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Effect of Partial Replacement of Fine Aggregate with Plastic Waste Aggregate on Workability and Strength of Concrete

Babatunde, O.Y[a]*, Adebayo, H.S[a] and Shuaib, Q.A[a]
[a] Department of Civil Engineering, University of Ilorin, Ilorin, Nigeria
*Corresponding author's email: abatundeyusuf990@gmail.com

Abstract
Continuous increase in the utilization of aggregate for concrete production has led to over-exploitation of natural rocks and an exponential increase in construction cost. However, serious environmental concerns have been raised about the ineffective management of the plastic waste generated. Interest in the environmentally friendly disposal of plastic waste as aggregate in concrete is considered. This study investigated the performance of concrete with the addition of Polyethylene Terephthalate (PET) plastic waste as aggregate. The PET plastic waste was processed into aggregate and used as a substitution for fine aggregate at 10%, 20%, and 30% replacement levels. Effects of the presence of the plastic PET aggregate on concrete workability, compressive strength, flexural strength, and water absorption were determined. The results showed that the workability increased as the proportion of the plastic PET aggregate increased in the concrete matrix. In comparison with the control concrete, a slight increase in compressive and flexural strength of concrete containing 10% of PET plastic waste was observed. However, a significant reduction in strength properties was obtained for concrete with 20% and 30% of PET plastic waste. Meanwhile, the water absorption property of the concrete composite increased as the proportion of the plastic PET aggregate waste increased. From the study, it can be said that sand can be substituted with PET plastic waste up to 10% replacement levels in the concrete matrix. Concrete with the addition of PET plastic waste can find applications for non-structural purposes such as waterproof surface, kerbs, and interlocks among others.

Keywords: *Alternative materials, Compressive strength, Environmental impact, Fine aggregate, Flexural strength, Plastic PET aggregate*

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1. Introduction

There has been yearly rapid growth in the demand for construction materials, largely due to the rise in population, urbanization, and industrialization. Concrete is one of the major construction materials, and aggregates represent about 65 – 85% by volume in concrete composite (Bahij et al., 2020). Currently, the yearly demand for concrete is estimated to be about 10 billion tons, which has been projected to increase to 18 billion tons by the year 2050 (Asadi et al., 2018). The high rate of usage of aggregates for day-to-day activities in construction has raised concern about the depletion and overexploitation of the natural resources, thereby, hindering the future needs of these resources by future generations. It becomes imperative to seek alternative materials that could match up with the engineering properties of the conventional aggregates for structural and non-structural purposes.

Ecosystem and ecological systems are becoming unsafe from generated plastic waste. Continuous increase in plastic usage and plastic waste generation growth has posed serious environmental concerns. In the year 2012, about 280 million tons of plastic wastes were generated globally, and it rose to 335 million tons in the year 2016. It has been forecasted to be rise to about 1 billion tons by the year 2050 (Bahij et al., 2020). However, the global management of the large chunk of plastic waste generated is still low, as 22 % was recycled, 27 % incinerated and the majority ended up in landfills and dumpsites (Li et al., 2020). In Nigeria, about 32 million tons of plastic waste is generated annually, below 12% is recycled and about 80% finds its way to landfills and dumpsites (Kehinde et al., 2020). Meanwhile, it has been reported that over 10 million tons of plastic waste ended up in the ocean annually, which contributed to the death of 100,000 marine animals and 1 million sea birds (Faraj et al., 2020). It has been forecasted that oceans will have more plastics than fish by 2050 (Kehinde et al., 2020). It becomes necessary to improve the management of plastic waste generated. One of the effective mediums is the recycling of plastic waste as aggregate for construction purposes. Being a new material, there is a need to assess the performance of concrete produced with plastic waste as aggregate. There are different types of plastics, but plastic Polyethylene Terephthalate (PET) is one of the larger percentages of plastic waste as it is commonly used daily by human. Hence, the study focused on recycling plastic PET as a partial replacement for fine aggregate in the concrete matrix.

