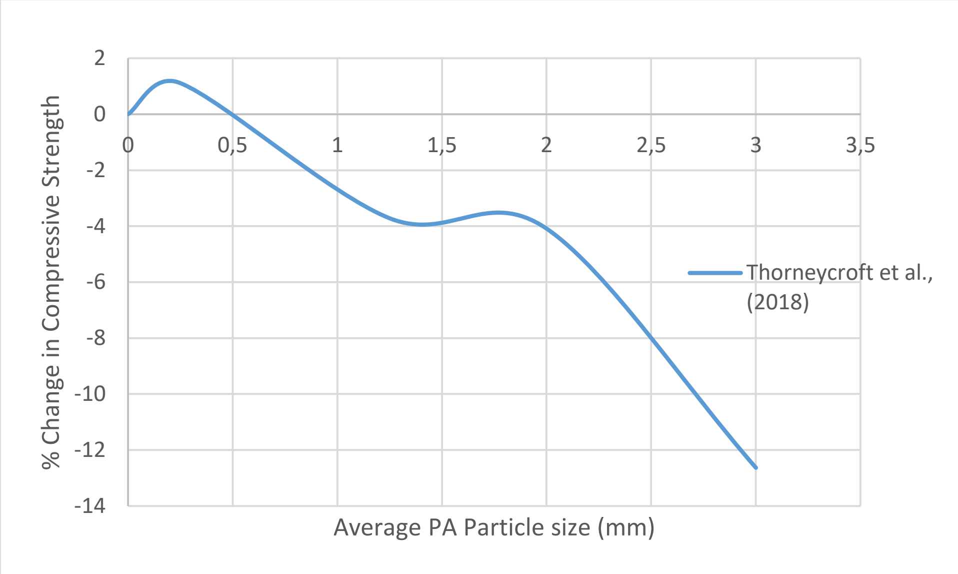


Figure 2: Effect of PA size on Compressive Strength.
Source: Thorneycroft *et al*. (2018)

Figure 2 indicates slight increase in compressive strength with small and graded PA sizes below 0.5mm. As the PA size increases beyond 0.5mm, loss of compressive strength occurs at 10% volume substitution of sand.

To reduce the loss in compressive strength due to inadequate bond between the plastic and surrounding matrix of concrete or mortar produced with waste plastic, some studies have adopted the use of chemical, physical or gamma ray treatment of the plastic prior to concrete mixing. For instance, in one of the novel mixes employed by Thorneycroft et al., (2018) sodium hydroxide and sodium hypochlorite were used to treat waste PET shredded into 2 – 4mm and washed. The result shows a considerable improvement in loss of compressive strength to approximately 1.9%. The study further reveals the improvement in reduction of loss of strength by washing PA after treatment.

On the use of waste plastic as fibre, there is wide variability on the findings of researchers. Some researchers reported improvement on the compressive strength of concrete upon addition of plastic fibre (Pereira, Junior & Fineza, 2017); while some others have shown that when the fibre content increased, the compressive strength of FRC degrades (Nibudey, Nagarnaik, Parbat & Pande, 2013). Nibudey et al., noted that beyond 1.0% fibre content the compressive strength decreases. Also, increase in ductility and reduced shrinkage cracking have been reported in Foti, (2011) including improvement on residual life of concrete as a result of fibre reinforcement. Figure 3 shows a stress – strain diagram of ordinary concrete and fibre reinforced concrete at various fibre content.

Again, previous studies have shown that the compressive strength of concrete or mortar with recycled plastic fibre varies with the type of plastic fibre. The use of recycled plastic fibres with a high ultimate tensile strength (such as recycled PP fibres) results in a more significant improvement in the compressive strength of concrete than that when fibres with a low ultimate tensile strength (e.g recycled PET fibres) are used.

In summary, qualitative study of previous research has revealed that utilizing PA with graded small particle sizes and at low percentage (not more than 10%) can yield concrete or mortar with improved compressive strength higher than larger particle sizes with rigorous treatment. Concrete or mortar modified with RPF of low aspect ratio (less than 100), short strands (not more than 30mm), treated with gamma ray or NaOH and washed, deformed is likely to improve the compressive strength and residual life of mortar or concrete.

