International Journal of Architectural, Civil and Construction Sciences
ISSN: 2415-1734
Vol:9, No:5, 2015

An Investigation on Fresh and Hardened Properties of Concrete while Using Polyethylene Terephthalate (PET) as Aggregate

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Abstract**—**This study investigates the suitability of using plastic, such as polyethylene terephthalate (PET), as a partial replacement of natural coarse and fine aggregates (for example, brick chips and natural sand) to produce lightweight concrete for load bearing structural members. The plastic coarse aggregate (PCA) and plastic fine aggregate (PFA) were produced from melted polyethylene terephthalate (PET) bottles. Tests were conducted using three different water–cement (w/c) ratios, such as 0.42, 0.48, and 0.57, where PCA and PFA were used as 50% replacement of coarse and fine aggregate respectively. Fresh and hardened properties of concrete have been compared for natural aggregate concrete (NAC), PCA concrete (PCC) and PFA concrete (PFC). The compressive strength of concrete at 28 days varied with the water–cement ratio for both the PCC and PFC. Between PCC and PFC, PFA concrete showed the highest compressive strength (23.7 MPa) at 0.42 w/c ratio and also the lowest compressive strength (13.7 MPa) at 0.57 w/c ratio. Significant reduction in concrete density was mostly observed for PCC samples, ranging between 1977–1924 kg/m³. With the increase in water–cement ratio PCC achieved higher workability compare to both NAC and PFC. It was found that both the PCA and PFA contained concrete achieved the required compressive strength to be used for structural purpose as partial replacement of the natural aggregate; but to obtain the desired lower density as lightweight concrete the PCA is most suited.

Keywords**—**Polyethylene terephthalate, plastic aggregate, concrete, fresh and hardened properties.

I. Introduction

LIGHTWEIGHT concrete (LWC) has become a prominent subject in modern concrete technology. To produce concrete that is light in weight, lightweight aggregate is an essential ingredient. By using LWC the dimensions of the load-bearing members, such as beams, columns, foundations, of a structure can be reduced. It has a higher seismic resistance as concrete can absorb shock better in lower density. It has a significantly low thermal conductivity and better sound absorption capacity. Because of these advantageous properties studies on finding suitable and cost effective lightweight aggregate has grown considerably in recent years.

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This days the use of beverage product is higher than ever before; and the old glass bottles are replaced by more convenient plastic or PET bottles. The outcome of such condition is the increased production of PET bottles. During the year 2010 – 2011, 0.75 million tons of recycled plastic waste has been produced in Bangladesh. Recycle and/or reuse of these huge piles of waste plastic are a big concern to sustain the soundness of the environment. The regular use of recycled PET as lightweight aggregate in concrete mix can reduce the cost and difficulty in waste management system.

A few studies have been performed in the past to determine the effectiveness of using plastic as aggregate. The majority of those studies were related to reusing of crushed waste PET bottles as a partial replacement of fine aggregates in concrete [1]-[4]. Marzouk et al. [4] used shredded PET particles as partial sand-substitute aggregates (2% to 100% volume replacement) within cement concrete composites for building purposes. Choi et al. [5], [6] used waste PET coated with slag and sand, respectively. They replaced fine aggregates, 25%, 50% and 75% by volume, with modified PET and obtained compressive strength of 33.8 MPa, 31.8 MPa and 24.1 Mpa, respectively for 0.45 w/c ratio. They also experienced improved workability of 52%, 104% and 123% in comparison with normal concrete for w/c ratios of 0.45, 0.49 and 0.53 respectively. Frigione [3] replaced sand with 5% (by weight) of un-washed waste PET in concrete with w/c ratio between 0.45 to 0.55 and found similar workability characteristics; but slightly lower compressive strength and splitting tensile strength than the reference concrete.

Ghaly and Gill [7] conducted research using particles of post consumer plastic (PET) as partial replacement (5%, 10% and 15%, by masses) of coarse aggregate and achieved compressive strengths of 52.12 MPa, 50.11 MPa and 43.63 MPa respectively for 0.42 w/c ratio. Based on the digital imaging of the concrete cube section they concluded that the reduction of compressive strength was proportional to the area of the plastic chips in the section.

Based on the previous studies, it is evident that the waste PET has the potential to be used in concrete as a partial replacement for aggregates. However, further studies needed to identify the best possible form of aggregate to be used in the concrete mix. Therefore, in this study both the fresh and hardened properties of concrete with melted waste PET used as coarse and fine aggregates have been examined to find out the applicability of waste PET bottles as aggregate in concrete with satisfactory workability and load bearing capacity.

