Mechanical properties of mortars with waste plastic as replacement of natural aggregate

Mortars containing waste plastic from WEEE as replacement of natural aggregate: different strategies to achieve good mechanical properties

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Abstract

The use of waste plastic from Waste Electrical and Electronic Equipment (WEEE) as a substitute for natural aggregate is an increasingly relevant issue. In fact, this would allow to recycle plastics destined for landfills and to decrease the use of new natural resources. However, replacing sand with plastic tends to reduce the mechanical properties of mortars due to the different mechanical properties between the natural aggregate and the waste plastic and the poor compatibilization between the plastic and the cement paste. This work used several strategies to improve the mechanical properties of mortars containing waste plastic. The addition of 1 % of superplasticizer coupled with a lower w/c ratio succeeds in restoring the mechanical properties to values equal to a standard mortar prepared with the natural aggregate, thus obtaining a material that can be used in the construction field.

Keywords: Mortar; Recycled materials; Mechanical properties; WEEE recycling; Waste plastic.

Introduction

Cement, sand, and water are the main constituent elements of the mortar. Aggregates constitute about 60% of a mortar's total quantity, thus strongly impacting the mechanical properties (Faraj et al. 2019). However, the construction industry estimates that at the end of 2025, the demand for natural aggregate will grow by about 59% (Almeshal et al. 2020). Given this, the number of natural resources consumed will be excessive, and there will undoubtedly be environmental consequences (Spiesz et al. 2016). Nowadays, research is directed towards using alternative sources with respect to natural resources to be used as aggregate in cement (Gu and Ozbakkaloglu 2016). Several studies have developed particular care in replacing the natural aggregate with waste materials such as rubber from end-of-life tires (Lavagna et al. 2020; Roychand et al. 2020; Tamborrino et al. 2021), shells (Suarez-Riera et al. 2021) and non-recyclable plastic waste (Almohana et al. 2022). The literature proposes a multitude of different polymeric substrates to be exploited as aggregate fractions, such as polyethylene terephthalate (PET) (Choi et al. 2005, 2009; Silva et al. 2005; Marzouk et al. 2007; Yesilata et al. 2009; Albano et al. 2009; Akçaözoğlu et al. 2010; Kim et al. 2010), poly vinyl chloride (PVC) (Kou et al. 2009; Merlo et al. 2020)], high density polyethylene (HDPE) (Naik et al. 1996), shredded and recycled plastic waste (Ismail and AL-Hashmi 2008; Saikia and de Brito 2012; Merlo et al. 2021), expanded polystyrene foams (EPS) (Kan and Demirboğa 2009b, a), polycarbonate (Hannawi et al. 2010), polyurethane foams (Mounanga et al. 2008; Ben Fraj et al. 2010). The substitution of the natural aggregate in the mortars leads to a reduction of the mechanical properties (El Bitouri and Perrin 2022). This phenomenon is linked to various factors, i.e., the density of the aggregate replaced or the poor compatibility with the cement paste (Saikia and de Brito 2012). Several works show how it is possible to use plastic in concrete, trying to maintain the material's original properties with natural aggregate. Abed et al. (Abed et al. 2021) replaced 5%, 15%, 25% and 50% of sand with waste PET with a proportional reduction of mechanical properties as a function of the amount of plastics added to mortar. The mortar containing 25% of PET still had satisfactory mechanical properties suitable for structural purposes. Ghernouti and Rabehi (Ghernouti and Rabehi 2012) reported a reduction of compressive and flexural strengths of 18 and 23% compared to plain mortars. Carneiro et al. (Carneiro and Reis 2011) replaced 20% of sand (by weight) with shuddered PET, decreasing 48% of the flexural strength and 59% of the compressive strength. Merlo et al. (Merlo et al. 2020, 2021) studied the reuse of waste plastics derived from WEEE as a partial substitute for sand to produce lightened mortars. The results obtained with ordinary Portland cement showed a strong decrease in both compressive and flexural strengths. It is also noteworthy the work of Makri et al. (Makri et al. 2019), who investigated the physical and mechanical properties of cement mortars, partially replaced with ABS-based aggregates from plastic. The replacement percentages used were 2.5%, 5%, 7.5%, 10% and 12.5%. The obtained results show a decrease in compressive strength except for the replacement of 7.5% and 10%, which exhibited an increase by 15.4% and 7.8%, respectively. Another more recent article regarding physical properties and microstructure of WEEE-based plastic aggregate mortars made with acrylonitrile-butadiene-styrene (ABS), polycarbonate (PC), polyoxymethylene (POM), polyethylene (PET) and ABS/PC blend waste was produced by Kaur and Pavia (Kaur and Pavia 2020). The loss of compressive strength is significant with PET and POM-based aggregates, up to 42% with 20% (by volume) of replacement. Several strategies used in order to reduce the loss in mechanical properties consist in the use of reinforcing fibers (Khalid et al. 2018), chemical compatibilization reactions (Kazemi and Fini 2022; Aldagari et al. 2022) or mechanical processes to obtain a material more compatible with the cement paste (Jaivignesh and Sofi 2017; Thiam et al. 2021). L'utilizzo di plastiche di scarto come sostituto dell'aggregato naturale all'interno di malte e calcestruzzi ha un buon impatto ambientale. Alqahtani et al. (Alqahtani et al. 2021) estimated that the use of LDPE (low-density polyethylene) as a substitute for aggregate could reduce the use of steel reinforcement by 7.2%. Javadabadi (Tahanpour Javadabadi 2019) estimated an environmental impact reduction of 58% for the reuse of PET as aggregate. Tahir et al. (Tahir et al. 2022) reported that the reuse of 15% plastic in place of natural aggregate can reduce carbon emissions by up to 16.1%. Meanwhile, Ersan et al. (Ersan et al. 2022) estimated a 13% reduction in CO_2 emissions compared to the use of natural aggregate with partial mixed plastic waste replacement. In this work, different solutions are studied that can lead to an improvement of the mechanical properties of the substituted composite, managing to restore the mechanical properties to their original result. Surely this solution will make it possible to produce environmentally compatible materials that preserve the environment by reducing the use of natural aggregate.