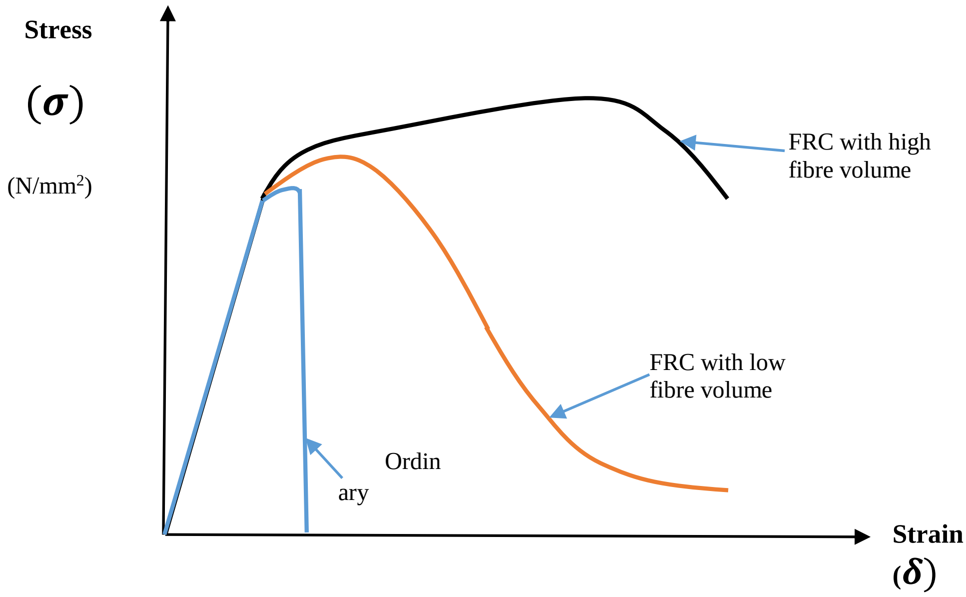


Figure 3: Stress – Strain behaviour of concrete reinforced with various amount of fibre

Source: Foti (2011)

On the use of waste PET as binding agent, few studies have reported the compressive strength of PET-sand mortar/brick. Ge, et al., (2013) investigate the physical and mechanical properties of mortar using waste Polyethylene Terephthalate bottles and found that the compressive strength is considerably influenced by aggregate sizes, gradation and curing temperature. In the study, 32.7 N/mm2 compressive strength was achieved at room temperature using 1:3 PET-to-sand mix ratio. The study reveals that 24-hour curing is adequate for sand-PET mortar as evident in the compressive strength result - 32.7 N/mm2 for both 24 hour and 7 days curing at 1:3 PET-to-sand ratio. At a curing temperature of 180 0C a compressive strength of 34.9 N/mm2 was achieved. This implies that high curing temperature enhances the compressive strength of PET-sand mortar. A maximum compressive strength of 35.7 N/mm2 was achieved with a 1:4 PET-to-sand mix ratio by weight. The compressive strength of sand-PET mortar in the study is considerably high compare to Dinesh et al. (2016) in which 5.12 N/mm2 optimum compressive strength was found at 1:4 PET-to-sand mix ratio by weight. The differences on the results might be attributable to the products, type of sand and experimental procedures such as loading rate. Hence, there is need for further studies to understand the strength characterisation of PET-sand mortar and bricks.

