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Innovative Sustainable Concrete: Fresh and Hardened Properties Incorporating Plastic Waste

Md. Saniul Haque Mahi*, Tanjun Ashravi Ridoy, Fatima Antara Islam Mounata, Meheron Khan

Department of Civil Engineering, Dhaka International University, Satarkul, Badda, Dhaka-1212, Bangladesh

***Corresponding Author:** Md. Saniul Haque Mahi (saniulmahice@gmail.com)

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Abstract

Plastic waste generation has become a global environmental crisis that requires immediate, innovative, and sustainable solutioning. Concrete, being one of the most consumed construction materials, may provide a viable route for recycling plastic waste in accordance with the principles of the circular economy. However, the incorporation of plastic into concrete is a big challenge due to its hydrophobic nature and poor interfacial adhesion, which can compromise mechanical properties. This study will investigate the effects of the inclusion of plastic waste on some mechanical and durability properties of concrete. The review has pointed out some critical gaps in the existing literature, such as the lack of comprehensive studies focusing on the optimization of plastic content without compromising structural integrity. A systematic experimental approach was followed wherein plastic waste in various forms, for instance, PET, PP, was used at variable percentage incorporation, and the concrete derived was tested for compressive strength, tensile strength, flexural strength, and durability parameters. The results indicate that while the plastic incorporation increases the ductility and decreases the density of concrete, there is a loss in strength parameters. The novelty of this study is to propose strategies to overcome these drawbacks by surface treatment of plastic particles and optimal mix design. This research underlines the potential of plastic-reinforced concrete as an environmentally sustainable material, offering a dual solution for waste management and resource conservation.

Keywords: Plastic Waste, Cncrete Strength, Non-degradable Material, Cement Replacement, Concrete

Introduction

Following the discovery of 'Bakelite' as the inaugural synthetic plastic in 1907, the manufacturing and utilization of plastics have increased dramatically. Annual global output climbed from an estimated two million tons in the 1950s to around 381 million tons by 2015 [1]. The usefulness and adaptability of plastics, also known as synthetic polymers, have made them vital in modern life. Since the 1950s, about 83 billion metric tons of plastics have been manufactured. However, just 9% of this amount has been recycled, 12% has been burnt, and the other 79% still remains in landfills or natural ecosystems [1, 2].

The persistence of plastic garbage in the environment is a serious concern due to its protracted breakdown durations under natural circumstances [3]. This problem underscores the critical need for adequate and sustainable techniques for the disposal and management of plastic garbage. Current options for post-consumer plastic management include landfilling, incineration, and recycling to minimize the carbon footprint [4]. However, among these, recycling provides an economically advantageous approach. Of particular importance is the management of plastic carry bags, which are largely constructed from low-density polyethylene (LDPE) and are tough to dispose of properly [5].

Plastic reutilization is a vital aspect of the recycling process, which may be classified into three basic technologies: mechanical recycling, chemical (or depolymerization) recycling, and thermal processing [6]. One possible route for plastic waste reuse is its integration into concrete. Studies have demonstrated that shredded waste plastic, employed as lightweight particles in concrete, can lower the total weight of the material while delivering additional benefits such as better brittleness and greater heat resistance [7].

Despite these developments, gaps exist in knowing the overall impacts of plastic waste on the mechanical and durability qualities of concrete. Most research focus on certain types of plastics or restricted performance parameters, leaving a lack of consensus on optimal integration techniques, dose, and long-term performance. Moreover, the environmental consequences of employing such waste in concrete, notably concerning microplastic release and lifespan assessment, remain underexplored. This work intends to solve these gaps by exploring the integration of plastic waste in concrete, concentrating on its implications on mechanical characteristics, thermal behavior, and environmental sustainability.

