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The Effects of Partial Replacement of Sand by Recycled Plastic on Concrete Properties

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Plastic has become an essential part of our life. Unfortunately, it has a negative environmental impact due to its limited recycling rate. This study investigates the effect of replacing 10% of sand with recycled polyethylene terephthalate (PET) in concrete and the effect of particle size of PET used in the concrete mix. The impact of these two factors on the physical and mechanical properties of concrete was examined. Two types of PET particle sizes, 2.36 mm (sieve #8) and 4.75 mm (sieve #4), were investigated. Concrete was cast to determine the behavior of fresh and hardened concrete in terms of workability, unit weight, and compressive strength. The experimental results showed improvement in all three of these critical characteristics of concrete. Replacing 10% of the sand with 4.75 mm PET resulted in better properties than other mixes used in the trials. We think that using a specific size of PET particles rather than a randomly selected PET size combination is the reason behind this improvement. This study proved that utilizing plastic waste in specific ratios and specific particle sizes within concrete mixes can be effectively used in industrial applications. This is a pilot study to explore this specific topic.

Key Words: PET, Particle Size, Compression, Workability, Unit Weight

Introduction

Without a doubt, plastic waste is one of the most critical environmental problems. Five to thirteen million metric tons of plastic waste end up as debris in rivers and oceans every year (Jambeck et al, 2015). In the united states, the recycling rate of PET bottles and jars was 29.1%, while overall the amount of recycled plastics is relatively small three million tons for a 8.7% (EPA, 2018). Therefore, there is a persistent need to find different applications to utilize plastic waste.
Concrete manufacturing is one of the most suitable applications for using plastic waste since plastic preparation in the concrete mixture doesn't need a high purification process compared to other uses of plastic waste. With the increasing scarcity of space for landfilling and its ever-increasing cost, waste utilization has become an attractive and necessary alternative to disposal (Siddique et al, 2008). Using plastic in concrete will help solve a critical environmental problem that the world faces with waste, especially its oceans, which are polluted faster than ever. Plastic pollution poses a great deal of

risk to the environment and, by extension, human and animal health. The ecosystem is plagued with severe problems stemming from the indiscriminate disposal of plastic debris from post-consumer streams onto land and marine habitats.

Literature Review

Various forms of plastic such as high-density polyethylene (HDPE), polyethylene terephthalate (PET), low-density polyethylene (LDPE), polystyrene (PS), polypropylene (PP), polyvinyl chloride (PVC), and glass fiber reinforced plastic (GFRP), etc., are used in various essential products and applications. Plastic is extensively used as a waste disposal material. It is preferred for many more applications because it is flexible, durable, lightweight, moisture-resistant, and costs relatively less to produce compared to other materials (Babafemi et al, 2018). The utilization of waste plastic in concrete production has been reported as a cost and energy saver and potentially a viable alternative to burning or landfilling (Jacob-Vaillancourt & Sorelli, 2018).

Some researchers investigated the effect of replacing sand with PET at different levels (10-50)% by volume. They reported decreases in slump, unit weight, and compressive strength for all levels. For a replacement ratio of 10% of PET, the slump decreased by 12%, fresh unit weight reduced by 6.28%, and compressive strength dropped by 1.2% at age 28 days (Almeshal et al, 2020). Other researchers studied replacing fine and coarse aggregate with non-biodegradable plastic waste. They investigated replacement of fine aggregate weight by 10%, 15%, 20% with Plastic fine (PF) aggregate and for each replacement of fine aggregate 15%, 20%, 25% of coarse aggregate replacement also conducted with Plastic Coarse(PC) aggregate. They reported a reduction in mechanical properties of concrete due to replacement at all levels (Jaivignesh & Sofi, 2017).

Materials and Methods

Cement and Aggregates

The commercial-grade Portland cement No. 1124 was used for this research that complies with ASTM C150 Type II specifications. According to ASTM C-150, this type of cement is meant for general use, where moderate sulfate resistance is desired (ASTM C-150, 2021). The coarse aggregates used in the samples were crushed stones variably sized 1/2 inch or smaller. The aggregates were washed and already graded as all-purpose gravel, which complies with ASTM C33 standard specifications. The fine aggregates used for the study were the No. 1152 all-purpose sand, with a relative density of 154 Ib/ft^3. Cement, gravel, and sand were sourced from Home Depot. Grading of sand was done per ASTM C33, as shown in Figure 1.