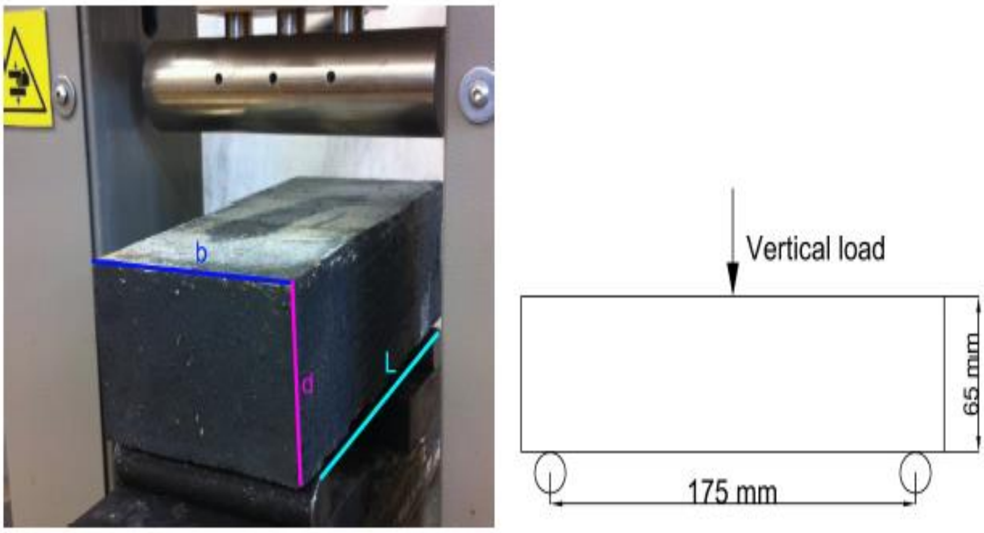
2.2. Splitting tensile strength

Varying results have been reported by researchers on the effect of RPA on the splitting tensile strength of concrete and mortar. Thorneycroft et al. (2018) report 25% improvement on splitting tensile strength at 10% substitution of sand with graded small size RPA. Also, Chaudhary, Srivastava and Agarwal, (2014) found that the split tensile strength of concrete produced with less than 1% fine aggregate replacement with waste plastic increases with increase in waste plastic aggregate content. On the contrary, considerable number of studies, Saikia and de Brito, (2014); Wang & Meyer, (2012) found that splitting tensile strength of PA concrete decreases with increasing RPA. Gu and Ozbakkaloglu (2016) note that more significant reductions in the splitting tensile strength occur in concrete containing non-uniformly shaped PAs than that containing uniformly shaped PAs. In addition, the splitting tensile strength of PA concrete decreases with a reduction in the elastic modulus of low modulus PAs.

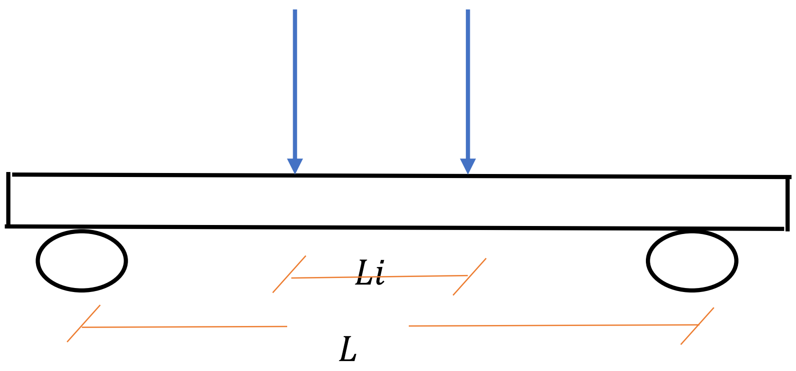
On the application of waste plastic as fibre, previous researches demonstrate that the splitting tensile strength of concrete increased upon the addition of PF (Nibudey et al., 2013; Bagherzadeh Sadeghi & Latifi 2011). The improvement on the splitting tensile strength is a function of the tensile strength of plastic fibres. Nibudey et al. (2013) observed that the splitting tensile strength of concrete containing PET fibre increased by 18.6% at 1% fibre level, and then reduced by 19% at 3% fibre content. The fibres bridging across the split portions of the matrix acts through the stress transferred from the matrix to the fibres, therefore gradually supporting the whole load. The stress transfer improved the tensile strain capacity of the two FRCs, and therefore, the splitting tensile strength of the reinforced concretes was higher than that of the unreinforced control counterpart. Nibudey, et al., (2003) also found that the splitting tensile strength improved only when the concrete had small fibre content up to 0.56% beyond which the splitting tensile strength decreases.

2.3. Flexural tensile strength (modulus of rupture)

Flexural strength is the stress in a material just before it yields in a transverse bending test. It is also known as bend strength, or transverse rupture, or modulus of rupture. The flexural strength signifies the maximum stress experienced within a material at its moment of yield. The test is usually conducted on specimen with either rectangular or circular cross-section under the influence of a three-point or four-point flexural loading. Typical set up rig for flexural test is shown in Figure 4 and the numerical models employ in the determination of flexural strength is stated in equations 1 and 2.



(a) (b)



(c)

Figure 4: Typical flexural strength test set-up for brick specimen (a) test rig (b) schematics (c) four-point set up

Source: Sukontasukkul *et al*. (2018)

$$\sigma = \frac{3FL}{2bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. } 1 \ldots\ldots\ldots three - point\ bending\ support$$

$$\sigma = \frac{3F(L - L_i)}{2bd^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{eq. } 2 \ldots\ldots\ldots\ldots four - point\ bending\ support$$

Where, σ= flexural strength (N/mm2); F= maximum load at yield point (kN); b= width of section (m); d= depth of section (m); L= distance between supports (m); L_i= distance between applied load in a four-point bending support test.

