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Review

Polyethylene terephthalate aggregates in structural lightweight concrete: a meta-analysis and review

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Abstract

There is growing interest in the use of recycled materials in the building sector as a way to reduce waste and improve environmental sustainability. Polyethylene terephthalate (PET) is a thermoplastic polymer that has attracted the attention of researchers due to its application in the building industry. In the recent past, many studies have reported on the application of PET aggregates in structural lightweight concrete. This paper presents a review of the findings of 20 studies conducted between 2010 and 2022 randomly. The preliminary findings highlighted include the method of production of PET aggregates and their physical/thermal properties. The review extended further to focus on the extent of incorporation, physical properties, strength properties, and durability of concrete with PET aggregates. The substitution of PET aggregates up to 20% reflected positively on the compressive strength, while tensile and flexural strength had positive responses up to 10%. Water absorption as a measure of concrete durability increased with the addition of PET aggregates. A meta-analysis of these findings was performed using hypothesis testing (t-test and f-test) to identify significant differences between the experimental outcomes of PET incorporation in concrete. Experimental procedures with greater tolerance for PET inclusion and satisfactory concrete properties were highlighted. The paper recommends the formulation of hybrid mix proportions, developed from experimental designs with noteworthy inclusion of PET aggregates and those that attained high values of desired concrete properties. Furthermore, optimization should be performed to provide robust mix designs for high-strength or lightweight concrete with PET aggregates.

Keywords Polyethylene terephthalate · Aggregates · Structural lightweight concrete · Hypothesis tests (t-test and f-test)

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1 Introduction

Plastic is widely used in a variety of productive activities since it is affordable, lightweight, and long-lasting. This recognition and use cause a significant amount of plastic waste to be produced. Since the turn of the century, the amount of plastic produced worldwide has doubled, reaching almost 400 million metric tonnes annually in 2021. More than 350 million metric tonnes of plastic trash are presently produced annually by humans. Less than 10% of discarded plastic is currently recycled annually, with the vast majority of plastic waste being dumped or burned, which releases dangerous chemicals. Another quarter is mismanaged or left in disarray [1]. The majority of this created waste was produced in three different parts of the world. The following is a breakdown: 35 million tonnes came from North America and 45 million tonnes produced came from Europe, Central Asia, East Asia, and the Pacific. Africa, south of the Sahara adds 17 million tonnes to the world's plastic waste [2, 3]. The eight ranked producer of plastic waste in the world is Nigeria with 2.5 million tonnes annually, while Uganda produces 219,000 tonnes of plastic waste annually [4, 5]. The polyester family of polymers includes the strong, rigid synthetic fiber and resin known as polyethylene terephthalate (PET). PET can be used as a fiber for fabrics that are printed permanently as well as disposable beverage bottles [6]. PET is a thermoplastic polymer that is clear, robust, and lightweight and has a wide range of uses in the food and beverage sector as a packaging material. Its usage is highly facilitated when end-user convenience is crucial in the packaging of food, water/liquids etc. [7]. There were 480 billion plastic drinking bottles produced worldwide in 2016 [8].

Concrete is a widely utilised material in the building industry worldwide [9]. This is because of its low cost, durability, strength, flexibility to be produced in any shape or size and simplicity of handling. It is considered the most extensively used material in buildings and the second most commonly used substance after water [10–12]. Over time, urbanisation and development have been on the rise, which has resulted in the overuse and depletion of the natural resources utilized to produce concrete [13]. The rising demand for concrete, however, has resulted in a high consumption of the raw materials used to make concrete for a variety of construction applications [14–16]. These materials mostly consist of cement (limestone), sand, and gravel. Approximately 65 to 80% of concrete is made up of aggregates, which are also what give the concrete its durability, workability, porosity, density, and strength [17]. The annual production of enormous volumes of concrete requires significant amounts of both fine and coarse materials. Waste materials can be used in concrete to address trash disposal issues more sustainably while also conserving natural resources [18–20].

The lightweight building material industry is considered useful in promoting reused materials [21]. Concrete that uses Light Weight Aggregates (LWAs) is known as Light Weight Aggregate Concrete (LWAC). These aggregates comply with ASTM C330's requirements. From the structural applications point of view, the advantages of LWAC include their better thermal and sound insulation capabilities and their lightweight, including reductions in money and time spent on handling and manufacturing [22]. Using structural lightweight concrete can improve a building's structural efficiency compared to normal-weight concrete. By using structural lightweight aggregate concrete instead of normal-weight concrete, buildings in European countries could use 15% less heating energy [23]. Given that the self-weight of developed structures is believed to be linearly related to seismic forces, a decrease in this self-weight will lessen the impact of an earthquake [24].

Natural stone deposits have been substantially depleted as a result of the extensive usage of normal-weight aggregates like granite and gravel in concrete construction, causing catastrophic environmental harm [25]. The main factor contributing to the recent acceleration of global warming and the rise in sea levels above their pre-natural levels, as well as the threat of mass extinction for various species of living things, has been the increased consumption of natural resources [26]. One of the features of sustainability that minimizes global pollution issues is the usage of lightweight aggregates made from waste (such as PET) [27]. Recycling and reducing waste are key parts of a waste-management system since they contribute to conserving natural resources, reducing requests for waste landfill space, and reducing pollution of water and air [17, 18, 28, 29]. The persistence of PET in the environment negates the benefits of landfill disposal methods as the rate of generation of PET waste could outpace the availability of landfill sites. Reusing waste and recycled plastic in the construction and related industries is one of the many recycling management strategies that is regarded as the best way to get rid of plastic waste [30].

In recent years, there has been growing interest in the use of products from recycling in the construction industry as a way to reduce waste and improve sustainability. Costs associated with the current waste management practices of burning and burying PET waste will be considerably reduced with its recycling and incorporation in concrete [31, 32]. Recycled plastic aggregates have the advantage of less complex processing methods, low density, moderate chemical resistance and mechanical properties that are obtained at a low cost compared to other recycled materials [33]. Among the different recycling techniques, recycling polyethylene terephthalate (PET) to provide composite materials for the construction of buildings and roads, is recognized as the most effective approach to eliminating waste plastics [34]. In structural lightweight concrete, PET aggregates are used as a replacement for traditional aggregates, such as sand and gravel, to reduce the overall density of the concrete and improve its mechanical properties. Thus, waste plastic can be reused without causing quality to be compromised, replacing quickly decreasing natural materials and promoting conservation [24, 35, 36].

