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# The use of plastic waste as fine aggregate in the self-compacting mortars: Effect on physical and mechanical properties

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## HIGHLIGHTS

- Plastic waste in self-compacting concrete (mortar) production.
- Effect of plastic waste type on self-compacting mortar performance.
- Effect of the plastic waste form on interface cementitious matrix/plastic.

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ABSTRACT

This work aims to study the possibility of recycling waste plastic (polyethylene terephthalate (PET) used for the bags manufacture) as a fine aggregate instead of sand in the manufacturing of the self-compacting mortars. For this, an experimental study was carried out to evaluate physical and mechanical properties of the self-compacting mortars (SCMs) with plastic wastes. The sand is substituted with the plastic waste at dosages (0%, 10%, 20%, 30% and 50% by weight of the sand).The physical (bulk density, porosity, water absorption and ultrasonic pulse velocity testing) and mechanical (bulk compressive and flexural strength) properties of SCMs were evaluated and a complementary study on micro-structural of the interface of cementitious matrix and plastic waste. The measurements of physical and mechanical properties show that, in term of the density for materials, the mortars with 50% of plastic waste give better results than other proportion of the waste. Those mortars have a mechanical strength acceptable for lightweight materials. According to results obtained a reduction of 15% and 33% for mortar containing 20–50% plastic waste. A microscopic study of the interfacial zone (plastic–binder) has shown that there is an adhesion between plastic and cement paste (case 28 days of hydration).



## 1. Introduction

Due to the very low biodegradability and the presence in large quantities of plastic waste, the disposal of these wastes constituted a major benefit to the environment protection. Today, research tends to the study of the possibility of recycling of these wastes in concrete where strength of concrete may not be major criteria under consideration, such as heavy mass of concreting in PCC (Portland Cement Concrete) in pavements. Recently, research works showed that, the plastic is becoming a major research issue for its possible use in concrete of in self-compacting concrete and light weight concrete [1,4,6,7,16,17,20]. Although some of these wastes can beneficially be incorporated in concrete, both as fine aggregates or as supplementary cementitious materials, it is important that not all waste materials are suitable for such use.

Several studies have been conducted on the use of plastic waste in concrete. The works of Rebeiz showed that the resins based on recycled PET can be used to produce a good quality of precast concrete [18]. Many studies have been conducted on the use of scrap tire/rubber in mortar and concrete, and a research work has been published by Siddique a review paper (2008) on the use of recycled plastic in concrete [20,23]. In the other study, Choi et al. [8] investigated the effect of plastic waste (PET bottles) as aggregate on properties of concrete. The results obtained in this study showed that these wastes could reduce the weight by 2–6% of normal weight concrete and the compressive strength was reduced up to 33% compared to that of normal concrete. Sikalidis et al. [24] investigated the utilization of municipal solid wastes (MSW) for the production of mortar. Batayneh et al. [6] have shown, in theirs work, that the decrease of compressive strength was in function of increase in the content plastic content. For a 20% substitution of sand by the waste, the compressive strength was reduced up to 70% compared to that of normal concrete. Also, researchers

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[11,16,19,25] have also studied the use of consumed plastic bottle waste as sand-substitution aggregate within composite materials for building applications. These authors showed that the density and compressive strength were decreased when the PET aggregates exceeded 50% by volume of sand. Also, It was found that the addition of plastic waste (fractions < 10%) in volume inside of cementitious matrix does not imply a significant variation of the concrete mechanical features [13]. As regards the ductility of concrete, the results obtained by Khaloo et al., shows that the addition of tire rubber particles significantly improved the ductility of concrete compared to the control concrete [14]. For this, the main gaps or differences between this present study and past studies cited are, first, the self-compacting concrete (or mortar) used has high fluidity which may be segregation between the plastic waste (low weight) and the concrete matrix. Secondly, the adherence of plastic and cement paste of concrete, which is always a problem. This study proposes to investigate the possibility of using waste plastic in self-compacting concrete without phase separation (plastic, concrete) and also examines the adhesion between the waste and the concrete matrix.