Studies have shown that the shape of PF affects plastic modified concrete and mortar's modulus of fracture. Foti (2011) examines the preliminary analysis of concrete reinforced with waste bottles PET fibres and found that fibre reinforced concrete produced using fibre strips (lamellar) exhibits better bending strength than fibre reinforced concrete manufactured with round shape PET fibres. The study was conducted using 32 mm PET fibre strips and 30 – 50mm diameter round fibre as additives in separate concrete mixes. In the study, 4.8 N/mm2 flexural strength was record at 0.75% optimum content of concrete mass for fibre reinforced concrete produced with round fibres, whereas, concrete produce with the PET strip at 50% strip fibre content and the control (without any fibre) achieved 3.7 N/mm2 and 4.7 N/mm2 flexural strength. In a similar study, Pereira et al. (2017) observe increase in flexural tensile strength with the addition 10mm to 20mm PET PF from 0.1% to 0.3% of total volume.

Results of flexural tensile strength have been presented in two forms – as load deflection curves and as a single stress in N/mm2. Some studies, for instance Sukontasukkul *et al.* (2018), have presented findings on flexural strength of fibre reinforced mortar with respect to load-deflection (deformation) curve which is considerably an appropriate method of presenting the fibre performance rather than single parameters such as the compressive strength. Figure 5 presents the graph of fibre reinforced mortar under flexural loading.

The Figures 5 (a) and (b) indicate that the load increases in unswerving proportional to the increasing deflection at the beginning. Immediately after the initial cracks, a high-pitched drop in load occurs. In Sukontasukkul *et al*. (2018), Figure 5 (b), the load increases again after the drop due to the effect of fibres spanning across the cracks. This section of the graph is known as post-peak response region and it is the region that actually signifies the performance of the fibres. Similarly, high-pitched drop in load was reported in Foti (2011), Figure 5 (a), but the post-peak response region was found below the peak value contrary to Sukontasukkul *et al*. (2018) where the post-peak region lies above the peak value. Although, different types of plastic fibres and steel were used, the implication of these studies is that the true responses of waste plastic fibre to flexural loading is not yet established and therefore requires concerted research efforts.

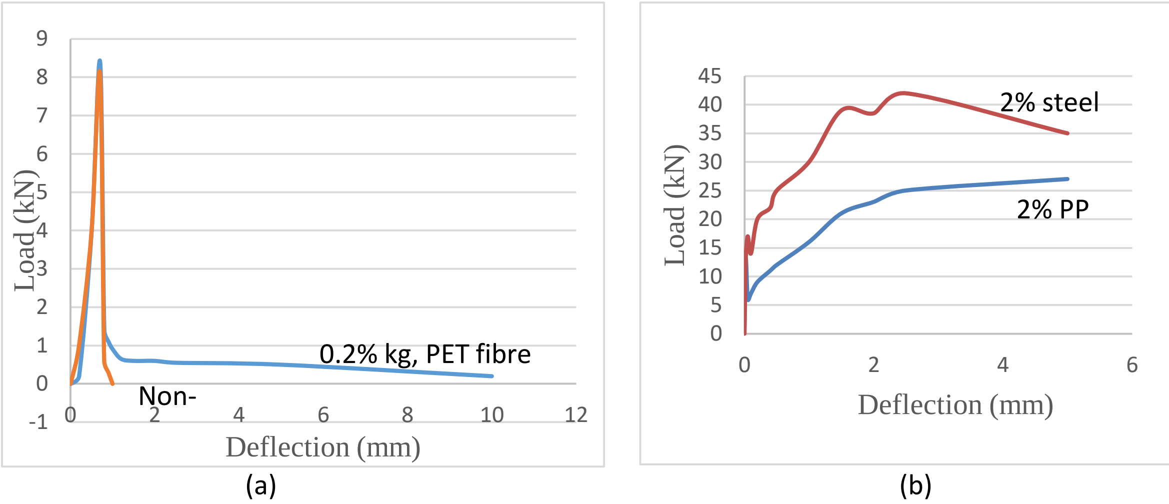


Figure 5: Typical Fibre reinforced mortar response to flexural loading
Sources: (a) Foti (2011) (b) Sukontasukkul *et al*. (2018)

Furthermore, the area under the load deflection curve represents the Toughness (kN-m) of the brick (Sukontasukkul *et al*., 2018). Toughness designates the amount of energy the brick is able to absorb under loading up to specific deflection. Usually, two toughness values are determined at 2 different deflections - L/600 and L/150. The corresponding flexural strength denotes the load bearing capacity of the brick after first cracking as a percentage of the first peak load.

