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Modified Concrete Using Polyethylene Terephthalate Plastic Waste as a Partial Replacement for Coarse Aggregate

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Abstract

The present work evaluated the properties of modified concrete using polyethylene terephthalate (PET) bottle waste as a partial replacement for coarse aggregate. Modified concrete samples were designed using a water/cement (W/C) ratio of 0.50 and varying percentages of PET replacement (3%, 7%, 10%, and 15% by volume). Dreux Gorisse's formulation approach was used to make the final products, and the mechanical properties of the samples were determined using Controlab presses. This modified concrete with PET chips has shown that with a 10% replacement of PET chips, the fresh density decreases by 3.56%, and the hardened state density decreases by 2.01%. The water absorption and thermal conductivity of the formulated concretes decreased. However, the results showed that the slump of these fresh concretes increased as the percentage of plastic aggregate replacement increased. Based on the results, incorporating PET aggregates into concrete contributes to good workability, and lightweight concrete structures, and provides some thermal comfort in concrete structures.

Keywords

PET Waste, Concrete, Dreux Gorisse Approach, Thermal Conductivity, Mechanical Properties of Modified Concrete

1. Introduction

Nowadays, concrete is part of our daily life. It is one of the most widely used construction materials in the world due to the simplicity of its manufacture and installation, its durability and economy, and the mechanical performance it provides. These properties have legitimized its use in various construction infrastructures (building, bridge, pipes, blocks, beams, floors, partitions, stairs, etc.) [1]. For the improvement of its properties, various materials are incorporated into concrete, including plastic materials.

However, the consumption of various forms of plastic material is growing exponentially and most of these plastics are abandoned and require large landfill areas for storage. More importantly, the low biodegradability of plastics poses a serious threat to environmental protection [2]. To counteract this threat, plastic waste is generally incorporated into concrete or mortar as aggregates [3].

Aggregates generally represent 65% to 80% of the volume of concrete and play an important role in the properties of concrete, such as workability, strength, dimensional stability, and durability [3].

The wide range of applications of concrete and the amount of space occupied by aggregates in concrete justify their use in the context of plastic waste recycling, which has become a major concern of environmental policies around the world [4].

In general, plastic waste is used as aggregate in the formulation of concrete due to some of its properties, such as low apparent density, low density and very low water absorption. These different properties have been evaluated in the majority of reported studies [5] [6] [7] [8] [9]. Some authors' works affirm that the standard procedures used to evaluate properties such as bulk density, density, and water absorption of natural coarse and fine aggregates can be used for plastic aggregates with slight modifications [10]. On the other hand, properties such as hardness, tensile and compressive strength, modulus of elasticity, decomposition temperature, melting and initial degradation temperatures, hot flow index (HFI), specific heat capacity (SHC), and thermal conductivity (TC) of plastic aggregate are also studied [8] [11].

Several studies focus on the water-to-binder ratios and the amount of polymer in the mixture. In the context of studies on the miscibility of plastic aggregates in concrete, Akçaözoglu *et al.* reviewed the use of crushed PET bottle waste as aggregates in lightweight concrete. Samples made of only PET aggregates and those consisting of a mixture of PET and sand with a water-to-cement ratio (W/C) of 0.45 were compared to the reference concrete. The tests showed that the samples can be classified in the category of structural lightweight concrete in terms of unit weight and strength properties [12]. Albano *et al.,*'s work on the influence of the content, particle size, and thermal degradation of PET bottle waste on the behavior of concrete at different water/cement ratios (0.50 and 0.60) indicated that in concrete filled with PET, as the volumetric proportion and particle size of PET increase, a decrease in compressive strength, tensile strength, modulus of elasticity, and ultrasonic pulse velocity is observed. However, water absorption increases. On the other hand, when concrete-PET is exposed to a heat source, the flexural strength of the concrete-PET decreases significantly as the temperature, water/cement ratio, content, and size of PET particles increase [11].

The works cited prove that the optimal properties of modified concrete mixes with plastic aggregates would depend on the water/binder ratio, but do not specify the exact ratio or the amount of polymers required for these corresponding optimal properties, for a common use of these concretes. Therefore, the general objective of this study is to evaluate the effect of incorporating PET chips with dimensions of 10 - 15 mm wide on the properties of modified concrete mixes with PET aggregates using a water/cement ratio commonly used in the formulation of concrete.

