Research Article

Comparative Study of Concrete with Polypropylene and Polyethylene Terephthalate Waste Plastic as Partial Replacement of Coarse Aggregate

Md. Jahidul Islam

Department of Civil Engineering, Military Institute of Science and Technology (MIST), Dhaka, Bangladesh

Correspondence should be addressed to Md. Jahidul Islam; mjislam@ce.mist.ac.bd

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Production of plastic has risen significantly in the last 60 years worldwide, and around 10% of this plastic is turned into solid waste. This plastic becomes an environmental hazard in the absence of appropriate recovery methods. Incorporating waste plastic in concrete is an alternate way to recycle this waste plastic. Polypropylene (PP) and polyethylene terephthalate (PET) are two of the most widely used plastic scarcely recovered and recycled. Therefore, in the present study, both PP and PET are used as a partial replacement (10%, 20%, and 30% by volume) of coarse aggregate. These concretes are compared for three different water-cement ratios (0.42, 0.48, and 0.57). Properties such as workability, density, compressive, and tensile strengths are compared. Concrete with PP aggregate has shown as much as 39% higher compressive strength and 9% lower density than brick aggregate concrete. On the other hand, concrete with PET aggregate has displayed as much as 53% reduction in compressive strength compared to the reference concrete. Furthermore, it demonstrates higher workability and lower density. Equations are proposed to describe relationships between compressive and splitting tensile strengths of concrete, including the effect of plastic aggregate percentages. Cost analysis of the concrete reveals that incorporating waste plastic in concrete is more expensive than the regular brick aggregate concrete. Still, up to 10%, PP can be used in concrete, considering the gain in compressive strength.

1. Introduction

Plastics are used for various sectors, such as packaging applications, building and construction, automotive, electrical, electronic, household and consumer products, medical products, and furniture. The worldwide production of plastics climbed sharply from 1.5 million metric tons in 1950 to 368 million metric tons in 2019. In 2019, China was the highest producer of plastic with 31%, followed by the European Union countries (16%) and the North American Free Trade Agreement (19%). The rest of Asia produced 20% of the total world production in 2019 [1]. In Bangladesh, polypropylene (PP) (high density and low density) is used for containers, flower pots, buckets, furniture, door, folder, etc. Applications of PP are widespread. Besides that, polyethylene terephthalate (PET) is also used in large quantities for bottling products, especially as a bottle for mineral water. Although large numbers of these plastic products are recycled, they are turned into drainage systems, streams, and landfills. These plastics cause water clogging and flood during the monsoon season [2]. Therefore, it is paramount that these household waste plastics, especially PP and PET, are collected and recycled. There are many ways these plastics can be reused, and among these applications, using them as a replacement for burnt brick coarse aggregate is one of the best ways to dispose of them.

Brick aggregate is one most popular construction materials for Bangladesh, which is going through a rapid urbanization process. Brick aggregate has higher water absorption, aggregate impact value, aggregate crushing value, Los Angeles abrasion values, and lower compressive strength and unit weight [3]. Despite that, brick aggregates are used as concrete ingredients in Bangladesh and many parts of the world. Concrete containing brick aggregate has shown similar compressive strength [4–6], higher tensile strength [4, 5], and lower modulus of elasticity [5]. Besides, brick aggregate
concrete has a lower density and cost than stone aggregate concrete. Hence, brick aggregate has been adopted for structural concrete in many construction projects. In Bangladesh, each year, around 12,000 brick kilns produce 8.6 billion bricks [7]. According to Sarker and Abir [7], these brick kilns are causing air and land pollution and destroying the precious topsoil used for agricultural production. Therefore, replacing waste plastic aggregate with brick aggregate in concrete will relieve pressure from producing more bricks at the expense of environmental pollution.

A significant number of studies have already been conducted, where various types of plastic waste, recycled plastic waste [8], high-density polyethylene (HDPE) [9], polyethylene terephthalate (PET) [10–18], polypropylene (PP) [19–24], polyvinylchloride (PVC) [25], and E-plastic [26], were used. Plastic aggregates are used as a cementitious material [22], as a fine aggregate [10–13, 15, 17, 18], or as coarse aggregate [14, 21, 23], or fiber in concrete composites [27]. Plastic replacement percentages vary between 0% and 100%. Among the various plastic waste, PET and PP have the most potential to be used as coarse aggregate in concrete. Most studies focus on the fresh properties, like slump value, and hardened properties, like density, compressive, and tensile strengths.

