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(Research Article)

Properties at room temperature of concrete containing 1, 3 and 5% of plastic wastes as partial substitute of Sand

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Abstract

This work investigates at room temperature the evolution of concrete properties containing 1, 3, and 5% plastic waste as partial substitute of sand. This research proposes a new material for civil engineering that addresses the challenges of plastic waste management while meeting the strength and cost-effectiveness requirements of natural materials. To this end, literature reviews were conducted and laboratory experiments were performed. These experiments involved adding polymers derived from plastic waste to concrete as a sand substitute at varying proportions (1, 3, and 5%) of the aggregates (sand and gravel) dry mass. The resulting concrete mixes were subjected to tensile and compressive tests to determine their strength. A comparative study was then conducted between the concrete containing plastic waste and samples of conventional concrete as reference, all cured at room temperature at different curing ages.

Keywords: Concrete; Ecology; Plastic; Strength; Recycling

1. Introduction

With the impact of industrial sector worldwide, industrial waste has increased in the past decades, with its volume playing a significant role in environmental pollution [1-4]. Among these wastes, there are plastics with huge challenges for recovery and recycling [1-4]. These plastic wastes, regardless of their origin, are generally not biodegradable and contribute to pollution that is dangerous for both humans and the environment [1-4]. Furthermore, with the modernization of society, numerous construction projects are underway in Mali and around the world, leading to an ever-increasing demand for concrete [2-3]. This increased demand for concrete results in the overconsumption of natural aggregates [1-4], which could lead to a scarcity of local natural deposits in the medium term. The solution to this dual problem could be the substitution of some of the natural aggregates with plastic waste in the manufacture of concrete [2 - 3].

Following this line of reasoning, several researchers have investigated the issue, demonstrating the benefits of replacing some natural aggregates with plastic waste in concrete mixes [1-6]. Some have studied the mechanical properties of concrete containing plastic waste particles in the form of fine aggregates [3-5]. They concluded that using these particles in concrete saves on natural aggregates, reduces waste disposal, and results in lower density with compressive and tensile strength values suitable for non-structural applications [3-5]. Others have used them as binders to develop lightweight, eco-friendly concretes for secondary construction projects for building and public works sector [2-3].

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This article proposes reusing plastic waste in concrete, which is a material widely used in the field construction. This allows the valorization/recycling of plastic wastes, in order to help addressing the scarcity of natural materials used in concrete, and ultimately offers a new, environmentally friendly material for the civil engineering sector, contributing to reduce its environmental impact [2-3]. To achieve these results, an experimental study was conducted to determine certain properties of virgin concrete and concrete containing (1, 3, and 5%) of plastics as partial substitute of sand in the concrete mix, in order to assess the impacts and draw conclusions and/or recommendations.

2. Materials and Lab tests

2.1. Materials

Concrete is one of the most widely used materials in the world today, due to its compressive strength, fire resistance, sound insulation properties, and the diversity in uses which allows to have flexibility in terms of shapes, colors, and finishes [1-6]. Concrete used in building construction and civil engineering encompasses several categories. Generally, the optimal concrete mix is always the result of a compromise between a range of requirements, taking into account laboratory work and real-world construction site conditions [2-3].

A concrete composition method may be considered satisfactory if it allows the production of concrete that meets the requirements of low shrinkage and low creep, not forgetting the ease of implementation with the means and methods used on the construction site, while exhibiting, after hardening, a certain resistance to compression [4 - 7].

Concrete is a composite material made of coarse and fine aggregates (gravel or crushed stone, sand), cement, and water. The mixture of cement and water forms a paste that hardens [7]. The hydrated cement paste and sand constitute the mortar. The mortar's role is to bind with the coarse aggregates to form a solid conglomerate. Admixtures and additives are used to improve certain characteristics of fresh or hardened concrete [8].

Natural gravel and sand from the Niger River were used to prepare the various cementitious materials. ASTM C136/C136M procedures were used to determine the particle size distribution of the granular materials (Fig. 1) [9]. Then, HDPE (high-density polyethylene) plastic waste (Fig. 2) from landfills was ground to the desired particle size for addition into the concrete.

Two formulations were made, namely that of conventional/ordinary concrete as a control sample with gravel, sand, water and cement; and the ones containing a quantity of crushed plastic waste as a partial substitute of sand.