However, it has recently been observed, it is necessary to see the possibility of recycling plastic wastes in the formulation of new concretes especially self-compacting concrete (SCC). Indeed, these concretes are known for their properties in fresh (flowability, stability and homogeneity) and hardened (better mechanical properties and good durability). For this, our study will focus on the use and recycling of plastic wastes in the formulation of the self-compacting mortars as a fine aggregate instead of sand given the non-availability of natural resources such as sand in Algeria. An experimental study was carried out to evaluate fresh and hardened properties of the self-compacting mortars (SCMs) with different proportions of substitution of sand by plastic wastes.

## 2. Experimental study

### 2.1. Materials used

The materials used in this work were Portland cement (CEM II 42.5), limestone fillers, sand (0–5 mm), the plastic wastes and a polycarboxylate based superplasticizer. The sand is obtained from local sources and the plastic waste (Fig. 1) resulting from the rejected of plastic bags. The plastic waste is obtained according to the manufacturing technology of plastic waste by using plastic recycling machines. The characteristics of cementitious materials (cement and limestone fillers) are given in Table 1. The fillers limestone used in this work, is a crushed limestone from the career of Boumerdes region (Algeria). The physical properties of sand and plastic waste are given in Table 2. The Particle size distribution of sand and plastic waste is represented in Fig. 2.

### 2.2. Mix design and proportion of self-compacting mortars

The self-compacting mortars (SCMs) were established made using the design method of concrete equivalent mortar (CEM) developed by Schwartzentruber and Catherine [22]. This method is based on the replacement of coarse aggregate by a mass of fine aggregate at equal specific surface. Table 2 shows the mixes details of three SCM mortars [22]. The water–binder ratio used is keep constant (W/B = 0.45) and the fine-cement ratio is also keep constant (Fillers/Cement: F/C = 0.10). The mixing process was kept constant for all mixtures (see Table 3).

### 2.3. Test methods

#### 2.3.1. Preparation and samples conditioning

To conduct the study prismatic $40 \times 40 \times 160\ mm^3$ samples were manufactured for each mixture. One day after casting, samples were stored in water under 21 ± 1 °C, and various tests and measurements were carried out in order to study physical (weight loss, porosity and absorption), and mechanical (bending strength and uniaxial compression) properties.

#### 2.3.2. Physical properties

The fluidity was evaluated by test flow immediately after 5 min of mixing. The flow was measured at 20 °C by the mini-cone of the mortar of top diameter 70 mm, bottom diameter 100 and height 60 mm.

The porosity was determined by the knowledge of the saturated and oven-dried mass of samples. Two half-prismatic samples ($40 \times 40 \times 80\ mm^3$) were tested at the ages of 14 and 28 days. The dried mass was obtained after drying saturated in an oven at 60 °C until constant weight. The apparent volume of each sample was determined using a pycnometer.

The water absorption test was carried out on the same samples which were served for the determination of porosity according to ASTM C642 [3]. The oven-dried dry mass of each sample was recorded and then they were totally immersed in water at 20 °C until they achieved a constant mass. The constant mass was taken as the saturated mass of sample after 48 h. The absorption percentage was then obtained by the ratio of the amount of water absorbed to oven-dried mass.

The ultrasonic pulse velocity testing (UPV testing) system consists of several functional units which are pulser/receiver, transducer and display devices as schematically described in ASTM C597-97 (The UPV testing – ASTM C597-97) [2].

#### 2.3.3. Mechanical properties

Three-point bending test and uniaxial compression are carried out at 1, 7, 14 and 28 days on water stored samples. Three-point bending tests were carried out using a classical machine, with a capacity of 150 kN, on prismatic samples ($40 \times 40 \times 160\ mm^3$) according the European Standard EN 196-1 [9]. After the failure of the three samples in bending tests, the two parts of each prism were subjected to compressive stress by using a hydraulic press with a capacity of 3000 kN with the help of a device consisting of two steel plates of 40 mm width, according also the European Standard EN 196-1 [9].