Plastic

Crushed polyethylene terephthalate (PET) plastic (shown in Figure 2), sourced from a local materials recycling facility, was used as the plastic aggregates for this research. The relative density of the plastic grains used is 70.80 lb/ft3.

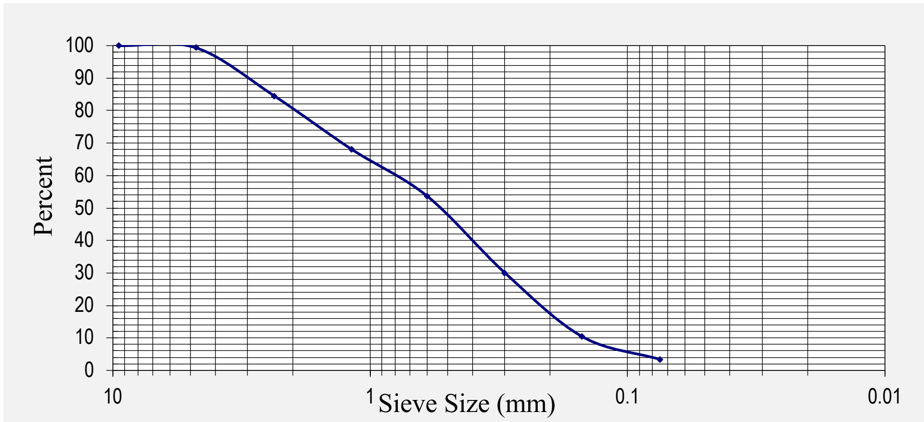

Figure 1. Particle size distribution curve of sand

Figure 2. Crushed polyethylene terephthalate (PET)

Specimens Preparing

A concrete mix proportion of 1:3:3 (Cement: Sand: Gravel), and water-cement ratio (w/c) of 0.55 were used to prepare the samples. Therefore, 33.33 Ib cement;100 Ib sand: 100 Ib gravel were mixed with 18.33 Ib of water in the reference case, against which the results from samples with PET were checked.

First, gravel was added to an electric mixer, and then sand was added gradually, followed by plastic and cement at sequent. The electric mixer kept operating for 5 to 10 minutes between adding the materials. Then water was added, and the mixer ran for 30 minutes before the samples were cast. That produced a homogenous blend of mixing. Poly-ethylene terephthalate (PET) grains size 2.36 mm (sieve #8), and 4.73 mm (sieve #4) were used to replace 10% by volume of the sand, particle size 2.36 mm (sieve #8).

Fresh Concrete Tests

The workability of each concrete mix was determined through a slump test according to ASTM C143 guidelines. The concrete was placed in the slump cone in three (3) approximately equal layers and then tamped 25 times for each layer.

The density of fresh concrete was measured according to ASTM C29. Three measurements were taken for each case, and the average was used for each case.

Specimens Casting and Curing

The casting and curing of test specimens were done following ASTM C31. Concrete cylinders were cast in 4" (diameter) x 8" (height) cylindrical plastic molds and used as compressive strength specimens. The molding was done in three (3) equal layers, each tapped 25 times with the 3/8 inch tapping rod. All concrete samples were removed from molds after 24 hours and remained fully submerged in the curing bath until the date compression testing, Figure 3 shows the specimens while curing in water.

Figure 3. Specimens cured in the container

Figure 4. Humboldt/compression machines

The compressive strength of cylindrical concrete specimens were tested in moist conditions after curing at 7, 14, and 28 days following the ASTM C39 standards. Steel retainer rings fitted with Neoprene pads were placed centered at both ends of the concrete specimen for unbonded capping. The capped specimen was placed in a power-operated machine (Figure 4) and continuously loaded axially at a constant loading rate until failure occurs. The maximum compressive loads are recorded. The compressive strength was determined in lb/in^2 to be the ratio of the maximum load attained and the area of the cross section of the test specimen.

$$\text{Compressive strength} = \frac{\text{Maximum Load}}{\text{Cross-sectional Area of Specimen}} = \frac{4P_{max}}{\pi D^2}$$

Where, P_{max} = Maximum load (lbf)

D = Average measured diameter (in.)

