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Use of waste plastic aggregation in concrete as a constituent material

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Abstract

The amount of Plastics consumed annually has been growing increasingly in Bangladesh. Consequently, waste plastic recycling has become one of the major challenges in recent times. The present study has selected waste PET, a polymer compound of Polyethylene Terephthalate, to investigate its possible use as plastic aggregate in concrete application. The shredded waste plastic was used in concrete with partial replacement of 5%, 10% and 20% by volume of conventional coarse aggregate. Four types of concrete specimens including one without plastic aggregate, for comparison purpose, were prepared. All the concrete specimens were tested for its different mechanical properties after a curing period of 7, 21 and 28 days. Various physical properties of all aggregates and fresh concrete properties were also tested in the laboratory. The specific gravity of waste plastic aggregate was found 1.4 and the maximum density of concrete containing plastic aggregate was 115 lb/ft^3. The density of concrete specimens containing plastic aggregate decreased with the addition of more amount of plastic aggregate. It was found that the concrete specimen containing waste PET at 10% volume showed higher compressive strength and higher modulus of elasticity than other specimens. The splitting tensile strength was about 8-11% of compressive strength. The flexural strength of concrete specimens containing plastic aggregate was lower than that of concrete without plastic aggregate. It was found that the strength of concrete containing PET aggregate falls in the category of lightweight concrete in terms of their strength, specific gravity and density. Thus, the waste PET aggregate could be effectively used to reduce the unit weight of concrete which results in a reduction in the dead weight of a structural concrete. Furthermore, it is concluded that the use of waste PET in concrete provides some advantages such as reduction in the use of conventional aggregate, disposal of wastes, prevention of environmental pollution, and energy saving.

Key words: Waste plastic, pet aggregate, lightweight concrete, mechanical properties, stress-strain behavior

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Introduction

Plastics have become an inseparable and integral part of our lives. Its low density, strength, user-friendly designs, fabrication capabilities, long life, light weight, and low cost are the factors behind such phenomenal growth. Plastics have been used in packaging, automotive and industrial applications, medical delivery systems, artificial implants, other healthcare applications, water desalination, land/soil conservation, flood prevention, preservation and distribution of food, housing, communication materials, security systems, and other uses. With so large and varying applications, plastics contribute to an ever increasing volume in the solid waste stream. The production and consumption of plastic and the rate at which solid plastic waste (SPW) is created have increased considerably since the first industrial scale production of synthetic polymers (plastics) in the 1940s. According to the Central Pollution Control Board, the world produces nearly 150 million tonnes of plastics per year, which is nearly 4.8 tonnes per second and a per capita production of 25 kg/year (Al-Salem et al. 2009). In Bangladesh, due to the rapid increase in the use of PET bottles, solid waste problem is raised. It is known that a long time (more than a hundred years) is needed to degrade the waste PET bottles in the nature (Silva et al., 2005). In recent times, waste plastic recycling has become one of the major challenges in Bangladesh (Islam, 2011). At present there are many plastic industries in our country. They are using a huge number of plastics for recycling and many other purposes.

Different forms of the common materials, using waste plastic granules as lightweight aggregate in the production of lightweight concrete has attracted much attention from the researchers. Lightweight aggregates are generally used to reduce the unit weight of concrete by replacing the conventional aggregates. Nowadays, there are many lightweight concrete applications made with natural or artificial lightweight aggregates are found in the literature. Several researches have been carried out to investigated the use of recycled Polyethylene Therephtalate (PET) as light aggregate, such as Rebeiz et al. (1991), Rossignolo and Agnesini (2002), Silva et al. (2005), Marzouk et al. (2007) and Choi et al. (2005). Koide et al. (2002) used PET and other plastic wastes (PE and PP) together in concrete by partially replacing with mineral aggregates. Albano et al. (2009) determined the mechanical behavior of concrete containing waste PET, varying the water/cement ratio from 0.50 to 0.60, PET aggregate content (10 and 20 % by volume) and the particle sizes of 2.6mm and 11.4mm. The results found that, as the volume proportion and the particle size of PET aggregate increased, the concrete showed a decrease in compressive strength, splitting tensile strength, modulus of elasticity and ultrasonic pulse velocity. Moreover, the water absorption was increased. It was reported that the concrete specimens were not fully compacted and showed the formation of honeycombs which affected the strength characteristics significantly.