II. Materials and Methods

A. Cement

As binding material Portland Composite Cement was used which conform to cement type I according to ASTM C150-94. It contained 65-79% clinker, 21-35% lime stone, fly ash, blast furnace slag and other minor additional constituents. Chemical analysis of the PC was performed according to the ASTM C114 standard test method and shown in Table I.

TABLE I
Chemical Composition of Portland Composite Cement

Components	%
Calcium oxide	55.17
Silicon dioxide	22.14
Aluminium oxide	6.36
Ferric oxide	3.44
Sulphur trioxide	2.56
Magnesium oxide	1.60

B. Coarse and Fine Aggregates

Fine aggregates used in this study were local river sand and PET fine aggregate (PFA). The PFA were produced by melting waste pet bottles at 270°C. The dense and cooled PET product was then shredded into very finer pieces and passed through 4.75 mm sieve. Specific gravity of the local river sand was 2.43 with a moderately high water absorption capacity of 7%. On the other hand, PFA had a relatively low specific gravity of 1.27, but very high water absorption capacity of 19.6%.

The lightweight PET coarse aggregate (PCA) was manufactured by the same process used for PFA, where the final product was shredded into larger sizes having maximum size of 25 mm using a different cutter. Compare to PFA, PCA showed almost non-existing water absorption capacity (of 0.43%). Burnt clay bricks are most common source of aggregate in Bangladesh, and hence, crushed brick chips were used as coarse aggregate in the study where maximum size of the crushed bricks was 25 mm. Brick chips had a very high water absorption capacity (9.75%) along with 48% larger specific gravity compare to PCA.

Particle size distributions of all the aggregates were preformed according to the ASTM 136-01. Figs. 1 and 2 describes the particle size distributions for the fine and coarse aggregates along with the ASTM upper and lower limits, respectively. As observed from the figure, the local river sand was much finer than the PFA. However, the PCA and crushed brick chips had similar particle size distributions. The physical properties of the various aggregates are tabulated in Table II.

C. Concrete Preparation

In preparation of natural aggregate concrete (NAC), the local river sand and crushed brick chips were used as fine and coarse aggregate, respectively. On the other hand, to produce PFA concrete (PFC) 50% of sand (by volume) was replaced with the PFA and to produce PCA concrete (PCC) 50% of brick chips (by volume) were replaced with the PCA. For the experiment, three water-cement ratios, such as 0.42, 0.48 and 0.57 were selected. Aggregates were used in saturated surface dry (SSD) condition. Concrete mix design was performed for three different types of concrete and the resultant mix designs by weight for all the combinations are shown in Table III.

TABLE II
Summary of Aggregate Properties

Characteristics	PFA	Sand	PCA	Brick Chips
Specific gravity	1.27	2.43	1.58	2.33
Water absorption	19.6%	7%	0.43%	9.75%
Fineness modulus	3.15	1.74	6.7	6.86