Waste plastics are primarily used as plastic aggregates, replacing natural aggregates, in cement-based composites, and the recycling of waste plastics has been extensively studied. These investigations looked at the changes in the plastic and hardened qualities of the altered composites and noted differences in performance, usually characterized by a loss in strength and an increase in workability [35–41]. Utilizing these waste plastics in the construction industry reduces the concrete's weight and density, thus reducing the risk of earthquakes [42]. Using waste plastic as an aggregate in concrete constructions results in concrete and steel quantity reductions of up to 7.23% and 7.18%, respectively, and life cycle cost reductions of up to 5.9% [43]. More effective thermal insulation, lower building costs, and quicker manufacturing and processing are some other advantages [44]. The aim of this paper is the review and meta-analysis of PET application as aggregates in structural lightweight concrete based on its antecedents and potentials.

2 Materials and methods

The study conducted a review of 20 relevant literature, randomly selected from 2010 to 2022. Information on the methods of producing PET aggregates and their physical properties was acquired. The review extended to glean information on the extent of incorporation of PET aggregates in concrete and the properties of concrete produced using PET aggregates. Specifically, the physical properties of fresh and hardened concrete, the strength properties of hardened concrete, and the durability of concrete were considered. Statistical tools, t-test and f-test (two–way analysis of variance, ANOVA), embedded in Microsoft Excel were used to perform a meta-analysis of these properties to test the null hypothesis regarding the multiple independent studies for novel conclusions. The test of hypothesis for two groups employed a t-test, whereas multiple groups used an f-test accordingly. The outcome portrays either a significant or insignificant difference between the property groups. Statistical inference is carried out on the test statistics to ascertain experimental concrete mixes with desirable concrete properties. Further inference isolates the experimental concrete proportions that need to be enriched, which calls for further action to be carried out. This could be achieved through reformulation or hybridization of the experimental concrete proportions to improve the peculiar properties of the concrete mixture. The methodology is described in a flow chart in Fig. 1.

2.1 Production of polyethylene terephthalate (PET) aggregates

Aggregates from PET are usually produced through the mechanical method (shredding and grinding), thermal method, or a combination of both methods. The mechanical method is a quick and affordable way to get recycled PET aggregates, while the thermal or combination method produces materials with more identical dimensions and features [45]. In the study [24], waste PET bottles were cleaned to remove contaminants, and then they were ground in a blade mill to a size of 4–0.075 mm to substitute fine aggregates in concrete [46], using a specialized shredder machine with a hopper measuring 116 cm by 45 cm for plastic bottle input, a rotating shaft with two blades added for cutting plastic bottles and nine moving blades, as well as a filter in the bottom to sift the shredded plastic to the necessary grade; produced PET aggregates close to natural sand gradation. An electric motor with a 30 kW output powers the device.

[34, 47] and [40] employed the thermal method of producing aggregates from PET waste. The PET bottles were cleaned, shredded manually or mechanically, and heated in a steel container until a molten state at 300 ℃. A mould was used to receive the molten plastic and it was allowed to cool for a minimum of 6 and a maximum of 24 h. After cooling, the plastic block was manually smashed to obtain various sizes of aggregates that were classified as fine or coarse aggregates.

The mechanical and thermal approach was adopted by [48]. Plastic bottles were collected, washed, and ground to obtain flakes that were heat extruded by a plastic granulator machine to produce pellets with a diameter of approximately 1.5 mm and a length of 3 mm. Saikia & DeBrito [12] obtained PET aggregates after PET wastes are ground up, then cleaned and separated using physicochemical techniques, the product is coarse flakes and fine fractions. The plastic

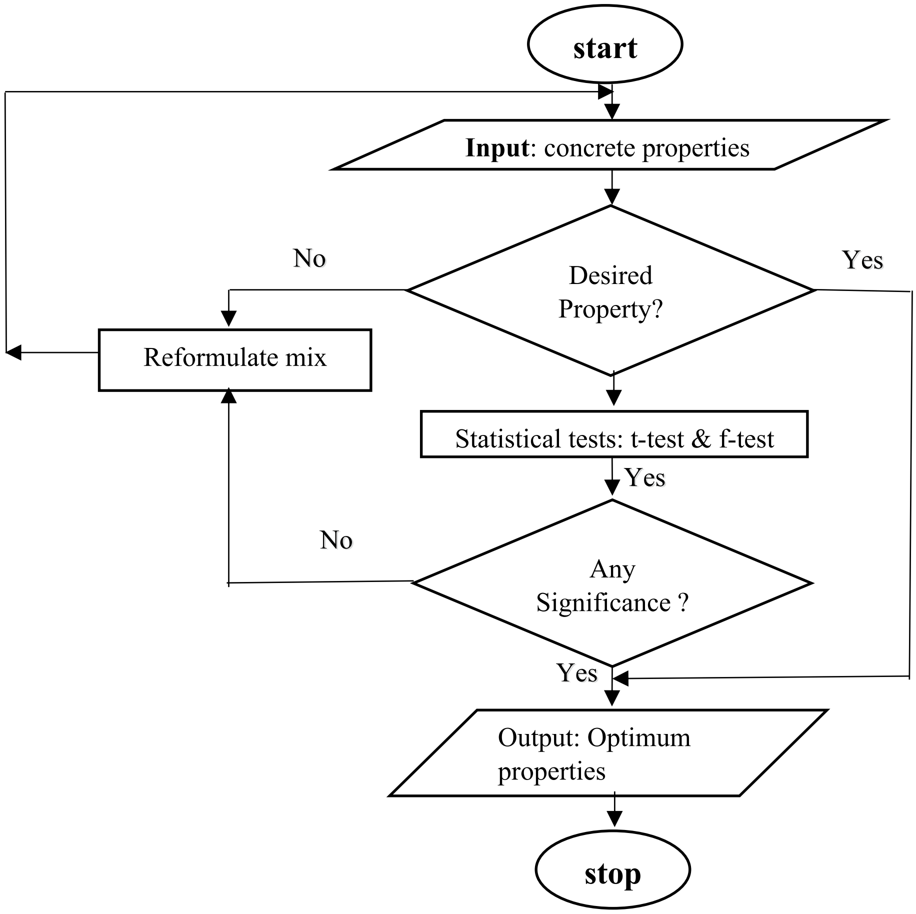


Fig. 1 Flowchart for evaluation of concrete mixture proportions and specimens

flakes were used to create the plastic pellets. This substance is made up of PET granules with precise dimensions and no tiny impurities. To create pellets, PET flakes are dosed into a reactor using a device that can keep the reactor vacuumed by employing a dosing screw under specified settings. A spinneret with holes, a polymer filter, and an extruder spindle are used to extrude the heated material. Vacuum is used during the process of heating the material to melting point, which enables the extraction of volatile pollutants. A cooling bath is used to collect the melt, after passing through a spinneret, which hardens the polymer before it is placed in a submerged rotary cutter and then granulated. After passing through a vibratory separator, the water and polymer particle mixture is centrifuged to remove any excess water. Table 1 presents the methods of producing PET aggregates reported in the literature.