Materials and Methods

2.1 Materials

Mixed plastic waste derived from WEEE was provided by IREN S.p.A.. Ordinary Portland cement 52.5 R Ultracem supplied from Italcementi was used to prepare the mortars; details about cement are summarized in Table 1. CEN standard sand purchased from Societé Nouvelle Du Littoral was used as fine aggregate. The size distribution of sand lies within the specific limits of UNI EN 196-1. The granulometric distribution of waste plastic was obtained using a column of sieves and a mechanical shaker. A RADWAG PS 510/C/1 analytical balance evaluated the quantity of retained materials per sieve. The mix design for every sample prepared is shown in Table 2. The sand was substituted in volume percentages of 15% and 30%, with the relative samples indicated by the acronyms 15PW (polymer waste) and 30PW, respectively. MgO and SiO_2 were purchased from Merck to prepare some samples. Biochar was supplied from Nera Biochar; the Biochar (B) was ground for 7 hours using the ball milling method in a ceramic jar with agate balls. Then, the ground biochar was sifted for 30 minutes using an ASTM mesh 80 (180 microns) sieve using a short-period oscillatory movement produced by the compact vibration sieve. Polypropylene fibers (PP) were purchased from SikaFiber, the fibers have a length of 12 mm and a diameter of 18 μm. Superplasticiser (SF) was purchased from Mapei.

