Waste/Recycled Plastics in Concrete

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Abstract: **While the use of plastics has gradually increased in our daily lives due to its user-friendly features, lightness and cost-effectiveness, scientific and engineering communities have raised their concerns in recent decades regarding the harmful effects caused from the usage and disposal of plastics on our environment. Also, from an environmental point of view, concrete production heavily contributes to greenhouse gas emissions and the majority of construction materials are produced from natural resources. Therefore, there exists a need for developing sustainable concrete that leaves less carbon footprint and requires fewer natural resources. In this regard, utilizing waste/recycled plastics in concrete can be a viable alternative that offers obvious ecological and environmental benefits. Numerous researchers and engineers have investigated the feasibility of using various types of plastics in concrete production. Since different types of plastics possess engineering properties that are different from conventional constituents of concrete, it is important to understand how adding plastics would alter the characteristics and behavior of concrete. This paper presents a methodical review on recent researches that used waste/recycled plastics as an additive or a partial replacement of aggregates in concrete, and discussed their effects on various properties of concrete.**

Keywords: **Waste Plastic; Recycled Plastics; Concrete; Compressive Strength; Flexural Strength.**

I. INTRODUCTION

With the rapid technological advances and improvement in standard living, the quantity of plastic consumed throughout the world has gradually increased in various fields for domestic, industrial and commercial purposes such as packaging, manufacturing, building and construction, and automotive and industrial applications. The usage of plastic is so wide spread that it nowadays seems as if plastics have become integral part of our daily lives. This is due to a numerous advantages of plastic over other materials including its user-friendly features, lightness, flexibility, and cost-effectiveness. While the use of plastics provides a wide range of benefits to our society, scientific and engineering communities have begun to raise their concerns in recent decades regarding potential harmful effects of plastic usage on our environment. These increased concerns have prompted numerous engineers searching for ways to recycle and reuse these waste plastics.

Construction industry has been also facing a few issues associated with the global carbon footprint and limited natural resources. Concrete production heavily contributes to greenhouse gas emissions and the majority of construction materials are produced from natural resources. Therefore, there exists a need for developing sustainable concrete that causes less greenhouse gas emissions and requires fewer natural resources. In this regard, the use of waste/recycled plastics as aggregate in concrete production may be a viable alternative that offers obvious ecological and environmental benefits. It would not only reduce the exploitation of natural resources but address the environmental concerns such as a disposal of non-biodegradable waste plastics, a limited landfill space, and emission of harmful chemicals. A recent study estimated that over 20 billion tons of concrete are annually produced worldwide, which makes it the second most consumed substance following fresh water [1]. In a typical concrete production, aggregates occupy approximately ¾ of concrete volume and 25% to 35% of aggregates are comprised of sand. Some researchers predict that more than 800 million tons of sand could be saved per year in the US by replacing 10% of the sand used in concrete with finely ground plastic particles [1]. Concrete production contributes approximately 4.5% of the world's human-induced carbon dioxide emissions. Scientists and engineers believe that a substantial amount of carbon emission and global carbon footprint can be prevented if natural aggregates are replaced by recycled materials such as plastics in concrete production [2].

Different types of plastics have their unique engineering properties that are different from conventional constituents of concrete mix. Therefore, before the use of plastics in concrete is considered, it is important to understand how adding plastics would alter the characteristics and behavior of concrete. This paper presents a methodical review on numerous investigations that utilized waste/recycled plastics as an additive or a partial replacement of aggregates in concrete production, and discusses their effects on the properties of concrete. The purpose of this study is to provide potential researchers with a source of valuable experimental results and research findings so that more meaningful outcomes can be produced in their future researches.

II. TYPE OF WASTE/RECYCLED PLASTICS USED IN CONCRETE

There are various types of plastics used for domestic, commercial or industrial purposes including polypropylene, polyethylene terephthalate, high density polyethylene, and low density polyethylene. Polypropylene is a thermoplastic polymer used in a variety of applications such as packaging for consumer products, plastic parts for automotive industry, special devices, etc. Polyethylene terephthalate (PET) is the most common thermoplastic polymer, a plastic resin and a form of polyester, which is a popular material used for packaging food or non-food products. High density polyethylene (HDPE) is a thermoplastic polymer plastic made from the monomer ethylene, commonly used in manufacturing plastic bottles, plastic lumber, toys, etc. Low density polyethylene (LDPE) is a flexible light weight plastic made from petroleum and is commonly used in manufacturing plastic products such as plastic bags. Table 1 provides a brief description and original usage of the above mentioned plastics. If adequately recycled and processed, these plastics can be used in the forms of additive fibers, strips, aggregates, and other forms in concrete production. Different characteristics of waste/recycled plastics, such as types, sizes and shapes of plastics used in concrete, may have different influence on concrete properties. The next paragraph describes how these plastics are typically collected and processed in preparation of making concrete specimens for testing.