Researchers have found increased workability with increasing PET and PP content in the concrete mix [10, 14, 21]. Choi et al. [10] and Choi et al. [11] utilized waste PET aggregate to replace river sand and observed increased slump values for concrete with PET. According to these studies, the increased slump is due to the frictionless surface and lower absorption capacity of the PET. Islam et al. [14] found that the smooth surface and round shape of PET aggregates helped improve the workability of the concrete. Islam and Shahjalal [21] applied PP coarse aggregate to replace stone and brick coarse aggregate partially. They found that slump value increased with increased PP content irrespective of the w/c ratios. However, an opposite trend is observed for fine PET aggregate where workability decreases with increasing PET aggregate [13, 15, 18, 28]. Albano et al. [13] found workability reduced for higher PET fine aggregate concrete due to the changed rheology. Batayneh et al. [15] adopted PET as a fine aggregate replacement and found that for 20% replacement, 25% slump value was reduced. The lower slump value was due to the irregular shape of the PET. Dawood et al. [28] and Umasabor and Daniel [18] used fine PET aggregate. They found that workability decreases with an increase in PET content because of the increased surface area of the PET aggregate.

Waste plastic has a relatively higher specific gravity than virgin plastic. However, the specific gravity of the waste plastic is still lower than the natural aggregates used in concrete [14, 21]. Therefore, replacing those ingredients with plastic can reduce concrete's unit weight. Islam et al. [14] adopted PET aggregate to replace brick aggregate and found that a maximum 10% hardened density reduction for 50% PET replaced concrete. Saika and Brito [29] used heat-treated PET aggregate in concrete and observed a linear decrease in density. With maximum 15% PET aggregate replacement, the reduction in density was 5.6%. Islam and Shahjalal [21] also found a linear reduction of hardened density with PP replaced concrete. Up to 8.4% and 7.4%, the reduction was observed for concrete with 30% PP aggregated compared to control concrete with stone and brick aggregates.

Ghaly and Gill [8] partially replaced (5, 10, and 15% by weight) coarse aggregate with postconsumer plastic aggregate and studied cube compressive strength, stress-strain behavior, and Young's modulus. Three water-cement ratios, such as 0.42, 0.54, and 0.69, were used in their study. At 28 days after casting of concrete, compressive strengths for 10% plastic replaced concrete were 50.1 MPa, 40.8 MPa, and 30.2 MPa for w/c ratios of 0.42, 0.54, and 0.69, respectively. For a particular w/c ratio, compressive strength of concrete decreases with increasing plastic percentage, and as much as 18% reduction was found for w/c ratio of 0.42 for 10% plastic replaced concrete. Marzouk et al. [12] substituted fine aggregate in cement composites with PET aggregates of various sizes. A wide range of replacement percentages was chosen with 2% to 100% volume. The compressive strength results showed a slight reduction of 15.7% in strength for PET replacement up to 50%. Choi et al. [10] replaced fine aggregate with recycled PET aggregate, 25%, 50%, and 75% by mass. However, PET aggregate was coated with powdered sand. Three different water/cement ratios of 0.45, 0.49, and 0.53 were adopted for the concrete mix proportion. Furthermore, compressive strength tests of concrete cylinders after 28 days of casting showed about 30% lower strength with increasing PET content. Albano et al. [13] likewise performed compressive and tensile tests of concrete with PET aggregate for two different water/cement ratios (0.5 and 0.6). The fine aggregate was substituted with PET aggregate of 10 and 20% by volume for the concrete mix. Furthermore, the results indicated a decreasing trend in tensile and compressive strength with increasing PET content in the concrete mix. Reduced strength was reasoned with honeycomb and weaker bonding between PET aggregate and cement mortar. Islam et al. [14] partially interchanged recycled PET aggregate with coarse aggregate with varying replacement percentages (up to 50%) by volume of coarse aggregate in preparation for concrete mix. However, compressive strength showed a declining trend while replacement percentages of PET aggregate grew. Lower compressive strength was attributed to a weaker interfacial transition zone (ITZ) due to the higher water accumulation and the smooth surface of the PET aggregate. A similar observation was reported by Silva et al. [30]. They used 7.5% and 15% pellet-shaped PET aggregate in concrete and found a 5.1% and 11% reduction in compressive strength, respectively.