Once the fresh materials were ready, they were poured into lubricated molds to facilitate demolding. These samples were kept at room temperature (24–30°C) in a control chamber for 1, 3, 7, and 28 days of curing. Concrete samples (ordinary and those containing plastic waste) at different ages were subjected to various tests to determine certain properties such as density (ASTM C 138/C138M-17a) and compressive strength (ASTM C39/C39M-18) according to ASTM standards [10–11].

Figure 1 Natural aggregates used in the production of concrete

Figure 2 Polymer (HDPE) used for the production of ecological concrete

To successfully formulate the concrete mix, the granular materials underwent quartering, which involves classifying the grains into four (4) groups to obtain a representative sample and determine the grain size class using the particle size analysis [2-3]. This test consists of classifying the different grains of the sample using a series of sieves, nested one on top of the other, with decreasing aperture sizes from top to bottom [9]. The material under study is placed on the upper part of the sieves, and the grain classification is obtained by vibrating the sieve stack. This allows the dimensions and proportions of the grains to be determined, and other characteristics such as the fineness modulus (Mf) of the sand to be deduced [9].

Figures 3 and 4 show the particle size distribution graphes of gravel (G5/15), sand (S0/2) and samples of recycled plastics/polymers (P0/2).

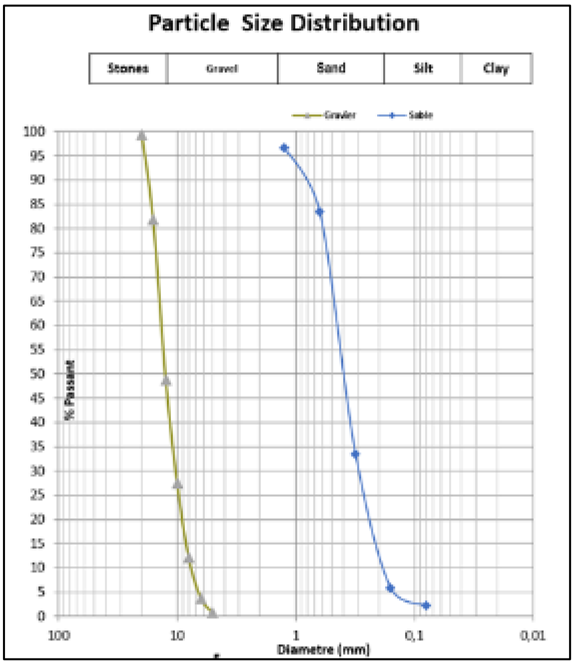

Figure 3 Sand and Gravel grain size distribution curves

Sand fineness modulus: Mf = (96.7+83.45+33.5+5.9+2.2) /100=2.22

A good concrete sand should have a fineness modulus of about 2.2 to 2.8. Thus, this sand is within the permissible range [2-3].

The polymers (P0/2) were sieved to better understand the particle size distribution (Fig. 4) and get an idea of the rate of replacement of natural aggregates by plastics.

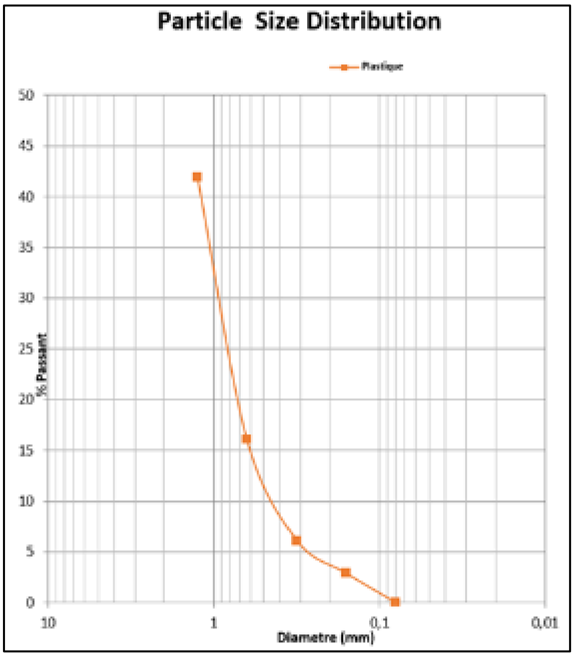

Figure 4 Plastic polymer particle size distribution curve

Further tests were carried out to better understand the materials before using them in the different formulations. Specific weight and density tests (Fig. 5 and Fig. 6) provided the results for gravel and sand in Table 1, following the procedures of the French standards NFP [7, 12-14].