Table 1: Typical waste/recycled plastics used in concrete.

Plastic type	Description	Original usage before recycled	Modulus of Elasticity (ksi)	Tensile Strength (ksi)
Polypropylene	Thermoplastic polymer, hard, flexible.	Straws, containers, snack bags, lunch boxes.	180 to 260	3.6 to 5.8
Polyethylene terephthalate (PET)	Most common thermoplastic polymer resin of polyester family: clear, strong and lightweight.	Fibres for clothing, bottles for water and soft drink.	300 to 450	8 to 11.6
High density polyethylene (HDPE)	Thermoplastic polymer made from monomer ethylene; high chemical resistance; white or colored; hard or soft.	Plastic bottles (e.g., bottles for milk, cream, shampoo, cleaners, etc.), plastic lumber, piping, crinkly shopping bags, freezer bags.	85 to 220	3.3 to 4.8
Low density polyethylene (LDPE)	Thermoplastic made from monomer ethylene; soft, flexible.	Container lids, garbage bags, garbage bins, plastic sheet.	30 to 45	1.3 to 2.6

Plastic wastes can be retrieved or recycled in two ways: collecting plastics before or after they enter the municipal waste stream. Plastics collected before they enter the municipal waste stream are relatively clean and therefore can be easily recycled, only requiring some separation and minor purification processes. On the other hand, most post-consumer waste plastics that end up on the municipal waste stream are usually contaminated and, often times, difficult to recycle economically. Once collected, these plastics undergo, depending on the purpose of how they will be used, a mechanical recycling, a mechanical grinding or a melting process before they can be used in a concrete mix as plastic aggregates or plastic fibers. In comparison between the mechanical recycling and the melting process, the mechanical recycling is known to be more economical while the melting process allows the materials with more uniform in size and properties. After these plastics are adequately processed, they can be used as an additive or a partial replacement of fine (sand) and/or coarse (gravels) aggregates. Mix design, proportioning and casting of concrete mixes containing waste/recycled plastics generally follow the procedures similar to that of conventional concrete. Some of the recent research efforts on the use of waste/recycled plastics in concrete production, and discussion on their effects on various concrete properties are given in the subsequent paragraphs and in the next section, respectively.

Thorneycroft et al. [1] explored the possibility of using recycled plastics as a partial replacement for fine aggregate to produce structural concrete. The authors utilized fine-graded plastic particles made from recycled plastic bottles and plastic bags and investigated their impact on the structural strength of concrete tubes and cylinders. A study by Al-Manaseer and Dalal [3] demonstrated the use of post-consumer plastic aggregates made from recycled car bumpers to replace conventional aggregates in concrete. A total of twelve concrete mixes were made with varying quantities of plastic aggregates (0%, 10%, 30%, and 50%). In a similar study by Batayneh et al. [4], ground plastic particles were used to partially replace fine aggregates. Different plastic proportions were planned in concrete mixes ranging from 0 to 20% by volume of fine aggregates while keeping the constant water-cement ratio and the coarse aggregate content. In a recent investigation by Rai et al. [5], the research team considered various mix proportions with waste plastics, superplasticizer and other conventional ingredients of concrete to produce concrete specimens. The waste plastics selected were virgin plastics used to replace portion of conventional fine aggregates. The mix proportions used in this investigation are presented in Table 2. An experimental research by Sjah et al. [6] that investigated the effect of using crushed polypropylene waste plastics on the strength of concrete, the research team added various proportions of crushed polypropylene plastics to concrete mixes. The plastic contents used were 0.10%, 0.15%, 0.20%, 0.25%, 0.30%, 0.50%, 0.70%, 1.0%, 2.0%, and 3.0% in fraction volume. Kumar et al. [7] conducted an investigation to assess the flexural strength of concrete reinforced with PET plastics. Different forms of PET plastics were used. Some concrete specimens were reinforced with PET hollow rebars placed in the tension region. In other specimens, PET short strips were used to replace 1% of fine aggregates. Bayasi and Zeng [8] compared the changes in the properties of concrete mixtures containing polypropylene plastic fibers. Table 3 presents the various sizes and quantities of the polypropylene fibers used in this study and its resulting fresh properties. In a research [9] that investigated the effects of polyethylene terephthalate (PET) plastic bottles lightweight aggregate (WPLA) on concrete properties, various mix proportions were applied with water-cement ratios of 45%, 49%, and 53%, and WPLA replacement ratios of 0%, 25%, 50%, and 75% by volume of fine aggregate. PET plastic bottles were cut into 0.20-in. to 0.60-in. fractions and coated in ground granulated blast-furnace slag (GBFS) to solidify the surface of the aggregates. Saikia and Brito [10] incorporated three different forms of recycled PET aggregates – coarse plastic flakes (PC), fine plastic fractions (PF), and plastic pellets (PP) – to produce concrete specimens for laboratory testing. A sieve analysis of these PET aggregates utilized in this study is given in Table 4. A study by Marzouk [11] demonstrated the use of post-consumer waste PET plastic bottles as sand-substitution aggregates in manufacturing cementitious concrete composites for building application. Various quantities of PET plastics ranging from 2% to 100% were incorporated to replace find aggregates.