Frigione (2010) attempted to substitute 5% by weight of fine aggregate (natural sand) with an equal weight of PET aggregates manufactured from the waste un-washed PET bottles (WPET), in concrete. The specimens were made with different cement content and water/cement ratio. Rheological characterization on fresh concrete and mechanical tests at the ages of 28 and 365 days were performed on the WPET/concretes as well as on reference concretes containing only natural fine aggregate in order to investigate the influence of the substitution of WPET to the fine aggregate in concrete. He found that the WPET concretes display similar workability characteristics, compressive strength and splitting tensile strength slightly lower than that of the reference concrete and a moderately higher ductility.

The present work attempted to utilize the waste PET aggregate as partial replacement of conventional coarse aggregate in making concrete. Various physical and mechanical properties of concrete have been evaluated incorporating different percentage of plastic aggregate by volume. The influences of plastic aggregate on concrete properties have also been analyzed and discussed.

Materials and Methods

Waste Plastic Aggregate

The plastic aggregates were produced mainly from waste PET bottles (Figure 1). The plastic bottles were crushed and cut into small pieces using a crushing machine. The plastic aggregates were washed properly to make them clean and to ensure that no other dust particles were present there (Figure 2).

Polyethylene terephthalate (PET) is thermoplastic polyester with tensile and flexural modulus of elasticity of about 2.9 and 2.4GPa, respectively, tensile strength up to 60 MPa and excellent chemical resistance. It is a semi-crystalline polymer, with a melting point of about 260°C and a glass transition temperature ranging from

70 to 80°C, in relation to the amount of crystalline region enclosed in the amorphous phase. The specific gravity is around 1.3-1.4 g/cm^3 (Van Krevelen, 1990). In this study, the specific gravity of plastic aggregate used was found to be 1.4 g/cm^3. The sizes of plastic aggregate were taken between 4.75 to 9.5 mm. The grading of the plastic aggregate is presented in Figure 3.

Figure 1. Waste PET bottles at a dumping site.

Figure 2. Waste PET aggregate

Fine and Coarse Aggregates

Readily available natural river sand of Fineness Modulus 1.97 was used as fine aggregate. Brick chips were used as coarse aggregate. Gradation of fine and coarse aggregates was accomplished by sieve analysis method. The specific gravity and water absorption tests of fine and coarse aggregates were determined according to ASTM C127 and C128 standards. The physical properties of fine and coarse aggregates are shown in Table 1.

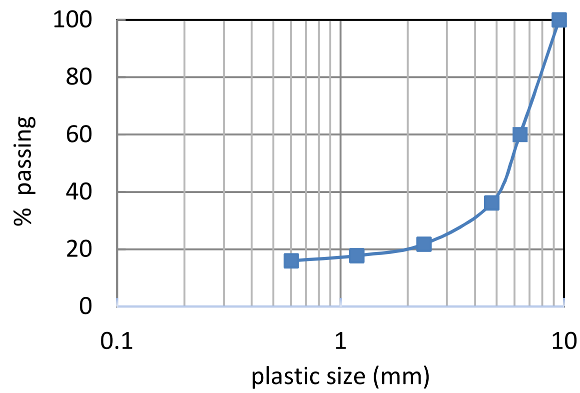

Figure 3. Particle size distribution of plastic aggregate

Table 1. Physical properties of aggregates

Properties of aggregates	Fine aggregate	Coarse aggregate
Bulk specific gravity (oven dry)	1.22	1.42
Bulk specific gravity (SSD condition)	-	1.45
Apparent specific gravity	1.19	1.50
Water absorption (%)	-	9.30
Size range (mm)	<4.75	4.75-9.5
Fineness modulus	1.97	-

Preparation of concrete specimens

Mix design of concrete was performed according to British (DOE) method (Nevile, 1981). The aggregates were in saturated and surface-dry (SSD) conditions, such as all the pores in the aggregates were full and cannot absorb water from the fresh mix. The coarse aggregate was replaced by 5%, 10% and 20% volume of concrete mix with the plastic aggregates. Four types of concrete specimens were prepared maintaining the same water:cement ratio of 0.45. The specimens were designated as C0PA, C5PA, C10PA and C20PA having 0%, 5%, 10% and 20% plastic aggregate by volume respectively. The densities of fresh mix concrete were measured immediately after each mixing. A cone of 12 inch height and 6 inch diameter was used to measure the slump. After 24 hours of casting, all the specimens were transferred into a curing tank at room temperature till the day before testing.