Table 1. Composition and properties of ordinary Portland cement 52.5 R

Oxide	[wt.%]	Phase	[wt.%]
SiO_2	20.0	C3S	49.1
CaO	63.2	C2S	19.7
Al_2O_3	4.1	C3A	7.9
Fe_2O_3	1.9	C4AF	5.2
MgO	4.2		
SO_3	3.4		
Na_2O	0.003		
K_2O	0.0015		
Loss on ignition	0.80		

Table 2. Mix design for the mortars prepared with plastic waste

Name of sample	Cement (g)	Water (g)	Sand (g)	PW (g)	PP Fibers (g)	Biochar (g)	MgO (g)	CaO (g)	SiO_2 (g)	SF (g)
0PW	80	40	240							
15PW	71.24	35.62	166.84	12.41						
30PW	71.24	35.62	154.43	24.82						
15PWMgO	71.24	35.62	166.84	12.41			2.32			
30PWMgO	71.24	35.62	154.43	24.82			4.23			
15PWSiO_2	71.24	35.62	166.84	12.41					2.10	
30PWSiO_2	71.24	35.62	154.43	24.82					3.34	
15PWCaO	71.24	35.62	166.84	12.41				1.98		
30PWCaO	71.24	35.62	154.43	24.82				4.23		
15PWPP	71.24	35.62	166.84	12.41	0.36					
30PWPP	71.24	35.62	154.43	24.82	0.36					
15PWB	71.24	35.62	166.84	12.41		0.71				
30PWB	71.24	35.62	154.43	24.82		0.71				
15PWSF	77.09	26.98	180.54	13.43						0.77
30PWSF	77.09	26.98	167.11	26.86						0.77

2.2 Specimens preparation

The mortar mixing and preparation followed the guidelines of UNI EN 196-1, with a water-to-cement weight ratio w/c equal to 0.5 and an initial (sample 0PW) sand-to-cement weight ratio of 3. The mix was poured into prismatic molds of 20 × 20 × 80 mm size, and the samples were then cured at 20 °C in water according to the ordinary Portland cement 52.5 R requirements for 7 days.

In samples prepared with MgO and SiO_2, the plastic waste was placed in a mixer along with the right amount of magnesium oxide powder and left to mix for 2 days.

In the samples prepared with 0.5 % BWOC polypropylene fibers, the fibers were premixed in water before adding cement and aggregate.

2.3 Density, mechanical properties and optical characterization

Density, compressive tests and 3-point flexural tests were performed in order to evaluate the influence of plastic waste as a replacement of the natural aggregate in mortars and if the additives used can increase the mechanical properties. Microstructural investigation was performed using a stereomicroscope Leica EZ4 W, this analysis aimed at assessing the interfacial adhesion between plastic aggregates and cement in the mortar. Density was evaluated by measuring width, length and height with a caliper on polished samples; a RADWAG PS 510/C/1 analytical balance was employed to measure the sample's weight. A Zwick-Line Z050 single-column machine having a maximum cell load of 1 kN, with a pre-load of 5 N and a test speed of 0.01 mm/min, was used for three-point flexural tests with a span of 65 mm. Compressive strength was performed using 20 × 20 × 20 mm cubic samples cut from the flexural test specimens. Following the ASTM C109 standard, compressive tests were performed using the same machine, switching to a load cell of 50 kN, a pre-load of 30 N and a test speed of 600 N/s in force control. At least four samples per mixture were tested both for flexural and compressive tests.

2.4. Characterization of plastic waste

The cumulative granulometric distribution of plastic waste particles was shown in a recent paper by some authors (Merlo et al. 2021). The maximum size of these particles is 5 mm, slightly higher than 4 mm, generally used as an upper limit for the fine aggregate used for mortar preparation. The fineness modulus of plastic waste used is 2.5, while for standard sand used is 3.0. The composition of the plastic mix is shown in the figure 1.