Boucedra et al. (2020) conducted an experimental study on concrete containing plastic wastes as aggregate. The plastic waste was substituted for fine aggregate at 25%, 50% and 75% replacement levels. Their findings showed reduction in density of concrete as the contents of plastic waste aggregate in the concrete increased. Nevertheless, replacement levels of up to 50% gave density that falls within the range of lightweight concrete. Similarly, behaviour of concrete with addition of plastic waste aggregate at 25%, 50% and 75% replacement levels were studied by Belmokaddem et al. (2020). Their study results indicated that the content of plastic aggregate was inversely proportional to the density of concrete. The higher the contents of plastic aggregate, the lower the density of concrete. Almeshal et al. (2020) incorporated plastic waste aggregate in concrete matrix in dosage of 10%, 20%, 30%, 40% and 50% replacement of fine aggregate. Results revealed slight reduction in compressive strength for 10% and 20% incorporation of plastic waste aggregate compared to control mix. Beyond that, reduction became significant. There are over 30% compressive strength reduction when 40% plastic waste aggregate was incorporated in concrete mix. The decreasing trend was attributed to the reduction in composite bulk density. Effect of 5, 10 and 20% of plastic waste aggregate in concrete matrix was experimentally studied. The plastic aggregate was added as replacement for sand. Compare to the control concrete, it was observed that the compressive strength declined by 7, 12 and 24% for concrete containing 5, 10 and 20% plastic aggregate respectively. The reduction trend was explained to be as a result of lower compressive strength of plastic aggregate compared to sand (Mustafa et al., 2019). Needhidasan et al. (2020) used plastics from electronic materials (E-plastic) as replacement for conventional coarse aggregate in concrete mix. It was found out that, up to 22% of E-plastic waste can be incorporated into concrete mix with minimal reduction in compressive strength. At 28 days, the target strength of 40MPa was achieved for concrete with 22% E-plastic waste. Visweswara and kumar (2018) carried out experimental investigation of the performance of concrete containing Polypropelene (PP) and Low-density Density Polyethylene (LDPE) plastic waste. The results revealed that the presence of plastic waste in concrete reduced the bending strength of concrete mix of all replacement levels. Meanwhile, concrete with PP plastic waste showed better flexural strength performance than LDPE aggregate concrete. This can be explained to be as a result of the higher tensile strength of PP plastic aggregate over LDPE plastic aggregate. Concrete mix with 5% of PP as replacement for fine aggregates indicated 18% variation to the control concrete. However, concrete with incorporation of 5% and 10% PP plastic waste and 5% LDPE plastic waste gave considerable variation of 18%, 38% and 41% to conventional mix respectively. It was observed that there is decreasing trend of flexural strength as the contents of plastic waste increased and decreased in fine aggregate contents.

In this study, the performance of concrete with the addition of Polyethylene Terephthalate (PET) plastic waste as aggregate was investigated. The PET plastic waste was processed into aggregate and used as a replacement for fine aggregate at 10%, 20%, and 30% replacement levels. It is believed that research into the use of PET plastic waste will enhance concrete performance.

2. Materials and methods

2.1 Materials

In this study, the materials employed for the experimental study comprised Ordinary Portland Cement (OPC) produced by Dangote Cement Company. The cement was 42.5 grade and conformed to Standard Organization of Nigeria (SON) and Nigeria Institute of Standards (NIS) 444-1:2003 certification. Sand with maximum size of 4.75mm was used as fine aggregate and was adjudged to be sharp sand through visual inspection. Crushed rock with maximum size of 20mm was used as coarse aggregate. Plastic PET waste bottles were locally sourced from plastic waste retail shop. The plastic wastes were thoroughly washed, cleaned, melted and crushed to give plastic PET aggregate with maximum size of 4.75mm. The plastic wastes were melted at temperature range of 250 – 270°C. The molten plastic waste was transferred into a mould and allowed to cool and solidify. Then, the solidified plastic PET was crushed into maximum size of 4.75mm. The materials physical properties; particle size distribution, specific gravity and Aggregate Impact Value (AIV) were determined in accordance with BS EN 933-1, 2012; BS EN 1097-2, 2020; BS EN 1097-3. 1998, respectively.

2.2 Mix proportion

Conventional mix ratio of 1:2:4 for cement, fine aggregate and coarse aggregate was employed for the proportioning of ingredient materials for the control concrete mix. The water-cement ratio was fixed at 0.5 for all the concrete mixes. The plastic PET aggregate was incorporated as substitution to the fine aggregate at 10%, 20% and 30% levels. Table 1 shows the mix design of the relative proportion of each material in concrete production.