2.4. Poisson's ratio

Poisson's ratio is a ratio between a change in the direction of an applied load on a material and a corresponding change in dimension in a direction perpendicular to the applied load. It describes the constraining relationship between a finite transverse strain and the originating axial stain. When a specimen is squashed to a contraction in the direction of an applied load, there is a corresponding extension in a direction perpendicular to the applied load. The ratio between these two quantities is estimated as the Poisson's ratio. Poisson's ratio is therefore estimated by comparing the axial and transverse stain of material at failure.

Taaffe *et al*. (2014) note that eco-brick produce using PET bottle as an encapsulate exhibits slight elastic rebound and regains some of its shape when load is removed and therefore suggest that measurement of axial strain should be taken as the distance between the two platens of a compression test machine upon failure and then divided by its original length. However, assuming the distance between the platens of a compression test machine at sample failure may not give a truly axial stain rather the change in distance of the platens divided by the distance between the platens at the point of loading may give a better picture of axial strain. The study (Taaffe *et al*., 2014) recorded Poisson's ratios of Eco-bricks within a range of 0.27 – 0.35.

2.5. Bulk density

The bulk density of a material is the mass of particles of the material with respect to the volume the particles occupy. Aouba, Coutand, Perrin and Lemercier (2015) observe the bulk density of virgin EPS aggregates is 35 kg/m3, and that of recycled EPS aggregates is 24–27 kg/m3. The study measured open porosity and bulk density through a vacuum saturation test. The formulae for computing bulk density and porosity are stated in equations (3) and (4) respectively.

$$p = \frac{m_{dry}}{m_{air} - m_{water}} \, X \, p_{water} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.3$$

$$\varepsilon = \frac{m_{air} - m_{dry}}{m_{air} - m_{water}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.4$$

where $\boldsymbol{m_{dry}}$ is the oven-dry weight (kg), m_{air} is the saturated air weight (kg), $\boldsymbol{m_{water}}$ is the saturated submerged weight (kg) and $\boldsymbol{p_{water}}$ is the density of water at 200C. ε is the porosity (%).

Bulk density of 2282 kg/m3 to 2111 kg/m3 was found in Thorneycroft et al., (2018) at 10% PET substitution by volume of sand in the production of concrete. Taaffe et al., (2014) report a bulk density of 520 kg/m3 for bottle bricks filled with waste plastics. The low bulk density may be attributed to the eco-bricks being filled with waste plastic but if filled with soil materials it expected that higher bulk density will be achieved.

2.6. Thermal characterization of brick modified with waste PET

The UK Building Regulations (2010) recommends that the limiting external wall thermal transmittance (U- Value) of both new and existing building should not exceed 0.30 W/m2K for energy efficiency of buildings. This is expected to guide the optimization of waste PET content in PET modified bricks in relation to the value (0.30 W/m2 K) and in comparison, with other building walling materials. Previous studies have reported considerable improvement on thermal transmittance by the substitution of natural aggregate with waste plastic aggregate. For instance, Yesilata *et al*. (2009) investigated the effect of waste PET material addition on the thermal transmission properties of ordinary concrete. The study found that waste PET substantially reduced the thermal transmittance of ordinary concrete. Yesilata *et al*. (2009), further noted that thermal improvement was highest circa 17.16% when irregular waste PET fibres were used compare to 10.27% improvement when square PET fibres were used. Hence, the thermal property of polymeric concrete does not only depend on the waste plastic content but also on the shape of the waste plastic.

In another study, Wang and Meyer (2012) studied the performance of cement mortar made with recycled high impact polystyrene (HIPS) and found remarkable improvement on the thermal conductivity - approximately 87% at 10% fibre content in mortar. The study attributed the improvement to the low thermal conductivity of HIPS compared to that of natural sand. Furthermore, previous studies have also shown that thermal conductivity reduces with increase in waste plastic fibre content. Fraternali *et al*. (2011) found that the thermal conductivity of concrete containing 1% volume of PET fibres decrease by 18% while the same fibre content with polypropylene, PP fibres had 21.8 % reduction in thermal conductivity compared to conventional concrete.