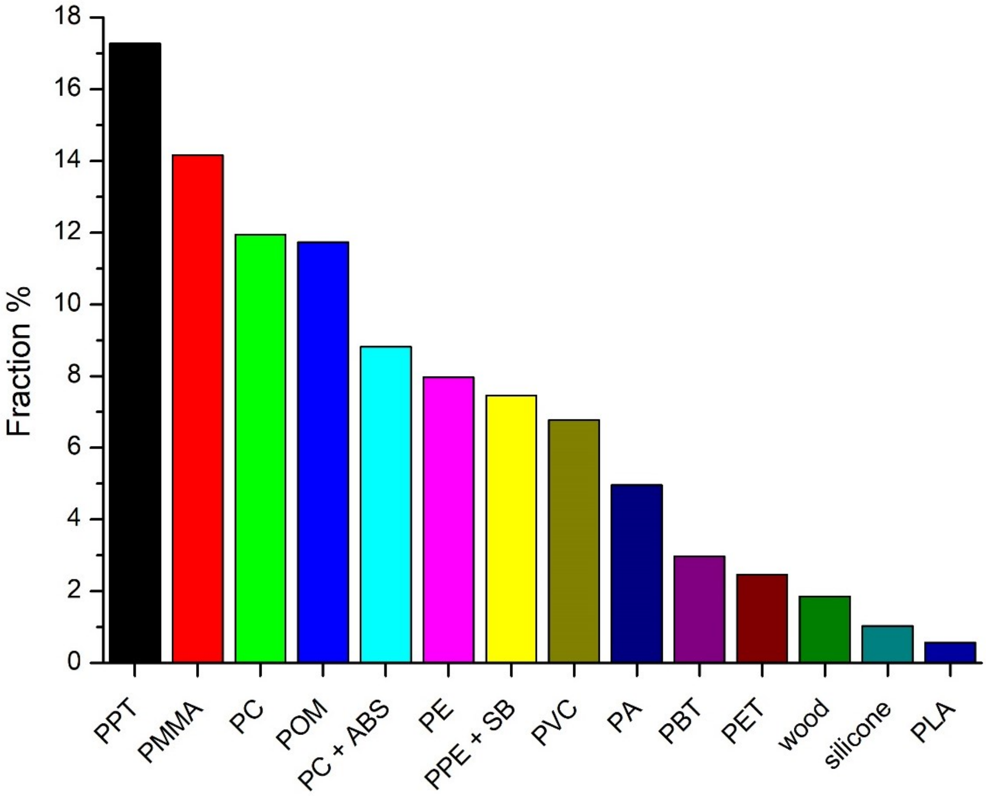

Figure 1. Composition of plastic waste used

Plastic waste means particle density was estimated to be 1.2 g/cm^3, following similar literature assessments (Thorneycroft et al. 2018). Since the sand density is the substitution of sand reduces approximately 2.6 g/cm^3, the density of the mortar with plastic: the higher the substitution, the lower the density of the mortar, as shown in Table 3.

3. Results and discussion

Table 3. Density and mechanical performances of samples prepared.

Name of sample	Density [g/cm^3]	Flexural strength (7 days) [MPa]	Compression strength (7 days) [MPa]
0PW	2.20	7.3 ± 0.5	37.9 ± 4.1
15PW	2.02	5.8 ± 0.5	29.9 ± 1.5
30PW	1.83	4.8 ± 0.5	20.8 ± 3.2
15PWMgO	2.06	5.5 ± 0.8	28.7 ± 0.4
30PWMgO	1.95	4.3 ± 0.3	22.0± 1.6
15PWSiO$_2$	2.07	5.7 ± 0.6	31.1 ± 2.7
30PWSiO$_2$	1.90	4.3 ± 0.3	21.5 ± 1.1
15PWCaO	2.06	5.9 ± 0.5	30.8 ± 3.3
30PWCaO	1.90	4.8 ± 0.2	21.6 ± 2.4
15PWPP	1.97	5.5 ± 0.7	23.5 ± 3.4
30PWPP	1.84	4.2 ± 0.4	15.9 ± 1.4
15PWB	2.11	5.4 ± 0.9	31.5 ± 2.0
30PWB	2.00	5.1 ± 0.3	27.5 ± 2.8
15PWSF	2.22	7.5 ± 0.3	36.4 ± 4.3
30PWSF	2.07	6.8 ± 0.6	34.1 ± 1.6