2.3 Test specimens

The materials were batched by weight and mixed thoroughly for homogeneity. For the concrete workability, slump test was carried out on the fresh concrete in accordance to BS EN 12350-2, 2019. Concrete cubes and beams with dimension of 150 x 150 mm, 100 x 100 x 500 mm and 150 mm x 150 mm were casted for compressive strength, flexural strength and water absorption tests specimens. All the concrete specimens were cured in water for 7, 14 and 28 days. At elapse of curing age, the specimens were taken out from the curing tank and air dried. Mean density, compressive strength and flexural strength properties for the concrete specimens were noted and recorded for all curing ages. Universal Testing Machine (UTM) was employed for the compressive and flexural strength tests on the concrete specimens in compliance with BS EN 12390-3: 2019 and BS EN 12390-5, 2019. Concrete cubes were oven dried for 72 hours at 110°c. Then, it was removed and allowed to cool for a day. Afterwards, the cubes were weighed and recorded. Then, it was immersed in water for 30 hours. The weight was measured and recorded after expiration of 30 hours. The water absorption was determined in accordance with the provisions of BS 1881-122, 2011. The casted concrete cube specimens are shown in Fig. 1 while the results of the concrete mix proportion obtained from mix design are presented in Table 1.

Fig. 1: Casted concrete cubes

Table 1: Concrete Materials Mix Proportion

% Mix of PET	Cement (kg)	Fine Aggregate (Sand) (kg)	Coarse Aggregate (kg)	Plastic PET Aggregate (kg)	Water-cement ratio
0%	10.93	21.86	43.71	0.00	0.5
10%	10.93	19.67	43.71	2.19	0.5
20%	10.93	17.49	43.71	4.37	0.5
30%	10.93	15.30	43.71	6.56	0.5

3. Results and discussion

3.1 Physical Properties of Constituent Materials

The particle size distribution of plastic PET aggregate and sand were presented in Fig. 2. The maximum aggregate size of both materials is 4.75mm. Similar size distributions were observed for both materials. As shown in Table 2, the physical properties for plastic PET aggregate indicated that it is a lightweight material. Plastic PET aggregate has lower density, specific gravity and coefficient of gradation compared to sand. Also, zero water absorption was obtained for plastic PET aggregate.

