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Mechanical strengths of modified PET mortar composites in aggressive $MgSO_4$ medium: ACI & B.S predictions

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Abstract. Composites mortars based on plastic aggregates are often considered as an innovative materials of the future because of their potential and the advantages they present. In this paper, a comparative study was carried out on the effect of magnesium sulfate $MgSO_4$ (5%) attack on the durability of composite mortars modified by recycled polyethylene terephthalate (PET). Laboratory tests were accomplished on limestone sand and cement mortars where the blended Portland cement was partially replaced by various volume fractions of PET plastic aggregates. Mechanical properties measured on specimens were used to assess the changes in the compressive strengths of PET-mortar composites exposed to $MgSO_4$ attack at different ages, mainly the Young modulus of elasticity. Based on experimental compressive tests on selected specimens and there densities, the evolution of static Young modulus of elasticity has been discussed in accordance to predicted models proposed by (ACI-318) and (BS-8110) codes of practice. In addition, a comparative analysis has been carried out for corrosion resistance coefficients K of referenced mortar to those modified with plastic aggregates. It can be noted that, the corrosion resistance coefficients decrease as much as composite specimens are exposed to $MgSO_4$ corrosive medium. For the case of modified composites, the values of K based on predicted Young modulus before and after immersion are better than the ones calculated for the unmodified mortar. Therefore, ACI 318 prediction model is recommended code for design and investigation works related to reparation mortars, screeds, pavements…etc. Also, it can be concluded that adding PET plastic aggregates by volume to blend Portland cement act to improve the corrosive resistance of this cement against $MgSO_4$ aggressive medium.

Key words: Recycled polymer aggregates, Composite mortars, $MgSO_4$ Solutions, Mechanical properties, Sustainable materials.

1. Introduction

In the recent previous decades, polyethylene terephthalate (PET) is produced within large amount in industrial countries (planetoscope, html) and since waste PET is not biodegradable, then, it can remain in nature for hundreds of years and causes too many ecological problems.

Several research works were carried out recently by too many authors in the field of material science applied to building industries, such as (Alfahdawi et al. 2016; Benosman, 2013; Gu and Ozbakkaloglu, 2016; Rahmani et al. 2013; Sharma and Bansal, 2016) in order to find ecologic and green ways to dispose and recycle polymer wastes.

One of the main proposed technics by researchers is to introduce PET in the technology construction materials by substituting volumetric amount of cement (Benosman et al. 2017a) and/or aggregates (Azhdarpour et al. 2016; Hannawi et al. 2010; Zuccheratte et al. 2017) in concrete and mortars mix-design.

In this paper, the influence of magnesium sulfate attack on the durability of composites produced with waste polyethylene terephthalate (PET) is studied. Experiments were accomplished on cement mortars and limestone sand where the blended Portland cement was partially replaced by various volumetric fractions of PET particles (6%, 12% and 17%^{v}).

Test solution used to provide the sulfate attack was 5% of $MgSO_4$ solution. Tap water was used as the control medium. Compressive strengths measured on specimens were used to assess the changes in the mechanical properties of modified mortars subjected to $MgSO_4$ attack at different ages, mainly the Young modulus of elasticity.

2. Raw materials

2.1. Cement

The cement used was a blended Portland cement type CPJ-CEM II/A42.5 supplied by Zahana factory, located in western Algeria, with 1022 kg/m^3 bulk density; its compressive strength at 28 days was 42.5 MPa. The absolute density of the cement used was 3.15 g/cm^3 and its specific surface area measured with the Blaine method was 3532 cm^2/g. Its initial and final setting times were 170 and 245 min, respectively. Mineralogical and chemical compositions of cement are listed in Table 1. The chemical composition was obtained using an X-ray fluorescence spectrometer.

Table 1. The chemical and mineralogical compositions of cement (wt.%)

Chemical compositions	SiO_2	20.91
	Al_2O_3	5.52
	Fe_2O_3	3.56
	CaO	63.50
	MgO	0.64
	SO_3	2.79
	K_2O	1.23
	Na_2O	0.13
	CaO free	2.35
	LOI	1.19
Mineralogical compositions	C_3S	49.39
	C_2S	22.97
	C_3A	8.61
	C_4AF	10.83

2.2. Sand

The crushed natural limestone sand was obtained from the quarry of Kristel, in Oran, West Algeria. The maximum size of sand grains was 5 mm. The absolute density and absorption coefficient of crushed sand were 2.53 g/cm^3 and 0.5%, respectively. The grading of crushed sand is presented in Table 2, according to standard NF P18-560 (AFNOR, 1990).