Table 1 Methods of producing PET aggregates in the literature

References	Production method
[24]	Crushing and shredding
[49]	Shredding and grinding
[50]	Cutting and grinding
[34]	Melting and grinding
[51]	Crushing
[52]	Grinding
[46]	Shredding
[53]	Pulverization
[48]	Grinding and thermal extrusion
[12]	Grinding and thermal extrusion
[47]	Melting and crushing

2.2 Physical properties of PET aggregates

Aggregate properties have a profound influence on concrete properties, and a proper understanding of these properties is mandatory to create high-quality concrete [54]. PET aggregates have several properties that make them attractive for use in structural lightweight concrete, such as low density, high tensile strength, and low thermal conductivity. The low density of PET aggregates contributes to a decrease in the overall density of the concrete, which makes it more suitable for applications where weight reduction is desired. The high tensile strength of PET aggregates also contributes to the overall concrete's durability and strength. Furthermore, the low thermal conductivity of PET aggregates helps to reduce heat transfer through the concrete, making it more energy efficient.

Saikia and De Brito [12] listed the features of waste PET plastic to be incorporated as aggregates in concrete mixtures as follows:

1. The particle size distribution of PET aggregates is usually determined following standard established procedures for aggregate size classification [12, 42, 47, 50].
2. Bulk density, specific gravity, and water absorption of PET aggregates were determined following the standard procedures used for coarse and fine natural aggregates, albeit with slight modifications [55].

2.3 Incorporation of PET aggregates in concrete mixtures

PET aggregates have been incorporated either as coarse and/or fine-sized aggregates in concrete mixes to varying extents. Several references have reported on the partial and complete replacement of natural aggregates with PET aggregates. Table 2 presents the extent of PET aggregates' inclusion in the preparation of concrete mixes.

2.4 Design, batching, and curing of concrete mixes with PET aggregates

The design, preparation, and casting of concrete mixes incorporating PET aggregates typically follow various standard specifications and are similar to those for regular concrete mixes [65]. However, [56] used an approach slightly different from the norm.

Table 2 Extent of incorporation of PET aggregates in concrete

References	Extent of incorporation
[56]	Fine aggregate; 10 and 20% vol
[57]	Fine aggregate; 5% wt
[58]	Fine aggregate; 25, 50, 75% vol
[59]	Fine aggregates; 30, 40, 50, 60% wt
[60]	Fine aggregates; 5% wt
[61]	Fine aggregates; 10, 20, 30, 40, and 50% wt
[49]	Fine aggregate; 2.5, 5.0 and 7.5% vol
[50]	Fine aggregates; 1.0, 2.5 and 5% vol
[34]	Fine aggregates; 10, 20, 30, 40 and 100% wt
[51]	Fine aggregates; 0%, 1%, 2%, 3%, 4%, 5%, 6%, 7% and 8% wt
[52]	Fine aggregates; 5%, 10%, 15% & 20% vol
[46]	Fine aggregates; 5%, 7.5%, 10%, 12.5%, 15%, 20% wt
[53]	Fine aggregates; 2%, 5% and 10% wt
[62]	Fine aggregates; 25%, 50% and 75% vol
[63]	Coarse aggregates; 40%, 50%, 70% and 100% wt
[48]	Fine aggregates; 1%, 2%, 4% and 8% vol
[12]	Fine aggregates; 5%, 10%, and 15% wt
[47]	Fine and coarse aggregates; 100% wt
[64]	Coarse aggregates; 100% wt

2.5 Evaluation of concrete properties

The concrete properties are evaluated in terms of the slump, density, strength properties, and elastic modulus. These properties include durability characteristics and other unique qualities, including fire behaviour, thermal insulating properties, microstructure, and plastic reactivity in alkaline solution [65]. The evaluation of these performance criteria was carried out following the standard practices used for conventional concrete.

3 Overview of results from the literature

3.1 Physical properties of PET aggregates

There is a considerable difference in the physical properties of PET aggregates compared to aggregates of natural origin, which are obtained by quarrying activities and dredging of river beds. The physical properties of the PET aggregates are presented in Table 3.

In contrast to two widely-used concrete aggregates, sandstone (1.7 Wm^{-1} K^{-1}) and limestone (1.26–1.33 Wm^{-1} K^{-1}). PET aggregates have a very low thermal conductivity (0.13-0.15-0.24 Wm^{-1} K^{-1}). In addition, PET has specific heat capacity which is larger than that of sandstone (0.92 kJkg^{-1} K^{-1}) and limestone (0.84 kJkg^{-1} K^{-1}) [59, 65]. The thermal expansion coefficient of PET has a minimum value of 6.0×10^{-5}/℃ and a maximum value of 8.0×10^{-5}/℃ [66]. The low thermal conductivity and high specific heat capacity of PET over concrete aggregate improves the energy efficiency of buildings and high resistance to harsh environments. Polyethylene terephthalate has hardness values in the range of 80.0–96.0 HRR and 105–125 HRM on the Rockwell hardness scale, D 71.4–87.0 on the shore hardness scale and 117–170 MPa for ball indentation hardness [67].