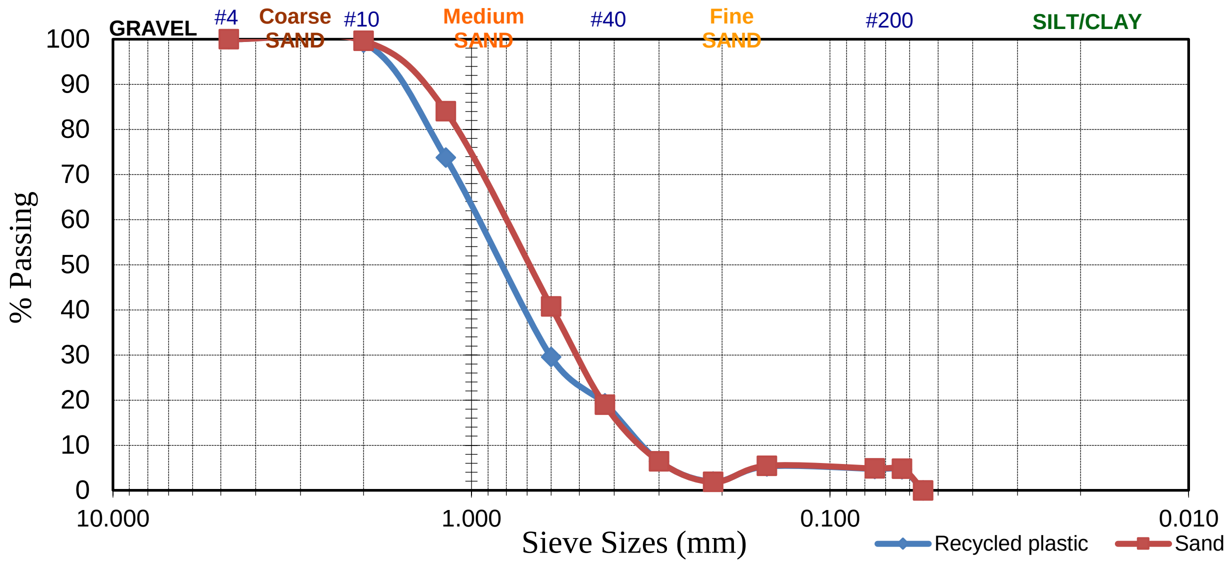

Fig. 2: Particle size distribution of plastic PET aggregate and sand

Table 2: Properties of constituent materials

Materials	Specific Gravity	Aggregate Impact Value	Water Absorption (%)	Density (g/cm^3)	Maximum Aggregate Size (mm)	Coefficient of Gradation (Cc)
Coarse Aggregate	2.65	10.3	0.7	-	20	1.17
Sand	2.43	-	2.2	1.81	4.75	1.12
Plastic PET Aggregate	1.53	-	0	1.02	4.75	1.01

3.2 Effect of plastic waste aggregate on concrete slump value

The result for the slump test is presented in Fig. 3. It can be observed that the slump value increases as the percentage content of the plastic PET aggregate in the concrete composite increases. The increase in workability can be explained to be as a result of impermeability of plastic PET aggregate leaving behind more water in the concrete matrix that would have been absorbed by the substituted portion of sand.

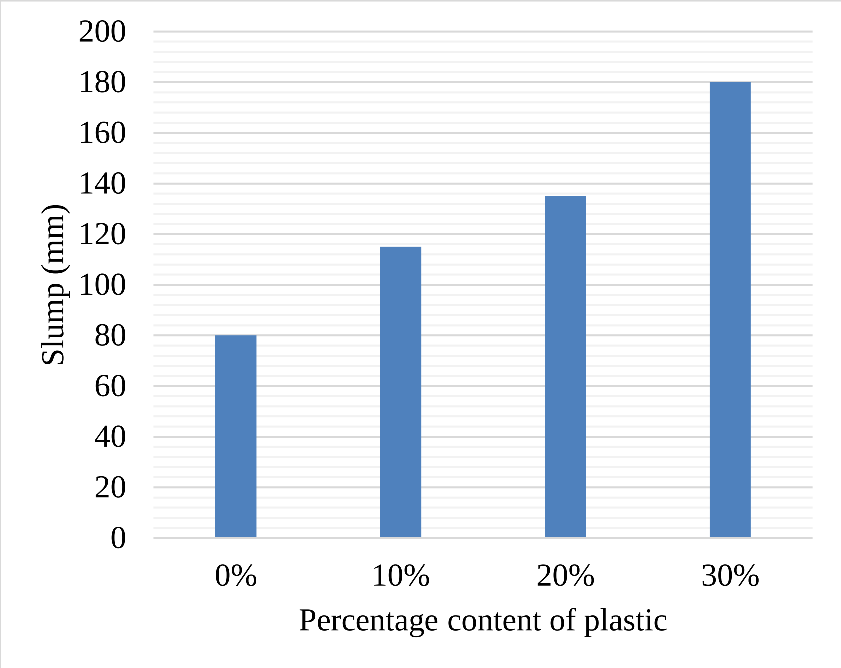

Fig. 3: Slump at various percentage content of plastic as fine aggregate

3.3 Effect of plastic PET aggregate on concrete bulk density

Fig. 4 shows the density of concrete with different proportions of plastic PET aggregate. As seen, the presence of plastic PET aggregate in concrete mixes led to reduction in concrete density. The reduction trends intensified as the content of percentage of plastic PET aggregate increases. There was minimal loss of density of 3% at 10% content of plastic PET aggregate. However, the reduction in density became significant above 10% incorporation of plastic PET aggregate in concrete composites. This can be attributed to lighter weight of plastic PET aggregate compare to fine aggregate (sand). The higher the proportion of plastic PET aggregate, the lighter and lower the density of the concrete.

