



# Chemically treated plastic aggregates for eco-friendly cement mortars

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## Abstract

The use of waste plastic as aggregate in cement composites can solve the problem of the disposal of waste plastics in a sustainable way, and it reduces the need for extracting traditional materials like sand and gravel, which causes erosion and environmental degradation. The reaction of plastics with certain oxidizing chemicals is believed to result in chemical or electrostatic bonding between the plastic surface and the cement matrix. The present study investigates the effect of pre-treating plastic aggregates (with sodium hydroxide and sodium hypochlorite) on certain engineering properties of cement mortars. Five types of recycled plastics are used as partial sand replacements. Two replacement levels (5 and 15% by volume of sand) and two methods of chemical treatment are investigated. The results showed a decline in the properties of mortars made with chemically treated plastic aggregates: the addition of treated plastic aggregates makes the matrix porous, thereby degrading the mechanical properties. This behaviour intensifies with increasing plastic dosage. The polyoxymethylene (POM) and acrylonitrile butadiene styrene (ABS) plastic mortars performed best, while the polyethylene terephthalate (PET) mortars achieved poor results. Water-rinsing the treated aggregates removed reactive species from the plastic surface, and neutralized the matrix alkalinity resulting in comparatively less porous structures.

**Keywords** Chemical treatment · Sodium hypochlorite · Sodium hydroxide · Plastic aggregates · Chemical bonding · Strength properties · Waste plastic management

## Introduction

Managing waste plastic has become one of the most challenging problems worldwide due to its unprecedented growth owing to a continuously growing population and to the prevalent lifestyle. Plastic has outgrown most man-made materials and has long been under scrutiny for its negative environmental impact [1]. The production of plastic has reached to 311 million tonnes in 2014, and it is expected to increase three times by 2050 [2]. Industrial sources revealed that the global plastic production rates of different plastics for the year 2016 were: polyoxymethylene (POM) 18.5 million tons/year, acrylonitrile butadiene styrene (ABS) 10.8 million tons/year, polycarbonate (PC) 5100 kilotons/year

and polyethylene terephthalate (PET) 30.3 million tons [3, 4]. This substantial growth in the consumption of plastic has led to huge quantities of waste plastic. Annually, approximately 300 million tonnes of plastic waste are produced worldwide.

Plastic is non-biodegradable, and it contains various toxic elements such as heavy metals like cadmium and lead which can leach, polluting the surrounding environment. Therefore, disposal of waste plastic by illegal dumping, landfilling, or incinerating is not a viable solution. Recycling of waste plastic is considered as the best solution to reduce the environmental impact [5]. Recycling of virgin plastics is limited to a few cycles, generally 2–3, as the plastic loses some strength and stability, after each recycling cycle, due to thermal degradation [6]; thereafter it ends up in landfills. On the other hand, recycling plastic for construction applications can solve the solid waste management problem in an environmentally friendly and economical way. The use of recycled plastic in the form of aggregates in cementitious mixtures, eases environmental concerns arising from the over-dredging of natural sand and gravel resources that are depleting rapidly. The use of recycled plastic as an alternative material

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to produce lightweight composite material, asphalt mixtures, filler and insulation materials, concrete and mortars for structural and non-structural applications has been continuously investigated in the last decade [7, 8].

## Plastic aggregates in cement based composites: effect on physical and mechanical properties

A worldwide review on the performance of recycled plastic aggregates in cement composites revealed weaker interfacial adhesion between plastic particles and cement matrix due to the smooth surface of the plastic. The cracks or flaws present in the plastic-cementitious matrix interface become nuclei for further crack growth and propagation during loading [9], thereby affecting the mechanical and durability properties of cement composites.

Previous authors state that it is possible to develop good quality, lightweight cementitious composites using plastic aggregates [10]. The characteristics of the plastic aggregates including shape, size and texture, as well as the recycling techniques greatly influence the properties of the resultant composites. Through an appropriate mix design and the right choice of plastic, structural performance can be maintained [11]. Plastic aggregates have also been used in the preparation of high-performance concretes. Sadrmomtazi et al. [12] studied the combined effect of waste PET particles and pozzolanic materials, namely fly ash and silica fume, on the properties of self-compacting concrete wherein pozzolanic materials compensated the loss of strength caused by adding PET.

Addition of plastic aggregates lowers the slump value of fresh mix, and this effect intensifies with further increase in plastic aggregate content [13, 14]. The morphology of plastic aggregates also alters the fresh properties [5, 15] e.g. non-uniform shapes lower fluidity [5]. In addition, the grading and particle size distribution of plastic aggregates influence workability [16]. PET aggregates (being angular and flakier) decreased the workability of fresh concrete [15]. Many researchers observed 43–95% reduction in workability of cement composites containing 0–20% of shredded PET as sand replacement [17]. Plastic fibres are usually more detrimental to workability than particles [18]. However, a few studies [19, 20] report improved slump with increasing substitution levels of PET aggregates. According to the authors, the smooth surface and hydrophobic nature (almost zero water absorption capacity) of plastics led to increased slump value due to reduced internal friction between plastic particles and the cement matrix.

Plastics usually have lower density than natural aggregates, so adding plastic aggregates in concrete or mortar reduces its density proportionally. Hence, the relationship

between the unit weight of plastic-modified mixtures and plastic aggregate content is linear with a decreasing trend. Compared to the reference sample, a density reduction of 8%, 16% and 36% was obtained for mortar containing 10%, 25% and 50% (by volume) of porous foamed aggregates, replacing natural quartz sand [21]. Badache et al. [22] reported 5–25% reduction in the apparent density of a control mortar on increasing HDPE content (15–60%) as sand replacement. The reduction of bulk density remains small at low substitution levels (0% and 30%), however, when the volume exceeds 50%, the bulk densities of the composites decrease significantly reaching values of 1000 kg/m<sup>3</sup> [23]. Similarly, the dry density of a control mortar (0% of plastic aggregates) decreased from 2173 kg/m<sup>3</sup> to 1755 and 1643 kg/m<sup>3</sup>, respectively, for mortars containing 50% of PET and PC aggregates [24, 25].