Table 2: Mix Proportion [5].

plastic content, %	cement (C), lb	coarse aggregate (CA), lb	fine aggregate (FA), lb	waste plastic (WP), lb	water/cement ratio	proportion ratio (C:CA:FA:WP)
0	933	2826	1034	0	0.44	1 : 3.03 : 1.100 : 0.000
5	933	2826	981	19.31	0.44	1 : 3.03 : 1.052 : 0.021
10	933	2826	930	38.58	0.44	1 : 3.03 : 0.997 : 0.042
15	933	2826	880	58.20	0.44	1 : 3.03 : 0.943 : 0.060

Table 3: Content of polypropylene fibers and fresh concrete properties [8].

Mix No.	Fiber length (in.)	Fiber volume fraction (%)	Air content (%)	Slump (in)
1	–	0	2.0	8.5
2	0.50	0.1	1.5	9.5
3	0.50	0.3	2.5	8.0
4	0.50	0.5	4.5	7.5
5	0.75	0.1	1.5	10.5
6	0.75	0.3	3.5	9.5
7	0.75	0.5	5.0	1.0

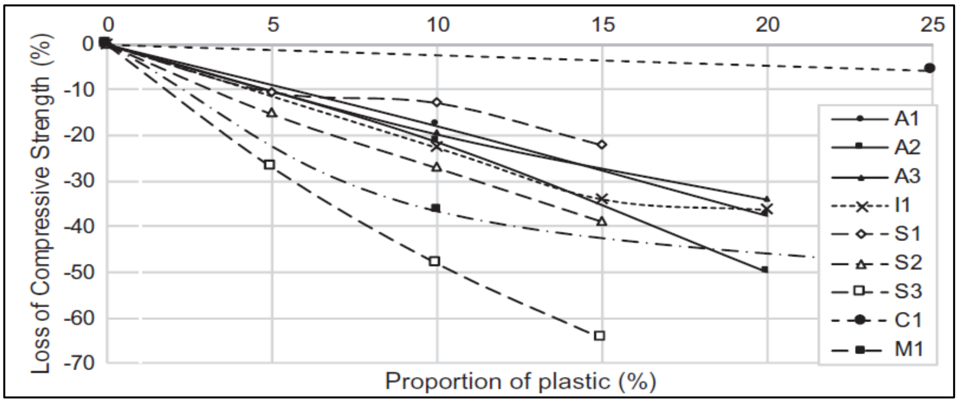
Table 4: Sieve analysis of three PET aggregates [10].