Like the compressive strength behavior of concrete containing PET aggregate, splitting tensile strength also reduces. Kou et al. [25] used PVC pipe scraps to replace sand, and the replacement percentage varies up to 45%. Test results indicated a downward trend for splitting tensile strength with increased PVC content, and it was explained with a smooth surface of PVC and additional water at the ITZ. They also proposed a linear relationship between the compressive and splitting tensile strengths. Juki et al. [31] replaced the sand with PET, and the replacement percentage...
varies between 25% and 75%. The splitting tensile and compressive strength correlation indicated that ACI 318 [32] proposed correlation underestimated the splitting tensile strength at lower PET replacement percentages. However, it overestimated for higher PET replacement percentage.

Compared to PET aggregate concrete, PP aggregate is subjected to very little research. It is mainly used as short fiber in concrete [33, 34]. Yang et al. [24] studied the influence of PP as fine aggregate in concrete. Sand replacement level was 10 to 30%. At 15% PP replacement, the highest compressive and splitting tensile strength was achieved. Yang et al. [24] theorized that plastic particles could more effectively fill up voids in concrete at a lower replacement level. Akinyele et al. [35] replaced fine aggregate with PP up to 16% and compared the compressive strength data. The test results showed a gradual decrease in strength. At 16% replacement, the compressive strength was 9.62 MPa compared to the 19.07 MPa of the control specimen without PP. Özbakkaloglu et al. [23] replaced up to 30% coarse aggregate with PP. They observed a linear decrease in workability and hardened density. Compressive strength test results showed reduced strength with increased PP content, especially for high-strength concrete. Lower compressive strength was reasoned with weak PP and reduced hydration process at the ITZ due to the hydrophobic nature of PP. A similar trend was also observed for splitting tensile strength. While comparing with the code predicted equations, it was revealed that ACI 318 [32] underestimated the splitting tensile strength data, and it was more pronounced with increasing PP content. Islam and Shahjalal [21] replaced coarse aggregate with PP in natural stone and brick aggregate concrete. Compressive and splitting tensile strengths at 7, 28, and 90 days increased value with 10% PP replacement. However, strength decreased with PP content more than 10%. Furthermore, ACI 318 [32] code predicted equation overestimated the test data of tensile strength.

The literature review suggests that waste plastics, such as PET and PP, can be used as fine and coarse aggregates in concrete. In general, the compressive and tensile strengths of concrete containing PET aggregate decreased with increased PET content. Concrete containing PP aggregate showed better results at lower PP content. However, mechanical properties deteriorate at a higher percentage of replacement. Although several studies have been performed on PET coarse aggregate, very few studies have yet reported on the mechanical properties of PP aggregate concrete. Furthermore, it is revealed that code predicted equations cannot predict the tensile strength from the compressive strength. Moreover, very few reported studies have been found where PET and PP aggregates are used to partially replace brick aggregate in concrete and compare their relative performances. Therefore, PET and PP aggregates are used in the present study to partially replace coarse brick aggregate in composite concrete with three different w/c ratios. The fresh and hardened properties of concrete are measured and evaluated to determine which plastic accomplishes better performance for structural concrete. Furthermore, a correlation between the compressive and tensile strengths is proposed considering the effect of waste plastic aggregate. Comparative cost analysis of concrete is also performed to evaluate the cost-effectiveness of concrete with PET and PP waste plastics.

2. Materials

2.1. Cement. In Bangladesh, Portland composite cement (PCC) is the widely accepted cementitious material for the construction industry. It is widely produced and relatively cheaper than ordinary Portland cement (OPC). Therefore, for the present study, cement with specification PCC BDS EN 197-1:2010, CEM II/B-M (S-V-L) 42.5 N [36] has been incorporated in the concrete. It has 65–79% clinker and 21–35% blast furnace slag, fly ash, limestone, and 0–5% gypsum. Several bags of the same brand of cement were purchased from the local market for this study. Cement was tested for various physical properties, as represented in Table 1. Density and fineness of cement were tested according to ASTM C188 [37] and ASTM C115 [38]; values were found to be 3010 kg/m³ and 365.4 m²/kg, respectively. Compressive strength tests were performed following ASTM 109 [39], and the 7 and 28 days compressive strengths were observed as 29.8 MPa and 39.2 MPa, respectively.