2.3. Waste Polyethylene Terephthalate

Waste PET bottle granules (PET) used as particles were supplied by TRAMAPLAST PET Bottle Plant, in Tlemcen, Algeria. These particles were obtained by collecting the waste PET bottles and washing them; they are then crushed by granules into machines. In addition, they have an irregular shape and a rough texture surface, which enables the adherence of the particle-matrix. The bulk density of the WPET particles used was 401.4 kg/m^3.

After preliminary tests, PET particles of size lower than 1 mm were used in this study. The sieve analysis of PET particles was carried out according to standard NF P18-560 (AFNOR, 1990) and is presented in Table 2.

Table 2. The sieve analysis of waste PET-Particles and crushed limestone sand

Sieve size (mm)	Cumulative passing (%)	
	PET	Sand
5	99.92	99.83
2.5	98.16	98.37
1.25	96.82	65.37
0.63	55.78	38.3
0.315	35.48	19.07
0.16	18.28	8.20
0.125	9.56	3.325

3. Composite mixing conditions

The mortar manufactured without WPET particles was first optimized on the basis of its mechanical criteria and was then used as a reference composite. The composites containing PET particles were produced in accordance with the results of the works of Benosman et al. (2017b). A massic ratio of 3 between sand (S) and cement (C) was respected. Four different mixtures were prepared (the control mixtures without plastic waste and three PET# mixtures including 6%, 12% and 17% waste PET particles by volume). Mixture name of the different composites were: PET0 (without plastic waste), PET6, PET12 and PET17. The water to binder ratio was kept constant at 0.5. So, after pouring fresh material into the molds (EN 196-1, 2005), the samples were stored in a room where hygrometry and temperature were controlled for 24 h (98% relative humidity, and 20 ± 1 °C). After removal from the molds, at 1 day of age, mortar specimens were cured in saturated lime water at 20 ± 1 °C, until the time of testing.

4. Test methods of resistance to $MgSO_4$ attack

The mortar specimens were cured in water saturated with lime at 20 ± 1°C for 28 days before being exposed to sulfate attack. Three specimens of each mortar and composite mixes (40x40x160 mm^3) were immersed in two types of solutions: fresh water (reference medium) and 5% magnesium sulfate ($MgSO_4$), Figure 1. According to the standard ASTM C1012-04 (2004), the pH of the sulfate solution should be between 6 and 8 and the solution must be renewed each week, which requires huge amounts of magnesium sulfate.

Fig 1. Immersion of the specimens in the aggressive solution

For this, Mehta's method (1975) and that of Siad et al. (2013) were adopted; they all recommend the control of the pH within a range of 6.0–8.0 by adding a suitable amount of sulfuric acid solution (0.1N H_2SO_4), Figure 2. The correction is performed daily during the first weeks of immersion, and then becomes weekly, for the rest of the test. In addition, the aggressive solutions were totally renewed each 12 weeks. After immersion in magnesium sulfate solution ($MgSO_4$) for the required period of time, ASTM C1012-04 (2004), the specimens were tested for residual mechanical properties. The Young modulus loss (YML%) is calculated as follows:

$$YML(\%) = \frac{E_{cr} - E_{cs}}{E_{cr}} \times 100 \quad (1)$$

Where E_{cr} is the Young modulus of the specimens before immersion (MPa) and E_{cs} is the average Young modulus of the specimens after immersion in magnesium sulfate solutions for the required period of time (180 days).

Fig 2. Correction of the sulfate solution by adding small quantities of 0.1N H_2SO_4, up to a pH equal to 6-8.

5. Results and discussion

5.1. Prediction models of Mechanical Properties

The static modulus of elasticity E (Young Modulus) represents the one of the most important mechanical characteristics of construction materials (Concrete, Reinforced concrete, mortars, composites …etc). This intrinsic property is considering as the basic parameter for the computing strain-stresses in construction structures. Various countries have been established their design codes based on this empirical relationship between static modulus of elasticity E, and compressive strength of plain concrete at 28 days of curing. The ACI code (ACI-318, 2005) defines the relationship between elastic modulus of concrete and compressive strength as:

$$Ec = w^{1.5}\, 0.0043\, f^{\,0.5} \quad (2)$$

The British Code of practice (BS-8110, 1997) recommends the following expression for static modulus of elasticity with cube compressive strength of concrete as:

$$Ec = w^2\, 0.0017\, fc^{0.33} \quad (3)$$

Where, Ec represents the static modulus of elasticity at 28 days in MPa

fc : Compressive strength at 28 days in MPa

w : Air dry density of mortar

Based on experimental compressive tests on PET-Mortar composite specimens (Benosman et al. 2013), and there densities, graphs in (Figures 3, 4) bellow show the evolution of Young modulus evaluated by empirical relationships in accordance to (ACI-318) and (BS-8110) codes.