3.2 Properties of concrete with PET aggregates

3.2.1 Slump

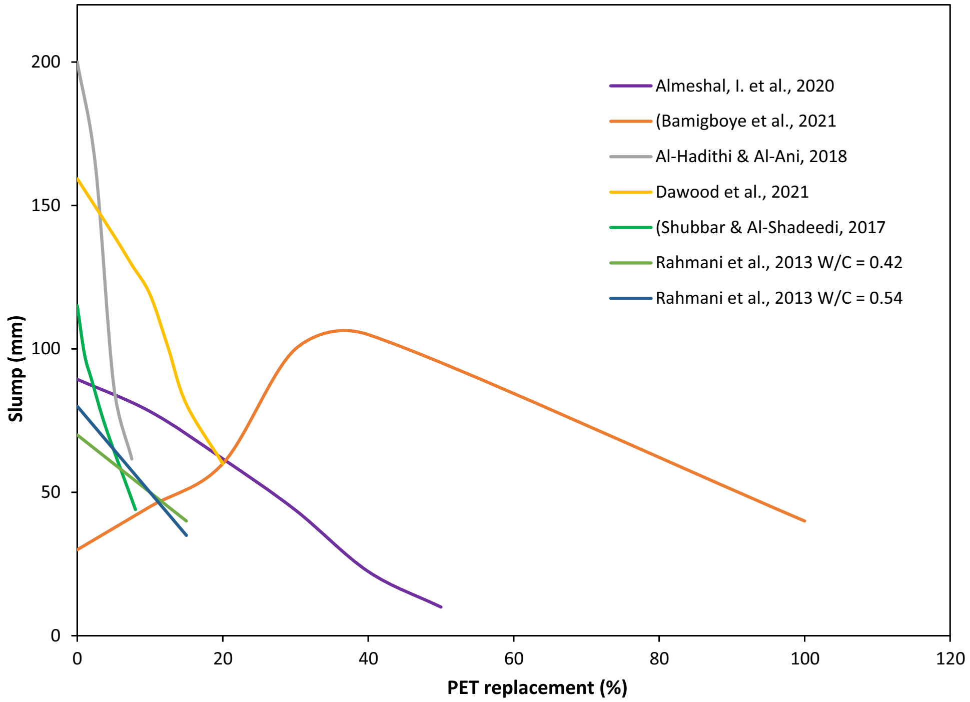
The slump of concrete is an important characteristic that is utilized to gauge the consistency or workability of a fresh concrete mix containing PET aggregate. This was studied extensively by various scholars. Several variables, including the water-cement ratio (w/c), the replacement level of PET aggregates, and the shape and specific surface area of the aggregate, might affect the slump of concrete when PET aggregates are used. The results of slump tests obtained from the literature are presented in Fig. 2.

The majority of studies revealed a substantial effect on the slump of fresh concrete when PET aggregates were added, with a tendency for the slump to decrease. This has to do with the decreased fluidity brought on by the irregular morphologies of PET aggregates. Despite a considerably lower workability, the inclusion of PET produced concrete mixtures

Table 3 Physical properties of PET aggregates

References	Particle size (mm)	Bulk density (kg/m^3)	Dry Unit weight (kg/m^3)	Specific gravity	Water absorption (%)
[24]	4–0.075	–	1410	–	0.49
[49]	4.75	447	–	1.285	0.00
[50]	0.5, 1.5 and 3	–	–	1.38	0.1
[34]	–	_	_	–	0.27
[46]	< 4	–	–	1.38	0.02
[68]	–	–	–	1.34	0.17
[59]	4	–	–	1.27	–
[48]	1.5–3	–	–	1.38	–
[12]	4	351; 555; 827	–	1.34	0.1; 0.18; 0.25
[69]	0.3–4.75	464.3	–	1.11	–

Fig. 2 Slump of concrete specimens



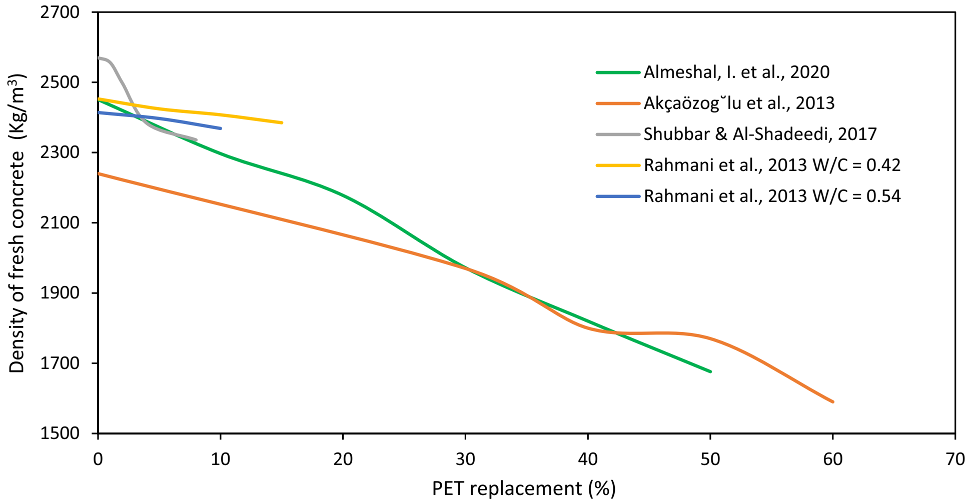
that could be used [24, 46, 48, 49, 69]. In the study of [34], workability increased steadily as PET percentages rose to 40% replacement, after which it declined to unacceptable levels for light to minimal reinforcing works.

3.2.2 Density

Aggregate made of plastic is lightweight, which influences the downward trend in the fresh and dry densities of the resulting concrete, notwithstanding the type and size of substitutions. When compared to the high threshold dry density value needed for structural lightweight concrete, which is 2000 kg/m^3 [70], these readings were occasionally lower. The results of the fresh and dry density of concrete with PET aggregates are presented in Figs. 3 and 4.

As the percentage of PET aggregate in the concrete mixture increased, the fresh and dry unit weights of the concrete samples decreased [24, 49, 69]. This was explained by the fact that PET aggregates had a lower density than natural sand (52% less dense) [49]. PET plastic has a specific gravity of 1.27 g/cm^3, which is lower than the standard aggregate of 2.45 g/cm^3 and 2.57 g/cm^3 [59]. With a 20% increase in the percentage of PET aggregates, the density of concrete specimens