Table 1. Strength variation with change in replacement percentage of fine aggregates

Sl. No	Hardened Properties	Percentage replacement of plastic as Fine Aggregate						Reference
		0	5	10	15	20	30	
1	Compressive strength	43.07	36.11	30.79	25.33	-	-	[8]
2		18.55	-	17.8	-	10.72	-	[9]
3	Flexural strength	3.4	3.06	2.28	2.2	-	-	[8]
4		3.41	-	2.74	-	-	-	[9]
5	Split tensile strength	4.7	4.2	3.7	2.9	-	-	[8]
6		2.31	-	1.91	-	-	-	[9]

Replacement Approach

Plastic as Fine Replacement

The replacement of waste PET and PC as fine aggregates in concrete increased the dry density by only 19% and 24%, respectively, at 50% replacement. In the case of plastic fines replacing fine aggregates, the development of microcracks in the concrete matrix is drastically reduced. Through various research work in Table 1 (see above), the optimal percentage of PET replacement was found to be within the range of 5%, 20%, and 50%. Besides, HDPE was also used as a fine aggregate up to 20%. It came out that 1% and 7% replacement levels provided improved compressive strength and flexural strength, respectively. Addition of 10% by volume of polypropylene waste resulted in a significant improvement of compressive strength to the tune of 16%, and the stiffness index increased by 8.9% while reducing water absorption. Other wastes, including styrofoam, were tested as fine aggregates in concrete up to 50% replacement.

Table 2. Strength variation with change in replacement percentage of coarse aggregates

Sl. No	Hardened Properties	Percentage replacement of plastic as coarse aggregate								Reference
		0	5	10	15	20	30	40	50	
1	Compressive strength	30	-	-	-	-	15	-	16	[10]
2		43.07	31.34	22.42	15.10	-	-	-	-	[11]
3		21.14	-	25.34	-	-	-	-	-	[12]
4		35.0	51.0	38.1	31.0	29.0	22.0	19.0	-	[13]
5	Flexural strength	5.4	-	-	-	-	3.6	-	3.7	[10]
6		4.7	3.8	3.09	2.38	-	-	-	-	[11]
7		3.4	-	2.7	-	-	-	-	-	[12]
8		2.5	3.1	3.3	2.9	2.8	2.2	1.6	-	[13]
9	Split tensile strength	3.48	2.28	2.28	1.82	-	-	-	-	[11]
10		2.2	1.9	1.9	-	-	-	-	-	[12]
11		4.4	4.9	4.9	4.8	4.3	4.1	3.0	-	[13]

Plastic as Coarse Aggregate Replacement

Mechanical recycling allows for processing waste materials consisting of HDPE. The process involves grinding waste into smaller pieces before cleaning, drying, melting, ventilation, and then shredding into finer particulates. The current research examined the viability of PET plastic as a replacement for fine, coarse, and pallet aggregates and found there is very minimal loss in strength when replacing at the coarse replacement level. For HDPE, the thermal properties of recycled concrete indicated only a small decline of 12% at a 4% volume replacement. The values of different mechanical properties for recycled concrete with E-plastic at 10% level of replacement are listed in Table 2 above, where the flexural strength increased by 1.2%, the split tensile strength increased by 20%, and the compressive strength decreased. Workability improved with the increase in PS content when incorporating PS at 10% by volume with fly ash. Concurrently, the density decreased, while other mechanical properties decreased slightly compared to the conventional mixes: approximately by 44%. With tests carried out replacing plasticizing aggregates with the addition of 20%, the compressive strength in the samples showed a reduction by 44%. In addition, increasing the content of plastic aggregate reduced the tensile splitting strength, bending strength, and dry density of the concrete mix.

Plastic as Fiber/filler

Recycled plastic is prepared as aggregate by mixing it with filler material to form an a uniform mixture, processing it in a mold, producing a sheet/slab of composite material, and again grinding the sheet/slab to make fine or coarse aggregate for concrete production and ash Additionally, tests via scanning electron microscopy were performed in order to verify the uniformity of the filler material and plastic[1]. It was reviewed that if pet plastic is used by fiber, it enhances the performance of concrete as well with replace aggregate it reduces the strength parameters.

As shown in Table 3 (a), it was found that a combination of MWP fiber up to 1% in the concrete mix was feasible, guaranteeing that the fresh properties will not be affected. Table 3 (b) shows concrete strength discrepancies for various percentage combinations of plastic as fine filler material.