2. Experimental

2.1. Materials

A CEM II B-M 32.5 R Portland cement, as shown in **Figure 1**, was used in this study. The chemical and physical properties are presented in **Table 1**. Crushed gravel with a size of 5/15 from Mountougoula was used as coarse aggregate. The Niger River sand from Kalaban-Coro was used as a natural fine aggregate. PET plastic waste, used as a partial substitute for the coarse aggregate, was collected from the Badalabougou landfill. The waste was sorted and washed. Then, it was perforated and cut into chips of the dimensions indicated in **Table 2**.

Figure 2 shows the chips of the PET aggregates.

Table 1. Physical and chemical characteristics of the Portland cement used.

Elements	(%)	
Chemical analysis		
CaO	44	
SiO_2	26	
Al_2O_3	5.76	
Fe_2O_3	4.88	
MgO	1.63	
K_2O	3.27	
SO_3	2.3	
Cl	0.03	
	Normal consistency (mL)	165
Stability Volume	Initial curing (mn)	249
	Final curing (mn)	449
	2 days	16.33
Compressive strength (MPa)	7 days	29.235
	28 days	37.336

Figure 1. Portland Cement CEM II 32.5 R.

Figure 2. Plastic waste - PET bottles and PET chips.

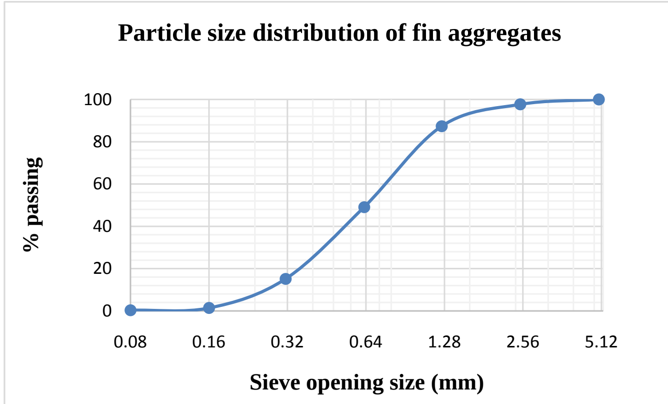
Table 2. Dimensions of PET chips.

Type of plastic	Apparent volumetric mass (kg/m^3)	Thickness (mm)	Width (mm)	Hole diameter (mm)	Spacing between holes (mm)
PET	220	0.25	10 - 15	1 à 2	5 - 8

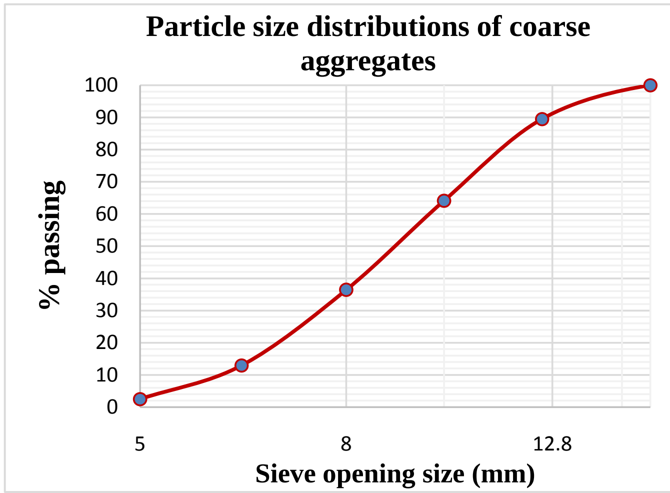
2.2. Methods

The materials used have been characterized and evaluated according to the European standard testing methods indicated in Table 3. The determination of the mechanical properties of the cement mortar was carried out on 4 × 4 × 16 cm prismatic specimens. The experimental results of the different properties of the natural aggregates are illustrated in Figure 3 and Table 4.

The concrete samples were formulated using the Dreux Gorisse formulation method, which involves using the natural aggregate mixing curve to obtain the aggregate quantities in volume. The cement content and water quantity were obtained through the Bolomey formula and the cement quantity estimation chart. The proportions of the preliminary concrete samples based on the variation of the water-to-cement ratio (W/C) are shown in Table 5. The modified concrete samples with PET chips were formulated using 3%, 7%, 10% and 15% PET replacements in molds with dimensions of 16 × 32 cm. The proportions of the PET aggregate modified samples are illustrated in Table 6.