Mokhtar *et al*. (2016) conclude that both plastic bottle green house and normal brick house use in the study did not achieved the thermal comfort zone as temperature range is 30℃ to 34℃. Same goes to the normal brick house which range from 29℃ to 34℃ for plastic bottle green house and normal brick house respectively. However, the study noted that both standard brick house and plastic bottle green house (59% - 73%) have met the indoor air quality standard at the aspect of relative humidity which are 40% - 70%.

Fioretti and Principi (2014) examine the thermal performance of hollow clay brick and blocks with low emissivity treatment in surface enclosures. The study utilized a two-dimensional steady-state simulation using a simplified and standardized equivalent conductivity method. The method combines the effects of heat conduction, convection and radiation through algorithm developed in accordance with the calculation procedure suggested in EN 1745 (Annex D) and EN ISO 6946 (Annex B-C).

2.7. Sound insulation

The sound insulation property of a material is usually determined on an entire room where the walls are built with the material to be tested. However, researches have been conducted on the sound insulation of materials using the sound reduction index, R. Sound reduction index (R) is a quantity, measured in laboratory which characterises the sound insulating properties of a material or building element in a stated frequency band. The sound reduction index R is a viable option where construction of entire room is not feasible. Taaffe *et al*. (2014) calculated the sound reduction index of bottle eco-brick and compare the result with other bricks used in construction as a method of assessing the sound insulation property of eco-brick. Another method of determining the sound reduction index of a wall is the application of Mass Law provided the mass per unit area is known.

Furthermore, the main frequency range used to assess sound insulation lays in building acoustics is between the 100 and 3150 Hz one-third octave- bands and an optional extended frequency range is defined between the 50 and 5000 Hz one-third-octave-bands. The range between 50 and 5000 Hz is referred to as the building acoustics frequency range. It is possible to define frequency ranges using one-third-octave-band centre frequencies low frequency range (50–200 Hz), mid-frequency range (250–1000 Hz) and high frequency range (1250–5000 Hz). Taaffe *et al*. (2014) assumed that 'typical rooms' have volumes between 20 and 200 m3 and this covers the majority of practical situations. Measurements of sound insulation may be laboratory measurements that provide information at the design stage, field measurements validate whether the required sound insulation has been achieved in a building, and field measurements also help in disentangling sound insulation problems in existing buildings.

For many buildings the acoustic requirements are described in building regulations; hence repeatability, reproducibility, and relevance (i.e. the link between the measured sound insulation and the satisfaction of the building occupants) are particularly important for airborne and impact sound insulation. Laboratory measurements of the acoustic properties of materials and building elements (e.g., walls, floors, windows and doors) are primarily used for comparing products and calculating the sound insulation in situ. Measurements of material properties are particularly useful in assessing whether one material in the construction could be substituted for a different one, and for use in prediction models. Testing may also be carried out in situ with limited number of samples. Sound insulation is heavily dependent on the quality of construction and workmanship.

3. METHODS

Research method of the study involved review of relevant literature to explore the characterization of PET modified concrete and mortar. In addition, PET related articles such as PET bottle bricks were considered relevant in the review process to understand the potential application of such waste in construction. Literature materials were gathered from a range of databases and online repositories of Elsevier, Emerald Insight, Google Scholar, Springer link and Taylor and Francis publishers. The databases were searched for peer review papers that reported the application of waste PET in concrete, mortar or brick production between 2009 and 2019. The research design (Figure 6) adopted for the study involves four stages similar to the three-stage research approach employed in Ramafalo, Awuzie and Aigbavboa (2018) study on probable challenges facing servitization in the construction industry.

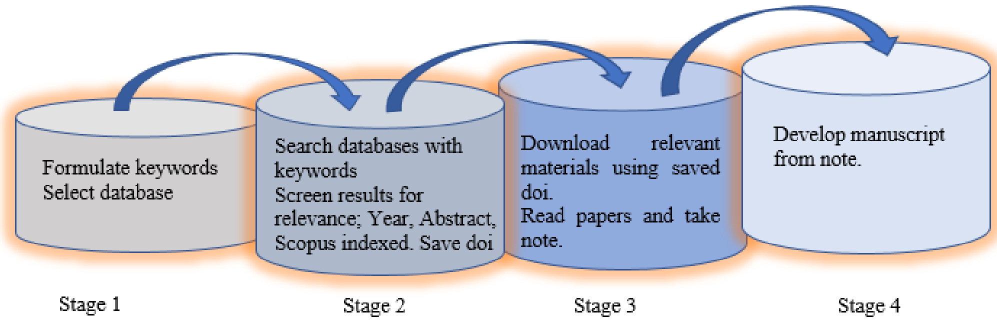


Figure 6: Research approach

In the first stage of the research, keywords and keywords combinations were selected based on relevance to the research topic. Also, preliminary search was conducted on several databases to selected suitable databases and time range. At the second stage, each of the selected databases were searched using the keywords in combination with either concrete, mortar, brick or masonry and the total number of papers within the required period was record (see Table 1).