Figure 5 Determination of the specific weight of gravel

Figure 6 Apparent density of gravel

Table 1 Specific weight of granular materials (gravel and sand)

	Poids spécifique : Gravier		Poids spécifique : Sable	
Poids	E1	E2	E1	E2
	350	400	300	250
Volume 1	400	450	350	300
Volume2	530	590	460	400
Volume net	130	140	110	100
PS (g/cm^3)	2,69	2,85	2,72	2,50
PS Moyen (g/cm^3)	2,77		2,61	

Another important parameter is apparent density. In physical terms, this is the degree to which a body's mass is filled by solid matter [14]. It is calculated by dividing the density of these materials by that of water at a given temperature and is expressed without units [7, 14]. After the calculation of apparent density for various materials, the results obtained are given in Table 2.

Table 2 Apparent density of gravel and sand

Densité apparente : Gravier			Densité apparente : sable	
Poids	E1	E2	E1	E2
	5330	5369	4929	4920
Volumes	3301	3301	3301	3301
DA (g/cm^3)	1,61	1,62	1,49	1,49
DA Moyenne (g/cm^3)	1,61		1,49	

In general, sands contain other particles, such as clay or organic impurities, which can affect their behavior [2-5]. Therefore, in this paper, sand equivalent test was performed to determine the cleanliness of the sand used. This test involves separating the sand from the very fine particles that rise by flocculation to the top of the test specimen where the sand has been washed [4]. The test is performed only on the 0/2 mm sand fraction. The so-called "piston sand equivalent" test measures the cleanliness of the sand. The PS value should be greater than 60 or 65, depending on the case. The results of this sand test are presented in Table 3.

Table 3 Sand Equivalent Test

		Équivalent de sable	
		E1	E2
Agitation. Lavage t+10min		11h33	11h38
Mise au repos T		11h35	11h40
Lecture T+20min		11h55	12h00
Hauteur du floculat h_1 (cm)		10,80	10,80
Hauteur du sédiment au piston h_2 (cm)		10,10	9,40
Hauteur du sédiment a vue h'_2(cm)		10,00	9 ,90
Équivalent de sable sur prise d'essai	Piston	93,51	87,03
	À vue	92,59	91 ,66
Équivalent de sable sur prise échantillon	Piston	90 ,27	
	À vue	92 ,12	

2.2. Concrete formulation, specimen preparation and Lab tests

The mix design was created in the laboratory using the software called (CEBÉTON), which is based on the characteristics of the simplified DREUX GORISSE method. This method is suitable for standard construction projects carried out with limited resources (volumetric dosing). It uses simple charts to prepare the concrete (a mixture of cement, sand, gravel, and water) based on several available data points, including the maximum aggregate size D; workability, which can be defined by plasticity measured using the Abrams cone; and the desired 28-day strength [15]. Various ratios were thus obtained, such as the aggregate percentages (G=61.5%, S=38.5%), and a water/cement ratio of 0.5. The proportions used for the different mixes are detailed below (Table 4).

Table 4 Composition of concrete containing polymers (plastic waste)

Composantes	quantités	
0% de polymère	sable	2,061kg
	polymère	0kg
1% de polymère	sable	2,040kg
	polymère	0,02061kg
3% de polymère	sable	1,999kg
	polymère	0,061kg
5% de polymère	sable	1,957kg
	polymère	0,103kg
Gravier	3,293 kg	
ciment	1,050kg	
Eau	0,563L	

Cylindrical molds with a diameter of 5 cm and a height of 110 cm were used in this research to prepare concrete test specimens for different formulations (Fig. 7). The materials (water, cement, and aggregates) were placed in the mixer in precisely defined proportions. The sand and cement were then mixed until the mixture with uniform color (Fig. 7a), and the gravel is added to the first mixture (Fig. 7b). This step was followed by the gradual addition of water until the desired plasticity achieved (Fig. 7c). Finally, the resulting paste was poured into the molds and compacted by vibration (Fig. 7d).