2.2. Sand. Natural siliceous sand was adopted in the concrete mix proportion as fine aggregate. The sand was first sieved using a 4.75 mm sieve and then washed in a tub to remove unwarranted materials. The sand was tested for its various physical properties, such as specific gravity, water absorption capacity, unit weight, and fineness modulus following ASTM C128 [43], ASTM C29 [44], and ASTM C136 [45], respectively. The test results are tabulated in Table 2. The grading size distribution analysis of the sand, as shown in Figure 1(a), and fineness modulus of the sand reveal the material to be particularly coarser. Moreover, the water absorption capacity of 8.4% is also at the upper range.

2.3. Brick Aggregate. Bangladesh has significantly low rock formations available for using natural stone aggregate, and in most cases, stone aggregates have to be imported at a higher price [46]. Such shortcoming is avoided by adopting burnt brick clay as the filler material in concrete [47]. Many bricks were purchased from the local brickfields and crushed manually into the desired size to form coarse brick aggregate, as shown in Figure 2(a). Brick chips have a rough surface along with an angular shape. Brick aggregates were tested according to ASTM C 29 [44], ASTM C 128 [43], and ASTM C136 [45] for physical properties, such as unit weight, absorption capacity, specific gravity, and fineness modulus. The test results are summarized in Table 2. The data show that brick aggregate has significantly lower unit weight and specific gravity than the natural stone aggregate. Furthermore, the porous brick aggregate has a very high water absorption capacity which is also reflected in the test at 14.87%. Figure 1(b) shows the grading size distribution of the brick chips along with the upper and lower limits of the ASTM standard [48]. Based on the fineness modulus of 6.38, it is clear that brick chips are consisting of relatively finer particles.

2.4. Plastic Coarse Aggregates. In this study, two different types of plastic, namely polypropylene (PP) and polyethylene terephthalate (PET), were used as a partial replacement...
Preparation procedures for both plastic aggregates were almost similar. Waste plastics were first collected, sorted into various types, and then prewashed. Prewashed plastic then moved to a shredder, transforming it into smaller particles. Small plastic particles were then melted into an oven and poured into a mold to cool down. Finally, cooled samples were crushed with a crushing machine. Figures 2(b) and 2(c) represent crushed PP and PET,

| Description                              | Test results | Test methods |
|------------------------------------------|--------------|--------------|
| Normal consistency (%)                   | 29.6         | ASTM C187 [40]|
| Initial and final setting time (minutes) | 175/240      | ASTM C191 [41]|
| Specific gravity (kg/m³)                 | 3010         | ASTM C188 [37]|
| Water absorption capacity (%)            | 365.4        | ASTM C204 [42]|
| Compressive strength (7/28 days) (MPa)  | 29.8/39.2    | ASTM C109 [39]|

| Description | Test results | Test methods |
|-------------|--------------|--------------|
| Maximum size (mm) | PP aggregate | PET aggregate | Sand |
| Specific gravity (SSD) | 19 | 19 | 19 | 4.75 |
| Water absorption capacity (%) | 1.96 | 0.85 | 1.18 | 2.33 |
| Unit weight (kg/m³) | 14.87 | 0.75 | 0.36 | 8.4 |
| Fineness Modulus | 1182 | 510 | 786 | 1778 |

Figure 1: Grading size distributions of (a) fine aggregates and (b) coarse aggregate along with ASTM limits.

Figure 2: Physical representation of various coarse aggregates. (a) Brick chips. (b) PP aggregate. (c) PET aggregate.
respectively. Both PP and PET aggregates have different surface characteristics. Polyethylene terephthalate aggregate (PTA) has a smoother surface [14], whereas polypropylene aggregate (PPA) has a relatively rougher surface [21]. Physical tests, such as specific gravity, water absorption capacity, and unit weight, have been conducted according to ASTM C 128 [43] and ASTM C 29 [44] for PPA and PTA. Results of the physical tests are displayed in Table 2. The test results show that PPA has the lowest specific gravity of 0.85 and PTA (1.18) and brick chips (1.96). Furthermore, PPA has a higher number of voids in them, and thus, it has the lowest unit weight of 510 kg/m³ compared to PTA (786 kg/m³) and brick chips (1182 kg/m³). The water absorption capacity of both PPA and PTA is almost negligible (less than 0.76) compared to the brick chips. Particle size distributions of both PPA and PTA have been performed according to ASTM C136 [45] and are shown in Figure 1(b). The fineness modulus (FM) of both aggregates is calculated and tabulated in Table 1. As described in Table 2, PTA has a lower FM value of 6.19 than PPA (6.40) and brick chips (6.38).