## 3. Results and discussion

### 3.1. Physical properties of used materials

The plastic waste used in this study has a low weight and a tight particle size compared to sand. Also, the specific surface area of the

**Fig. 1.** The plastic waste.

**Table 1**
characteristics of cementitious materials.

| Compounds | Cement% (by weight) | Limestone fillers% (by weight) |
|---|---|---|
| $SiO_2$ | 17.45 | 10.5 |
| $Al_2O_3$ | 4.29 | 2.51 |
| $Fe_2O_3$ | 2.98 | 1.23 |
| CaO | 63.6 | 47.1 |
| MgO | 1.12 | 0.35 |
| $SO_3$ | 2.08 | 0.08 |
| $K_2O + Na_2O$ | 0.8 | 0.68 |
| Loss of ignition | – | 37.34 |
| $C_3S$ | 60.50 | – |
| $C_2S$ | 18.86 | – |
| $C_3A$ | 6.45 | – |
| $C_4AF$ | 12.26 | – |
| Specific gravity (g/cm$^3$) | 3.10 | 2.71 |
| Specific surface (m$^2$/kg) | 370 | 480 |

**Table 2**
The physical properties of sand and plastic waste.

| Properties | Sand | Plastic wastes |
|---|---|---|
| Apparent density (kg/m$^3$) | 1520 | 510 |
| Specific gravity (kg/m$^3$) | 2610 | 960 |
| Water absorption (%) | 1.03 | 0.01 |
| Specific surface (m$^2$/kg) | 6.24 | 1.67 |

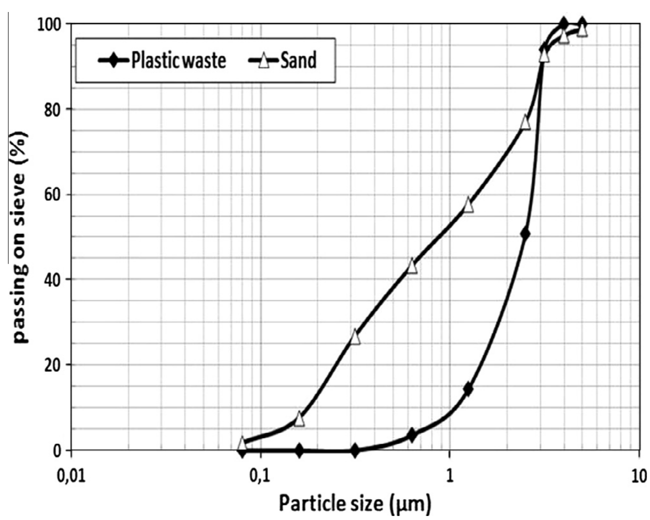


**Fig. 2.** The particle size distribution of sand and plastic wastes.

waste is lower compared to that developed by the sand. Which helps to have a mass gain for the mortars based waste. Also a smaller amount of water to wet the surface of the waste compared with sand, which greatly affects on the mortars fluidity. It was mentioned in the review paper of Saikia et al., as compared to natural aggregates, the plastic cannot absorb water when mixing [21]. This fact has been proven by researchers Al-Manaseer and Dalal [1].

### 3.2. Fluidity of SCMs (flow testing standard)

The results of the fluidity of mortars as function the different content of waste is represented in Fig. 3. It was observed according these results, that more waste content increases the fluidity of mortars improves, that is favorable for self-compacting concretes. This improvement can be attributed to the fact that plastic particles have an outer smoother surface than that of the sand [5]. Improving the fluidity of the concrete in the presence of plastic has been proved by the work of Ferreira et al. These authors concluded that the plastic cannot absorb water, therefore an excess of water which improves the workability.

**Table 3**
Details of mortar mixtures.

| Constituent | SCM(R) |
|---|---|
| Cement (kg/m$^3$) | 664.1 |
| Limestone fillers (kg/m$^3$) | 66.41 |
| Sand (kg/m$^3$) | 1372.4 |
| Water (kg/m$^3$) | 276 |
| Superplasticizer (SP) (kg/m$^3$) | 10.6 |
| Fillers/Cement | 0.10 |
| W/B (Water/Binder) | 0.38 |

SCM(R): Mortar control (without plastic wastes);
The sand is substituted by the plastic waste at dosages (0%, 10%, 20%, 30% and 50% by weight of the sand).