Fig. 3 Fresh density of concrete specimens



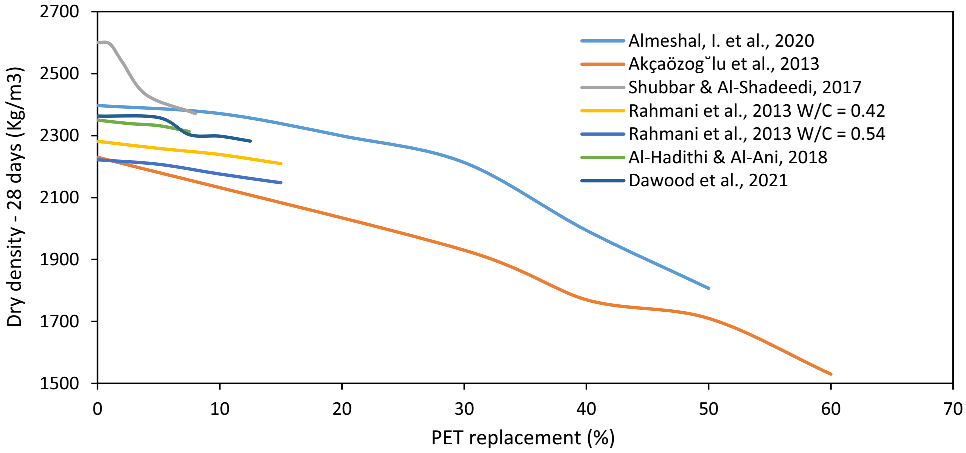


Fig. 4 Dry density of concrete specimens

decreased compared with the reference mix because of the low density of PET aggregates [46]. The fresh and dry density reduction of concrete samples was 9% and 8.8%, respectively, with a PET replacement level of 8%. This is a result of the PET aggregate's lower specific gravity, which was 13.75% lower than the fine aggregate used. [48].

3.2.3 Compressive strength

According to [45, 65], in practically all research projects involving PET aggregate, the concrete's compressive strength is a basic feature that is investigated at length. In each of these studies, it was discovered that adding PET aggregate reduced the compressive strength of concrete. The following are some potential causes of the poor compressive strength of concrete made with plastic aggregate:

- The hydrophobic character of PET aggregates slows the cement hydration process by limiting water flow.
- The very weak binding strength at the interface of the plastic waste and the cement paste.
- The water/cement ratio.
- The shape of PET aggregates.
- The elastic modulus of PET aggregates.

The results of compressive strength tests reported in the literature are presented in Fig. 5.

As observed in Fig. 5, the results indicate that beyond 20% PET replacement, the compressive strength of concrete reduces with an increase in the percentage of PET aggregates in the concrete mixture. The cohesion between the concrete matrix and PET aggregates becomes less as the percentage of PET aggregates increases, and the PET aggregates also act as a barrier between the paste and the conventional aggregate [51]. The compressive strength of mixtures

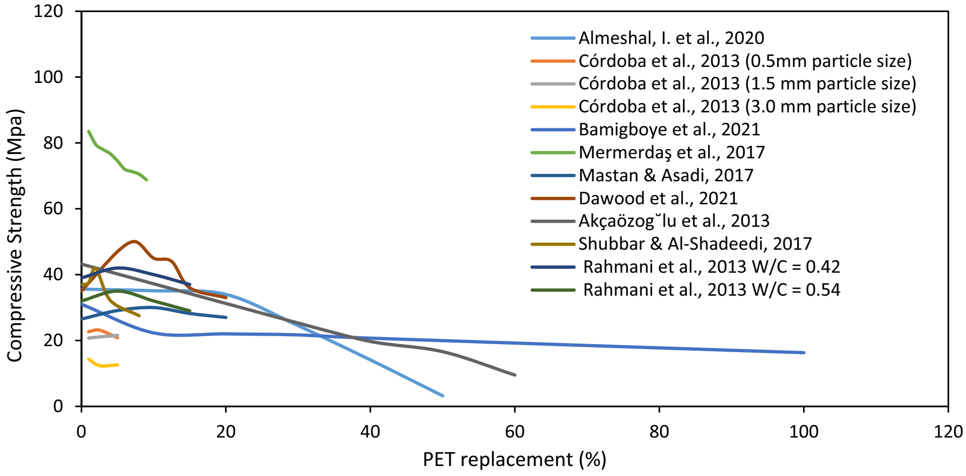


Fig. 5 Compressive strength of concrete specimens

reduces at each curing age with an increase in the proportion of PET aggregates to conventional aggregates. Compressive strength reduced marginally at 10% and 20% replacement ratios and drastically at 40% and 50% by 31% and 60% at 28 days, respectively [24]. In the study of [50], a maximum 40% enhancement in concrete strength can be achieved by adding 1.5 mm PET aggregates, with concrete strength values ranging from 10.0 to 21.3 MPa. Concrete with 1.5 mm PET aggregates has greater strength values than concrete with 3.0 mm PET particles. Furthermore, 2.5% by volume of PET particles yields the highest values.

It was observed by [46] that 7.5% is the ideal proportion for the greatest gain in compressive strength (43.64%) after 28 days. At 28 days, increases of 34.03, 42.16, 28.31, and 26.8% were seen in the samples with PET aggregates percentages of 5, 7.5, 10, and 12.5%, respectively. Experimental results of Rahmani et al. [69] demonstrated that the compressive strength of cubes made with 15% PET aggregates in place of sand is comparable to that of the reference cubes. The compressive strength of the cubes with 20% PET aggregate replacement was reduced by 5.3%. With a w/c ratio of 0.42 and 0.54, respectively, the compressive strength shows an initial increasing trend of 8.86% and 11.97% at 5% replacement of PET aggregates. Additionally, w/c ratios of 0.42 and 0.54 and the replacement of 15% of the sand content with PET aggregates resulted in 5.11% and 8.45% reductions in strength, respectively. According to [24], the compressive strength of concrete mix with 1% substitution of sand with PET aggregates rose by 3.7 and 1.6% after 7 and 28 days respectively. At comparable curing intervals, 2% replacement recorded increases in compressive strength of 15% and 13%. After replacing 8% of the original aggregates with PET aggregates for both curing times, a loss of 25% in compressive strength was noted.

According to published data by [34], compressive strength steadily rises with curing time and falls with increasing PET aggregate substitution rates. On the 28th day, the mix with 100% PET aggregate substitution had a compressive strength drop of up to 34.8%. Compared to the control mix, the concrete mixes with PET aggregates only met the desired compressive strength on the 7th day and did not do so on the 14th or the 28th day. Concrete with 10%, 20%, 30%, and 40% PET replacement of the aggregate recorded compressive strengths of 20 to 22 MPa, which is sufficient for structural grade concrete. Results obtained from [59], indicate that the 28-day compressive strength values of concrete samples with 30%, 40%, 50%, and 60% PET aggregate substitution decreased by 41, 54, 62, and 78%, respectively, when compared to the control mix. At 28 days, the compressive strength of the concrete samples with 40% and 50% substitution levels exceeded 17 MPa, thus qualifies as structural lightweight concrete as its dry density was below 2000 kg/m^3 (refer to Fig. 4 for values of dry density of concrete).