The porosity and water permeability of cementitious mixtures containing plastic aggregates are higher than those of conventional cement composites, and this is usually attributed to a weak bond at plastic–matrix interface [25–28]. The non-absorbent nature of plastic generates a greater amount of free water in the mortar, which leads to a higher porosity after its evaporation [29]. Few authors claimed that the inability of plastic and natural aggregates to mix sufficiently in the matrix results in porous mortars [26, 30]. The flat shape of PET particles leads to higher porosity in the interface between PET and the hydrated cement [31]. Recycled plastic substitution (10–50%) by weight of sand enhances the open porosity of mortars, causing an increase in the water vapour permeability [18]. Hannawi et al. [25] showed that replacing a small volume of sand in PC and PET based mortars does not exert a significant influence neither on water absorption nor on apparent porosity of the composites; however, both values increased with increasing plastic content.

Researchers have found that replacement of 0–20% of sand with PET decreased the compressive strength of concrete by 9–62% [18]. However, some authors report slightly increased strength at lower replacements. For instance, mortars containing 7.5% and 10% of ABS as sand replacement by volume, increased the compressive strength of the control specimens by 15.4% and 7.8%, respectively [32]. Kaur and Pavia [33] reported a mild increase in the compressive strength of mortars made with ABS, PC, POM, PET, and ABS/PC plastic particles at 5% substitutions. In general, specimens containing plastic aggregates were found to fail in a ductile manner, being more capable of resisting loads after failure without fully disintegrating [34]. Liu et al. [35] reported superior energy absorption capability and impact resistance of concrete containing different content of ABS/PC (5–20% by volume of sand) when compared to normal concrete. Hannawi et al. [25] illustrates that substituting 3–50% of sand with PET and PC plastic particles not only

improves the equivalent flexural strength and the toughness factor, but also causes the composites to absorb more energy.

## Surface modification of plastic aggregates

To enhance the bonding characteristics between the cement matrix and the plastic, certain surface treatments have been proposed in the literature. Plastic aggregate surfaces have been modified by granulation, coating with sand or with slag powder [19, 20] or by treating the plastic with oxidizing chemicals [9, 11, 36]. These treatments are expected to improve mechanical performance by enhancing the interaction between cement paste and plastic aggregate.

Purnomo et al. [37] reported that concrete specimens made of sand-coated plastic aggregates have higher compressive strength than those with untreated plastic aggregates. The authors claim that the improved compressive strength is an indirect measure of the improved bond strength between plastic and matrix. Choi et al. [19, 20] also confirmed promising results using blast furnace-coated plastic aggregates.

The bond formed between plastic and matrix is assumed to be based on nonpolar van der Waals forces, which are considered weak. Chemical treatment introduces the R-OH (alcohol) and R-COOH (carboxylic acid) species into the polymeric chains of plastic, and these species are polar and hydrophilic, which allows stronger hydrogen bonds to be formed [24]. Therefore, to induce chemical bonding, treating plastic with strong chemicals like bleach, caustic soda, and hydrogen peroxide has been proposed in the literature. Naik et al. [9] illustrated the positive effect of chemical treatment on the HDPE plastic particles, by showing the improvement in compressive and tensile strengths of concrete including 4.5% plastic. Lee et al. [36] claimed that the higher compressive strength, lower porosity and lower permeability of recycled plastic concrete are due to the reduced ITZ between the cement matrix and chemically treated PET aggregates. Although treating plastic aggregates chemically is expected to improve the plastic-matrix bond, contradictory results exist in the literature. Thorneycroft et al. [11] reported significant lowering of compressive strength and density upon using chemically treated PET.

## Research significance

To boost the mainstream uptake of post-consumer/recycled plastic in construction, it is important to be able to employ a substantial amount of plastic in cementitious composites, which is currently restricted (< 10% volumetric sand replacement) in the literature. Moreover, the scanty literature on chemically treated plastic aggregates is limited to compressive strength and density measurements only. The

present study investigates the influence of chemical treatment on plastic aggregates, measured in terms of physical (density and water absorption by capillarity) and mechanical properties (compression, tension and flexure), in mortars containing 5% and 15% plastic aggregates as sand replacement. As a novelty, this paper applies previously adopted chemical treatments to waste plastics (PC, POM, ABS, and ABS/PC) that have not been treated to date.