Table 1: Keywords and databases

Keywords	**Elsevier**		**Emerald Insight**		**Google Scholar**		**Springer**
	Result	**Relevant**	**Result**	**Relevant**	**Result**	**Relevant**	**Result**
Pet aggregate mortar	1060	21	8	0	1700	28	31
Pet aggregate concrete	2820	61	28	0	4010	35	122
Pet fibres concrete or mortar	1502	12	155	5	3560	18	33
Bottle brick	2809	6	90	0	6550	8	260
PET bottle brick	402	5	2	0	16500	6	49

Note: Some papers appeared in more than one database and keywords.

For instance, a search for “pet aggregate mortar” between 2009 and 2019 on Elsevier database yielded 1060 results of which 21 of the articles were considered relevant to the current study. Search results were screened for relevance through analysis of the topics, abstracts, year publication and journal indexes with emphasis on Scopus. The doi of articles that were considered relevant were saved for down. At the third stage, relevant and accessible papers were downloaded using the saved doi and thereafter, thorough reading of the downloaded papers and notetaking was carried out. The manuscript was then developed from the in-depth analysis of the findings of previous studies summarized in the note and research gaps identified.

4. Results and Discussion of Findings

The distribution of studies on performance properties of waste plastic modified building materials is presented in Table 2. From the Table, majority of the studies (Thorneycroft et al., 2018; Pereira et al., 2017; Borg et al., 2016; Chaudhary et al., 2014; Saikia & de Brito (2014); Nibudey et al., 2013; Bagherzadeh et al., 2011; Foti, 2011; Yesilata et al., 2009) considered the application of waste plastic in the production of concrete. Sukontasukkul, et al. (2018); Ferrandiz-Mas et al., (2014); Ge et al., (2013); Wang & Meyer (2012) discuss the application of waste plastic in production of mortar and a study (Gu et al., 2016) examine the application on both productions of concrete and mortar. Badejo et al., (2017) applied waste plastic for asphalt modification.

On the use of waste plastic for brick production, only a few studies (Oyinlola et al., 2018; Mokhtar et al., 2016 and Taaffe et al. 2014) considered the application of waste PET bottle as an encapsulate for eco-brick (bottle brick) production. However, the inconsistency of the findings of the studies demands further studies on the mode of application to enable characterization of such eco-bricks.

On the mode of application of waste plastic in the production of construction material, the use of recycled waste plastic as an aggregate or fibre has attracted considerable number of studies in the area of concrete and mortar production but studies on the application of RPA or RPF in the manufacture of bricks is not substantial. Hence, studies should be directed towards utilization of RPA or/and RPF in the production of eco-bricks.

The use of waste plastic, especially waste PET, as a binding agent has not been substantially explored. For instance, in the table above only Ge et al., (2013) considered the use of waste plastic as a binding agent in place of cement in the production of mortar. Another study that considered waste plastic as a binding agent is Dinesh et al., (2016). However, the variability of the results of the two studies necessitates further investigation of such mode of application of waste plastic in construction.

On the performance properties, the strength tests of concrete and mortar are significantly considered. However, the characterization of masonry walls constructed of waste plastic material (bricks) has not been explored as indicated in the young modulus and probability of survival columns in Table 1. Oyinlola et al. (2018) report an average compression yield load of 25.30 kN at failure for six 440mm×480×200mm bottle bricks masonry prisms while Budiwati (2009) investigate the compressive strength and modulus of elasticity of masonry prisms constructed of clay bricks and concrete blocks. It is expected that masonry prisms constructed with different material may yield at different stress levels, exhibit unique strains and modulus of elasticity. The Young Modulus of masonry is essential in the determination of the characteristic strength of masonry; an indispensable parameter employed in the analysis and design of masonry walls. The probability of survival is also one of the important parameters in S-N-P curve use in the investigation of the serviceability limit of masonry. These parameters have not been explored with waste plastic impregnated brick masonry.