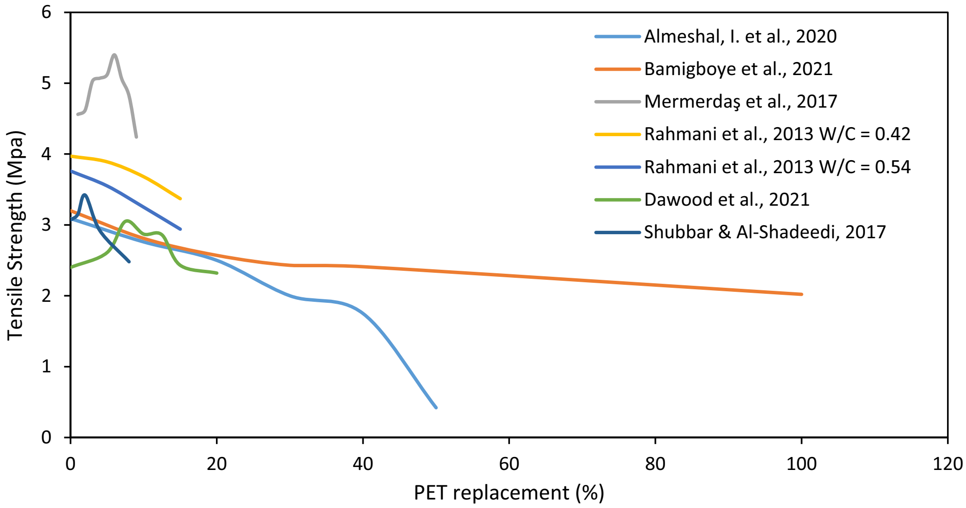
3.2.4 Splitting tensile strength

The splitting tensile strength of concrete with PET aggregates is similar to compressive strength, as it is often lower than that of traditional concrete at the same w/c ratio [45]. Any sort of plastic aggregate reduces the splitting tensile strength of concrete, which is similar to how compressive strength behaves. The factors used to explain the drop in compressive strength brought on by the addition of PET aggregates were comparable to those for the reductions in splitting tensile strength that was observed and described in various sources [65]. Figure 6 shows splitting tensile strength values as reported in the literature.

The results of [34] exhibited behaviour in contrast to compressive strength. Up to 5% replacement of PET aggregates resulted in a marginal improvement in tensile strength. However, going over this threshold reduced the tensile strength due to the higher replacement level. The findings of [46] reveal that at 28 days, the splitting tensile stresses of specimens with 5, 7.5, and 10% PET aggregate replacement, respectively, increase to 7.88, 26.97, and 19.08%. In contrast, mixes containing 20% PET aggregates have a 3.7% lower splitting tensile strength than the reference mix. Shubbar and Al-Shadeedi [48] observed a progressive rise in split tensile strength up to 2% replacement of the fine aggregate with PET aggregates to achieve a maximum point (2.57, 3.423 MPa) for 7 and 28 days of curing, respectively, which equals 18.2 and 11.5%. Following this, there was a drop of 8% in replacements to reach roughly 18.5% as compared to normal concrete for both 7 and 28 curing days.

Tensile strength is generally trending downward as PET aggregate content rises. For instance, the drop in tensile strength was 15.9% and 18.06%, respectively, for the w/c ratios of 0.42 and 0.54 when 15% of the volume of sand was replaced with PET aggregates [69]. According to [24], the splitting tensile strength of concrete is negatively impacted by the inclusion of PET aggregates when the replacement ratio is increased. After 28 days of curing, the splitting strength for 10%, 30%, and 50% PET aggregate content decreases from 3.11 for the reference mix to 2.78, 2.01, and 0.45 MPa. In the study of [34], the split tensile strength increased steadily with curing age, similar to compressive strength, and

Fig. 6 Splitting tensile strength of concrete specimens



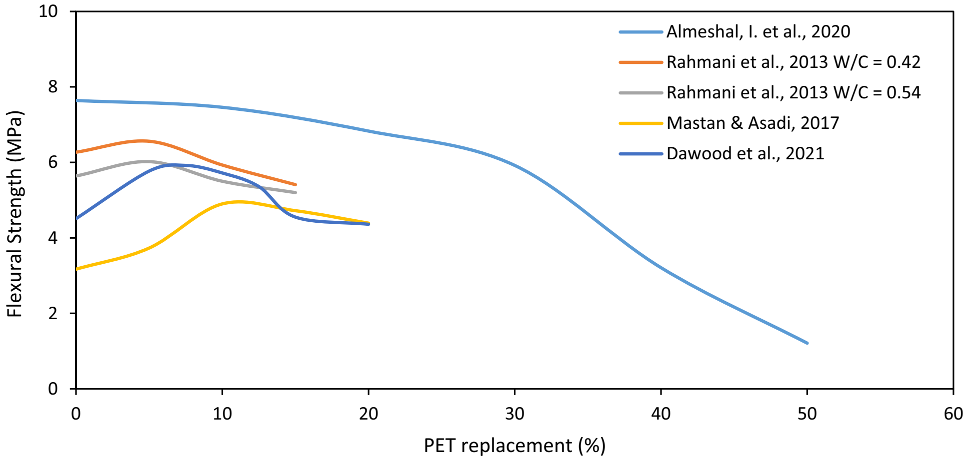
declined gradually with the addition of PET aggregates at all ages. All mixes including PET aggregates, except the mix that contained 100% PET aggregates, met the split tensile strength target of 2 N/mm^2 after 21 days.

3.2.5 Flexural strength

Flexural strength, which is evaluated in terms of stress, is the capacity of a material to withstand flexural load-induced deformation. It indicates the material's greatest internal stress at the collapse load [65]. The flexural strength of concrete with PET aggregates, as with compressive strength, is often lower than that of typical concrete with the same water content [45]. Figure 7 presents the results of the flexural strength test reported in the literature.