Laboratory Testing Methods

The tests of Compressive strength, Tensile strength, Moduluous of elasticity, Flexural strength and Shrinkage were performed according to ASTM C39, ASTM C496, ASTM C469, ASTM C78 and IS:1199-1959 standards, respectively. Figure 4 shows the machine used in the laboratory. The load was applied continuously until the specimen failed. The load and deformation were measured at a fixed interval.

Figure 4. Compression testing machine used in the study

Results and Discussion

Water absorption and unit weight

The percentages of water absorption of various concrete specimens are presented in Figure 5. It was found that the percentage of water absorption was increased with the addition of plastic aggregate. For concrete specimen containing 20% volume of plastic, water absorption was higher than that of the specimen without plastic aggregate.

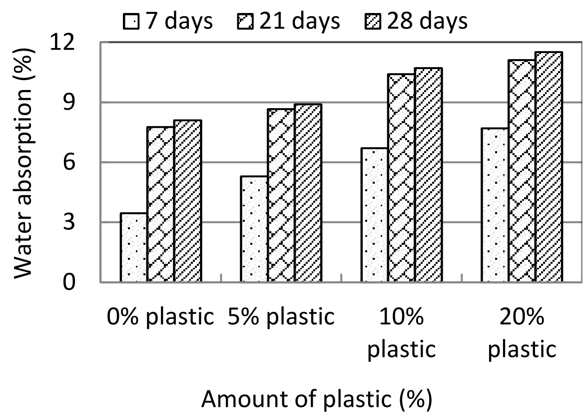

Figure 5. Water absorption of the specimens containing plastic aggregate

According to Albano *et al.* (2009), this behavior is caused since the aggregate can influence on the porosity in two ways: one, providing a proper porosity, and the other, altering the paste. In other words, when substituting part of the natural fine aggregate by PET (with a different granulometry), the latter creates a proper and different porosity to that one created by the sand since its shape is plane and elongated. ACI Committee (1987) definition states that the air dry unit weight of a structural lightweight concrete should be lower than 1850 kg/m^3.

Compressive and Tensile Strength

The compressive strength of the reference concrete specimen and other specimens containing 5, 10 and 20% of plastic aggregate was determined at 7, 21 and 28 days of curing. Figure 6 shows the results of compression tests on various concrete specimens. From Figure 6, an accelerated increase in resistance can be noticed and the strength value of concrete containing 10% plastic was about similar to 0% plastic cylinder at 21 and 28 days. It can also be seen that the PET addition decreased the concrete resistance when compared to the fresh concrete at different curing ages, since the recycled PET does not contribute to the strength of the concrete as does the natural fine aggregates (Neville, 1981). However, even though there is a loss in strength, the blends with 10% plastic presented a high grade of compressive strength. The compressive strength value for 10% plastic content specimen was found about 2400psi at 28days (Figure 6). According to ACI (1987), the compressive strength of a structural lightweight concrete at 28 days should be within 2200–2500psi.

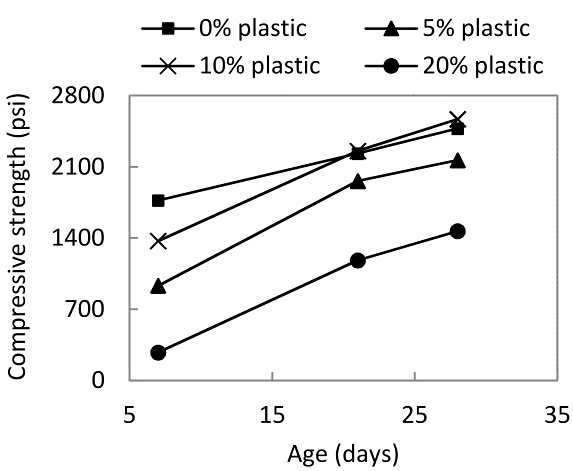

Figure 6. Compressive strength of the concrete specimens containing different percentage of plastic aggregate

Albano *et al.* (2009) found that the standard strength values for concretes with moderate resistance lies between 21 and 30 MPa for a curing age of 28 days. Similar behavior was observed by Rebeiz and Fowler (1996) and Rossignolo and Agnesini (2002), when they added recycled PET and rubber particles to concrete, respectively. The factors that may be responsible for low compressive strength of concrete containing plastic aggregate are: (1) the very low bond strength between the surface of the plastic aggregate and the cement paste; and (2) the hydrophobic nature of plastic, which can inhibit cement hydration reaction by restricting water movement. The tensile strength test results of the concrete specimens containing 5%, 10% and 20% plastic are presented in Figure 7.