Table 3 (a). Strength variation with change in replacement percentage of fibres

Sl. No	Hardened Properties	Percentage replacement of plastic as Filler						Reference
		0	0.5	1	2	4	6	
1	Compressive strength	31	32.7	40.4	40.1	38.4	38.3	[14, 15]
2	Split tensile strength	1.88	1.99	2.05	2.12	2.08	2.05	[14, 15]

Table 3 (b). Strength variation with change in replacement percentage as fine filler

Sl. No	Hardened Properties	Percentage replacement of plastic as Filler							Reference
		0	5	10	20	30	40	50	
1	Compressive strength	53.4 42	- -	59.03 40.5	51.07 39.5	51.59 38	49.28 33.5	48.32 -	[16] [17]
2	Split tensile strength	3.5	-	3.3	3.2	3.15	2.8	-	[17]

Mechanical Properties

Compressive Strength

Compressive strength is defined as the maximum load that a material can withstand before failure, divided by its cross-sectional area. In conventional procedures, samples are fabricated in geometries, normally cube, prism, or cylinder, and are tested under progressively increasing applied loads with a compression-testing machine, as specified in EN 12390-3. This research investigates the properties of concrete made with recycled PET bottles without and with the addition of different kinds of plastic waste; it specifically considers its effect on compressive strength. Concrete mixes were made in an experimental investigation with 5.0% substitution of fine aggregates with recycled PET bottles. Different concrete mixtures of different water-to-cement ratios were prepared, which exhibited only a marginal reduction in compressive strength with the addition of PET aggregates. The reduction in compressive strength was dramatically in greater amounts in mixtures that contained lower cement contents and higher water-to-cement ratios. This is associated with the greater amount of bleeding water surrounding the PET aggregate particles, which acts to weaken the bond between the cement paste and the plastic aggregates, as indicated by Frigione [18].

Other further investigative tests were conducted to evaluate the suitability of the use of fabiform-shaped plastic waste aggregates, using replacement percentages by volume, i.e., 0%, 10%, 15%, and 20%. The compressive strength with waste plastic aggregates showed great reduction. This is as a result of the particles of plastic increasing in size, the adhesive strength between the cement paste and the plastic aggregate surface decreases, and that plastic is hydrophobic limits water, which is essential during hydration of cement. Ismail and Al-hashmi [19] Further efforts focused on the mechanical properties and abrasion behavior with shredded PET bottles as partial replacement of natural aggregates in the mix at 5%, 10%, and 15% PET partial replacement levels. The PET aggregates existed in three types: fine (PF), medium (PC), and pellet-shaped (PP). Results showed compressive strength to be reduced with the addition of PET aggregates as against the first drop indicated with PC aggregates, followed by PF and PP [20].

Likewise, experimental work on concrete and mortar properties with plastic waste addition has proved that with increasing content of plastics, the compressive strength decreases [21, 22]. Another study investigated adding PVC plastic waste to ecological mortar. The compressive strength was significantly reduced as the content of PVC increased. Mortar with a replacement by sand of 50% of the PVC was classified as masonry mortar of class M20, while the replacement of 100% led to class M12.5, which is suitable for masonry or plastering only [23]. A separate investigation evaluated the physical and mechanical characteristics of mortar incorporating 3%, 10%, 20%, and 50% PET waste aggregates as substitutes for sand, alongside two different thicknesses of PET aggregates (designated as PET1 and PET0.1). The findings indicated a decrease in compressive strength associated with increased quantities of PET aggregates, with mixtures containing 0.1% PET demonstrating more significant reductions in strength relative to those with 1% PET. Hannawi et al. [24] conducted research on lightweight concrete incorporating 1% to 10% PET plastic waste, revealing enhanced compressive strength at 1.0% PET, followed by a decline in strength with greater PET concentrations, which was ascribed to inadequate bonding between the plastic aggregates and cement paste [25].