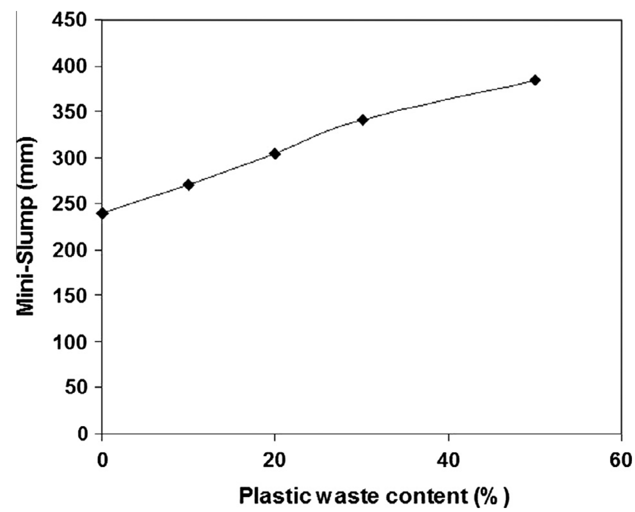


**Fig. 3.** Fluidity of self-compacting mortars with plastic waste.

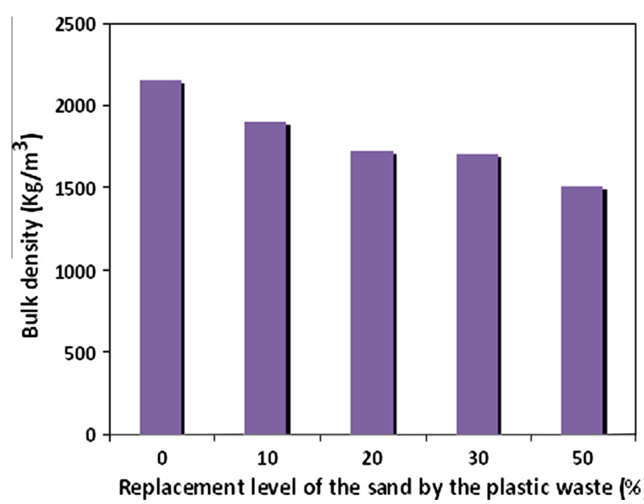


**Fig. 4.** Evolution of bulk density of SCMs as function of content plastic wastes.

### 3.3. Physical properties

#### 3.3.1. Bulk density

Fig. 4 give the bulk density of self-compacting mortars as a function the content difference of plastic wastes, after 28 days of