## Experimental design, materials, and methods

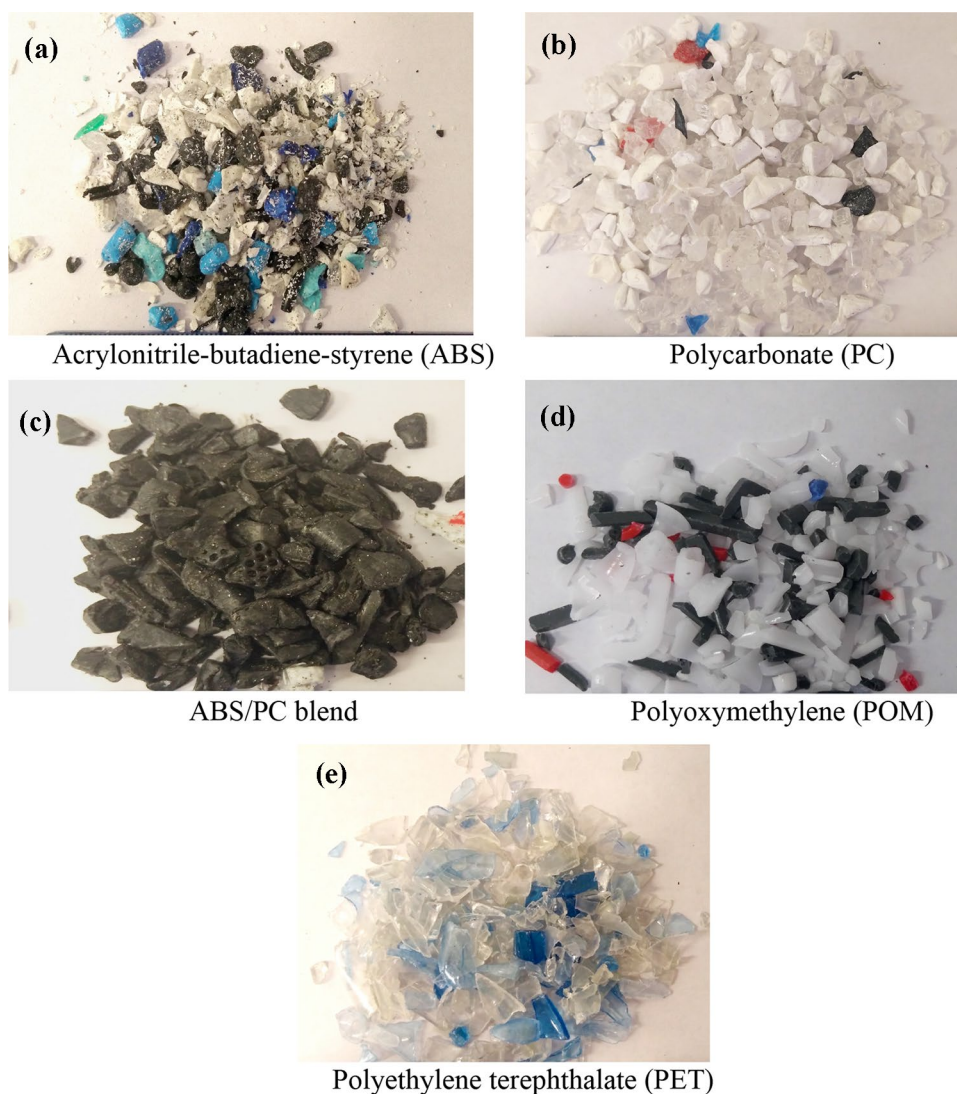
### Materials

Portland cement (CEM I 42.5R) manufactured by Irish Cement Ltd, with a specific gravity of 3.05 g/cm<sup>3</sup>, was used. Locally available sand of specific gravity 2.64 and bulk density 1.57 g/cm<sup>3</sup> was used as fine aggregate. Recycled plastic granules were procured from Wellman International Ltd and Polyfab Plastics Ltd (Fig. 1). The physical and mechanical properties of these aggregates were provided by the recycling plants and shown in Table 1. These plastics were tested according to the relevant polymer standards currently used by the polymer industry. The morphology of the plastic aggregates was qualitatively assessed with a digital camera. The PET aggregates were flat and angular in shape and smooth in texture; PC and ABS aggregates were sub-rounded and exhibited partially rough surfaces; ABS/PC aggregates appeared mostly sub-rounded in shape with a pored/scored texture; POM granules were mostly round and elongated in shape with a smooth texture. The gradation of sand and plastic aggregates by sieve analysis was carried out conforming to EN1015-1 [38]. Figure 2a presents the cumulative particle size distribution curves of sand and plastic aggregates. Figure 2b shows that the sand has a wide spread of particle size. Also, most of the plastic aggregates (PET, PC, and POM) show a predominant particle size range between 2 and 5 mm. However, ABS is partially coarse (c.50% of the particles are sized between 5 and 10 mm) and ABS/PC is comparatively coarsest, where the predominant particle size ranges between 5 and 10 mm.

### Chemical treatment of plastic aggregates

Plastic aggregates were treated with two chemical schemes. The first treatment (TS1) was adopted following the approach suggested by Naik et al. [9] wherein plastic aggregates were soaked in a solution of sodium hypochlorite (NaOCl) and sodium hydroxide (NaOH) (5% NaOCl + 4% NaOH) for 6 days and then dried at room temperature for 12 h before being used to prepare mortars. In

**Fig. 1** Types of plastic aggregates used in the experimental program. **a** Acrylonitrile butadiene styrene (ABS), **b** polycarbonate (PC), **c** ABS/PC blend, **d** polyoxymethylene (POM), **e** polyethylene terephthalate (PET)



**Table 1** Physical and mechanical properties of plastic aggregates used as sand replacement

	PC <sup>#</sup>	POM <sup>#</sup>	ABS <sup>#</sup>	ABS/PC <sup>#</sup>	PET <sup>a</sup>	Sand
Density (g/cm <sup>3</sup> )	1.20	1.38–1.40	1.05	1.15	0.45	1.57
Compressive strength (MPa)	86	31	70–85	–	24–77	–
Flexural modulus (GPa)	2.10	4.60	2.10	2.25	2.30	–
Tensile modulus (GPa)	2.60	4.90	2.10	2.27	2.7	–

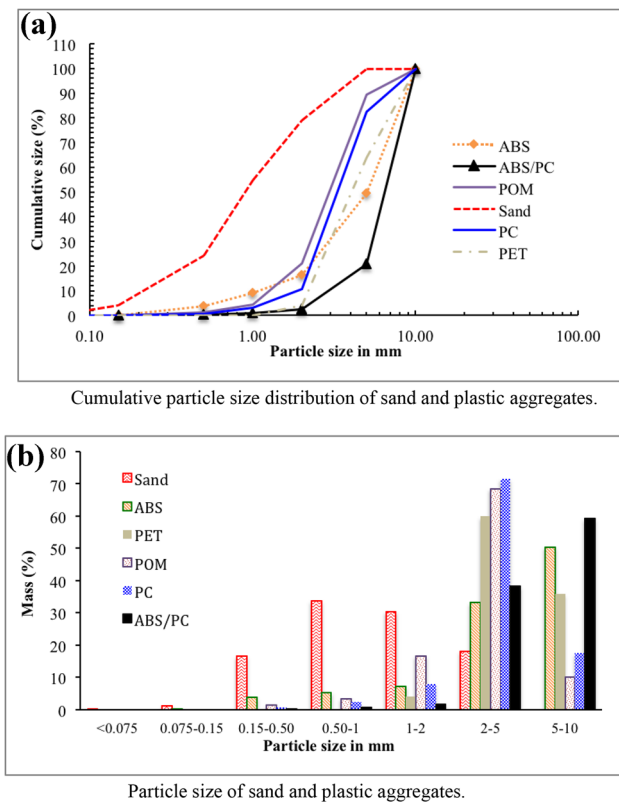
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the second treatment (TS2), a slightly modified method as implemented by Thorneycroft et al. [11] was used where plastic aggregates were first washed with the solution of common household bleach, sodium hypochlorite (NaOCl) and sodium hydroxide (NaOH) i.e. (5% NaOCl + 4% NaOH), and then with water, before being dried and further used in mix preparation.