Figure 7 a) Sand + cement; b) Sand + cement + gravel; c) Fresh concrete; d) Concrete poured into molds

2.3. Experimental setups and characterization tests

2.3.1. The setting of the cement

The purpose of this test is to determine the water content and setting time of cement (Figs. 8 and 9). This test is accompanied by verification of the cement class, an important parameter influencing the strength of hydraulic concrete and essential for concrete mix preparation. The results of the various tests are given in Tables 5, 6, and 7.

In the laboratory, this test is accompanied by a mortar test which consists of making six (6) prismatic specimens of 4*4*16 cm3 subjected to compression and bending [16-17].

Table 5 Cement setting tests

Type of cement	Water content ω %	Concrete mixing time	Begining of Cement binding phase	End of Cement binding phase	Time of Cement binding phase (min)	Duration of Cement binding phase (min)
CIMAF32,5R	33 %	10h57min	16h23min	18h17min	340	116

Table 6 Compressive Strength at 3 and 28 days

Curing Time (days)	Max Load (daN)	Area (cm^2)	UCS Strength (MPa)	Average UCS strength (MPa)
3 days	2700	16	16.87	21.88
	4170		26.06	
	3635		22.71	
28 days	5385		33.657	37.987
	7449		46.556	
	5400		33.75	

Table 7 Flexural Strength Tests at 3 and 28 days

Curing Time (days)	Max Load (daN)	Area (cm²)	Flexural Strength (MPa)	Average Flexural strength (MPa)
2 days	1550	64	38.75	40.83
	1750		43.75	
	1600		40.00	
28 days	1900		47.50	55.83
	2600		65	
	2200		55	

Figure 8 Cement test (Vicat apparatus equipped with a needle and an overload)

2.3.2. USC compression tests

Compressive strength has long been considered as the essential quality to look fora given concrete. It determines the concrete class [17]. It is obtained using a hydraulic press and is designated by Rcj and is measured by axial compression of a straight cylinder whose height is twice its diameter [17]. The cylinder used in our research has dimensions (D=5.5cm; H=11cm) with a cross-section of 23.758 cm^2. The test operation consists of crushing the specimens with the press (Fig. 9). During this test, the specimen undergoes vertical deformation, which was measured along the vertical axis by attaching a dial indicator to the specimen during the compression test to obtain the vertical deformations.

Figure 9 UCS compression test

2.3.3. Splitting tensile strength tests

This test consists of crushing a concrete cylinder along two opposing generatrices between the platens of a hydraulic press. This test is often called the "Brazilian Test". For this test, the specimen is placed horizontally between the two

(02) platens of the press; the contact of the upper and lower generatrices with the platens is ensured by means of measuring strips made of plywood (Fig. 10) [18]. The tensile strength by splitting is given by the following formula:

$$\mathrm{Rtj} = \frac{2\mathrm{P}}{\pi DL}$$

With j = age of the concrete (in days) at the time of the test ; D and L = diameter and length of the cylinder.

Figure 10 Splitting tensile strength tests

3. Results of various tests to determine properties of hardened concrete at ambient temperature

This section presents the results of various tests carried out on concrete mixes prepared according to the different compositions detailed in the previous section. These results concern the volumetric density of the concrete, the compressive strength at different ages of hardening, and the tensile strength at splitting. Throughout this section, particular attention is paid to the effect of incorporating polymers as a fine-grain substitute of sand in the concrete and the mechanical properties of different formulations of hardened concrete containing different percentages of plastic waste. In our research, the test specimens were weighed after formwork removal and before crushing.

3.1. The volumetric density of concrete

The test specimens were weighed after formwork removal and before crushing to determine the volumetric density of the concrete as a function of the percentages of incorporated polymers, and the results are shown in Table 8. The Figure 11 provides a clearer view of the evolution of the concrete's volumetric density as a function of the percentage of substituted plastics, with an average density around 2.5 kg/m^3, similar to other concretes containing recycled plastics from previous work, and the possibility of using them for various applications [1-7]. Increasing the percentage of plastics contributes to a decrease in the density of the new concrete, but this remains within the acceptable range for certain uses. Furthermore, the density of the concrete made with plastic waste (polymers) is lower than the density of ordinary reference concrete; this result is logical and expected, since the density of plastic is lower than that of the substituted sand [1-5].