Table 2: Distribution of studies on performance properties of waste plastic products

Authors	Products and Performance Properties																
	Pro.	**CS**	**FS**	**PR**	**SI**	**LT**	**RS**	**Tou**	**STS**	**ME**	**WA**	**E**	**FR**	**H**	**T**	**YM**	**P**	**Country**
Kim, et al. (2019)	bb	✓							✓							cs		UK
Sukontasukkul, et al. (2018)	mor	✓	✓				✓	✓										Thailand
Oyinlola et al. (2018)	bb	✓							✓							cs		UK
Akinyele & Ajede, (2018)	A; co	✓	✓						✓									Nigeria
Thorneycroft et al., (2018)	A; co	✓							✓									UK
*Twumasi – Ampofo et al., (2017)		✓													✓			Ghana
Badejo et al., (2017)	F; aspt	Bulk density, Marshal flaw, Marshal Stability, Void in Total Mix, Void Filled with Bitumen																Nigeria
Pereira et al., (2017)	F; co	✓	✓															Brazil
Borg et al., (2016)	F; co	✓	✓															Italy
*Gu et al. (2016)	mor/co	✓	✓						✓	✓	✓		✓	ab				Australia
Mokhtar et al., (2016)	bb	✓													t			Malaysia
#Auoba et al. (2015)			Bulk density, porosity and thermal conductivity												Thc			France
Fioretti & Principi (2014)	brick														Thc			Italy
Chaudhary et al., (2014)	A; co	✓							✓									India
Ferrandiz-Mas et al., (2014)	A; mor	✓													Thc			UK
Taaffe et al. (2014)	bb	✓		✓	✓	✓												Ireland
Saikia & de Brito (2014)	A; co	✓	✓						✓	✓				ab				Portugal
Ge et al., (2013)	B; mor	✓	✓								✓							China
Nibudey et al., (2013)	F; co	✓	✓						✓									India
Wang & Meyer (2012).	A; mor	✓							✓	✓					Thc			China
Bagherzadeh et al., (2011)	F; co	✓	✓					✓	✓		✓							Iran
Foti (2011)	co	✓	✓					✓										Italy
#Budiwati (2009)	Masonry	✓														✓		UK
Yesilata et al., (2009)	F; co														#			Turkey

[Pro]Product; [CS]compressive Strength; [FS]Flexural Strength; [PR]Possion's Ratio; [SI]Sound Insulation; [LT]Light Transmission; [RS]Residual Strength; [Tou]Toughness; [STS]Splitting Tensile Strength; [ME]Modulus of Elasticity; [WA]Water Absorption; [E]Efflorescence; [FR]Fire Resistance; [H]Hardness; [T]Thermal transmittance; [YM]Young Modulus of masonry; [P]Probability of survival; *A review paper; [bb]bottle brick; [t]temperature; [co]conctrete; [mor]mortar; *Review; [#]Study not involving waste plastic; [F]Fibre; [A]Aggregate; [B]Binding agent.

Hence, further studies should be directed towards investigating the characteristic strength and probability of survival of eco-brick masonry wall to enable understanding of the behaviour of waste plastic modified bricks (eco-bricks) masonry for wider applications in construction.

5. Conclusion and Recommendations

The study concludes that there are variations in the percentage loss of compressive strength results due to different sizes of plastic aggregate employed in the production of concrete and mortar in previous studies. Although the usage of plastic might cause reduction in compressive strength because of a weak bond to the surrounding matrixes, the reduction could be checked by suitable mix design and choice of plastic. Concrete or mortar produced of waste plastic with special mix design satisfies minimum standard requirement. Concrete or mortar produced with plastic aggregate (PA) below 10% substitution of natural virgin aggregates results in concrete or mortar of considerable strength performance. Beyond the 10% the concrete or mortar strength degrades. On the application of waste plastics as fibre reinforcement (PF), less than 1% addition in concrete or mortar results in improvement of strength performance. Thermal transmittance of concrete or mortar improves with increase in waste plastic content.

The utilization of plastic waste as an alternative material for the production of concrete and mortar with special mix design for the construction of nations infrastructure would help reduce and partly prevent the environmental nuisance cause by plastic waste. However, there is need to understand the behaviour and life span of whole building component constructed of waste plastic products. Hence, further studies should be directed towards investigating the characteristic strength and probability of survival of eco-bricks masonry wall to enable understanding of the behaviour of waste plastic modified brick (eco-bricks) masonry for wider applications in construction.

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