The results of the Young modulus loss using the specimens immersed in 5% $MgSO_4$ solutions (Figure 5) showed that there are variations in time and group. However, a decrease in Young Modulus values of all specimens was observed when Young Modulus of elasticity is computed via ACI-318 model. It was expected that the mechanical properties loss (YML%) values of modified mortars with PET plastic particles would be lower than those of unmodified mortar PET0, by 16.84%, 21.35% and 18.40% for PET6, PET12 and PET17, respectively for the case where the prediction model is BS-8110 and respectively by 12.00%, 18.30% and 13.40% when Young Modulus of elasticity is computed via ACI-318 model. It can therefore be concluded that modified mortars by PET plastic particles are resistant to the magnesium sulfate aggressive exposure conditions often encountered in the field.

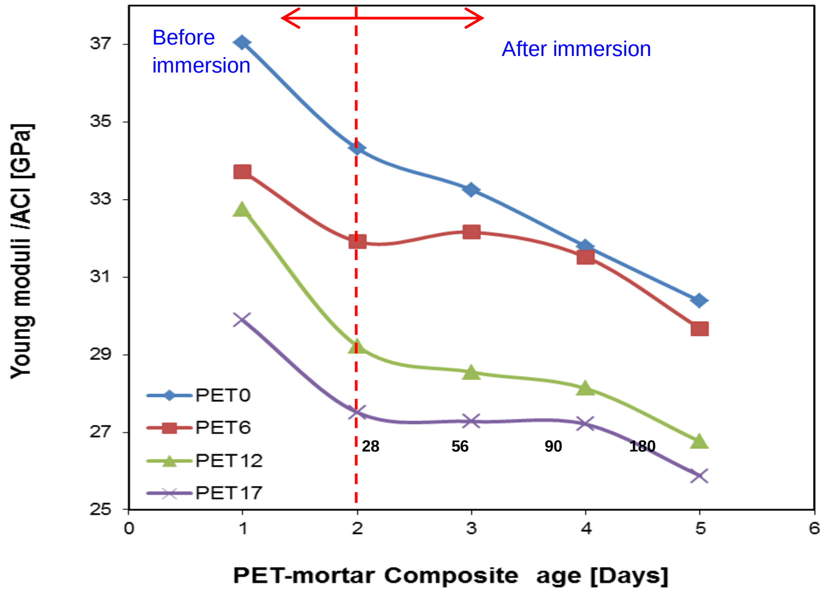

Fig 3. Evolution of Young modulus with volumetric PET rate and composite mortar ages via ACI-318 code before and after $MgSO_4$ attacks

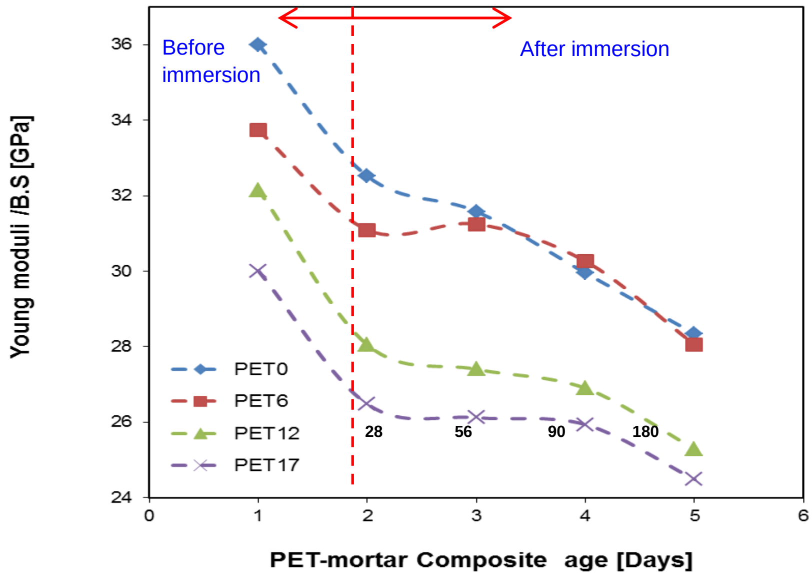

Fig 4. Evolution of Young modulus with volumetric PET rate and composite mortar ages via BS-8110 code before and after $MgSO_4$ attacks