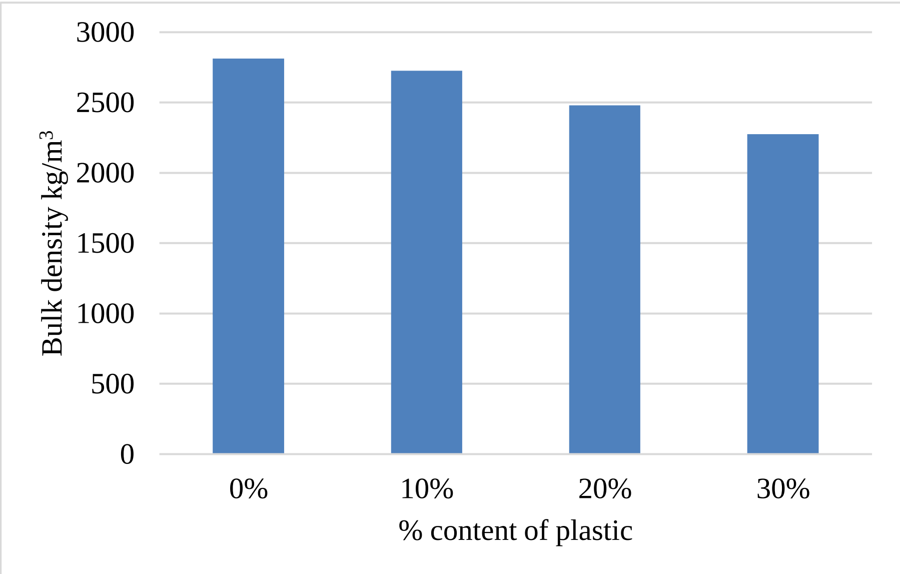

Fig. 4: Bulk density of plastic PET aggregate concrete

3.4 Effect of plastic PET aggregate on compressive strength of concrete

Fig. 5 depicts the compressive strength result of the Plastic PET aggregate concrete. The concrete strength increases as the curing days increases for all the concrete mixes. It was observed that there was slight increase in compressive strength value of 12 % when 10% plastic PET aggregate was incorporated as replacement for fine aggregate in concrete mix. Similar results trend was reported by (Azhdarpour et al., 2016; Nursyamsi & Zebua, 2017; Santhanam & Anbuarasu, 2020a). Azhdarpour et al. (2016) study results highlighted that concrete with 5% and 10% plastic fragment addition were 39% and 7.6% more than the control concrete. However, addition of plastic fragments in concrete matrix beyond 10% replacement levels, indicated loss of strength properties. This behaviour was attributed to the accumulation of flexible plastic fragments at the beginning of failure points and decrease in cohesion between components materials as result of smooth surface and flat shape of plastic used. Moreover, flexible plastic fragments at failure surface elongate concrete deformation before failure and reduce themodulus of elasticity. Nursyamsi & Zebua, (2017) reported that the fineness modulus of the PET plastic aggregate has an influence on compressive strength. The increase cut across the curing ages. Meanwhile, beyond 10% substitution of fine aggregate with plastic PET aggregate, significant reduction in strength values were gotten. The reduction continues as the content of plastic PET aggregate increases beyond 10% incorporation. In comparison with control concrete, there was loss of strength of 13% and 22% for concrete with addition of 20% and 30% of plastic PET aggregate respectively. The reduction in strength values can be said to have resulted from the failure of plastic PET aggregate to make effective bonding with the cement paste due to its smooth texture surface (Almeshal et al., 2020; Belmokaddem et. al., 2020; Mustafa et al., 2019; Needhidasan et. al., 2020; Olofinnade et al., 2020).