### Mix proportions, casting, and test methods

The composition of the reference mix i.e. 1:3 cement-sand mortar by mass and one-half part of water ( $w/c=0.5$ ) has been decided in compliance with EN196-1 [39]. EN 1015–2 [40] also suggests that mortar should be proportioned to a consistency to give a flow of  $120 \pm 10$  mm to  $160 \pm 10$  mm depending on its use. The target-flow and target air volume



**Fig. 2** Sieve analysis results of sand and plastic aggregates **a** Cumulative particle size distribution of sand and plastic aggregates. **b** Particle size of sand and plastic aggregates

were not pre-established before the mix design. The average value of slump flow of the reference mix at 0.5 w/c was observed to be 160 mm. The average of three values has been considered. The reference mixture in fresh state looked homogeneous and no segregation or bleeding was observed after mixing. This water-to-cement ratio (w/c=0.5) was kept

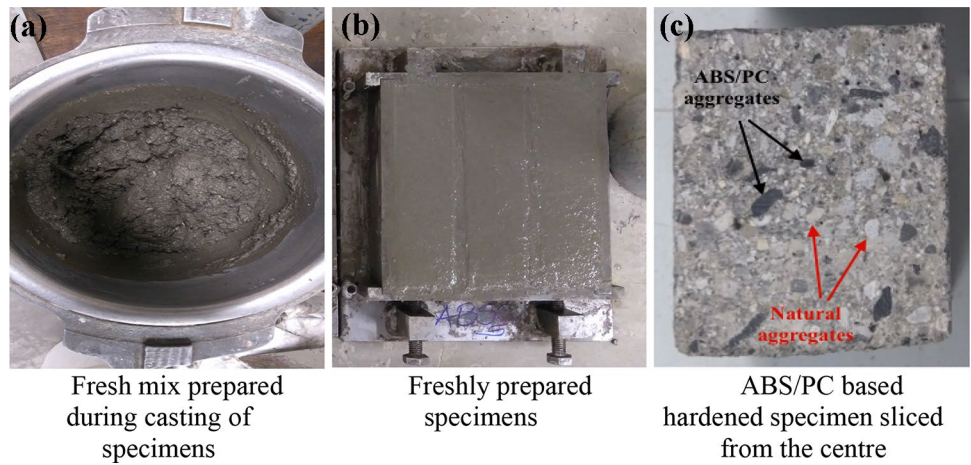
constant in all other mixtures. For the remaining mixtures, each plastic type is added at 5% and 15% volumetric substitution of sand without varying other ingredients. The mix proportions of eleven mortar mixtures are given in Table 2. The slump values of mortars containing plastic aggregates (Table 2) were obtained in the range 120 mm to 140 mm without making any adjustments in the water content. This observation is in agreement with the literature that reports lower slump values of fresh concrete due to the incorporation of several types of plastic aggregates than that of the conventional concrete mix.

The mix volume calculations were done considering the number of specimens to cast. For mixing, the different constituents of the mortar were accurately weighed, mixed and dry-homogenised. The mixing was done in a standard mixing machine of 5000 cm<sup>3</sup> capacity. The appropriate amount of water was gradually added to the mixture. The mixing duration was slightly raised with increasing content of plastic aggregates to get a homogeneous mixture. Figure 3 demonstrates that homogeneity was achieved practically while mixing and casting of plastic aggregate specimens. The fresh mortar mixtures were cast into prism and cylinder molds. Prism specimens of 40 × 40 × 160 mm size were cast to determine the flexural and compressive strength of hardened mortars. Split-tensile strength tests were carried out on cylinders of 150 mm diameter and 300 mm height. For the dry density, porosity and water absorption tests, additional prism specimens of 40 × 40 × 160 mm size were cast. Three specimens per each test were cast to evaluate the desired properties by obtaining the averaged results. The compaction of fresh mix was achieved using a vibrating table. The vibration was stopped once no air bubbles were seen at the surface and until a smooth surface was obtained i.e. approximately after 16 s. The freshly prepared specimens were covered with polythene sheets to avoid any loss of moisture and then kept as such under normal laboratory environment for

**Table 2** Composition and flow values of mortars

Mix	Cement (kg/m <sup>3</sup> )	Water (kg/m <sup>3</sup> )	Sand (kg/m <sup>3</sup> )	PAs (kg/m <sup>3</sup> )	Total aggregate cement ratio	Flow value (mm)
Control	473	236	1418.3	0	3.00	160
PC5	473	236	1347.38	54.96	2.96	135
PC15	473	236	1205.55	164.88	2.90	130
ABS5	473	236	1347.38	69.14	2.99	140
ABS15	473	236	1205.55	207.43	2.99	135
ABS/PC5	473	236	1347.38	46.54	2.95	140
ABS/PC15	473	236	1205.55	139.61	2.84	132
POM5	473	236	1347.38	50.97	2.96	130
POM15	473	236	1205.55	152.91	2.87	120
PET5	473	236	1347.38	60.19	2.98	130
PET15	473	236	1205.55	180.57	2.93	132

**Fig. 3** Representation of homogeneous mixture from casting to testing stage of specimens containing plastic aggregates **a** Fresh mix prepared during casting of specimens, **b** freshly prepared specimens **c** ABS/PC based hardened specimen sliced from the centre



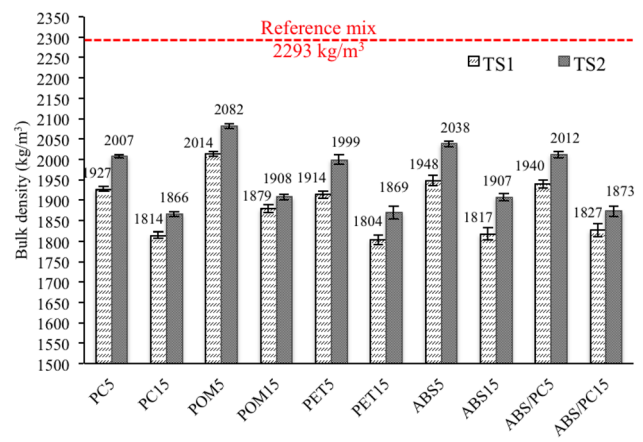
24 h. The specimens were demoulded after 24 h and cured in water bath maintained at  $20 \pm 2$  °C until the test age.

The methods described RILEM TC 25-PEM [41] were used to determine the real and bulk densities and porosity of hardened mortars at the age of 28 days. The water absorption coefficients of mortars due to capillary action were calculated in accordance to EN 1925–1999 [42]. To determine the 28-day compressive and flexural strength of hardened mortars the test method specified in EN1015-11 [43] was used. The splitting tensile strength test is an indirect method of testing the tensile strength of the mix, and it has been performed in compliance with IS 5816–1999 [44]. The physical and strength properties of mortars containing untreated plastic aggregates were determined previously in Kaur and Pavia [33]. The test results obtained from both treatment schemes are compared with their respective untreated counterparts and with the reference mortar.