The splitting tensile strength was evaluated at 7, 21 and 28 days of cure. It is seen that the nature of increasing tensile strength is similar to the compressive strength, attributing it to the same reasons mentioned above. There is a decrease in the splitting tensile strength with respect to the fresh concrete independently on the size of the PET aggregate added. However, when the amount of recycled PET is 20%, the decrease is more significant as a consequence of the great porosity the concrete can have with this amount of PET. On the other hand, Sakr and El-Hakim (2005) indicated that the variation in the mechanical properties analyzed can be attributed to the difference in shape and stiffness of the aggregate, since the PET has a plane and angular shape with smooth characteristics, different from the sand, which is round and stiff.

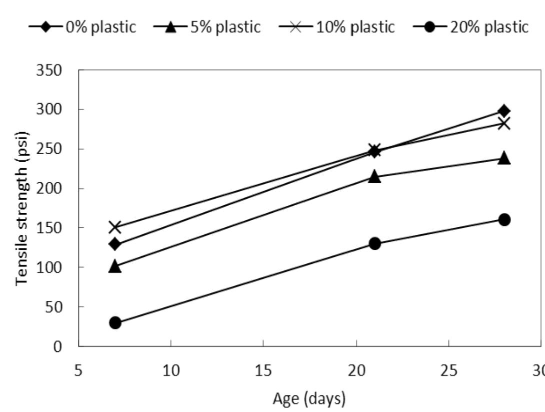

Figure 7. Tensile strength of the specimens containing different percentage of plastic aggregate

Stress-strain behavior

The stress-strain behavior of fresh concrete specimen and other specimens containing 5%, 10%, 20% plastic was observed at 7 , 21 and 28 days of curing. From Figure 8, it was seen that the stress was decreasing as the increasing of strain. The stress of fresh concrete specimen was higher and the concrete specimen containing 10% plastic aggregate provided higher stress from other specimens containing various amount of plastic aggregate. The fresh concrete specimen was more brittle than others. The plastic aggregate produced softening behavior in other specimens resulting lower stress.

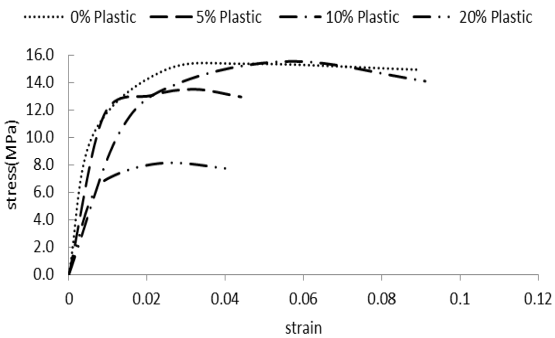

Figure 8. Stress-strain behavior of concrete specimens after 7 days.

From Figure 9, it is observed that the stress is decreasing as the increasing of strain. The stress of concrete specimen containing 10%plastic aggregate provided higher stress than fresh concrete and from other specimens containing various amount of plastic aggregate.

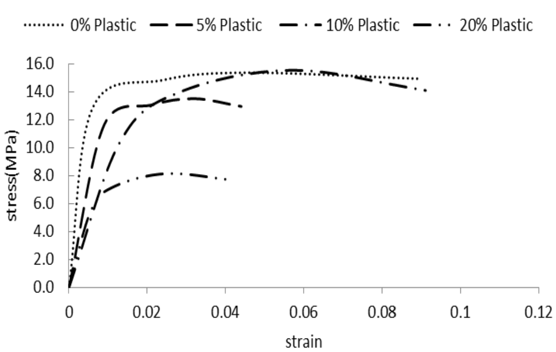

Figure 9. Stress-strain behavior of concrete specimens after 21 days.

From Figure 10, it was seen that the stress was decreasing as the increasing of strain. The stress of concrete specimen containing 10%plastic aggregate provided higher stress than fresh concrete and from other specimens containing various amount of plastic aggregate.

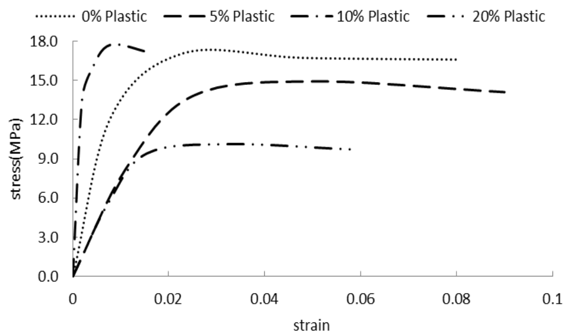

Figure 10. Stress-strain behavior of concrete specimens after 28 days.