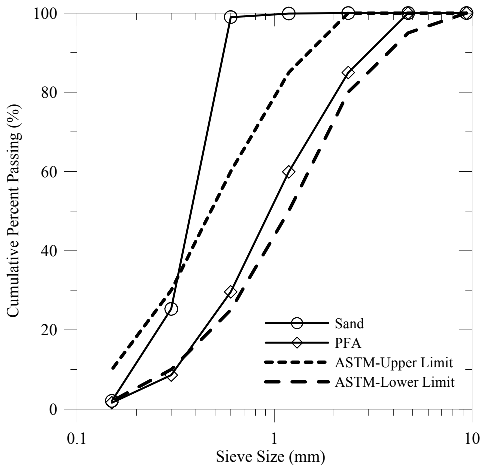

Fig. 1 Particle size distribution of fine aggregates

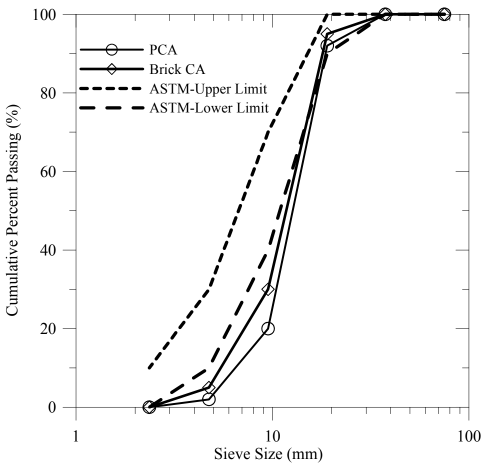

Fig. 2 Particle size distribution of coarse aggregates

D. Test Approach

Six (6"×12") cylinders were cast for each combination. Slump values for each sample were determined using slump cone to observe the workability of the mixed concrete. After 24 hours samples were taken out of the moulds and cured for 26 days in the curing tank at room temperature (20°C - 25°C). On the 28^{th} day after casting, compressive strength test of samples were performed according to ASTM standard C 39/C 39M – 03. Densities of the concrete specimens were also measured.

TABLE III
MIX DESIGN FOR 1 M^3 OF CONCRETE

Characteristics	Cement (kg)	Water (kg)	Sand (kg)	PFA (kg)	Brick Chips (kg)	PCA (kg)	W/C
NACWC42			534.2	-	1024.0	-	
PFCWC42	461.5	193.8	267.1	139.5	1024.0	-	0.42
PCCWC42			534.2	-	512.0	347.2	
NACWC48			519.8	-	996.4	-	
PFCWC48	449.0	135.8	259.9	135.8	996.4	-	0.48
PCCWC48			519.8	-	498.2	337.8	
NACWC57			499.6	-	957.7	-	
PFCWC57	431.6	130.5	249.8	130.5	957.7	-	0.57
PCCWC57			499.6	-	478.8	324.7	

III. RESULTS AND DISCUSSION

A. Properties of Fresh Concrete

The relationship of workability and replacement of coarse and fine aggregate is illustrated in Fig. 3. It shows a significant increase in workability with the replacement of coarse aggregate with PCA for the same water-cement ratio in comparison with the NAC. However, an opposite trend, that is, lower slump values are observed for the PFC.

Shape of aggregate has great influence on workability, and thus, the concrete with angular and flaky shaped crushed brick chips and relatively round shaped PCA showed a significant variation on the slump values. Due to its round shape and relatively smooth surface area PCA has less surface area and voids than brick chips which results in lower water absorption capacity and higher slump values. The round shape of aggregate also greatly reduces the frictional resistance and improves workability. On the other hand, PFA has more surface area resulting in higher water absorption capacity and lower workability.

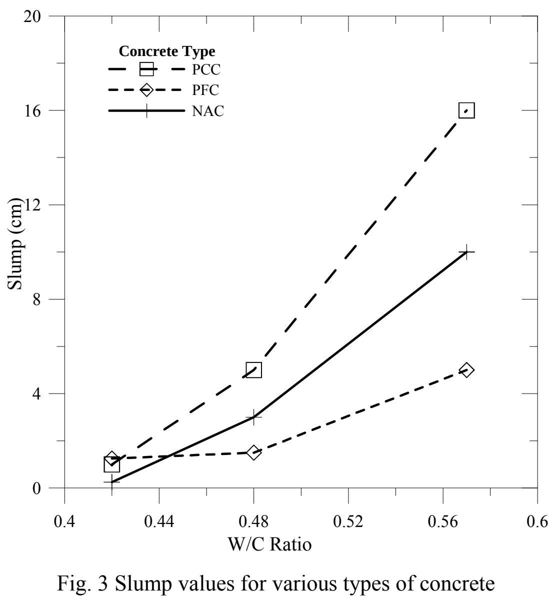

Fig. 3 Slump values for various types of concrete

B. Compressive Strength

The compressive strength test results at 28 days for all the samples are shown in Fig. 3. The result illustrates a decreasing trend for both PCC and PFC compressive strength with the increase in water-cement ratio. Absence of adequate bonding between the PCA and the mortar in the interfacial transition zone greatly reduces the compressive strength of the concrete. The PFC shows better strength compare to the PCC at lower water-cement ratios of 0.42 and 0.48. However, at high water-cement ratio of 0.57, the PFC demonstrates a sudden drop in strength. Although the PFC demonstrates better strength at lower water-cement ratios it is subjected to sudden strength reduction at higher water-cement ratio.