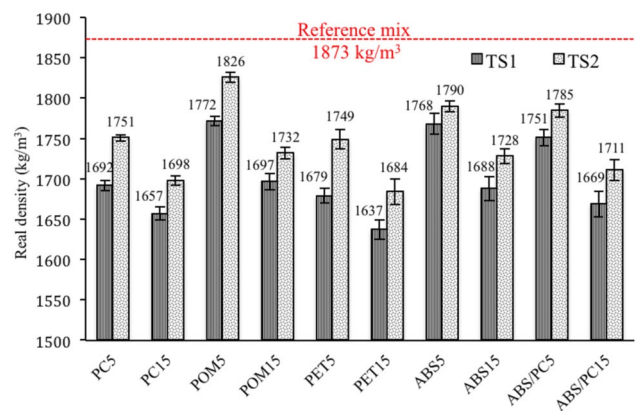
## Results and discussions

### Bulk and real density

The bulk and real densities of the reference mix were observed as  $2293 \text{ kg/m}^3$  and  $1873 \text{ kg/m}^3$  respectively. Figures 4 and 5 show the bulk and real densities of mortars containing treated plastic aggregates. In general, the investigated plastic types have a lower density than sand (Table 1); therefore, the weight of the plastic mortars is reduced when compared to the reference mix. As expected, the bulk and real densities of plastic aggregate mortars decreased further upon increasing the amount of plastic aggregates. These observations are consistent with many studies where natural aggregates/sand were substituted with plastics at different replacement levels [23, 24, 36]. The bulk densities of the plastic aggregate mortars ( $1804\text{--}2082 \text{ kg/m}^3$ ) are lower that



**Fig. 4** The bulk density of mortars containing treated plastic aggregates at 28 days



**Fig. 5** The real density of mortars containing treated plastic aggregates at 28 days

the reference mix ( $c.2293 \text{ kg/m}^3$ )—Fig. 4, meeting the dry density requirement for structural lightweight concrete [45].

In comparison to the reference mix, PET mortars containing 5–15% treated aggregates show a reduction (17–21%: TS1-series and 13–18%: TS2-series) in the bulk density. This outcome agrees with Thorneycroft et al. [11], which reported 19% reduction in the dry density of PET mix containing 10% treated PET aggregates as sand replacement. The authors attributed this behaviour to a large number of voids in the mix, which lowered the density values.

It can also be observed from Fig. 3 that irrespective of the type of plastic, the mortars carrying TS2 plastic aggregates have higher bulk densities than the TS1 counterparts. The bulk densities of TS2 based mortars ranged between 1839 to  $2082 \text{ kg/m}^3$ , whereas the corresponding bulk densities of TS1 mortars varied from 1804 to  $2014 \text{ kg/m}^3$ . The relative porous microstructure of TS1 mortars must have resulted in reduced bulk densities of these composites. This observation becomes quite evident with the matching downtrend in the real density values of TS1 mortars (Fig. 5). The prolonged soaking period of plastic aggregates in aqueous solution (TS1 method) affected the microstructure of the composites.

The lower density values of treated plastic aggregate mortars (Table 3), downplay the role of chemical treatment, especially for the TS1 samples. Literature suggests the formation of oligomers or alcohol (R-OH) and carboxylic acid (R-COOH) based reactive species on the plastic surface after chemical treatment. However, the likelihood of oligomers to remain precipitated on the plastic surface during mixing process is not confirmed. Moreover, the possibility of these reactive species dissolving or decomposing into the fresh mortar and altering the pH cannot be ruled out.

**Table 3** The bulk density ( $\text{kg/m}^3$ ) of plastic aggregate mortars at 28 days

Mix Code	Untreated plastic aggregates <sup>a</sup>	Treated plastic aggregates	
		TS1	TS2
PC5	2094	1927 (−8)	2007 (−4)
PC15	2008	1814 (−10)	1866 (−7)
POM5	2085	2014 (−3)	2082 (0)
POM15	1915	1879 (−2)	1908 (0)
PET5	2086	1914 (−8)	1999 (−4)
PET15	1892	1804 (−5)	1869 (−1)
ABS5	2136	1948 (−9)	2038 (−5)
ABS15	1980	1817 (−8)	1907 (−4)
ABS/PC5	2104	1940 (−8)	2012 (−4)
ABS/PC15	1949	1827 (−6)	1873 (−4)

Values in brackets represent the percentage reduction in density for treated samples against the untreated samples

<sup>a</sup>Density values for samples containing untreated plastic aggregates from Kaur and Pavia [33]

No distinct pattern from the density results (Table 3) of mortars could be observed on the five types of treated plastics used in this investigation. However, POM-based mortars appeared slightly denser and PET based mortars emerged somewhat lighter. This behaviour can be roughly correlated with the higher density value of the POM plastic ( $1.38\text{--}1.40 \text{ g/cm}^3$ ) and the low density of the PET ( $0.45 \text{ g/cm}^3$ ).

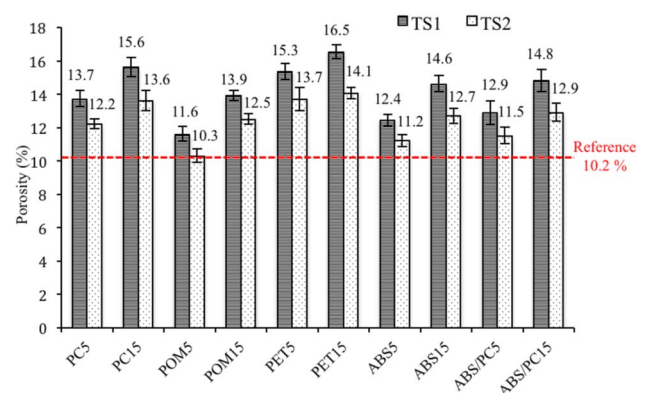
## Porosity and capillary absorption

The porosity and capillary test results of mortars containing treated aggregates are shown in Figs. 6 and 7, respectively.