Table 8 Average density as a function of the percentage (%) of added plastic (polymer) waste (kg/m^3)

Curing time (days)	0% of plastic polymer	1% of plastic polymer	3% of plastic polymer	5% of plastic polymer
3	2.764	2.706	2.683	2.593
7	2.743	2.674	2.599	2.582
28	2.687	2.662	2.588	2.570

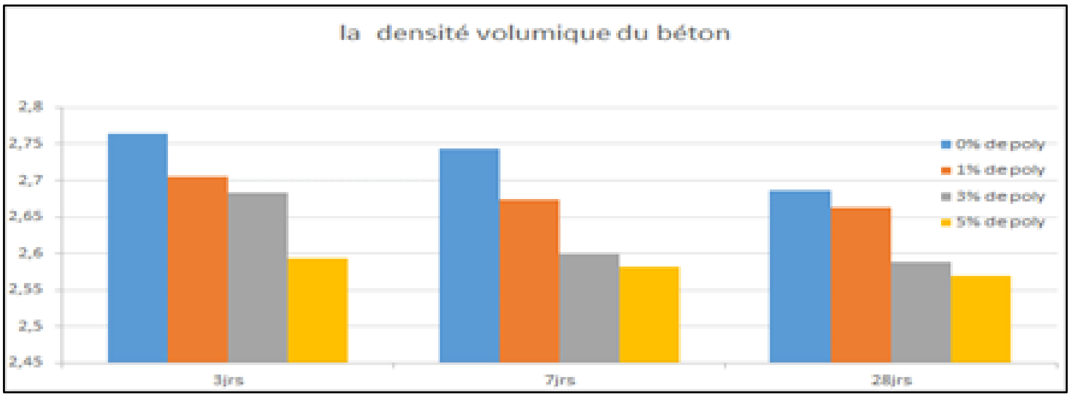

Figure 11 Density vs time for various formulations containing different percentages of plastics

3.2. UCS Compression Strength

The specimens were subjected to the compression test, and the results obtained (Table 9) show the evolution of the concrete compressive strength as a function of time and the addition of percentages of plastics (Fig. 12).

Table 9 UCS strength vs Time for different percentages of plastic

Curing time (days)	0% of plastic polymer	1% of plastic polymer	3% of plastic polymer	5% of plastic polymer
3	8.782	8.698	7.285	6.396
7	9.413	8.909	7.477	6.664
28	9.825	9.385	8.259	6.986

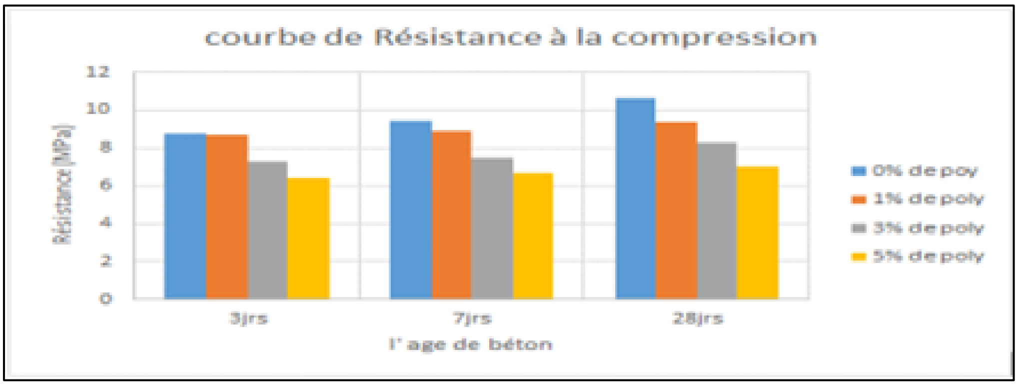

Figure 12 UCS strength vs Time for different percentages of plastic wastes

Regardless of the percentage of added plastic waste, compressive strength increases over time, which may be partly related to the evolution of cement properties over time [1-6]. On the other hand, as shown in Fig. 12, increasing the amount of polymers contributes to a decrease in compressive strength depending on the concrete's curing age, which may be related to the lower density of plastics compared to natural aggregates [1-6].