### 3. Methodology

The purpose of this study is to analyze the performance of concrete with partial replacement of waste plastic coarse aggregate, such as PP aggregate (PPA) and PET aggregate (PTA), compared to brick aggregate concrete (BAC). Plastic aggregate is replaced on a volume basis to keep the aggregate amount the same. Based on the previous study, it is observed that concrete containing more than 30% plastic aggregate has a significant deterioration of strength. Therefore, four replacement percentages are chosen, such as 0%, 10%, 20%, and 30%. A comparative study is also performed for low, moderate, and high water-cement (w/c) ratios, such as 0.42, 0.48, and 0.57, respectively. The trial mix shows that brick (burnt brick chips) aggregate concrete has a workability issue for a w/c ratio less than 0.42. Therefore, for the low w/c ratio case, 0.42 w/c ratio is chosen for this study. The target strength of concrete is 28 MPa, 20 MPa, and 15 MPa. The first two are for application in structural concrete, and the third one is for nonstructural concrete. Slump value indicates workability of freshly mixed concrete, and under laboratory conditions, slump value increases with increasing w/c ratio. Hence, slump values are measured immediately after the concrete mixing is finished. The hardened density of concrete is estimated at 28 days after casting of concrete. Furthermore, mechanical properties like compressive and tensile strengths are measured at 28 days. These values are then used to correlate the compressive strength and plastic percentages with the tensile strength. Finally, the cost of all three concrete types is calculated and analyzed.

#### 3.1. Mix Proportioning

American Concrete Institute (ACI)’s Standard Practice [31] detailing mix proportions for normal weight concrete is adopted for this study. The fineness modulus of three different coarse aggregates, such as brick chips, PET aggregate (PTA), and PP aggregate (PPA), is almost similar. Therefore, combining these aggregates becomes straightforward, and grading of the combined aggregates lies between the ASTM upper and lower limits. However, the specific gravity of these aggregates is widely varied. Hence, brick chips are replaced with PTA and PPA by volume basis (0%, 10%, 20%, and 30%). The mix design for one cubic meter volume of concrete is calculated and presented in Table 3.

#### 3.2. Test Procedure

Twenty-four combinations of concrete mixtures with 288 concrete cylinders (100 mm diameter and 200 mm height) were prepared in the concrete laboratory at room temperature using a motor-operated drum concrete mixer. At first, all the aggregates were placed in the mixture machine. Once the mixture machine started, water was added before and after the cement was added. All the aggregates were in saturated surface dry condition. Once the mixing of all the ingredients was adequately performed, concrete was poured into a large tray. Immediately after that, slump tests were conducted according to ASTM C 143 [49]. From the slump values, the workability of the freshly mixed concrete can be predicted. For each combination, twelve 200 mm (height) by 100 mm (diameter) cylindrical specimens were prepared with fresh concrete following ASTM C 192 [50]. The first half of the cylinder was filled with fresh concrete, and then, they were compacted using an internal vibrator. Immediately after the compaction, other halves of the cylinders were filled with concrete and compacted. The top of the cylinders was then smoothed out using a spatula.

After casting, specimens were kept in a humidity and temperature-controlled room for the first 24 hours. Molds were removed with care without any damage on the next day. After demolding, all the specimens were submerged in a curing tank at 23 ± 2°C temperature until the day of testing. Before the test, samples were removed from the curing tank and dried using cotton rags. After that, the dimensions and weight of the samples were measured. Compressive and tensile strength tests were performed using a compression device with 2000 kN capacity. Compressive strength and density of the concrete samples were calculated following ASTM C 39 [51], whereas splitting tensile strength of the concrete specimen was conducted following ASTM C 496 [52].