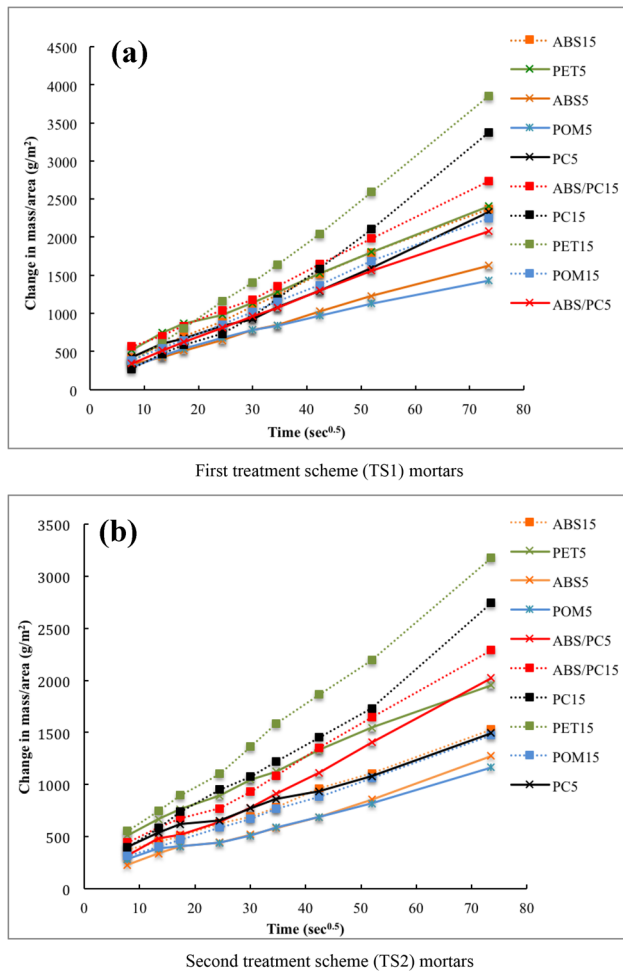
The mortars incorporating treated plastic aggregates increased porosity when compared to the reference mix (10.2%), hence it can be concluded that addition of chemically treated plastic aggregates resulted in porous mortars (Fig. 6). The increased porosity can be associated with the modified pore structure resulting from chemical treatment. This agrees with the results in Table 4, which indicate the percentage increase in porosity for TS1 and TS2 mortars when compared to the mortars containing untreated plastic aggregates. Previous authors [9, 25] attributed the increased porosity of plastic aggregate composites to the weak plastic–matrix bond, which in turn increased the permeability of mixtures.

Figure 6 also reports higher porosity for the TS1 mortars than the TS2 mortars. The TS1 mortars increased porosity by 12–15% (PC); 11–13% (POM); 12–18% (PET); 11–15% (ABS) and 12–15% (ABS/PC) when compared to the equivalent TS2 mortars.

In the TS1 mortars, the reactive oligomers resulting from the treatment might have decomposed during cement hydration, due to the high pH environment, and this could have increased the amount of pores in the matrix. However, in the TS2 mortars, washing the treated plastic aggregates with water before mixing must have washed away the reactive



**Fig. 6** Water accessible porosity of plastic aggregate mortars



**Fig. 7** Results of capillary suction tests. **a** First treatment scheme (TS1) mortars **b** Second treatment scheme (TS2) mortars

**Table 4** Porosity (%) of plastic aggregate mortars at 28 days

Mix Code	Untreated plastic aggregates <sup>a</sup>	Treated plastic aggregates	
		TS1	TS2
PC5	7.1	13.7 (93)	12.2 (72)
PC15	7.3	15.6 (114)	13.6 (86)
POM5	–	11.6	10.3
POM15	–	13.9	12.5
PET5	12	15.3 (28)	13.7 (14)
PET15	12.5	16.5 (32)	14.1 (12)
ABS5	6.4	12.4 (94)	11.2 (75)
ABS15	6.8	14.6 (115)	12.7 (87)
ABS/PC5	7.3	12.9 (77)	11.5 (58)
ABS/PC15	11.8	14.8 (24)	12.9 (9)

Values in brackets represent the percentage increase in porosity for treated samples against the untreated samples

<sup>a</sup>Porosity values for samples containing untreated plastic aggregates from Kaur and Pavia [33]

species from the plastic surface thus resulting in less pores. Thorneycroft et al. [11] claimed that mortars containing chemically treated PET aggregates, which were washed with water before mixing in concrete, are not distinctly different than untreated PET aggregates.

Porosity and water absorption are closely related. It is evident from the literature that the size, amount, and interconnectivity of pores affect the capillary suction of mortars.

All the treated plastic aggregate mortars at 5% replacements show either comparable or lower water absorption than the control mix. Plastics are hydrophobic which must have slowed down or disrupted the propagation of water. However, with an increase in plastic replacement, porosity and capillary suction increased. This effect is more prominent for TS1 mortars. Therefore, TS1 mortars have large number of interconnected pores thus displaying higher porosity and a greater amount of overall water absorbed. The higher values of capillary rise for PET15 i.e. 0.0052 g/(cm<sup>2</sup>.√sec) and 0.0043 g/(cm<sup>2</sup>.√sec) corresponding to TS1 and TS2 based treatments respectively, suggest that the PET15 mortars have the greatest capillary suction, both after one minute and long term (Fig. 7).

It can be concluded from Fig. 6 that the average coefficient of water absorption by capillarity for the TS1 and TS2 mortars lies in the range of 0.0020–0.0052 g/(cm<sup>2</sup>.√sec) and 0.0016–0.0043 g/(cm<sup>2</sup>.√sec), respectively, in comparison to the 0.0041 g/(cm<sup>2</sup>.√sec) for the reference mix. The TS1 mortars, being more porous, resulted in higher water absorption values (Fig. 7a) compared to the TS2 mortars (Fig. 7b).

### Compressive strength

The summary of 28-day compressive strength values of mortars containing plastic aggregates is presented in Table 5.

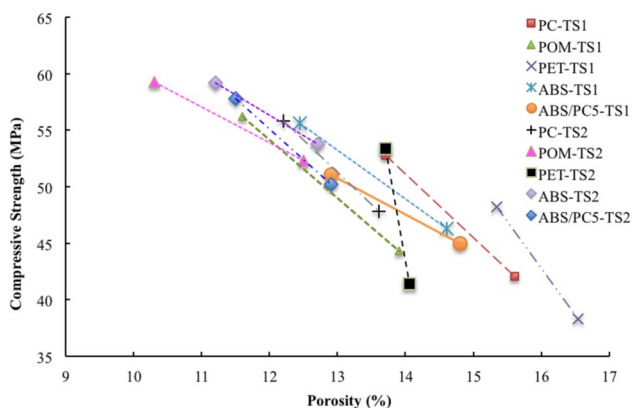
The plastic aggregate mortars from both treatment series showed reduced compressive strength values compared to the reference mix (60.61 MPa). The mortars containing treated (POM5 and ABS5) aggregates show a 2–6% reduction in compressive strength with respect to the reference mix. Both treatments result in strengths close to the control mix. These mortars are denser (Figs. 3 and 4) and less porous (Fig. 5) than other plastic types. Their aggregates contain more fines, which might have resulted in a denser packing. Mortars containing higher levels of treated plastic aggregates further lowered the compressive strength values: maximum reductions (up to 37% of the reference mix value) were observed for mortar including 15% TS1 treated PET.