The results from [69] show that the flexural strength initially increases with an increase in PET aggregate content before declining over time. Flexural strength increases by 6.71% and 8.02%, respectively, when 5% of the volume of sand is replaced by PET aggregates at w/c ratios of 0.42 and 0.54. But for w/c ratios of 0.42 and 0.54, 15% substitution of PET aggregates resulted in reductions in the flexural strength of 14.7% and 6.25%, respectively. In the study of [20], when fine aggregates are replaced with PET aggregates, the flexural strength of the concrete samples increases steadily up to a 10% substitution level. It subsequently decreases at other substitution levels. Concrete specimens with 5–12% PET aggregate replacement recorded an increase in flexural strength. At a replacement percentage of 7.5%, the largest increase of 30.2% is observed. The flexural strength of specimens with 15% PET aggregate replacement is also higher than that of the reference specimens. Conversely, specimens with a 20% replacement of PET aggregates have a 3.9% decrease in flexural strength [52].

Fig. 7 Flexural Strength of concrete specimens



The experiments by [24] showed that flexural strength was reduced by the addition of PET aggregates; this pattern was similar to compressive strength. Flexural strength measured at a 30% replacement ratio was 5.92 MPa. Flexural strength decreased by 2.4, 58, and 84.2% for PET aggregate replacement ratios of 10%, 40%, and 50%.

3.2.6 Durability

For concrete or mortar incorporating plastic as an aggregate, several durability criteria are assessed. These include resistance to shrinkage, carbonation, chloride ion penetration, freezing, and thawing, as well as water absorption and sorptivity. The results of the durability tests are presented in Fig. 8.

The study of [46] presented data showing that increases in the amount of PET aggregates caused the water absorption rate of concrete specimens to increase as well. The specimens with 20% PET aggregate substitution obtained an absorption rate of 2.41%, which is 55.48% greater than that of the reference mixture with an absorption rate of 1.55%. Inspection of water absorption tests results by [12] revealed, that concrete becomes more porous as the amount of PET aggregates increases.

The results of [49] indicated a continuous reduction in absorption values for all concrete specimens with curing age.

4 Results/Discussion

4.1 Presentation of results

The tables below show the results of the statistical analysis of values for different characteristics of concrete with PET aggregates as reported by various authors.

4.1.1 Slump

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

The t-test analysis of slump values from [34] and [24] (Table 4) shows that there is no significant difference between the two groups of data. From Fig. 2, [34] and [24] have greater accommodation of PET aggregates, albeit lower slump values were recorded. The f-test analysis of slump data from [24, 34, 49, 69] indicates that there is a significant difference between the results. The result of [49] in Fig. 2 stands out from the group, as it has a noticeably high slump, although with a lower accommodation of PET aggregates. Hybridization of the experimental approach of either [34] or [24] and [49] yields a mixture proportion for acceptable slump values, and incorporation of a greater percentage of PET aggregates should be considered.

Slump is a measure of the consistency and fluidity of concrete i.e. workability. Workability refers to how easily concrete can be mixed, placed, and finished without segregating or losing its homogeneity [71, 72]. Placing concrete with low workability poses great difficulties such as:

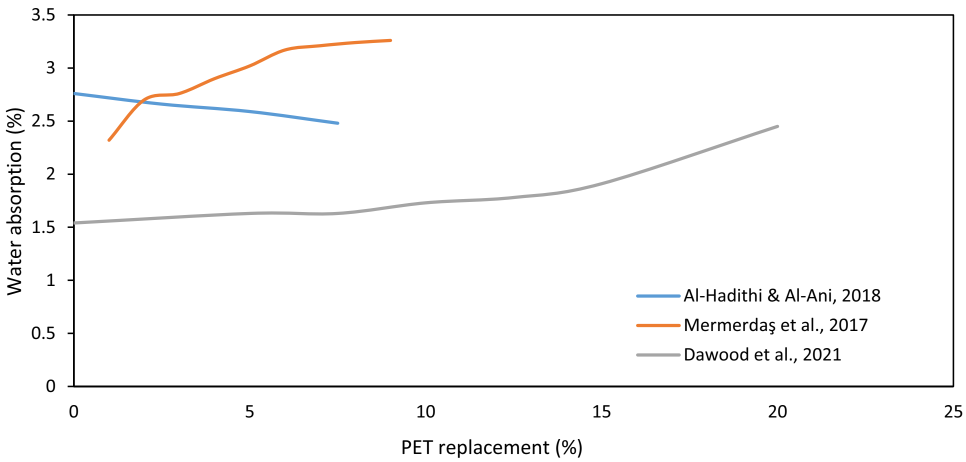


Fig. 8 Durability of concrete specimens

Table 4 The statistical analysis of the slump of the concrete mixtures

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[24] and [34]	2.179	± 1.106			Data from Fig. 2, the null hypothesis is accepted
[24, 34, 49, 69]			2.364	6.066	Data from Fig. 2, the null hypothesis was rejected

1. Weak or porous concrete due to inadequate consolidation.
2. A non-uniform distribution of materials in the mix because of heavier aggregates settling at the bottom which can result in concrete of varying strengths and durability.
3. Inadequate bonding between the concrete and reinforcement materials, thus compromising the structural integrity of the construction
4. More labour and specialized equipment such as vibrating screeds or mechanical compaction tools are required for the successful placement of concrete.

These difficulties could be overcome by the introduction of superplasticizers. These are chemical admixtures that can increase the workability of concrete even with low water content. Superplasticizers enhance the dispersal of the cement particles thus, better lubrication between aggregates [73, 74].

4.1.2 Fresh density

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

[24] and [59] from Fig. 3 had values of fresh density of concrete with no significant difference as inferred from statistical t-test analysis (Table 5). The experiments of both authors provided mixture proportions for incorporating PET aggregates in concrete for fresh density that falls into the category of lightweight concrete. F–Test analysis of the entire data set of fresh density values (Table 5) indicates that there is a significant difference between the values of fresh density from the various authors (as the null hypothesis is rejected). This further highlights the desirable qualities of [24, 59] in terms of lightweight concrete.

4.1.3 Dry density

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

The dry density results (Fig. 4) of [24] and [59] share similar trends in the extent of PET incorporation and lower density values. However, statistical t-test analysis (Table 6) shows a significant difference between the two sets of results. A further investigation using f-test statistical analysis leads to a rejection of the null hypothesis (i.e., significant difference) for the

Table 5 Statistical analysis of the fresh density of the concrete mixture

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[24, 59]	2.262	± 1.459			Data from Fig. 3, the null hypothesis was accepted
[24, 48, 59, 69]			2.866	26.517	Data from Fig. 3, the null hypothesis was rejected

Table 6 Statistical analysis of the dry density of concrete specimens

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[24, 59]	2.179	± 3.080			Data from Fig. 4, the null hypothesis was rejected
[24, 46, 48, 49, 59, 69]			2.237	427.513	Data from Fig. 4, the null hypothesis was rejected

whole group data for dry density. From this analysis, the mix proportion of [59] is appropriate for achieving lightweight concrete with PET aggregates.