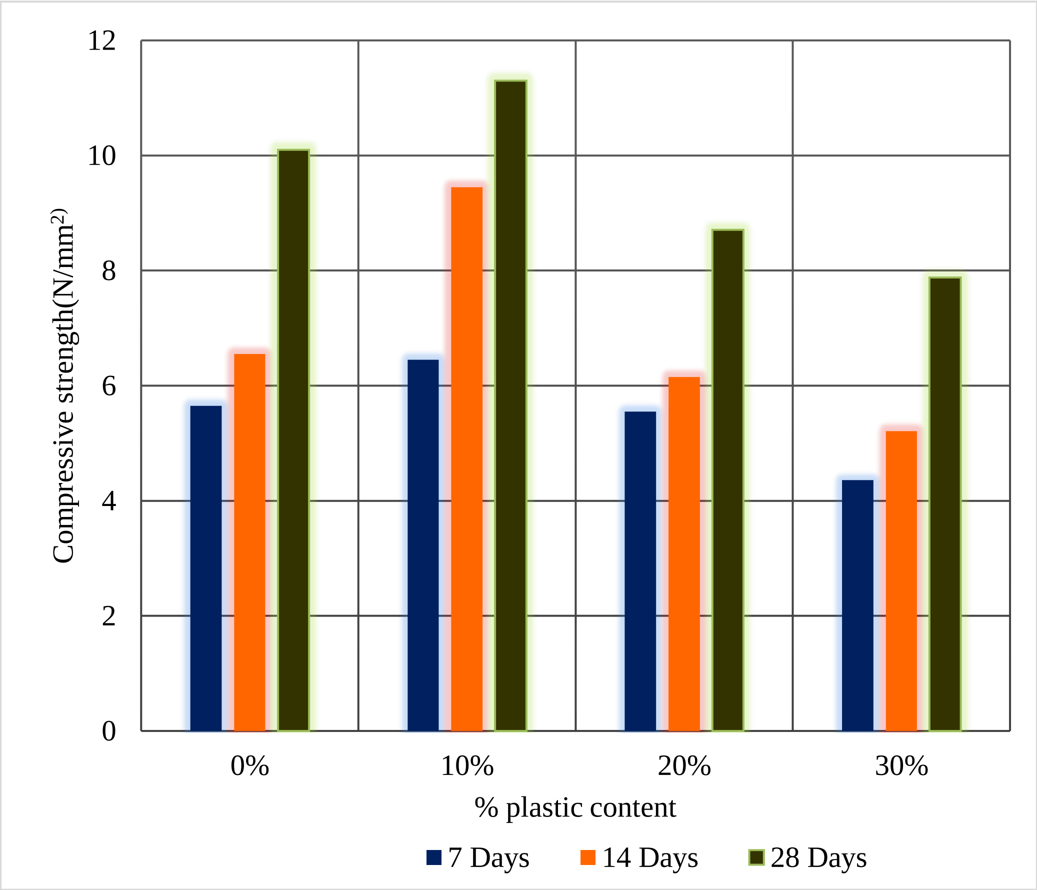

Fig. 5: Compressive strength of plastic PET aggregate concrete

3.5 Effect of plastic PET aggregate on concrete flexural strength

Fig. 6 presents the result of the flexural strength of the concrete with Plastic PET aggregate. From the results, the flexural strength of all the concrete mixes rises with respect to increase in curing days. Similar to compressive strength, there was a slight increment in the flexural strength at 10% incorporation of plastic PET aggregate as a substitution for fine aggregate. Such result trend was reported by (Azhdarpour et al., 2016; Needhidasan et al., 2020; Santhanam and Anbuarasu, 2020b). The increase cuts across the curing ages. However, a significant reduction in flexural strength values was obtained when the content of plastic PET aggregate goes beyond 10%. The reduction in flexural strength of 23% and 53% for concrete mixes containing 20% and 30% of plastic PET aggregate. The reduction trend can be explained to be as result of lesser plastic aggregates strength and poor bonding between plastic aggregates surfaces and cement paste (Almeshal et al., 2020).