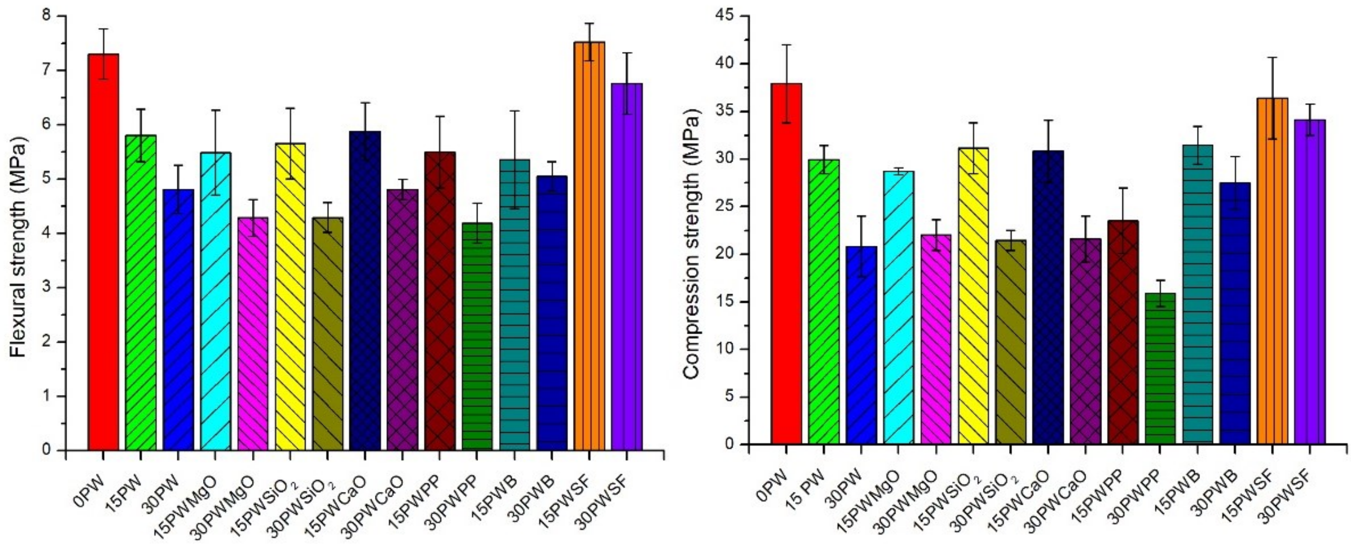

Figure 2. Mechanical properties of all samples prepared: (A) flexural strength, (B) compression strength.

The addition of the polymer mix in different volume percentages (15-30%) in place of sand led to the reduction of flexural and compressive strength. This deterioration can be attributed to two different factors:

- the difference in mechanical and physical properties between the natural aggregate and the plastic substitute (Belmokaddem et al. 2020),

- the different chemical interactions that natural aggregates or plastic substitutes have with cement (Mohammed et al. 2020).

Waste plastic used in this study has a Young's modulus of a few GPa, as opposed to sand which has a Young's modulus of several tens of GPa; furthermore, plastic waste also has a much lower mechanical strength. Moreover, sand particles interact well with cement's chemical structure; this is because both are polar, which results in good mechanical performance.

The chemical composition of plastic waste, on the other hand, differs widely from that of natural aggregates, as plastic is composed of organic compounds that have a much lower polarity and, therefore, cannot generate hydrogen bonds with cement (Merlo et al. 2020). As a result, the low adhesion of the interface between cement and plastic (indicated by red arrows in figure 3) results in a loss of mechanical properties (El Bitouri and Perrin 2022).