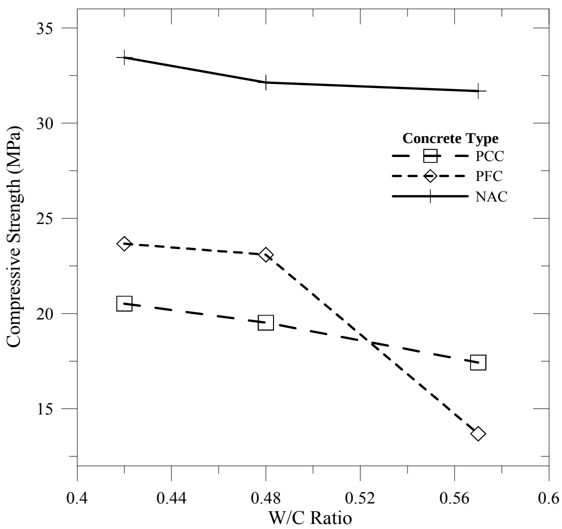

Fig. 4 Compressive strength of cylindrical concrete specimens

C. Density of Concrete

The density and compressive strength – density ratio variations with w/c ratios for three different types of concrete are presented in Figs. 5 and 6, respectively. As shown in the figure, both the PCC and PFC have lower density than the NAC. However, the PCC demonstrates better reduction in density compare to the PFC. At higher water-cement ratio the reduction in density is more prominent. The results also indicate that the NAC has better compressive strength – density ratio among all three concrete types. Therefore, 50% of natural fine and coarse aggregate replacement with the PET aggregate may not yield best results in terms of compressive strength. Furthermore, the PCC shows most consistent results among the PCC and PFC.

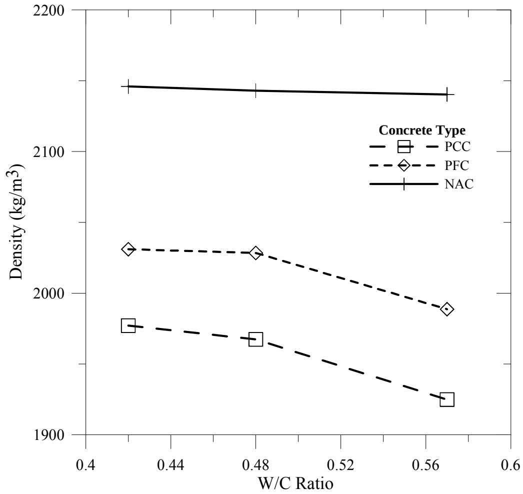

Fig. 5 Density variations with w/c ratios for various types of concrete

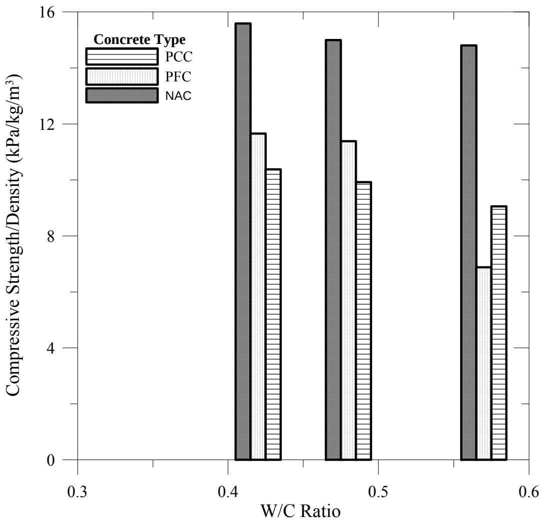

Fig. 6 Compressive strength - density ratio variations with w/c ratios for various types of concrete

IV. Conclusion

The investigation on fresh and hardened properties concrete with substitution of 50% natural coarse and fine aggregate by volume with PET produced aggregate leads to following conclusion:

- The specific gravity of the used PCA and PFA was almost 68% and 52% lower than the natural coarse and fine aggregates, respectively. The absorption capacity of the PCA was insignificant compared to natural aggregate; whereas, PFA had a considerably large absorption capacity.
- The introduction of the PCA in concrete had improved the workability. However, opposite was observed for the PFA concrete. Based on the results, it can be articulated that the PCC is more suitable to work with than other two types concrete for same water-cement ratio.
- The compressive strength at 28 days was slightly lower for the PCA contained concrete than the PFA concrete and NAC. This can be attributed to the weak bondage between aggregate and binding material due to the smooth surface of the PCA. This disadvantage can be resolved by roughing up the PCA surface.
- The density of the PCC is significantly lower than the other two types of concrete. Hence, PET as a lightweight coarse aggregate, in concrete mixture, is more effective.

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