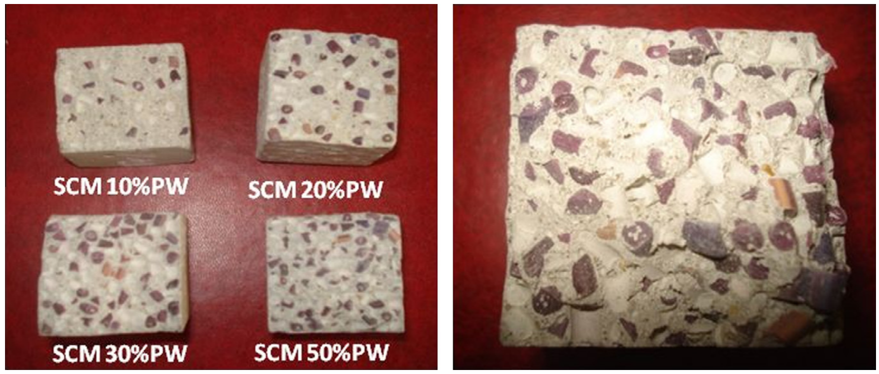


**Fig. 5.** The samples of self-compacting mortar with different content of plastic wastes.

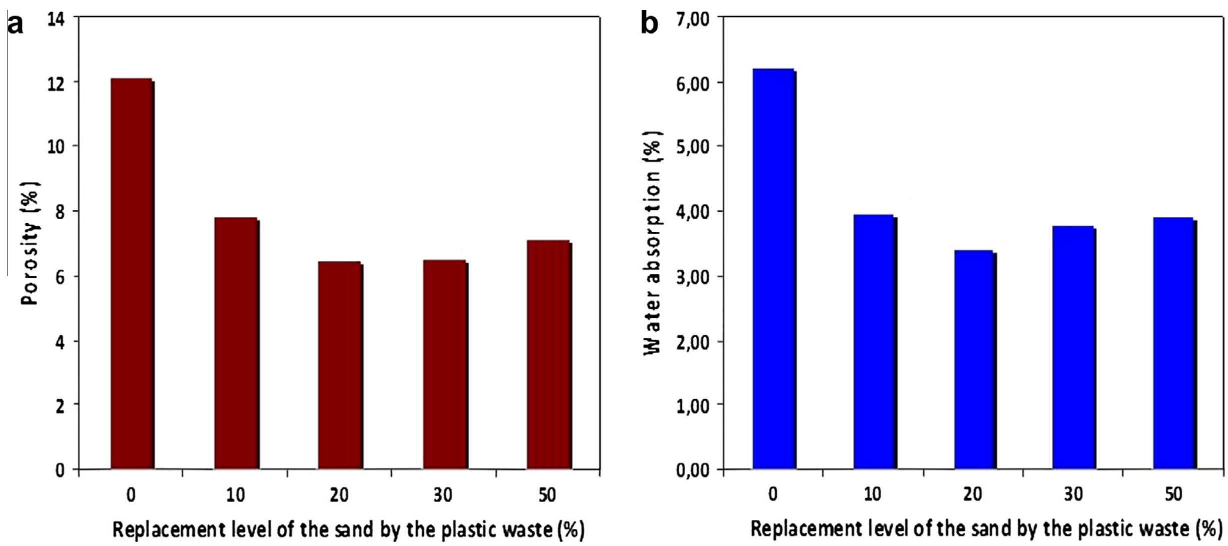


**Fig. 6.** Effect of the content plastic waste on the physical properties of SCMs: (a) porosity and (b) water absorption.

water maturation of the samples. The bulk density has decreased considerably for all mortars with the content of replacement of sand by plastic waste that also becomes than lighter with 50% of plastic waste. The substitution of sand by plastic waste for each curing age reduced the bulk density of all mixtures with increasing the waste plastic ratio, because the density of plastic is lower than that of sand by 70%. This observation was already verified by several authors [5,10,23]. This decrease in bulk density mortars is probably due to the substitution of a heavier material (sand) by the lighter material.

Up to 50% of the waste, the bulk density of mortars was reduced to 37.5%. The mortars with 50% of plastic waste, the bulk density were 1500 kg/m$^3$. This result has been proved by several authors [23]. Indeed, as an example, the results obtained by Al-Manaseer et al. showed that density of concrete was reduced by 13% for concrete containing 50% of plastic waste as aggregate [1]. The images shown in Fig. 4 clearly, show the good distribution of plastic waste in the mortar mixes. This distribution has favoured to obtain a lighter density (a light mortar). It should also be noted that this distribution of plastic waste in matrix of mortar favoured also the reduction of voids between granular [4,10,24,23] (Fig. 5).

*3.3.2. Porosity and water absorption*

Fig. 6a and b shows the evolution of porosity and water absorption according to time 28 days for all mortars. The results illustrate that the porosity decreases with the replacement percentage of sand by the plastic wastes for all mixtures. However, up to 30% of replacement, a slight increase of porosity of SCMs. The same phenomena are also observed for all mortars, but up to 30% of replacement the sand by plastic wastes. This comes from two roles played by the plastic waste. The first is related to the filing effect of voids in the cementitious matrix. The second is the replacement of