Results and Discussion

Slump

Figure 5 shows slump cone and base, and the measurement way. Replacing 10% of sand with PET produced a slight improvement in the workability of the concrete mix, as shown in Figure 6. In case 10% (A), in which 10% of sand is replaced with 2.36 mm (sieve #8) size of PET, the slump increased from 0.25 inches to 0.31 inches. While in case10% (B), in which 4.75 mm (sieve #4) size of PET is used instead, the slump is further increased to 0.708 inches. Even though the difference in slump measurements may seem small, these results suggest that using larger size plastic grain can improve the workability of concrete. Other researchers reported varying results regarding the effect of plastic grains on the workability of concrete. Many researchers reported decreasing in workability due to replacing sand with plastic aggregates (Albano et al, 2009), (Mustafa et al, 2019) and (Batayneh et al, 2007), while other researchers reported improvement in the workability of fresh concrete with increasing plastic content (Choi et al, 2009) and (Ghernouti et al, 2014). In addition to these two observations, some researchers claimed no significant impact on workability due to replacing sand with plastic aggregates (Kou et al, 2009) and (Tang et al, 2008). The variation in the recommendations in the literature may be attributed to several factors affecting slump results, such as water-cement ratio (w/c), substitution level of plastic aggregates, and the shape of the waste plastic grains (Gu & Ozbakkaloglu, 2016).

Figure 5. Slump measurement

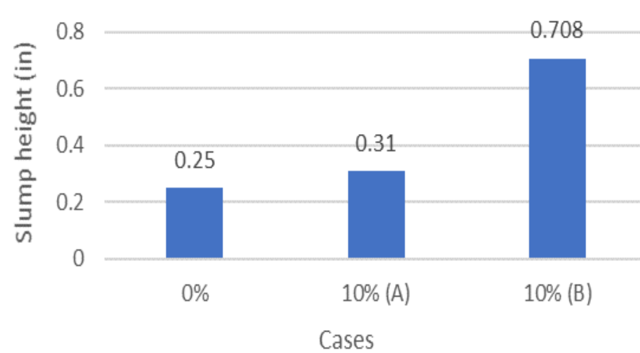

Figure 6. Slump results

Unit Weight of Fresh Concrete

Replacing 10% of sand by PET reduced the unit weight of fresh concrete, as shown in Table 1. The unit weight was reduced more in case 10% (B), where size 4.75 mm (sieve #4) plastic grains were used. The unit weight of concrete dropped from 148.90 Ib/ft^3 to 144.96 Ib/ft^3 and 138.37 Ib/ft^3 when PET sizes 2.36 mm and 4.75 mm, are used, respectively. These numbers correspond to 2.65% and 7.07% weight reduction, which is deemed reasonable since the density of PET size 4.75 mm (75.51 Ib/ft^3) is less than that for size 2.36 mm (76.46 Ib/ft^3).

Table 1

Unit weight of fresh concrete

Cases	Density (lb/ft^3)	PET size (sieve #)
0%	148.90	-
10% (A)	144.96	2.36 (#8)
10% (B)	138.37	4.75 (#4)