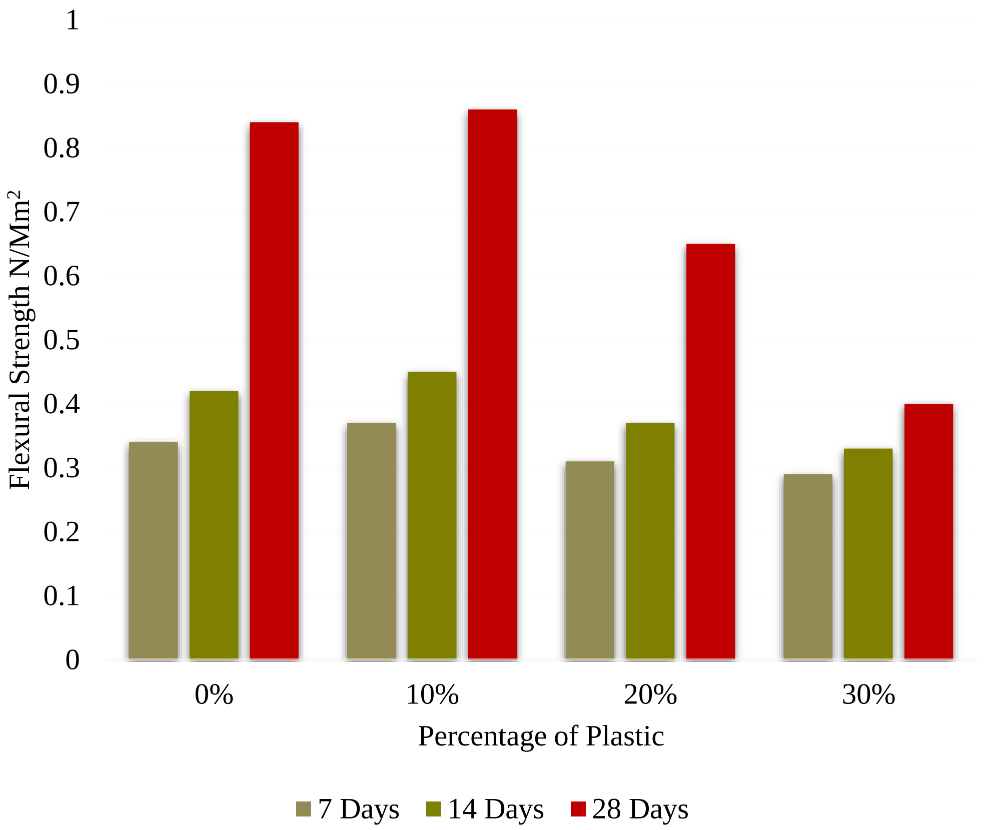

Fig. 6: Flexural strength of plastic PET aggregate concrete

3.6 Effect of plastic PET aggregate on concrete water absorption

Fig. 7 presents the water absorption capacity results for plastic PET aggregate concrete. Water absorption is measure of concrete durability against percolation of water into the concrete and which can result into concrete volume expansion to crack formation and disintegration. The water absorption capacity results for plastic PET aggregate concrete are shown in Figure 6. As indicated, the absorption property of the concrete decreases with increase in plastic PET aggregate content in concrete mix. The water insulation of concrete appreciates higher by 23%, 28% and 46% as the percentage content of plastic PET aggregate rose up to 10%, 20% and 30%, respectively. This can be explained to be as result of impermeability property of plastic PET aggregate.

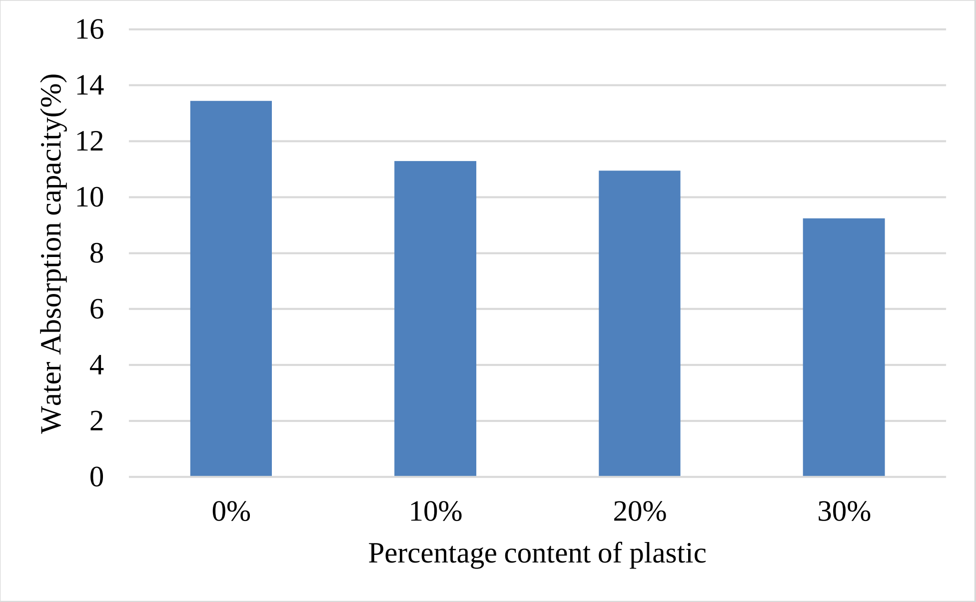

Fig. 7: Water absorption of plastic PET aggregate concrete

4. Conclusion

The following conclusions were drawn from this study:

a. The workability of concrete increased as the content of recycled plastic PET aggregate in the concrete matrix increased.
b. The density of concrete mix containing plastic PET aggregate decreased as the content of the plastic PET aggregate increased.
c. There was slight increase in flexural and compressive strength when 10% of fine aggregate was substituted with recycled plastic PET aggregate. Beyond 10% replacement, there was significant reduction of strength values.
d. Concrete mix with addition of plastic PET aggregate has lower water absorption property compare to the control concrete.

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