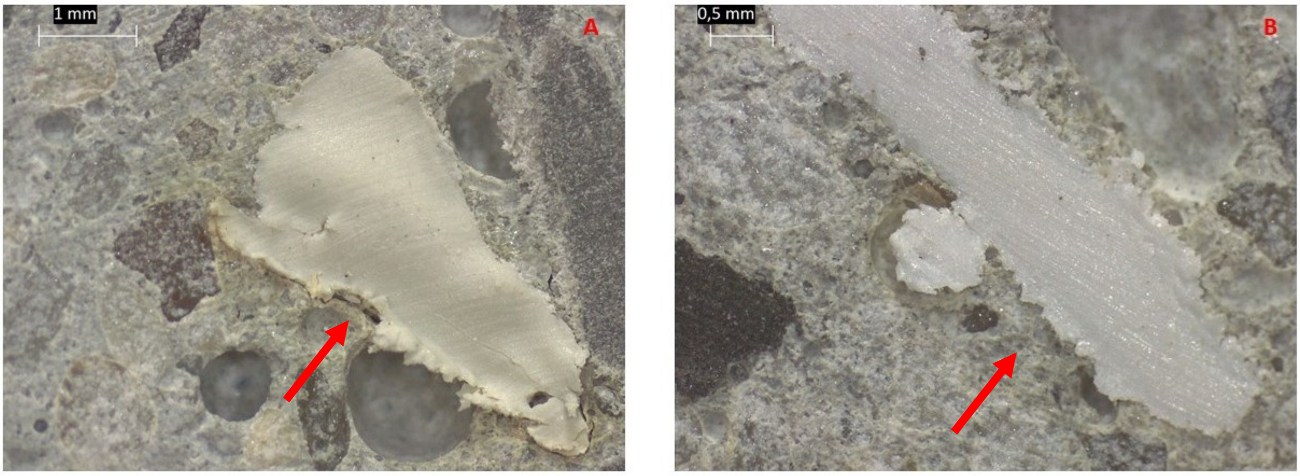

Figure 3. Stereomicrograph of A) 15PW and B) 30PW.

It can be seen from Figure 2 that the addition of only plastic as a partial replacement for fine aggregate causes a decrease in flexural strength. Specifically, the reduction in flexural strength for a 15% replacement is about 20%, while it reaches much higher values for a 30% substitution, about 44%.

In contrast, the best results, those that come closest to the flexural strength properties of the 0PW sample, are obtained with a 15% plastic replacement when the water/cement ratio is reduced to a value of 0.35 using 1% by weight of cement of superplasticizer. In fact, cement containing less water is stronger for the same amount of cement with a lower and smaller porosity (Lavagna et al. 2020; Lavagna and Nisticò 2022). Adding other additives, such as biochar, calcium oxide, magnesium oxide, silicon dioxide, and polypropylene fibers, did not yield satisfactory results; however, the flexural strength performance was slightly increased.

Similarly, as shown in figure 2B, the compression strength decreases when waste plastics are added. The reduction in compressive strength for specimens containing 15% by volume of sand replaced was 36%. For specimens having 30% of sand replacement, the decrease was almost 50%. For specimens with 15% by volume plastic waste, adding additives such as MgO and PP fibers provided similar results to the mortar containing only plastic waste.

In the case of PP fibers, the fibers used are too small to have a bridging effect within the matrix, as shown in Figure 4. The pores size (violet arrow) and waste plastic used do not allow the fibers to close the voids, thus defeating their reinforcing effect.