(a)



(b)

Figure 3. Gradation curve of natural aggregates.

Table 3. Methods for characterizing the materials used.

properties targeted	Method used
Particle size distribution	NF EN 933-1
Absolute density	NF P 18-554
Bulk density	
Cleanness	NF EN 933-8
Los Angeles coefficient	NF EN 1097-2
Micro-Deval coefficient	NF EN 1097-1
Compressive and flexural strength	NF EN 196-1

Table 4. Properties of natural aggregates.

Designation	Los Angeles (LA)	Micro deval (MD)	Sand equivalent	
crushed gravel 5/15	15%	10%	-	
rolled sand	-	-	**On sight**	**plunger**
			97	95

Table 5. Proportions of constituents for concrete samples as a function of W/C ratio.

Sample (SA)	Ratio W/C	Water (kg/m³)	Cement (kg/m³)	Sand (kg/m³)	crushed gravel (kg/m³)
SA-1	0.30	174	580	732.6	1041.3
SA-2	0.35	174	497.14	732.6	1041.3
SA-3	0.40	174	435	732.6	1041.3
SA-4	0.45	174	386.66	732.6	1041.3
SA-5*	0.50	174	350	732.6	1041.3
SA-6	0.60	174	290	732.6	1041.3

SA-5*: designates the w/c ratio for the formulation of modified concretes.

Table 6. Proportions of constituents of concretes modified with PET aggregate.

Sample	Cement (kg/m³)	Water (kg/m³)	Sand (kg/m³)	Coarse aggregates (kg/m³)	PET Plastic (kg/m³)
Reference	350	174	732.6	1041.3	-
3%PET	350	174	732.6	1010.06	4.68
7%PET	350	174	732.6	968.409	10.92
10% PET	350	174	732.6	937.17	15.6
15%PET	350	174	732.6	885.105	23.4

The modified concrete mixes were prepared and poured using standard methods. The slump and fresh density were determined immediately after mix preparation. They were then poured into 16 × 32 cm molds and their air content was reduced using a vibrating table. The samples were kept in these molds at room temperature for approximately 24 hours to harden before being demolded and transferred to a humid chamber for a curing period of 28 days. Then they were subjected to compression, tension, and water absorption tests.

The methods used to determine the properties of the concrete in the fresh and hardened state are illustrated in **Table 7**. The compressive strength of the hardened concrete specimens was determined after 7, 14, 21, and 28 days of curing using a Controlab C0070HP automatic Servotronique compression press with a maximum load of 3000 kN. The splitting tensile strength was determined using a Controlab traction press after 28 days of curing. Water absorption was determined as described in the NBN EN 13369:2014 standard [13], using a Memmert UN/UF universal oven (temperature up to 300˚C) to dry the samples.

Thermal conductivity was determined through the EI700 cell of the box method according to ISO 8990 (Thermal insulation - Determination of steady-state thermal transmission properties - Calibrated hot box method, 1996). For the determination of this parameter, a square mold with dimensions of 27 cm on each side and a thickness of 3 cm (2187 cm³) was used to make the samples. The proportions used for the samples are indicated in **Table 8**. After preparation, the samples were dried for a period of 28 days to prevent shrinkage phenomena.

Table 7. Experimental methods used for the characterization of concrete.

Properties	Method
Slump test	NF EN 12350-2
Fresh density	NF EN 12350-6
Compressive strength	NF EN 12390-3
Tensile strength	NF EN 12390-6
Water absorption	NBN EN 13369:2004
Thermal conductivity	NF EN ISO 8990

Table 8. Proportions of constituents for samples formulated with PET.

Sample	Cement (g)	Water (mL)	Fin aggregates (g)	Coarse aggregates (g)	PET (g)
Reference	760	400	1600	2300	-
7% PET	760	400	1600	2120	23.9
10%PET	760	400	1600	2050	34

Figure 4 shows the formulated samples for the EI700 cell.

Figure 5 illustrates the EI700 measuring cell used to determine thermal properties.