Modulus of Elasticity

The modulus of elasticity values of fresh concrete specimen and other specimens containing 5%, 10% and 20% plastic aggregate were determined at 7, 21 and 28 days of curing. Table 2 represents different modulus of elasticity found for different percentage of plastic aggregate in the concrete specimens. The modulus of elasticity was found higher for the specimen containing 10% plastic aggregate by volume. The value is about eight times higher than that of the specimen with 0% plastic aggregate. The modulus value decreases drastically by 20% replacement with plastic aggregate. It is identified that the deformation produced in the concrete is partially related to the elastic deformation of the aggregate. Ferreira et al. (2012) also observed that the modulus of elasticity decreases when addition of plastic waste aggregate increases.

Table 2. Modulus of elasticity of various concrete specimens.

Specimen	Modulus of Elasticity (Mpa)		
	7 days	21 days	28 days
C0PA	2405	5833	14500
C5PA	2480	6000	15000
C10PA	6500	8571	40000
C20PA	340	5000	8333

Flexural strength

The influence of PET aggregate on the flexural strength of concrete specimens at 7, 21 and 28 days were analyzed and presented in Figure 11. It was observed that the flexural strength was decreased as the amount of PET aggregate increased in concrete. The explanation for the loss of compressive and tensile strengths of concrete due to the incorporation of PET-aggregate applied to the flexural behaviour of concrete too. Saikia and de Brito (2014) also found lower flexural strength values for concrete containing PET aggregate than for concrete containing natural aggregate only.

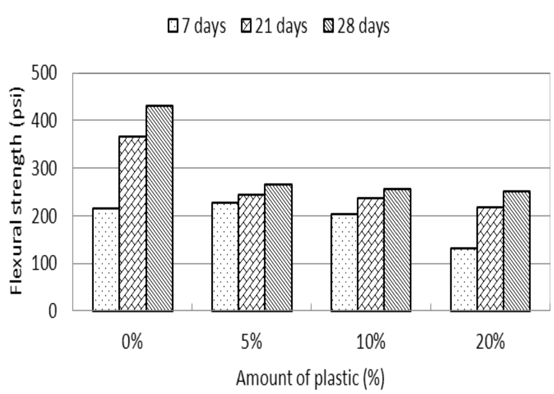

Figure 11. Influence of PET aggregate on the flexural strength of concrete.

Shrinkage

Table 3 shows the shrinkage values of the concrete specimens. It was clear that the length change of concrete increased more as the more addition of plastic aggregate. The change was higher at 20% volume of plastic aggregate than 0% volume of plastic specimen. Frigione (2010) measured the drying shrinkage property of one year cured concrete containing PET aggregate, which replaced 5% in weight of fine natural aggregate. He found an increase in drying shrinkage value due to the incorporation of PET aggregate in concrete for the different experimental conditions. According to the author, this behavior is primarily due to the lower elastic modulus of concrete containing plastic aggregate than that of conventional concrete. However, the range of shrinkage for concrete containing PET aggregate was acceptable for various uses of structural concrete.

Table 3. Shrinkage values of the concrete specimens

Specimen	Percentage of length change (%)	
	7 days	28 days
C0PA	0.20	0.40
C5PA	0.25	0.44
C10PA	0.28	0.45
C20PA	0.30	0.60

Conclusion

In this research, some selected physical and mechanical properties have been investigated for various types of concrete containing 5%, 10% and 20% of waste PET aggregate by volume of concrete mixes. The following conclusions can be drawn based on the laboratory test results.

1. The specific gravity of plastic aggregate was less than that of coarse aggregate and the apparent specific gravity of plastic aggregate was in the range of lightweight concrete aggregate category. So, it can be used as substitute aggregate of coarse aggregate according to mix design of concrete.
2. The density of concrete containing different percentages of plastic aggregate was lower than the fresh concrete.
3. The compressive strength of concrete containing different proportion of PET was different but the compressive strength at 10% volume of PET provided higher strength which allowed it to be used in structural application. The tensile strength, flexural strength and shrinkage values of concrete containing different proportion of PET indicated lower performances of concrete than the fresh concrete.
4. The modulus of elasticity of concrete containing 10% volume of PET indicated higher performance than fresh concrete.

5. The concrete containing 10% PET aggregate can be effectively used in producing lightweight concrete.

   However, further study is required to understand the durability aspects of the concrete containing PET aggregate.

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