Compressive Strength

The compressive strengths of samples prepared with regular concrete and concrete containing PET are shown in Table 2 and Figure 7, which show replacing sand with PET improves the compressive strength of concrete. Using larger PET particles (case B) resulted in better improvements than smaller ones (case A) at each curing age; 7, 14, 28 days. The compressive strength values of regular concrete (0% PET) prepared for comparison were 3322.96, 4045.07 and 4743.61 psi at 7, 14, and 28 days. Compressive strength increased to 3501.61, 4060.84, and 4902.77 psi at 7, 14, and 28 days for Case 10% (A). That represents 5.38%, 0.17%, and 3.36% increase at the three curing ages used in the study. On the other hand, the compressive strengths increased to 4191.15, 4562.71, and 5640.85 psi at 7, 14, and 28 days for Case 10% (B), representing 26.13%, 12.55%, 18.91% increase in comparison to reference case at the same curing age. Also, the compressive strength increased with increasing curing age in all cases, as expected. All similar past research reported drops in compressive strength due to the replacement of sand with PET particles (Juki, et al , 2013), (Saxena, Siddique, Gupta, Sharma & Chaudhary, 2018) and (Frigione, 2010). Even though 10% sand replacement with PET may be considered a small amount in the overall concrete mix, consistently higher compressive strengths noted for samples with PET tested in this study is a significant finding. The authors' opinion that using a specific size of PET particles rather than a randomly selected PET size combination is the reason behind the improved compressive strengths. It should be noted that PET particles in this study had been separated according to ASTM C33 size classification, then the samples were prepared by using PET from a specific size category only, an approach unique to this study.

Table 2

Compressive strength of concrete (psi)

Case	7 Days	14 Days	28 Days
0%	3322.96	4054.07	4743.61
10% (A)	3501.61	4060.84	4902.77
10% (B)	4191.15	4562.71	5640.85

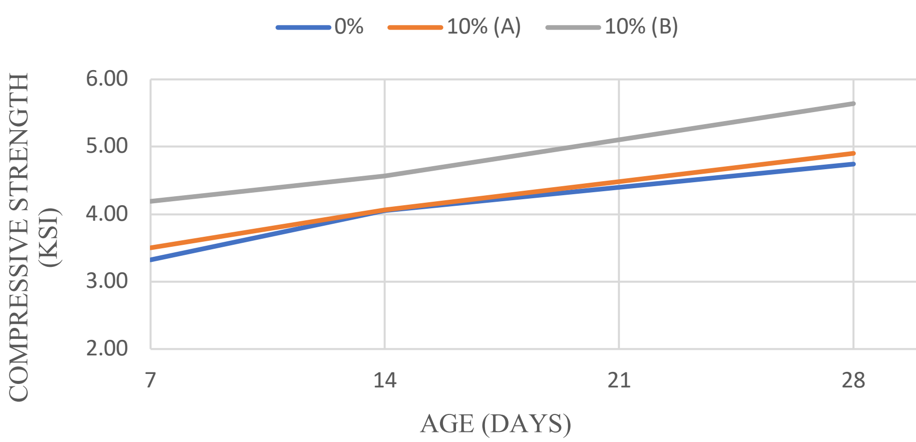

Figure 7. Compressive strength of concrete (ksi)

Conclusion

This research investigated the effect of replacing 10% of fine aggregate in the concrete mix with polyethylene terephthalate (PET) plastic and the impact of PET grain size used in the mixes. Regular concrete mix with cement:sand: gravel ratio of 1:3:3 was used to prepare the samples used as the base in comparisons. Then 10% of sand size 2.36 mm was replaced by PET size 2.36 mm (Case 10% A) and 4.75 mm (Case 10% B) in the trials. The results showed improved concrete properties due to replacing sand with PET. The workability of concrete increased by 24% and 183.2% when 10% sand was replaced by 2.36 mm and 4.75 mm PET grains, respectively. The improvement in workability is very likely attributed to the non-absorbent nature of PET. Since PET density is about 50% lower than sand density, unit weight was reduced by 2.65% (case 10%A) and 7.07% (case 10% B). The compressive strength increased by 5.38% (case 10%A) and 26.13% (case 10% B) after 7 days of curing, while the increases were 3.36% (10% A) and 18.91% (10% B) after 28 days of curing. Therefore, introducing plastic aggregates into fresh concrete mixes is a viable alternative to incineration or landfilling.

This is a pilot study, and the research is ongoing to explore the effect of other replacement ratios and other particle sizes. The limitations of the study is that a machine to grind the plastic was not available at the time of the testing therefore the sizes of the plastic waste had to be limited to what was available in the local market.

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