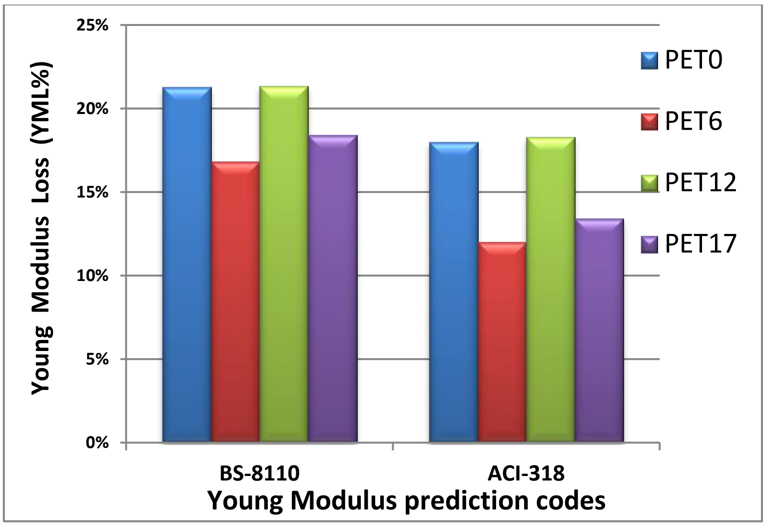

Fig 5. Young modulus loss (YML%) with volumetric PET rate and prediction codes (BS-8110 & ACI-318) before and after $MgSO_4$ immersion

5.2. Corrosion magnesium sulfate resistance

Furthermore, to compare, effectively, the corrosion resistance coefficients K of unmodified mortar (Eq. 4) to those modified with PET particles, as it was used by Benosman et al. (2017b) and Jiang et al. (2004):

$$K = Eci / Ecs \quad (4)$$

Where Eci is the Young modulus of composite mortars immersed in corrosive magnesium sulfate solutions, Ecs the Young modulus of the normally cured composite mortars.

The corrosion resistance coefficients of the specimens with and without PET plastic are given in Table 3. It can be seen from Table 3 that, for the composite immersed in a corrosive $MgSO_4$ solution, the corrosion resistance coefficients decrease with the increase of the immersion period. The corrosion sulfate resistance K based on Young modulus before and after immersion of PET-mortar composites is better than that of the control mortar (PET0).

Table 3. The corrosion resistance coefficients of PET-mortar composites in 5% $MgSO_4$

$MgSO_4$ Attacks	K (BS.8110)		K (ACI.318)	
	90 Days	180 Days	90 days	180 Days
PET0	0.832	0.787	0.858	0.820
PET6	0.897	0.832	0.935	0.880
PET12	0.836	0.786	0.859	0.817
PET17	0.864	0.816	0.910	0.866

For all studied cases, corrosion resistance coefficients K computed via ACI 318 are slightly higher than the ones evaluated by BS.8118 code of practice. Therefore, in order to obtain a safe design using PET-Modified mortar, ACI 318 is the recommended code for design and investigation Issues. Also, it can be concluded that adding PET by volume fractions to blended Portland cement renders this cement more resistant to the magnesium sulfate aggressive medium. (Miletic, 1999) reported that the resistance of cement to sulfate aggression is also related to its content in C_3A.

Consequently, using PET as cement substitutes reduces the energy consumption, contributes to save natural environment by reducing CO_2 emissions and is used to repair various reinforced concrete structures in magnesium sulfatic aggressive mediums.

Finally, the obtained results are in accordance with the ones reported by Alqahtani et al. (2017) which stated that recovering plastic waste would reduce the CO_2 emissions by 3.8 million tons. The advantages of durability properties of modified mortar exposed to $MgSO_4$ attacks indicate longer life of the repaired structures by using this type of green composite repair materials.

6. Conclusions

The main conclusions based on results plotted above, can be drawn as follows:

- PET-Mortar composites present a better behavior against aggressive medium such as magnesium sulfatic ($MgSO_4$) and it reduces significantly the consumption energy related to CO_2 emission.

- In $MgSO_4$ corrosive medium, unmodified mortar (PET0) and substitution volumetric rate of PET act to decrease the mechanical properties of PET-Mortar composites, mainly, the static modulus of elasticity (computed by ACI-318 and BS-8110 codes). In addition, Prediction model proposed by ACI-318 gives always the lowest values of elastic Young modulus which can be recommended for structural design issues.

- The loss in static Young modulus of elasticity (YML%) of modified mortars are lower than the ones of unmodified mortars. The optimal minimal values of (YML%) are given by ACI-318 code of practice, mainly, for the case of PET-Modified mortars within volumetric rate of 6%, 17%. The corrosion resistance coefficients K decrease with exposure time to $MgSO_4$ aggressive medium.

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