Incorporation of recycled PET and various plastic waste aggregates into concrete mixes generally decreases the compressive strength. This decomposition is a function of various factors, which includes the type and size of the plastic aggregates, their hydrophobic nature, and the bonding strength with the cement paste. Results continue to highlight the need for further research into optimized uses of recycled plastics in concrete applications that would not jeopardize the benefits of waste reduction but, rather, produce a sustainable practice.

Tensile Splitting Strength

The tensile strength of concrete is indirectly measured through the split tensile strength by applying a compressive load on a cylindrical specimen until it breaks along the vertical diameter. According to EN 12390-6, this tensile strength represents the stress at which the concrete specimen will probably begin to crack when exposed to a compressive force. This experimentation investigates the effects of the replacement of natural aggregates by variations along with dimensions of the recycled PET aggregates at 5%, 10%, and 15% substitution levels on the split tensile strength of concrete compositions.

The test results show a trend of reduction in split tensile strength with an increase in the content of PET plastic waste. This is due to the more polished surface of the plastic aggregates and the presence of free water on those surfaces, which weakens the bonding between the plastic aggregates and the cement paste. Among all studied types of PET aggregates, the maximum reduction in split tensile strength was recorded for concrete provided with coarse PET aggregates (PC), and the minimum reduction was noted for concrete provided with pellet-type PET aggregates (PP). The reduction in split tensile strength of the concrete provided with PC aggregates is somewhat higher, accompanied by an increased water-to-cement ratio in their mixtures, as remarked by Saikia and De Brito [26].Other mixes were made with 5%, 15%, 30%, 45%, 65%, and 85% replacement of fine aggregates by shredded PVC waste. In most mixes, the split tensile strength showed a reduction in magnitude, generally showing a trend of reduction with increasing PVC content. For 15% substitution of PVC, there was a partial violation in the general trend, probably because of the change in aggregate packing and size distribution. The study also found strong correlations of split tensile strength with the compressive strength of different concrete mixes. The lower reduction in split tensile strength with respect to other works was due to the flaky nature of the PVC particles, which provided a more significant but less effective transition zone [27]. Consistent with previous findings, further research on concrete and mortar with plastic waste confirmed that increased plastic content generally leads to reduced split tensile strength. PET plastic’s inability to absorb water and facilitate cement hydration results in poor adhesion between plastic particles and cement paste. Nonetheless, at lower percentages of PET aggregates, a slight improvement in split tensile strength was observed. This improvement is likely due to the relatively high tensile strength of the plastic particles compared to other concrete components, enhancing the overall tensile strength of the mixture [28]. In another study, concrete mixtures were prepared with 0%, 10%, 20%, and 30% replacement of fine and coarse aggregates with e-plastic waste. The results obtained showed that the split tensile strength decreased significantly with an increase in the amount of plastic waste in the concrete specimens [29]. When the engineering properties and durability of concrete that incorporated synthetic aggregates were studied, split tensile strength was reported to rapidly decline as plastic waste content increased. It has been ascribed to the low bonding between the synthetic aggregates and the cement paste, which reduces the concrete’s resistance to load-bearing [30]. The addition of recycled plastic also had an effect on the fracture energy, a critical parameter necessary for understanding the post-peak behavior of concrete. Gesoglu et al. [31] argue that the reason for deterioration in the fracture energy of concrete with an increase in the percentage of PVC added could be the intrinsic weak characteristics of PVC particles and the created additional air voids.

Flexural Strength

Flexural strength, not to be confused with the modulus of rupture, is the maximum bending stress that a material can handle before yielding. The property is determined by prismatic specimens, which are subjected to a bending moment by load applications using top and bottom rollers in accordance with EN 12390-5. Available literature reportedly indicates that the flexural strength decreases progressively with an increased percentage of waste plastic aggregates in a mix design.

Then, the effect of incorporating 5.0% recycled, unwashed PET bottles, as fine aggregates, into concrete mixtures having different water-to-cement (w/c) ratios, was determined through this research study. It was found that the flexural strength of concrete mixtures was slightly enhanced with the addition of PET aggregates. In particular, concrete incorporating waste PET showed higher maximum strain to stress, which was an indication of ductile behavior in comparison to the reference concrete. This phenomenon can be attributed to the relatively compressible nature of PET particles, which reduce the interactions of the cement paste with the stiff aggregates, subsequently lowering the overall stiffness of concrete [32].