The strength values of the treated plastic aggregate mortars are lower than the equivalent untreated plastic aggregate values in Kaur and Pavia [33]. As discussed earlier, the increased porosity of the plastic aggregate mortars due to the formation of pores and openings resulting from the



**Table 5** Summary of 28-day compressive strength results

Mix Code	Average compressive strength of treated mortars (N/mm <sup>2</sup> )		Average compressive strength of untreated mortars (N/mm <sup>2</sup> )	Change in TS1 mortars compared to the untreated equivalents (%)	Change in TS2 mortars compared to the untreated equivalents (%)	Change in TS1 mortars compared to the reference mix (%)	Change in TS2 mortars compared to the reference mix (%)
	TS1	TS2					
Reference	–	–	60.6	–	–	–	–
PC5	52.8	55.8	67.7	–22	–18	–13	–8
PC15	42.1	47.8	60.4	–30	–21	–30	–21
POM5	56.2	59.3	68.2	–18	–13	–7	–2
POM15	44.3	52.3	55.6	–20	–6	–27	–14
PET5	48.2	53.4	58.7	–18	–9	–20	–12
PET15	38.3	41.4	43.8	–13	–5	–37	–32
ABS5	55.6	59.2	71.2	–22	–17	–8	–2
ABS15	46.3	53.8	57.0	–19	–6	–24	–11
ABS/PC5	51.1	57.8	68.7	–26	–16	–16	–5
ABS/PC15	45.0	50.2	52.8	–15	–5	–26	–17

**Fig. 8** Compressive strength vs porosity of TS1 and TS2 mortars

interaction between the chemical treatments and the cement matrix, probably reduced the compressive strength. Figure 8 depicts the reduced values of compressive strength with the increasing porosity of the plastic aggregate mortars. Thorneycroft et al. [11] also reported a similar trend (77% compressive strength reduction for concrete containing TS1-treated, PET aggregates when compared with the untreated PET concrete mix).

The compressive strength of TS1 mortars containing 5–15% plastic aggregates reduced by 5–12% for PC, 5–15% for POM, 8–10% for PET, 6–14% for ABS and 10–12% for ABS/PC when compared to their equivalent TS2 mortars. This performance agrees with their reduced porosity, lower water absorption coefficient. The results evidence the inverse relationship between porosity and compressive

strength. For instance, PET15 exhibits the lowest compressive strength (TS1-treated: 38.26 MPa and TS2-treated: 41.42 MPa) and highest porosity (TS1-treated: 16.5% and TS2-treated: 14.1%).

It can be concluded from the compressive strength results that neither the TS1 nor the TS2 treatment have favored the compressive strength of any plastic type agreeing with previous authors [8, 9].

### Flexural strength

Flexural strength represents the highest bending stress experienced within the material at the collapse load [13]. Table 6 shows the summary of 28-day flexural strength of plastic aggregate mortars.

The flexural strength decreased with the substitution of sand with plastic aggregates. Numerous studies have reported lower flexural strength for cement composites containing PET aggregates, accrediting this trend to the weak interface/weak bond between matrix and plastic aggregate [24, 46]. The reduced flexural strength of TS1 and TS2-treated mortars disagrees with the chemical enhancing bond at the interface. There is no significant change in flexural strength for TS2 mortars containing 5% of treated plastic aggregates when compared to the reference mix except for PET5. The percentage reduction in the flexural strength for TS2 mortars are 7%, 2%, 13%, 3% and 5% for PC5, POM5, PET5, ABS5 and ABS/PC5, respectively. However, a significantly greater reduction in the range of 15–29% is observed for the TS1-treated mortars at lower replacements. The mortars containing 15% plastic content showed further reduction

**Table 6** Summary of 28-day flexural strength results

Mix Code	Average flexural strength of treated mortars (N/mm <sup>2</sup> )		Average flexural strength of untreated mortars (N/mm <sup>2</sup> )	Change in TS1 mortars compared to the untreated equivalents (%)	Change in TS2 mortars compared to the untreated equivalents (%)	Change in TS1 mortars compared to the reference mix (%)	Change in TS2 mortars compared to the reference mix (%)
	TS1	TS2					
	Reference	–					
PC5	5.7	7.5	8.4	–32	–11	–29	–7
PC15	5.4	6.1	6.9	–22	–12	–32	–24
POM5	6.0	7.9	8.1	–27	–3	–26	–2
POM15	5.4	6.7	7.3	–26	–8	–32	–16
PET5	5.6	7.0	8.4	–33	–17	–30	–13
PET15	4.9	6.3	6.9	–29	–8	–39	–21
ABS5	6.8	7.8	8.5	–20	–8	–15	–3
ABS15	5.5	7.0	8.3	–34	–16	–31	–13
ABS/PC5	5.9	7.6	9	–34	–16	–26	–5
ABS/PC15	5.5	6.6	6.9	–20	–4	–31	–17

in flexural strength (13–24% for TS2 mortars and 31–39% for TS1 mortars).

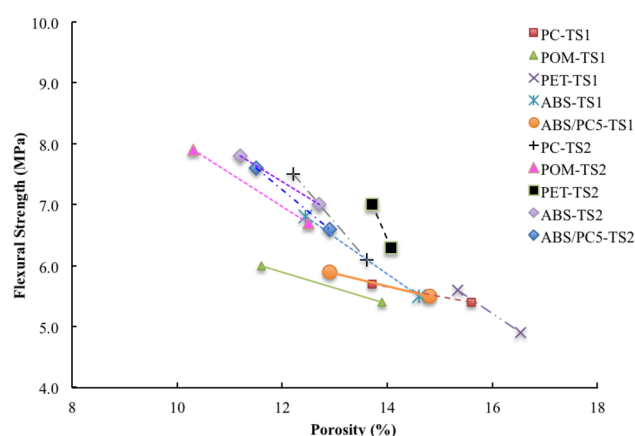
When comparing both treatments, for any plastic type, there is a clear difference between the flexural strength of the TS1 and the TS2 mortars, with percentage strength reductions of 11–23% for PC, 19–24% for POM, 20–23% for PET, 13–21% for ABS, and 17–22% for ABS/PC mortars. The TS1 mortars, being more porous, resulted in reduced flexural strength. The results from other properties discussed in previous sections also evidenced worse performance for the TS1-treated mortars.