3. Results and Discussion

3.1. Fresh Properties

The ratio water/cement (W/C) of the reference concrete used in this study is 0.50. The properties of the preliminary and modified concretes in the fresh state are presented in Table 9 and Table 10. These mixtures resulted in a slump of modified concretes ranging from 2 to 3 cm. The results showed that the incorporation of PET chips slightly increases the slump value of concrete as the percentage of replacement increases (Table 10). It was also found that between 10% and 15%, the obtained slump values are almost similar. The density of modified concretes in the fresh state decreases as the percentage of PET chip replacement increases. This trend is self-explanatory since the density of natural aggregates is significantly higher than that of PET aggregate.

3.2. Hardened Properties

3.2.1. Compressive Strength

The variation of compressive strength of modified concretes as a function of the percentage of PET replacement at 7, 14, 21, and 28 days is illustrated in Figure 6. The results show that, regardless of the PET aggregate content and curing time, the compressive strength decreases, which is in line with previous studies [15] [16]. A gradual increase in compressive strength up to the 28th day (normal curing duration) was observed. It was noted that the strength increases rapidly up to the 7th day, but beyond that age, between 14 and 21 days, the rate of strength evolution is slightly decreased. In Figure 7, a cone-type fracture was observed. This fracture corresponds to the ideal fracture according to the NF EN 12390-3 standard [17], although other types of fractures were obtained.

Figure 4. Formulated sample.

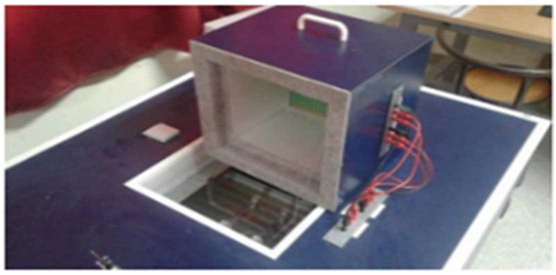


Figure 5. Cell EI700 [14].

Table 9. Fresh properties of preliminary concretes.

Properties	Formulation of preliminary concretes					
W/C	0.30	0.35	0.40	0.45	0.50	0.60
Slump test (cm)	0.7	1	1.3	1.6	2.00	3.00
Fresh density (Kg/m³)	2530.00	2525	2513	2506	2498	2493

Table 10. Fresh properties of PET-modified concretes.

Properties	PET modified concrete			
	3%	7%	10%	15%
W/C	0.50			
Slump test (cm)	2.2	2.3	2.40	2.45
Fresh density (Kg/m³)	2471	2446	2409	2403

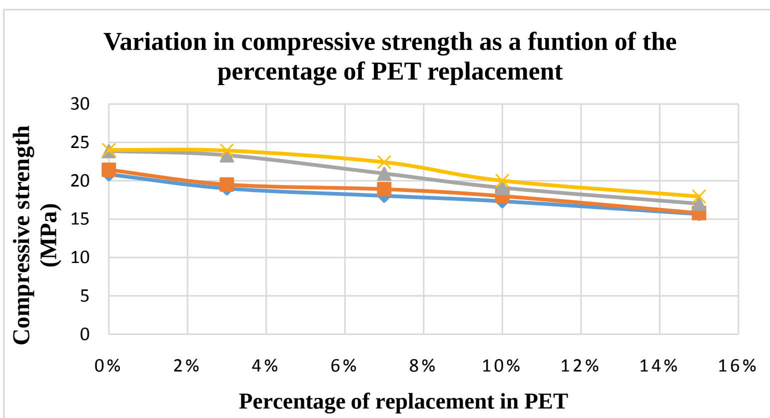


Figure 6. Variation in the compressive strength of concretes as a function of the percentage of replacement of PET.

Figure 7. Type of rupture obtained in the cylinders after compression resistance test.

This decrease in compressive strength is due to the very low adhesion of plastic waste to the cement paste, which has caused the appearance of cavities on the surface of the samples, as shown in **Figure 8**. Compared to the reference concrete, mixtures with 3%, 7%, 10%, and 15% PET chips present a decrease in compressive strength of 0.34%, 6.64%, 16.71%, and 25.25%, respectively. Despite this decrease in compressive strength compared to the reference, mixtures with 3%, 7%, 10%, and 15% of PET show an acceptable compressive strength, as the standard strength values for medium strength concretes are between 21 and 30 MPa for a curing age of 28 days according to Porrero *et al.* [18]. Moreover, according to ASTM C39 standard, for ordinary concrete, the minimum compressive strength value for any project typically starts around 2500 to 3000 Psi, or 17 to 20 MPa.