Subsequent investigations focused on concrete mixes with 10%, 15%, and 20% fabriform-shaped plastic aggregates to replace sand. The flexural strength decreases with an increase in plastic content in all curing conditions used. The significant explanation for the loss of strength is the low bond strength between the waste plastic and cement matrix and the hydrophobic nature of plastic interfering with the hydration mechanism of the cement. Inclusion of plastic waste, however lead to increased deflection and decreased micro-crack propagation compared to the reference concrete [33].

In a comparable manner, an experimental study evaluated the effects of replacing natural aggregates with three distinct shapes and sizes of PET aggregates at proportions of 5%, 10%, and 15%. Consistent with findings from other investigations, a notable decrease in flexural strength was identified at elevated percentages of plastic aggregates. During the testing procedure, control specimens usually cracked in two pieces, while in contrast those with PET aggregates did not show any fracture due to a bridging mechanism by PET particles that prevents brittle splitting. Among the three forms of PET aggregates, coarse PET aggregates (PC) exhibited the maximum decrease in flexural strength, followed by fine PET aggregates (PF), and pellet-shaped PET aggregates (PP) [34].

Derivative studies conducted on mortar with plastic waste content have shown a decreasing trend in flexural strength with the addition of plastic. This reduction is attributed to the agglomeration of plastic particles and reduction in levels of cohesion between the cement paste and plastic aggregates. Furthermore, the age of concrete is having an impact on flexural strength. Bhogayata and Arora [35] In studies on mortars that have used 3%, 10%, 20%, and 50% of plastic waste as a replacement for fine aggregates, no visible differences were seen in strength with respect to flexure even up to a 10% replacement by PET1 and PET0.1. However, having a higher percentage, beyond 10%, there is a drop of the flexural strength. This decrease is ascribed to the elasticity and non-brittle nature of plastic aggregates, which enhance concrete ductility and delay further crack development. Studies concerning partial replacement of coarse aggregates with E-plastic waste at rates of 10%, 20%, and 30% showed that the flexural strength significantly reduced with increased plastic content [36].

Flexural strength is generally decreased by the inclusion of recycled plastic aggregates, due to reasons such as a lack of adhesion between plastic and cement paste, and also due to the properties of plastic materials themselves. However, some types and proportions of plastic aggregates can increase ductility and reduce crack propagation, thus being advantageous for some specific uses. More research is needed to improve the use of plastic waste in concrete in as much as mechanical performance is not compromised.

Conclusions

Many studies have found that the partial replacement of concrete aggregates with plastic decreases the density of the concrete mixture, making it suitable for the production of lightweight concrete. The density of the concrete mixture is inversely proportional to the increase in the percentage of recycled plastic aggregate. This is due to the improvement caused by the fibers, which bridge cracks, preventing the formation of micro-cracks and further crack growth. The strength enhancement is pronounced with lower contents of fibers, whereas higher percentage contents of plastic fibers tend to decrease the mechanical properties of the composites. However, some studies have also shown opposing findings to enhancement, namely a loss in mechanical properties with increasing plastic fiber content. Such a loss can be due to factors such as aggregate strength, cement paste strength, and the bonding characteristic between concrete components. Other advantages found with the addition of fibers are the bundling during mixing and pouring that can further produce weak spots around the fiber surfaces, leading to early cracking under mechanical loads. Reuse of plastic, as a part of recycling, has been found to be extremely economical by quite a few manufacturers. Gainfully, plastic waste can be employed in lightweight concrete production.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Md. Saniul Haque Mahi: writing - original draft, resources. **Tanjun Ashravi Ridoy:** conceptualization, supervision. **Fatima Antara Islam Mounata:** visualisation. **Meheron Khan:** formal analysis.

Data Availability Statement

The data used to support the findings of this study are included within the article.

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