4.1.4 Compressive strength

The detailed results of the f-test are shown in the appendix or supplementary material.

The results of the f–test analysis depict that there is no significant difference between the results of [24, 34]; and [59]. This result was obtained despite the greater incorporation of PET aggregates by [34] (Fig. 5). F-test analysis of compressive strength data from the literature (Table 7) indicates that there is a significant difference between the results. The result of [51] is noteworthy due to the high compressive strength value achieved (Fig. 5). A hybrid mix proportion could be obtained from [34] or [59] and [51] to achieve high compressive strength with greater incorporation of PET aggregates.

The compressive strength performance of concrete with PET aggregates is related to the interfacial transition zone between the PET aggregates and the cement paste. The hydrophobic nature of PET aggregates causes more water to remain on the surface of the aggregates leading to an increase in the thickness of the interfacial transition zone which results in a weak bond with cement paste in the concrete matrix.

4.1.5 Splitting tensile strength

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

The tensile strength results of [34] and [24] are statistically similar, as the t-test analysis (Table 8) found that there is no significant difference between the two results, even as [34] had greater tolerance for PET incorporation in the concrete mix (Fig. 6). The tensile strength data from all the authors were analyzed using the f–test, with results showing a significant difference between the results provided. Noticeably, high tensile strength was recorded by the formulation of [51] in (Fig. 6). A novel mixture that possesses a PET tolerance of [34] and tensile strength of [51] could be achieved by combining the two mixtures.

4.1.6 Flexural strength

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

Table 7 Statistical analysis of the compressive strength of the concrete specimens

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[24, 34, 59]			3.634	0.677	Data from Fig. 5, the null hypothesis is accepted
[24, 34, 46, 48, 50–52, 59, 69]			1.899	103.306	Data from Fig. 5, the null hypothesis was rejected

Table 8 Statistical analysis of the tensile strength of the concrete specimens

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[24, 34]	2.228	± 2.126			Data from Fig. 6, null hypothesis accepted
[24, 34, 46, 51, 69]			2.295	72.577	Data from Fig. 6, the null hypothesis was rejected

The results of flexural strength tests from the authors considered were significantly different, as deduced from the f-test analysis (Table 9). The results from [24] in Fig. 7 are desirable because they had outstanding flexural strength with a greater amount of PET aggregates incorporated in the concrete mixture.

4.1.7 Durability

The detailed results of the t-test and f-test are shown in the appendix or supplementary material.

The f–test analysis of durability performance (Table 10), indicates a significant difference between the values as presented by the authors in Fig. 8. The experimental mix design of [46] is preferable because it has the lowest water absorption percentage with the highest incorporation of PET aggregates in its mixture proportions.

5 Conclusion

Numerous studies have been conducted on the use of PET aggregates in structural lightweight concrete. This study presents a review of this research. The findings reveal a positive review of the introduction of PET aggregates in structural lightweight concrete, albeit with some limitations.

1. The method of producing PET aggregates varied from mechanical approaches to thermal approaches and a combination of both approaches.
2. It was observed that the slump values for concrete had an inverse relationship with the incorporation of PET aggregates. This results in stiff concrete with placement difficulties.
3. The introduction of PET aggregates reduced the density of the concrete. This reduction relates specifically to the extent of the replacement of natural aggregates. Certain specimens recorded reductions to the extent of being regarded as structural lightweight concrete.
4. The compressive strength of concrete with PET aggregates trends in the positive direction with a substitution level equal to or less than 20%. This trend decreases with the addition of more PET aggregates across all curing intervals. The observed reduction is attributed to the low bonding between the surface of the PET aggregates and the cement paste. Additionally significant, is the hydrophobic nature of the PET aggregate, which prevents the hydration reaction of the cement at its surface. Some of the mixtures attained the strength threshold to be considered as structural lightweight concrete.

Table 9 Statistical analysis of the flexural strength of the concrete specimens

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[46, 52, 69]			3.160	13.277	Data from Fig. 7, the null hypothesis was rejected

Table 10 Statistical analysis of the durability of concrete specimens

Authors	t-test		f-test		Remark
	Critical	Calculated	Critical	Calculated	
[46, 49, 51]			3.634	45.230	Data from Fig. 8, the null hypothesis was rejected

5. Concrete specimens exhibited a general trend of reduction in split tensile strength with an increase in the quantity of PET aggregates. Some outlier studies recorded higher split tensile strength up to 10% substitution of natural aggregates.
6. Studies have shown an increase in the flexural strength with up to 10% substitution level of PET aggregates in concrete. This upward trend was reversed with an increase in the PET aggregate content beyond 10% in all cases.
7. The durability of concrete using PET aggregates was evaluated in terms of its water absorption. The water absorption rate of concrete increases as the PET aggregate content increases. This is attributed to poor mixing of the aggregates with the cement paste. The water absorption rate was also observed to decrease with curing age. This is due to the products of the cement hydration reaction filling the void spaces.
8. The outcome of the meta-analysis indicates that the limitations observed could be overcome by hybridizing concrete mixtures that possess properties that are considered complementary in terms of the amount of PET aggregates in the mixture and the desired value of the concrete property.

Furthermore, PET aggregates are used as a replacement for conventional aggregates to produce structural lightweight concrete. The benefit of this is the optimization of structural designs to reduce money and time spent on handling and manufacturing concrete members. Incorporation of PET aggregates in concrete helps to reduce the pressure on landfills as PET is non-biodegradable. This further reduces the costs and environmental impacts of burning and other disposal methods. The use of PET aggregates in concrete encourages the conservation of natural aggregate sources, leading to sustainability in the construction industry.

6 Recommendations

Recommendations for further research include the development of optimized mix designs for the incorporation of PET aggregates alongside natural aggregates in concrete for high-strength applications. PET aggregates could be considered as lightweight aggregates in the design and optimization process to produce a more robust mix design for structural lightweight concrete. This could be achieved through the use of statistical methods or artificial intelligence modelling.

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