Sieve Size (in.)	Cumulative amount passed (%)		
	Coarse flakes (PC)	Fine fractions (PF)	Plastic pallets (PP)
0.63	100.00	100.00	100.00
0.44	99.96	100.00	100.00
0.31	97.69	100.00	100.00
0.22	49.24	100.00	100.00
0.16	20.59	99.99	99.46
0.08	0.89	45.65	7.93
0.04	0.02	0.94	0.04
0.01	0.00	0.00	0.00
Residue	0.00	0.00	0.00

Al-Bakri et al. [12] recycled trash bag plastics collected from a local landfill to produce HDPE plastic aggregates that were processed into round-shaped particles with a size of approximately 1.0 in., and heat-treated at temperatures ranging from 320°F to 392°F for 10 minutes. These HDPE plastics were then used as a partial replacement of coarse aggregates in concrete production. Various mix proportions were considered with a constant water-cement ratio of 0.5 and crushed-stone aggregates to HDPE plastic ratios of 0:100, 15:85, 30:70, 45:55, and 60:40 in percentage. Rahim et al. [13] conducted a comparative analysis on workability and compressive strength of the concrete specimens containing recycled HDPE plastics. The HDPE to coarse aggregate replacement ratio used were 0% (control), 10%, 20%, and 30%. Sojobi [14] used pulverized LPDE waste plastics as a partial replacement of sand to investigate the effect on the concrete strength. The pulverized LPDE waste plastics were made from disposed plastic sachets collected from a local residential area. The LDPE plastics were ground and sieved with 0.08 in. test sieve to obtain fine LPDE plastic aggregates. Different mix proportions were used in concrete production with variable water-cement ratios ranging from 0.48 to 0.87 and the LDPE waste plastic to sand replacement ratios of 0% (control mix), 5%, 10%, and 15%. A recent research by Manikandran et al. [15] conducted a feasibility study on utilizing LDPE plastics as a modifier in cement concrete. An emphasis was placed on investigating the effect of adding LDPE plastic (3%, 4%, and 5%) under various temperatures (158°F, 176°F, and 194°F) and thermal curing duration (4, 8 and 16 hours).

III. EFFECT OF WASTE/RECYCLED PLASTICS ON CONCRETE PROPERTIES

Numerous studies that investigated the feasibility and practicability of plastics in concrete indicate that the incorporation of plastics have both positive and negative effects on concrete properties and strength. While some researchers reported that the use of plastic fibers or aggregates improved some of the fresh properties and durability of concrete such as workability, absorption capacity, toughness and abrasion behavior, the majority of studies showed that the use of plastics resulted in lower mechanical properties and poor bond strength. This trend is well illustrated in Fig.1 that shows the relationship between the quantity of plastics used and the corresponding compressive strength [1]. There exist, however, some studies [6, 15, 16, 17] that reported an improvement in the mechanical properties of concrete with a special processing of plastics and/or concrete mixes (e.g., heat treatment, radiation treatment, etc.). This section presents experimental results and research findings from some of the recent studies that utilized recycled/waste plastics in concrete production, and discusses their effects on various properties of concrete.



	References				
	A [18]	I [19]	S [20]	C [9]	M [21]
1	All small particles	PET/polystyrene	PP	PET coated in GBFS	Angular particles
2	All large particles	N/A	PF	N/A	N/A
3	50/50 mix of particles	N/A	PC	N/A	N/A

Fig. 1: Relationship between reduction in compressive strength and plastic content [1].

Rai et al. [5] conducted a comparative study on fresh and mechanical properties of several concrete specimens containing waste plastics and superplasticizer. The test results indicated that the fresh density of concrete decreased by 5%, 8.7%, and 10.75% for adding the plastic contents by 5%, 10%, and 15%, respectively. The authors speculated that the reduction in fresh density might be due to the density of the waste plastics being 70% lower than that of fine aggregates. Also, it was observed that the workability improved by approximately 10 to 15% when superplasticizer was added to the concrete mix and that the measured slump sharply decreased with an increase in waste plastic content. The results of compression testing revealed that the compressive strength of concrete decreased with increased use of waste plastics at all curing ages and that adding superplasticizer to the concrete mix increased the compressive strength by approximately 5%. Similarly, increasing the amount of waste plastics decreased the flexural strength of specimens. Sjah et al. [6] studied the effect of using crushed polypropylene waste plastics on compressive, tensile, flexural and shear strength of concrete. Laboratory testing results indicated that the strength of conventional concrete improved when a fraction of polypropylene plastics were added to the concrete mix. The results of a 7-day testing revealed that the compressive strength of a specimen containing 1% of crushed polypropylene plastic improved by 5% and that the tensile strength was increased by 11% when 0.5% of crushed PP plastics were added to the concrete. Moreover, a 28-day testing on the specimens with 0.5% of crushed polypropylene plastics resulted in 17% and 43% improvement in flexural and shear strength, respectively.