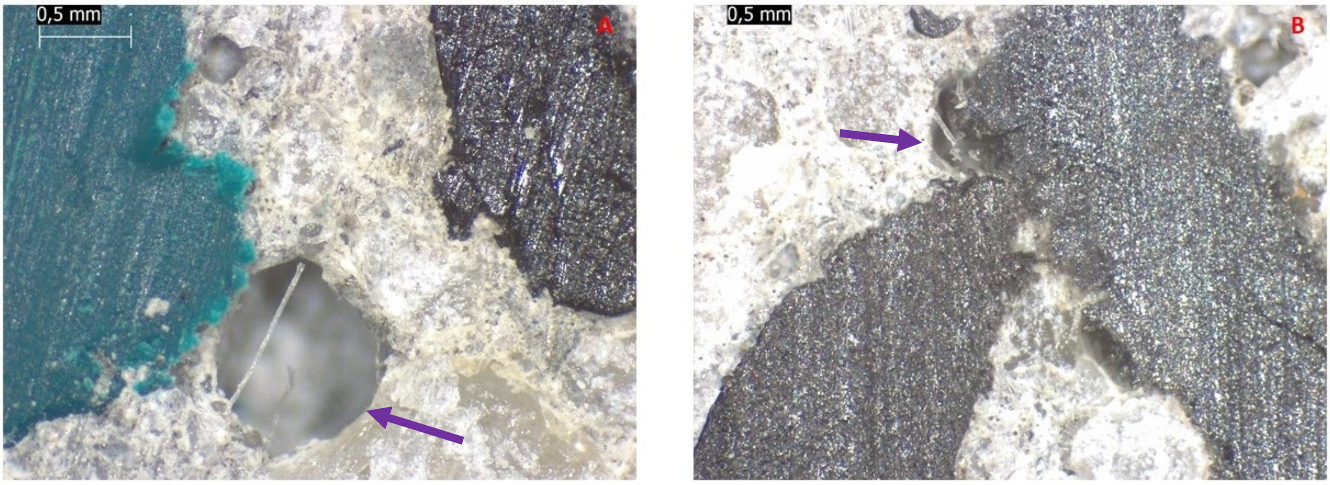

Figure 4. Stereomicrograph of A) 15PWPP and B) 30PWPP.

As for magnesium oxide (MgO), its kinetics of reaction with water is quite slow at the curing temperature (Thomas et al. 2014). Consequently, it did not have enough time to react with water to complete its reaction. In the case of SiO_2, this is due to the pozzolanic reaction between the calcium hydroxide produced by the hydration of Portland cement and the amorphous silica, which produces a secondary calcium-silicate-hydrate. This compound, because of the small size of the SiO_2 particles, fill the pores between hydrated cement grains; this is probably the main reason why specimens with silicon dioxide have slightly higher compressive strength than other mixtures [28]. For specimens admixed with 15% plastic by volume, improved results were achieved by adding SiO_2, CaO and biochar. Figure 5 shows the effect of SiO_2 at the interface between plastics and the matrix.