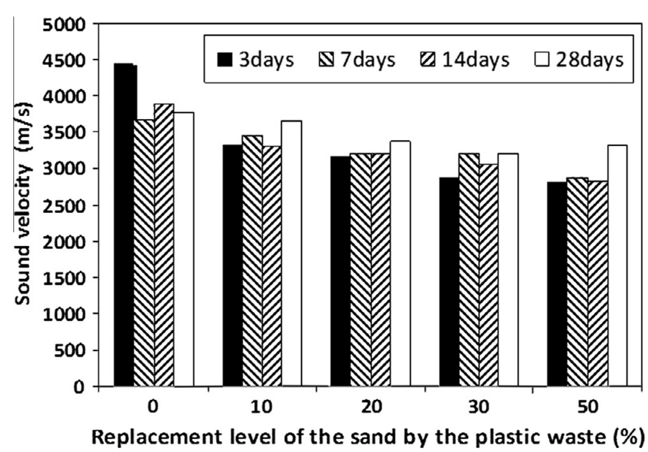


**Fig. 7.** Evolution the sound velocity of self-compacting mortar as function of curing time (3, 7, 14 and 28 days).

**Fig. 8.** The samples of self-compacting mortar with 50% content of plastic wastes.

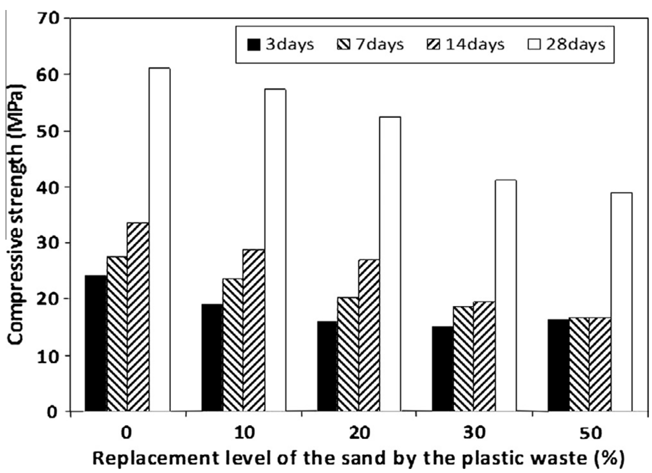


**Fig. 9.** Evolution of the compressive strength of mortars as function on the plastic waste content.

sand which is a porous material for mortars by the waste plastic material which is a less porous material.

### 3.3.3. Ultrasonic test of mortars

The effect of plastic waste content on the UPV was investigated for all mortar specimens. The results of sound velocity as a function of plastic waste content and curing time up to 28 days are shown in Fig. 7. The results show a slight decrease of sound velocity of SCMS at any replacement the sand by plastic waste with curing time, compared to the reference mortar specimens at all curing time. This can be attributed to the hydration products of cement which fill any voids of the material that happen to exist. Also as it is seen from the graphs, up to 30% of plastic waste, the sound velocity is practically constant. This result confirm by the work findings of Krezel et al., regarding porosity of the recycled concrete aggregate [15]. It should be noted also that the good distribution of plastic waste in cement matrix (see Fig. 8). These figures show the absence of segregation in the mixture.

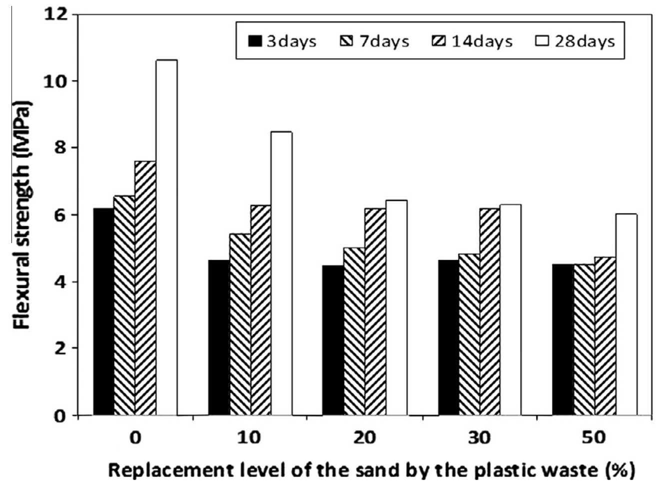


**Fig. 11.** Evolution of the flexural strength of mortars as function on the plastic waste content.

## 3.4. Mechanical properties

### 3.4.1. Compressive strength

Test compressive strength results are shown in Fig. 9. The compressive strength of self-compacting mortars decreased with increase in plastic waste content at all curing times. At 30% and 50% of substitution of waste, the percentage reduction of compressive strength was 15% and 33% respectively. This result is considered better compared to those obtained from the work mentioned in the review paper published by the author's Saikia et al. [21]. Indeed, in this paper, compared to control mixes, up to 72% reductions in compressive strength were observed for