In a study by Choi et al. [9], waste polyethylene terephthalate (PET) bottles light weight aggregates (WPLA) were used to investigate the effects of using recycled plastics on the fresh properties of concrete mixtures as well as compressive strength of hardened concrete specimens. WPLA were made from the waste PET bottles and granulated blast-furnace slag and was used to partially replace find aggregates. Various mix proportions were used in concrete production including the water-cement ratios of 45%, 49%, and 53%, and the WPLA replacement ratios of 0%, 25%, 50% and 75% by volume of fine aggregates. It was observed from the fresh property testing that an increased use of WPLA content resulted in a reduction of bulk density of concrete mixtures. At 75% of WPLA replacement ratio, the workability of fresh concrete improved to 123% but the compressive strength decreased by 33%. Saikia and Brito [20] demonstrated the use of PET plastic aggregates to investigate the effects on water absorption capacity and compressive strength of concrete. Figure 2 presents percentage differences in water absorption capacities and compressive strengths of concrete containing three different types of PET aggregates: coarse plastic flakes (C), fine plastic fractions (F), and plastic pellets (P). The percentage differences were measured with respect (w.r.t) to a control specimen. The results show that the water absorption capacities were the highest in the specimens with 15% plastic content indicating that the porosity of these specimens increased with higher content of plastic. Conversely, it can be seen that the compressive strength decreased with an increase in plastic content at all replacement levels. The authors pointed out that, in addition to the plastic content, the bonding between the PET aggregates and cement might be one of the factors contributing to the reduction in compressive strength. Although not shown in Fig. 2, the authors also stated based on the results of other testing that flexural strength characteristics were proportional to the reduction in compressive strength. It was also noted that, while the use of recycled plastics generally reduced the flexural and compressive strengths of concrete, the toughness of concrete containing recycled plastics seemed to be dependent upon the size and shape of the PET aggregates used in the concrete mix, that is, using coarse and flaky PET aggregates seemed to improve the overall toughness of concrete [4].

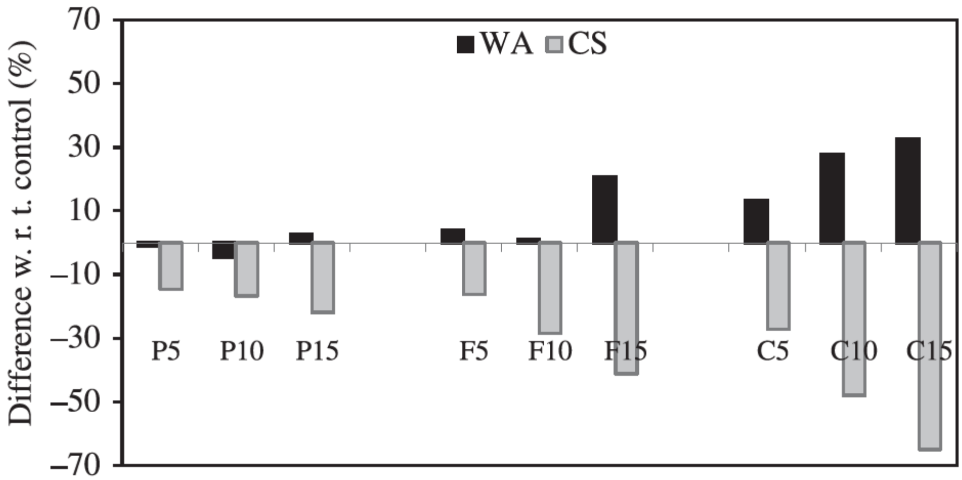


Fig. 2: Change in water absorption (WA) capacity and compressive strength (CS) [4].

Al-Bakri et al. [12] studied the effects of HDPE plastics on compressive and flexural strengths of concrete. Comparisons between conventional concrete and the specimens containing HDPE plastics showed that the use of HDPE plastics improved some concrete properties including toughness and thermal conductivity. However, both the compressive and flexural strengths of concrete decreased as the content of HDPE plastic increased. In a study by Rahim et al. [13], the authors reported that the workability of fresh concrete improved with an increasing HDPE plastic content. From numerous compressive testing conducted at 7, 14 and 28 days after the concrete mix, it was observed that the compressive strength decreased with a higher content of HDPE. The author speculated that this trend was due to the low strength of HDPE plastic and its ineffective bonding with other concrete constituents.