In general, among the different plastic types, there is no substantial difference in performance. However, the POM and ABS-based mortars tend to perform better than the PET mortars which achieved the poorest results.

The results suggest that the overall performance of the chemically treated, plastic aggregate mortars is governed by the enhanced porosity triggered by the chemical treatment. The downward trend of flexural strength with increasing porosity is also visible from Fig. 9.

### Splitting-tensile strength

All failure modes in concrete under everyday design situations are a consequence of tensile failure, and introducing plastic aggregates into the cement composites results in the loss of tensile performance [11]. The effect of chemically treated plastic aggregates on the tensile strength of the mortars followed the similar trend as observed for the compressive strength and flexural strength. For both treatments, the splitting tensile strength of plastic aggregate mortars was lower than that of the reference

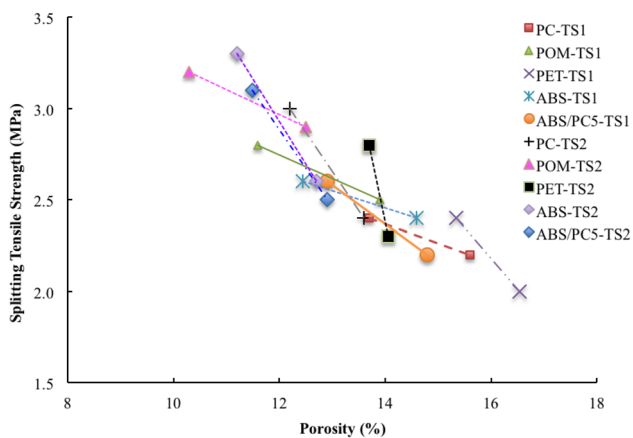
**Fig. 9** Flexural strength vs porosity of TS1 and TS2 mortars

mortar (3.42 MPa) and equivalent to the untreated samples (Table 7). Thorneycroft et al. [11] reported 50% reduction in tensile strength of chemically treated plastic aggregate concrete when compared to the untreated counterpart.

The splitting tensile strength of cementitious composites decreases further upon increasing the amount of plastics aggregates. Table 7 indicates significant reductions in the splitting tensile strength of TS1 mortars in comparison to TS2 mortars; the maximum reduction of 31–42% for TS1-based PET mortars was observed at 5–15% plastic additions. Similarly to the compressive and flexural strengths, the reductions in splitting tensile strength are attributed to the increased porosity and number of voids caused by the incorporation of plastic aggregates [5, 24].

**Table 7** Summary of 28-day splitting tensile strength results

Mix Code	Average splitting tensile strength of treated mortars (N/mm <sup>2</sup> )		Average splitting tensile strength of untreated mortars (N/mm <sup>2</sup> )	Change in TS1 mortars compared to the untreated equivalents (%)	Change in TS2 mortars compared to the untreated equivalents (%)	Change in TS1 mortars compared to the reference mix (%)	Change in TS2 mortars compared to the reference mix (%)
	TS1	TS2					
Reference	–	–	3.4	–	–	–	–
PC5	2.4	3.0	3.1	–22	–3	–30	–13
PC15	2.2	2.4	2.8	–23	–14	–37	–29
POM5	2.8	3.2	3.5	–20	–7	–18	–5
POM15	2.5	2.9	3.0	–19	–4	–28	–15
PET5	2.4	2.8	2.9	–20	–6	–31	–19
PET15	2.0	2.3	2.7	–26	–14	–42	–32
ABS5	2.6	3.3	3.5	–25	–7	–23	–4
ABS15	2.4	2.6	2.8	–16	–6	–31	–23
ABS/PC5	2.6	3.1	3.2	–20	–3	–24	–8
ABS/PC15	2.2	2.5	2.7	–19	–10	–35	–28

**Fig. 10** Splitting tensile strength vs porosity of TS1 and TS2 mortars

Alike the former mechanical properties, the splitting tensile strength lowers with increasing porosity—Fig. 10.

## Conclusions

The following conclusions can be drawn from the present investigation:

- Evidence obtained from the present study weakens the improved bond between chemically treated plastic aggregates and cement matrix proposed by former authors; and

strongly implies that chemically treated, plastic aggregates in cement mortars increase porosity and reduce strength.

- The results suggest that the overall performance of the chemically treated, plastic aggregate mortars is governed by the enhanced porosity triggered by the chemical treatment.
- The results also evidenced that one chemical treatment (TS2) is superior than the other, resulting in better mortar performance. Hence, the reactive species formed on the plastic surface by the chemical treatment might play a role on the mortar's performance.
- Water-rinsing the reactive species following chemical treatment (TS2) seems to benefit the resultant composites. It is likely that residues of the chemical treatment in the unwashed TS1-treated mortars have adversely interfered with cement hydration.
- There is no substantial difference in the performance of the different plastic types, but the POM and ABS mortars tend to perform the best and the PET the worst.
- The TS1 and TS2 mortars are strong with compressive strengths ranging from 38 to 59 MPa, tensile strength from 2 to 3 MPa and flexural strengths reaching 5 to 8 MPa, which are superior to those required by building standards for pointing/ bedding, rendering or plastering mortars.

## Recommendations

According to the literature, strong oxidizing agents result in a higher polarity of the plastic surface after treatment, which allows stronger hydrogen bonds to be formed. Further

research on chemically pretreated plastic aggregates is required to evidence the improved bond at the plastic–matrix interface as claimed by previous authors.

- The chemical interaction at the plastic–cement interface should be quantified using the surface tension or surface characteristics of the treated plastics such as friction coefficients.
- The type and characteristics of the reactive oligomers induced by the chemical treatments and their reaction with hydrated cement also need to be investigated to achieve better insight on the performance of chemically treated plastic aggregates in cementitious composites.
- More studies are required on the appropriate oxidizing agents and wetting times of plastic aggregates to review the effectiveness of the surface treatments.
- The durability of cementitious composites containing chemically pretreated plastic aggregates also needs to be studied to assess the resistance to aggressive environments.

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**Data availability** All data, models, and code generated or used during the study appear in the submitted article.

## Declarations

**Conflict of interest** The authors have no conflicts of interest to declare.

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