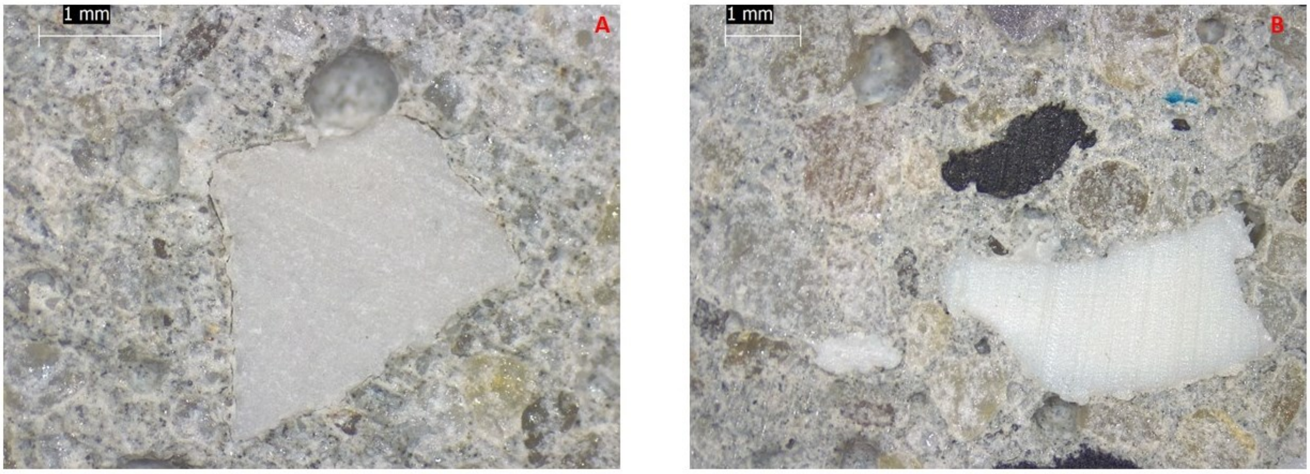

Figure 5. Stereomicrograph of A) $15PWSiO_2$ and B) $30PWSiO_2$

In the case of calcium oxide (CaO), the reaction with water leads to the formation of portlandite which generally has an expansive effect. This effect can also lead to a slight reduction of porosity despite the presence of plastic. As shown in Figure 6, the porosity at the interface is reduced as in the case of SiO_2, thus ensuring slightly better mechanical performance.

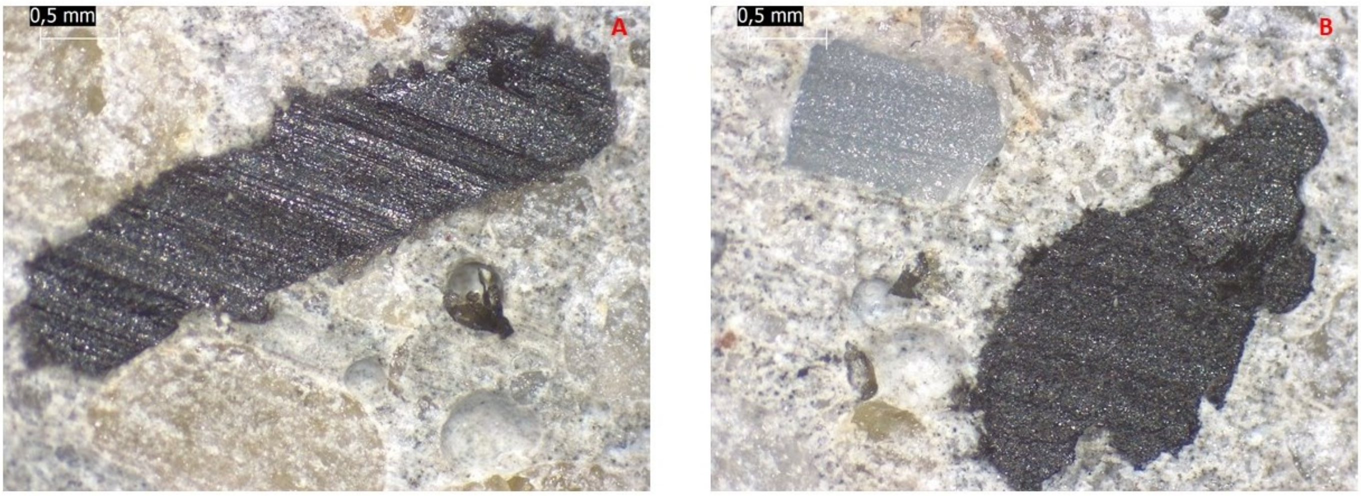

Figure 6. Stereomicrograph of A) 15PWCaO and B) 30PWCaO

Finally, the biochar used has a very small size, less than 180 μm. The addition of a micromaterial helps close porosity and partially improve cementitious materials' compression, as shown in the literature (Gupta and Kua 2018; Suarez-Riera et al. 2022).

4. Conclusion

This work showed how it is possible to maintain the mechanical properties of a standard mortar even by substituting natural aggregate up to 30%. The use of superplasticizer at a reduced water/cement ratio does not significantly affect the cost of the final product, and it is often already used in the industrial field to improve the workability of concrete. Substituting natural aggregates allows both the preservation of natural resources and the reuse of plastics that cannot be recycled in any other way and would therefore be destined for landfilling. All the proposed composites have the minimum mechanical strength required for use in not requiring structural and nonstructural applications in the building field, such as screeds or floor substrates.

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