### 4. Results and Discussion

#### 4.1. Workability

In the present study, slump values were measured immediately after completing the concrete mix. Slump test values of brick aggregate concrete (BAC), PP aggregate concrete (PPC), and PET aggregate concrete (PTC) show increasing workability with an increasing w/c ratio. Figure 3 demonstrates the slump values of all three concretes at three different w/c ratios. Among the three concrete variations, PTC showed by far the best workability. Furthermore, with increasing PET content in concrete, slump values increase almost proportionally. Especially, with 30% of PET aggregate (PTA) replaced concrete, a slump value of 20.3 cm was achieved for the w/c ratio of 0.57. Increased slump values were achieved due to three
contributing factors: (a) round shape, (b) smooth surface of aggregates, and (c) lower water absorption during concrete mixing. The glassy and relatively smooth texture of the PTA provided significantly lower frictional resistance between the aggregate particles. Ghaly and Gil [8] used postconsumer plastic waste in concrete as coarse aggregate and found almost zero slump values for concrete plastic compared to concrete without plastic. Choi et al. [10] observed up to 22 cm increased slump value for 75% waste PET fine aggregate replaced concrete. Islam et al. [14] found increased slump value with increased PET aggregate, as high as 16 cm.

On the contrary, PP aggregate concrete (PPC) showed minimal slump values compared to BAC and PTC. Especially for w/c ratio up to 0.48, slump values were less than

| Replacement (%) | Designation | Cement (kg/m³) | Water (kg/m³) | Fine aggregate (kg/m³) | Coarse aggregate (kg/m³) | W/C |
|-----------------|-------------|----------------|---------------|-----------------------|-------------------------|-----|
| PPA             | PTA         |                |               |                       |                         |     |
| Control         | P0-42 (BAC) | 454.6          | 190.9         | 526.3                 | 1008.8                  | 0.42|
| 10              | PPC1-42     | 454.6          | 190.9         | 526.3                 | 909.2                   |     |
| 20              | PTC1-42     | 454.6          | 190.9         | 526.3                 | 807.0                   |     |
| 30              | PPC2-42     | 454.6          | 190.9         | 526.3                 | 706.2                   |     |
| 10              | PPC3-42     | 454.6          | 190.9         | 526.3                 | 606.2                   |     |
| Control         | P0-48 (BAC) | 441.6          | 212.0         | 511.2                 | 979.9                   | 0.48|
| 10              | PPC1-48     | 441.6          | 212.0         | 511.2                 | 819.9                   |     |
| 20              | PTC1-48     | 441.6          | 212.0         | 511.2                 | 719.9                   |     |
| 30              | PPC2-48     | 441.6          | 212.0         | 511.2                 | 619.9                   |     |
| Control         | P0-57 (BAC) | 423.4          | 241.4         | 490.2                 | 939.6                   | 0.57|
| 10              | PPC1-57     | 423.4          | 241.4         | 490.2                 | 845.6                   |     |
| 20              | PTC1-57     | 423.4          | 241.4         | 490.2                 | 751.7                   |     |
| 30              | PPC2-57     | 423.4          | 241.4         | 490.2                 | 657.7                   |     |

Table 3: Mix design for 1 m³ of concrete.
1 cm for PPC and hardly increased up to 4 cm for w/c ratio of 0.57. Moreover, slump values appear to be decreasing with increasing PP aggregate (PPA) in concrete. Ozbakkaloglu et al. [23] observed up to 33% drop in slump value for normal strength concrete with 30% PP plastic replacement. Compared to both PTA and brick aggregate, PPA has a rougher surface and a large quantity of isolated and interconnecting voids, resulting in lower slump value and eventually lower workability of concrete. It should be noted that brick aggregate has a very high water absorption capacity, 14.87% for the present study, and tends to absorb moisture from the concrete mixture. Therefore, a higher slump value is difficult even with a high w/c ratio, evident from Figure 3.

4.2. Density. The density of the cylindrical concrete specimen was calculated at saturated surface dry (SSD) condition just before the compressive and tensile tests. Average concrete densities for the combinations are displayed in Figure 4. Both PPA and PTA have lower specific gravity and unit weight than the brick aggregate. Thus, in both cases, concrete density reduces with increased plastic aggregates content in the concrete mixture and increasing w/c ratio. This phenomenon is most significant for the PPA replaced concrete. During the experiment, as low as 1923 kg/m³ concrete density (9% lower than the BAC) was observed for PPC with 30% PPA replacement and a w/c ratio of 0.57. These data are consistent with Islam and Shahjalal [21] and Ozbakkaloglu et al. [23]. On the other hand, as much as a 7% reduction in density was observed for PTC for 30% PTA replacement. The reduction in density is due to the lower specific gravity and unit weight of both PP and PET aggregates, as shown in Table 2. Furthermore, PP aggregate has a lower unit weight than the PET aggregate and thus a lower density of PPC.