3.3. Slippting Tensile Strength

The test specimens were subjected to splitting tension, which the results are shown in (Table 10). To see the evolution of the splitting tensile strength of the concrete, a curve was drawn (Fig. 13).

Table 10 Average Splitting tensile strength vs time for various plastic ccontent

Curing time (days)	0% of plastic polymer	1% of plastic polymer	3% of plastic polymer	5% of plastic polymer
3	2.168	2.095	1.585	1.452
7	2.269	2.139	1.747	1.458
28	2.378	2.155	1.852	1.534

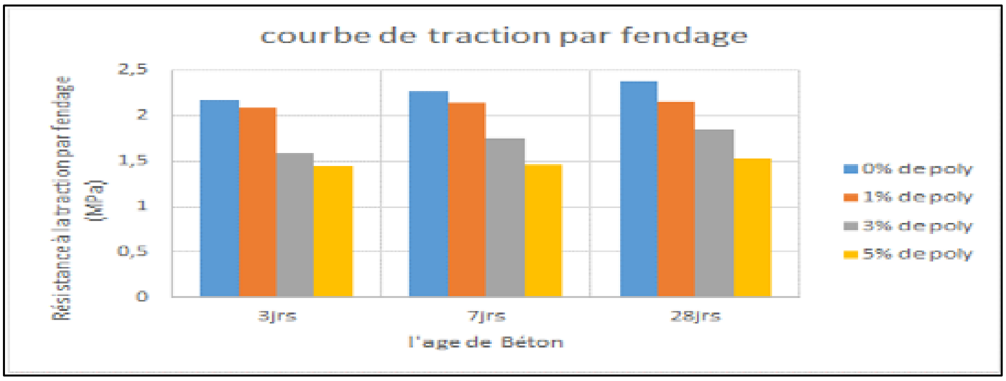

Figure 13 Splitting tensile strength vs Time

Similarly to the compressive strength results, Fig. 13 shows that the incorporation of polymers leads to a decrease in tensile strength, regardless of age, and for the same percentage of plastic waste, tensile strength increases with the concrete's curing age. The values found are similar to those found for some materials containing plastic waste in the literature [2-5].

4. Practical application

According to thas experimental studies, a decrease in compressive strength was observed, an important parameter for concrete, but various applications remain possible. The variation in compressive strength ranged from 0.10 MPa to 2 MPa, accompanied by a decrease in density, thus demonstrating a correlation between density and strength as found in some studies [2-4]. Moreover, the values obtained are acceptable for the production of paving stones (Table 11). Therefore, strength tests were conducted on paving stones made using the new product to better understand its behavior and compare it to conventional paving stones sold on the Bamako market made of cement. The molds (30x30x3 cm^3, 10x10x10 cm^3, and 10x10x5 cm^3) shown below were used for the production of the paving stones (Fig. 14).

Figure 14 Production of paving stones made using the new material and practical test of compressive strength in the laboratory

Table 11 Compressive strength of paving stones

Density (Kg/m^3)	Load (KN)	UCS Strength (MPa)	Average UCS Strength (MPa)
1436	259.713	25.97	25.035
1308	241	24.10	

According to the practical guide for compressive strength of paving stones, the strength should be between 20 MPa and 40 MPa, and the new products have an average strength of 25.035 MPa at 7 days, which is acceptable for certain uses in the construction sector [2-6].

5. Recommendation and conclusion

5.1. Recommandation

Based on the results, further work is needed to determine the optimum plastic content to guarantee minimum strength for various applications of the new product. The plastic allows the new concrete to be lightweight, thus providing a degree of flexibility in its use. For load-bearing elements, further work is required; however, given its low density, it can be used in place of lightweight concretes (such as those used for shaping and architectural design), as well as for the production of paving stones, slabs, etc.

5.2. Conclusion

This research has provided opportuity to reconvert plastic wastes in order to give it a new life by incorporating into the concrete, thus deveopping a new concrete for construction.

To assess the potential uses of this material, the particle size distribution, volumetric density, compressive strength, and tensile strength at splitting were determined in the laboratory. The experimental tests carried out as part of this research project led to the following conclusions:

- The addition of plastic waste decreases the volumetric density of the concrete, which confirms the lightness of the concrete depending on the percentage of plastic waste added;
- Compressive strength decreases as the plastic content increases, which can affect mechanical performance.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed

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