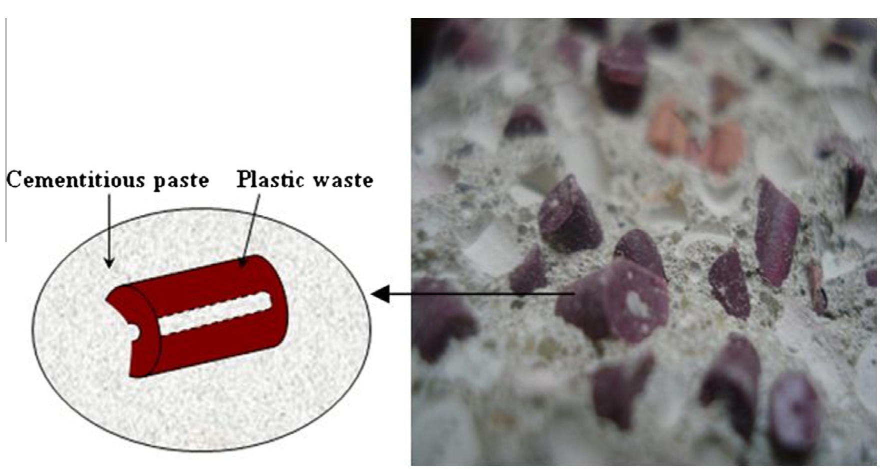


**Fig. 10.** The physical adhesion of plastic waste with cement paste (the annular cylindrical form of plastic waste.

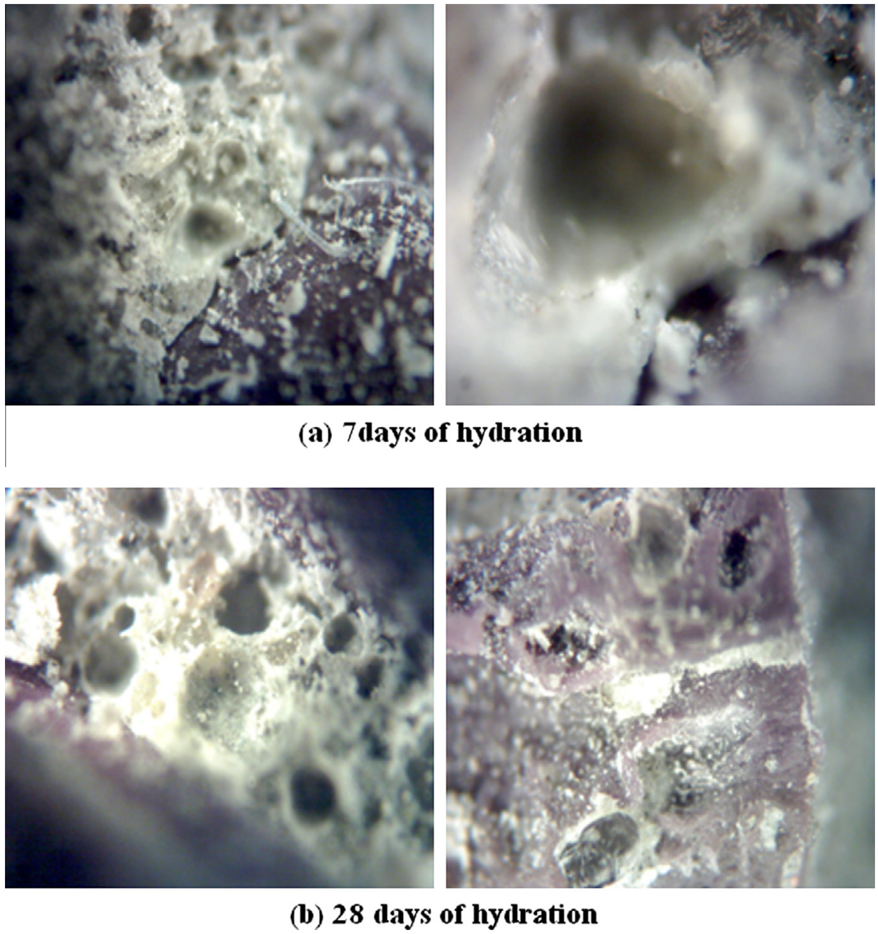


**Fig. 12.** Optical microscopy of the plastic waste–binder interface.

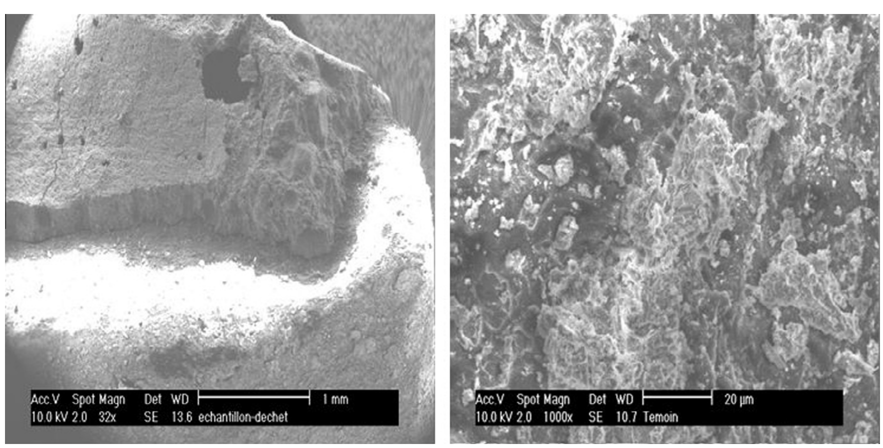


**Fig. 13.** SEM of the plastic waste–binder interface.

concrete prepared by replacing natural aggregate at the replacement level of 20% [10,21].