4.3. Compressive Strength. The results of compressive strength tests of cylindrical concrete specimens at 28 days are displayed in Figure 5. As illustrated in the figure, all the concrete variations demonstrated a declining compressive strength pattern with an increasing w/c ratio. Further data analysis showed that PPC has higher compressive strength than PTC for all plastic aggregate replacement ratios. Moreover, PPC showed higher compressive strength, from 8% to 39%, than BAC for 10% PPA replacement. The rough surface of the PPA contributed to the better bond between the aggregate and cement paste resulting in higher compressive strength. This result is consistent with the study performed by Islam and Shahjalal [21]. They adopted various percentages of PP aggregates and found that 10% PP aggregate showed higher strength than the concrete without any PPA for a w/c ratio of 0.45 and 0.55. Furthermore, the strength of PP aggregate concrete reduces with increasing percentages of PPA. Figure 6(a) demonstrates the failure pattern under compressive force for PPC with 30% PPA. The figure shows that concrete failed by combined aggregate and mortar failure with cracks passing through both brick and PP aggregates. However, the workability of PPC reduces significantly with increasing PPA contents at a w/c ratio of 0.42. PPC with 10% PPA only observed 10% higher compressive strength compared to BAC. However, with 20% and 30%, PPA replaced concrete, and a 17% and 22% reduction in compressive strength is observed. Reduced workability increases voids in concrete, which reduces compressive strength.

In contrast to PPC and BAC, PTC displayed a lower compressive strength for all three w/c ratios and replacement percentages. Reduction in strength was varied between 15% and 53%. It was especially high for PTC, with a lower w/c ratio of 0.42. The smooth surface of the PET aggregate (PTA) resulted in a weaker interfacial transition zone (ITZ) between the mortar and PET aggregate, where cracks are developed in the ITZ rather than passing through the PET aggregate. Reduction in compressive strength with increased percentages (20% to 50%) of PET aggregate was also observed by Islam et al. [14].

4.4. Tensile Strength. A compression machine conducted split tensile tests of cylindrical concrete samples at 28 days of age. Tensile strengths were calculated from the crushing load and are plotted in Figure 7. As illustrated in the figure for all three different concretes (BAC, PPC, and PTC), tensile strength appears to decline with an increasing w/c ratio. Furthermore, tensile strengths decrease up to 34% and 37% for w/c ratio of 0.57 with increasing aggregate replacement percentages for PPC and PTC, respectively. On the other hand, variations of strengths remain within 13% and 30% for PPC and PTC, respectively, with a w/c ratio of 0.42. In almost all cases, PPC shows higher tensile strength compared to PTC. Figure 8 shows the failure pattern for the concrete cylinders for PPC and PTC with 20% aggregate replacement, respectively.

4.5. Relationship between Compressive and Tensile Strengths. A relationship between the splitting tensile and compressive strengths is proposed considering the effect of plastic content. Experimental data from the current study are used for a regression analysis to assess the splitting tensile strength as a function of compressive strength. Two equations are developed for PP aggregate concrete (PPC) and PET aggregate concrete (PTC), as presented in Table 4. These equations included the effect of compressive strength ($f'_c$) and plastic aggregate percentages ($P$). Statistical data, such as covariance, mean absolute error (MAE), average absolute percentage error (AAPE), and the coefficient of determination ($R^2$) values, are also included in Table 4. As observed from the statistical data, both equations give good predictions. Figure 9 displays the variation of splitting tensile strength with compressive strength for all three types of concrete and the equation proposed by ACI Building Code 318M-14 [53]. As illustrated in the figure, the proposed equations closely predict the splitting tensile strength for both PPC and PTC compared to the equation proposed by the ACI code. The
ACI code equation underestimated the splitting tensile strength by as high as 21% and 33% for PPC and PTC, respectively. Therefore, the equation proposed by the ACI code may not be adequate to predict the tensile strength of concrete with plastic aggregates. On the other hand, apart from one case for PPC with a w/c ratio of 0.57, percentage variations of the proposed equations are well within 15% for both types of concrete.