A similar behavior was observed by some authors [19] [20], when incorporating recycled PET waste and rubber particles into concrete.

Figure 8 represents the cavities present in the concrete.

3.2.2. Tensile Strength

Figure 9 illustrates the variation in tensile strength of modified concretes as a function of the percentage of PET replacement. It was observed that the tensile strength of these different concretes decreases slightly as the percentage of replacement increases. This reduction is due to the same phenomenon that causes the decrease in compressive strength, namely the lack of adhesion between the PET chips and the cement. This trend of reduction is confirmed by the results reported by Saikia *et al.* [3], when they used these plastic aggregates as coarse aggregates. From all of the above, the incorporation of lightweight aggregates has a major influence on the mechanical properties of concretes, especially compressive and tensile strength.

Figure 8. Formation of cavities.

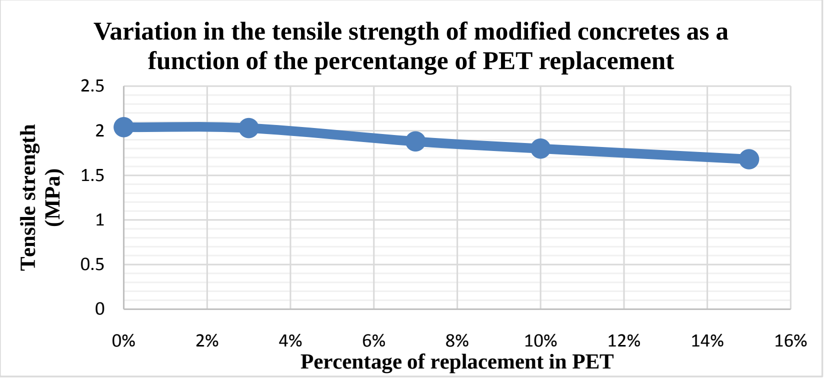


Figure 9. Variation in tensile strength of modified concretes as a function of the percentage of replacement of PET.

3.2.3. Water Absorption

The variation in water absorption as a function of the percentage of plastic aggregate replacement, as illustrated in Figure 10, shows a decrease in water absorption as the percentage of replacement increases. This decrease is due to the influence of plastic aggregates on the porosity of concrete and the low water absorption of the polymers used. It was observed that as the percentage of plastic aggregate replacement increased, the porosity of the formulated concrete also increased. This means that the plastic aggregates did not react properly with the cement paste, meaning that they altered the porosity of the concrete. This property was also observed by Porrero *et al.* [18], who suggested that plastic aggregate can influence porosity in two ways: one, by providing suitable porosity, and the other by altering the cement paste. According to the NBN B 15-001:2004 standard, the porosity of ordinary concrete should not exceed 15%, a value that is in agreement with the results presented in Figure 11. A similar trend was also observed by Saikia *et al.* [21]. Based on the water absorption results, the incorporation of plastic aggregates leads to a decrease in water absorption as the replacement percentage increases.

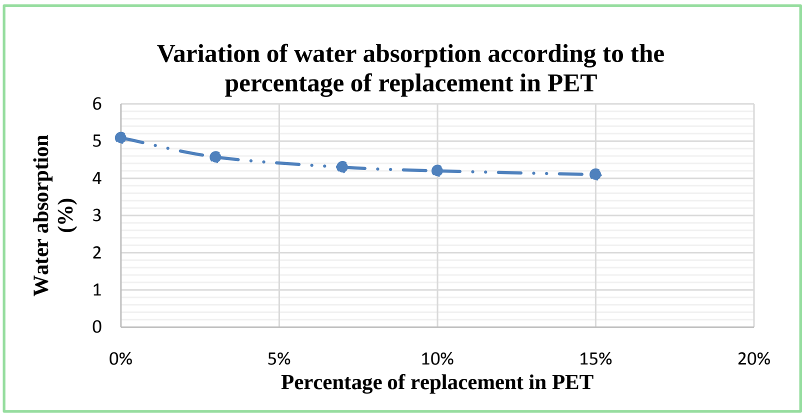


Figure 10. Variation of water absorption according to the percentage of replacement in PET.