In an investigation that studied the effect of pulverized LPDE waste plastics on concrete strength, Sojobi and Owamah [14] reported that the compressive strength decreased linearly with increasing LDPE plastic content. This reduction in compressive strength appeared to be more apparent in the test specimens with a higher coarse aggregate to cement ratio, which caused a larger amount of void and porosity in the concrete, thereby allowing more water to be absorbed and more LDPE plastic to fill up the voids. The authors recommended that LDPE concrete be used in production of non-critical, non-load bearing structural components such as tiles, partitions, etc. Manikandran et al. [15] showed that, when compared to the control concrete, adding LDPE plastic was effective in improving corrosion resistance and compressive strength of concrete for all percentages of plastic added (3%, 4%, and 5%) while the maximum compressive strength was obtained at 5% of LDPE plastic proportion. It was also found that 3% of LDPE plastic added to concrete resulted in an optimum corrosion resistance and that any further increase in LDPE content showed a reverse trend. In terms of both strength and durability criteria, the authors noted that the concrete with 3% of LDPE plastic at 176°F for 4 hours of thermal curing duration produced an optimum result.

In an effort to develop durable and sustainable concrete with a lower carbon footprint, a research team at MIT examined the possibility of adding irradiated plastic additives to cement for concrete production [16]. Irradiated plastics are basically the recycled plastic flakes that were exposed to harmless doses of gamma radiation. After several attempts, the research team learned that exposing plastics to adequate doses of gamma radiation changed the plastic’s crystalline structures at a Nano-level such that they had more effective molecular connections and became denser, stronger and stiffer. In making concrete specimens, irradiated plastic flakes were ground to fine particles and mixed with cement paste and other additives such as fly ash and silica fume. A series of compression testing were conducted and the testing results were compared with those of control samples (normal, non-irradiated concrete with no plastic). The results indicated that the compressive strength of the samples with irradiated plastics were higher than those without any plastic. Moreover, the compressive strength of the samples with high-dose irradiated plastics increased up to 15% when fly ash or silica fume were added. An important finding of this research is that a commonly known tradeoff of adding plastics into concrete mix is a reduced compressive strength of concrete. However, the test results of this study showed that the use of high dose of irradiated plastic could increase compressive strength [16]. Regarding the safety concern, the authors noted that the plastics exposed to gamma rays had no residual radioactivity and left no trace of harmful radiation.

IV. CONCLUDING REMARKS

Environmental concerns associated with the carbon footprint and rising needs for sustainable concrete have led to searching for suitable alternatives to reuse waste/recycled materials and replace aggregates made from natural resources in concrete production. This paper reviewed and summarized numerous researches conducted on the use of waste/recycled plastics and its effects on various properties of concrete. The following provides concluding remarks drawn from this study:

- Using waste/recycled plastics contributes to higher water absorption capacity and shrinkage but lower density and thermal conductivity of concrete. If adequately used, it would help improve durability, ductility and post-crack behavior of concrete. It can be useful in controlling cracks, shrinkage and creep of concrete.

- Although some researches show an improvement in compressive and flexural strength of concrete with a special treatment (e.g., irradiated concrete), the majority of recent studies report that replacing conventional aggregates with plastics results in a decrease in compressive and flexural strength. The dominant factors for strength reduction appear to be due to increased air content and a weak bonding between plastics and surrounding constituents of concrete.

- Although the use of plastics may weaken the strength of concrete, it can still be useful in manufacturing bricks, blocks and other non-structural, non-critical concrete elements.

- Shape and size of plastics used in concrete seem to have some influence on both fresh and mechanical properties of concrete. Strength reduction resulted from the use of plastics can be mitigated by altering the size, shape and surface of plastic aggregates.

- From an environmental point of view, incorporating waste/recycled plastics into concrete would lead to saving energy and natural resources, and help protect the environment as these waste plastics would otherwise be sent to landfill or incinerated. Adding plastics into concrete, however, generally weakens the load carrying capacity of concrete. Therefore, the key challenge is to find the balance between minimizing the strength reduction and incorporating a meaningful amount of plastics into concrete production.

- More research is needed to establish a guideline that provides an optimized plastic content and mix composition, preferable size and shape, adequate treatment and processing techniques that are essential to improve the overall performance of concrete. In addition, more effort is needed to investigate long-term effects of using waste/recycled plastics on the properties of concrete.

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