4.6. Cost Analysis. Cost analysis of the concrete with various percentages of PPA and PTA was performed. From the mix proportions of the concrete, the quantity of materials was available. As purchased from the market, the actual cost of individual materials was multiplied by the required amount of materials for one cubic meter of concrete. All the materials were purchased from the local market using the local currency, Bangladesh Taka (BDT). However, the materials’ cost was converted to USD (1 USD = 85 BDT). Figure 10 shows the total cost per cubic meter of concrete and compressive strength and cost ratios. As presented in Figure 10(a), the unit cost of concrete increases with increasing percentages of both PPA and PTA. The material cost of both PPA and PTA is zero. However, the collection, sorting, and preparation of...
Figure 6: Failure of concrete cylinders with plastic aggregate subjected to compressive force. (a) PPC3-57. (b) PTC3-57.

Figure 7: Variation in tensile strength of concrete with w/c ratio.

Figure 8: Failure of concrete cylinders with plastic aggregate subjected to the tensile force. (a) PPC2-42. (b) PTC2-42.
plastic aggregates required a higher cost (0.705 USD/kg) than the brick aggregate (0.02 USD/kg). This cost of plastic aggregates can be further reduced in the case of large production facilities. Because of this, unit cost increases from 24% to 104% with increasing PPA and PTA percentages. In the mix, proportioning of concrete PTA was required more than the PPA. Therefore, the unit cost of concrete with PTA is more than the unit cost of PPA-
contain concrete. However, a comparison of compressive strength and unit cost ratio revealed that concrete containing 10% PPA has higher strength over cost ratio at w/c of 0.48 and 0.57 compared to the concrete without any plastic aggregates, as shown in Figure 10(b). Besides these two, all the other combinations showed lower strength over cost ratio than the control concrete.

5. Conclusions

Based on the experimental results, the following observations can be made:

(i) PET aggregate concrete (PTC) has the highest workability compared to brick aggregate concrete (BAC) and PP aggregate concrete (PPC). On the other hand, PP aggregate concrete (PPC) has the lowest workability. With increasing PET contents, the workability of PTC increases. However, an opposite trend is observed for the PPC. The smooth surface and round shape of the PET aggregate improve the workability of concrete compared to the rough surface and angular form of PP aggregate.

(ii) Because of their lower unit weight, PPC has the lowest density compared to PTC and BAC. A maximum 9% reduction in density is achieved with 30% PP replaced concrete. However, due to the smaller percentages of replacement reduction in density, it is not enough to consider lightweight concrete.

(iii) Concrete with PPA exhibits up to 39% higher compressive strength than BAC. Reduction in compressive strength of PPC is only observed for lower w/c ratio of 0.42 at higher PP aggregate replacement ratios, that is, 20% and 30%. The rough surface and angular shape of PP aggregate improve the interlocking between the aggregate. On the other hand, the smooth surface of the PTA reduces the interlocking and demonstrates lower compressive strength than both PPC and BAC. Especially with higher w/c ratios and PET aggregate contents, reduction in compressive strengths is significant.

(iv) The inclusion of plastic aggregate in concrete does not affect splitting tensile strength at a lower w/c ratio. The tensile strength decreases with the increasing plastic aggregate concrete. However, concrete containing PP aggregate shows higher tensile strength than concrete containing PET aggregate.

(v) The relationship between the splitting tensile and compressive strengths is formulated and compared with the ACI recommended value for all three concrete types. The influence of waste plastic content is incorporated into the equation. The proposed equations give better predictions than the ACI code-predicted values.

(vi) Concrete with PPA and PTA is expensive compared to concrete with brick aggregate. However, 10% PPA concrete at a w/c ratio of 0.48 and 0.57 is 28% and 50% more efficient in compressive strength and unit cost ratio.

Concrete with PP aggregate has shown higher compressive strength than the brick and PET aggregate concrete. The tensile strength of PPC is lower than the BAC, but it is not significant for concrete with lower w/c ratios. Moreover, the tensile strength of PPC is higher than the PTC. Hence, PP rather than PET can be used in structural concrete. Therefore, further work should apply PP aggregate in beam and column as structural concrete. In terms of compressive strength and reduction in density, concrete with partially replaced PP aggregate can be a suitable alternative for the environmentally hazardous brick aggregate concrete in infrastructure projects. As much as 30% of the brick aggregate can be replaced depending on the design strength.

Data Availability

Data will be made available on request to the corresponding author.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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