The reduction in the compressive strength of SCMs might be due to either a poor bond between the cement paste and the plastic wastes or to the low strength of this plastic wastes. However, the fracture surface of mortars prismatic showed that most of plastic waste are not pulled out and remain stuck in the mortar specimens. This result obtained in this study is not the case that those obtained by several authors [12,14,23,24]. Because, at form view points the plastic waste has a particularity. Indeed, this form of plastic waste showed in Fig. 10 shows the annular cylindrical form which promotes the physical adhesion of plastic waste with cement paste.

### 3.4.2. Flexural strength

The results of the flexural tensile strength of mortars as function plastic waste content have given in Fig. 11. According these results, the flexural tensile strength decreases with the increase in plastic waste content. This is due to the low resistance of the waste as it was found by the authors [5,8,12].

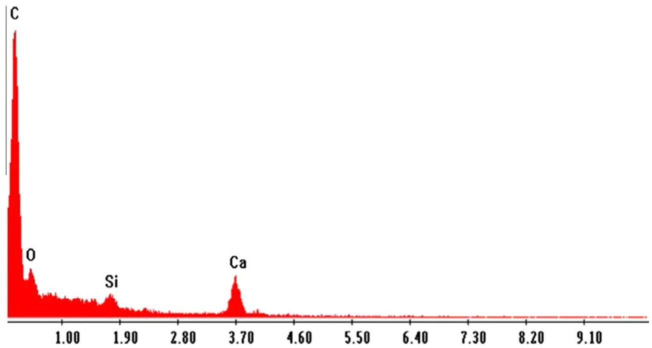


**Fig. 14.** EDX analysis at the interfacial zone (plastic waste–binder).

### *3.5. Micro-structural study of interface cementitious matrix/plastic*

A micro-structural study by optical microscopy and SEM of interface plastic-mortar was conducted to analyze the properties of the interfacial zone of these two materials.

In Fig. 12 the plastic waste–mortar interface in a specimen containing 50% plastic waste (7 and 28 days of hydration) is shown. It is observed in Fig. 12a that the zone is less dense with cracks and with a relatively poor adhesion between the plastic waste and cement paste. By cons, it is observed in Fig. 12b the absence of cracks and that the zone is dense enough without cracks and with a relatively good adhesion between these two materials (plastic–binder).

Being given, that weak interfacial zone may have many serious influences on a range of properties of mortar, a microscopic study of this zone is necessary. SEM images taken of the interfacial zone are given in Fig. 13. According those images, we clearly observe the poor adhesion between the plastic and cement paste. Also, it is observed that the cement grains bonded to the surface of waste. That is also confirmed by energy dispersive X-ray (EDX) analysis presented in Fig. 14 and which shows that the very near grains to the interface are grains of hydrated mortar.

## 4. Conclusion

This paper has presented the recycling and the use of plastic wastes (PET used for the bags manufacture) as fine aggregate in self-compacting mortars. The results which could be summarized and concluded as:

- This plastic waste type can be used successfully as a fine aggregate in self-compacting mortars (or concrete).
- Being given that the self-compacting mortar (or concrete) must have good flow (flowability at the implemented), fluidity is significantly improved by the presence of these waste.
- The results of mechanical test showed that the compressive strength at 28 days of self-compacting mortar containing up to 50% of plastic waste was acceptable for lightweight mortars with the bulk density 1.5 kg/m$^3$.
- Reduction in the compressive strength was between 15% and 33% for mortar containing 20–50% plastic waste.
- The annular cylindrical form for this plastic waste has favoured the physical adhesion of plastic with cement paste. A microscopic study of the interfacial zone of plastic-binder has shown that there is an adhesion between plastic and cement paste (case 28 days of hydration).

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