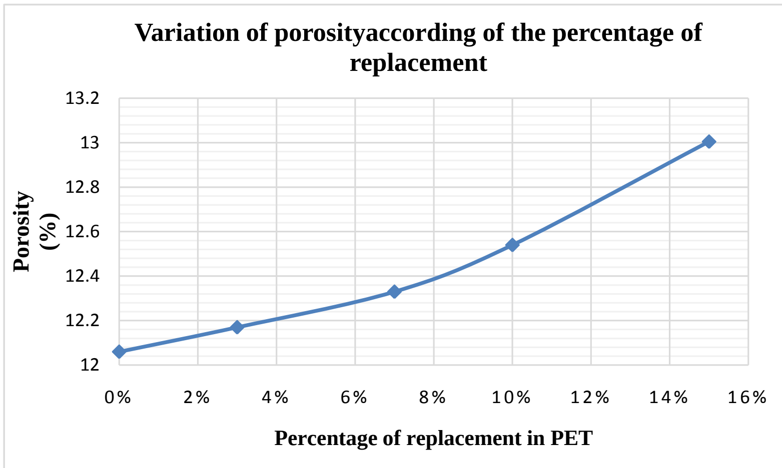


Figure 11. Variation of porosity according to the percentage of replacement in PET.

Table 11. Variation of the thermal conduction of the samples according to the percentage of replacement in PET.

Sample	T2 (K)	T1 (K)	Ti (K)	Ta (K)	Ptrans (W)	S (m^2)	e (m)	λ (W/mK)
Reference	347.1	344.89	357.9	300	9.105	0.0729	0.03	1.620
7% PET	346.7	344.3	357.6	300.5	9.145	0.0729	0.03	1.570
10%PET	346 .1	343.72	358.1	299	9.046	0.0729	0.03	1.564

T1: The temperature on the external face of the sample; **T2**: The temperature on the internal face of the sample; **Ti**: The temperature in the middle of the heating plate; **Ta**: Ambient temperature; **Ptrans**: The Power transmitted; **S**: The surface of the sample, **e**: The thickness of the sample; λ: The thermal conductivity of the sample.

3.2.4. Thermal Conductivity

Table 9 represents the results of thermal conductivity. A decrease in thermal conductivity was observed with an increasing percentage of plastic aggregate replacement. This decrease is due to the fact that the PET chips incorporated in the concrete have lower thermal conductivity, 0.3 W/m·K, compared to the cement matrix. The value of thermal conductivity obtained with 0% plastic waste shown in **Table 11** is in agreement with the classification proposed by energyPlus [22]. Compared to the thermal conductivity of the reference concrete, the incorporation of plastic aggregates provides some thermal comfort in buildings constructed with these concretes.

4. Conclusions

Based on the results of the basic trials, the materials used in this study meet the proposed standards and requirements for concrete formulation. The preliminary concrete formulations have shown that:

A concrete mix is workable when the water-to-cement ratio (W/C) increases, good compressive strength of the concrete depends primarily on the W/C ratio, particularly the cement content, an optimal compressive strength is achieved with a W/C ratio of 0.35, and a concrete mix with a W/C ratio of 0.50 (350 kg/m^3 of cement) is a typical dosage for ordinary structures.

Based on the trial results, the incorporation of PET aggregate in the concrete has led to the following observations:

The addition of PET as a partial replacement for crushed gravel contributes to a reduction in the unit weight of the concrete; it enhances the workability of the concrete; it decreases the density of both fresh and hardened concrete, depending on the replacement percentage; it reduces the weight of concrete structures; it leads to a decrease in mechanical properties, such as compressive and uniaxial tensile strength of the concrete; it increases the porosity of the formulated concrete but remains within acceptable limits; it provides a certain level of thermal comfort when incorporated.

Despite its effect on the mechanical characteristics of the concrete, the results confirmed that PET can be incorporated into the concrete with a replacement rate of up to 15% without major consequences, depending on the specific application of the concrete.

Based on this study, a W/C ratio of 0.50 is considered a suitable and commonly used ratio for concrete containing plastic aggregates.

Depending on the percentage of plastic aggregate replacement in the concrete, the modified plastic aggregate concrete can be used in construction. For example, concrete with a 15% replacement of PET, which has a compressive strength of 17.527 MPa at 28 days, can be used for sidewalks, stairs, interior walls, low-height concrete walls, storage tanks, coatings, non-structural slabs, etc.

However, the adhesion between the concrete matrix and the plastic remains the major problem for the mechanical parameters of the modified concrete.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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