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Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates

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ABSTRACT

The effect of curing conditions on the durability of concrete mixes containing selected plastic waste aggregates was investigated. Concrete mixes were prepared in which 0%, 7.5% and 15% of natural aggregates were replaced by plastic – polyethylene terephthalate (PET) – aggregate. The effects of fine and coarse aggregates, used separately, as well as of their shape were also investigated. The manufactured concrete specimens were subjected to outdoor environment, laboratory environment and wet chamber curing regimes. Tests for shrinkage, water absorption by immersion, water absorption by capillarity action, carbonation and chloride penetration were carried out. The test results showed a decline in the properties of concrete made with plastic aggregates, in terms of durability, compared with conventional concrete. All specimens performed worse when subjected to drier curing regimes. However, sensitivity analyses showed that the properties of concrete mixes containing plastic aggregates generally deteriorate less than those of conventional concrete, when subjected to progressively drier curing regimes.

1. Introduction

1.1. Preliminary remarks

Plastic is one of the most relevant innovations of the twentieth century. This material has been widely used as a raw material in the manufacture of packaging, electrical and household appliances, toys and various other goods. Total plastic consumption has been increasing in recent years and so contributing to an ever-growing volume in the plastic waste stream. This is considered a serious environmental threat, especially in Asia, where demand has been growing in China and India [1]. The estimated production of plastic bottles in India alone was about 20,000 million between 2005 and 2006 [2]. Western Europe consumes about 60 million tonnes of plastics a year, resulting in about 23 million tonnes of plastics waste [3]. Considering the huge quantities and given the resistance of these materials to degradation and fragmentation phenoena, it is extremely important to continue research on reusing and recycling solid plastic waste.

The use of plastic waste as a natural aggregate substitute in concrete is a relatively recent concept. One of the first significant reviews on the use of waste plastic in concrete [4] focused on the advantages and financial benefits of such use, besides their physical and mechanical properties. There was common ground in that the use of plastic waste aggregate is viable, even though the performance of most properties declined [1,2,5–16]. In this paper it is shown how curing conditions influence the durability-related performance of concrete with plastic waste of different sizes and shapes. The effects of using plastic aggregates on drying shrinkage, water absorption by immersion and capillarity, carbonation and resistance to chloride ion penetration on concrete were investigated.

1.2. Drying shrinkage

An attempt was made to replace 5% of fine concrete aggregate (natural sand) by weight with an equal amount of PET aggregates manufactured from unwashed PET bottle waste [13]. The results indicated a slight increase in drying shrinkage with variations between 2.3% and 2.8%. Kou et al. [14] observed a reduction in the drying shrinkage values as the amount of PVC aggregates in the mix increased. Reductions of 18.1%, 31.6%, 48.7% and 72.2% were registered 112 days after demoulding the concrete specimens with substitution rates of 5%, 15%, 30% and 45%, respectively. Soroushian [15] stated that the drying shrinkage cracking could be controlled with the addition of plastic flakes. The use of shredded waste PET bottle granules as aggregate in mortar mixes has been investigated [7]. The authors found that mixes containing only PET aggregate had a higher drying shrinkage than that of mixes with sand and PET. The effect of PET fibres on free and restrained shrinkage was also studied [1]. The results showed that free drying shrinkage

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Table 1
Concrete mixes' composition.

Concrete mixes	Cement (kg/m^3)	Water (kg/m^3)	Natural aggregate (kg/m^3)		Plastic aggregate (kg/m^3)			W/C
			Coarse	Fine	PC	PP	PF	
RC	350	189.0	1003.1	800.6	–	–	–	0.54
C7.5PC	350	213.5	855.0	750.4	61.4	–	–	0.61
C7.5PP	350	185.5	1008.2	668.4	–	66.9	–	0.53
C15PP	350	182.0	1013.4	534.7	–	134.4	–	0.52
C7.5PF	350	196.0	992.7	660.0	–	–	64.2	0.56
C15PF	350	213.5	966.9	513.9	–	–	125.0	0.61

strain was greater for recycled PET fibre reinforced concrete specimens than for specimens without fibre reinforcement. Under restrained shrinkage, however, the fibres enhanced tensile resistance and delayed macro-crack formation.

1.3. Water absorption

Chidiac and Mihaljevic [16] studied the performance of dry cast concrete blocks containing low density and high density polyethylene. The water absorption tests yielded higher values for all mixes containing polymer aggregates. In a paper that investigated the physical and mechanical properties of concrete mixes in which various volume fractions of sand were replaced with the same volume of plastic (3%, 10%, 20% and 50%) [9], the results showed higher water absorptions as the content of PET aggregates increased. Higher sorptivity coefficient values were obtained after the natural aggregates were replaced with PET fine aggregates in mortar mixes [10]. Albano et al. [8] studied the effect of different sizes and substitution rates of PET aggregates derived from shredded bottles. The results indicated higher water absorption values with the addition of increasingly bigger sizes and amounts of polymer aggregates.

1.4. Carbonation and chloride penetration

The use of PET as a natural aggregate substitute in mortars was studied by Akçaözoglu et al. [7]. Test results indicated lower carbonation depths in mortars containing only fine PET aggregates compared with mixes with both natural and plastic aggregates. Kou et al. [14] obtained an increase in the resistance to chloride ion penetrability as PVC increasingly replaced natural aggregate. The total charges passed in coulomb were reduced by 11.9%, 19.0%, 26.9% and 36.2% for concrete mixes with substitution rates of 5%, 15%, 30% and 45%, respectively.

2. Experimental programme

This paper studies the durability-related performance of several concrete mixes containing plastic waste aggregates. In addition, a parallel investigation was conducted in the same time-line to ascertain the influence of curing conditions on the mechanical performance of these mixes [17].

2.1. Materials

This research work used natural aggregates (NAs) and selected plastic waste aggregates (PAs). Calcareous coarse NA of three size ranges and quartzite fine NA of two size ranges were used throughout the study. Three types of PET PA were collected from Selenis, a plastic recycling plant located in Portalegre, Portugal: coarse and flaky (PCAs – plastic coarse aggregates), fine and flaky (PFAs – plastic fine aggregates) and fine and regular shape (PPAs – plastic pellet aggregates). PCA and PFA were manufactured by shredding waste PET bottles to sizes between 2 and 11.2 mm and 1 and 4 mm, respectively (PFA are a by-product of PCA production). PPA were produced in sizes 1–4 mm, by applying a thermal process to shredded PET bottle particles. Every aggregate type was sieved to the various sieve sizes listed in the Portuguese standard NP EN 933-1 [18] and subsequently proportioned according to the Faury size grading curve to achieve uniformity in all concrete mixes. Cement type CEM II A-L 42.5 R and tap water were used in all the concrete mixes.

2.2. Characterization of the aggregates

All aggregates were characterized in terms of size grading [18] particle density and water absorption [19] and loose bulk density [20]. The shape index [21] and Los Angeles wear [22] were determined for the coarse NA.

2.3. Concrete mixes' composition

Based on Faury's method [23] six mixes were produced: a reference concrete (RC), a concrete mix with an NA/PCA replacement ratio of 7.5% (C7.5PC), two concrete mixes with an NA/PPA replacement ratio of 7.5% and 15% (C7.5PP and C15PP) and another two concrete mixes with an NA/PFA replacement ratio of 7.5% and 15% (C7.5PF and C15PF). Faury's method is based on an empirical reference grading curve that optimizes compacity for a given mix, whose main design characteristics are known. All mixes in this experiment have the same aggregate size distribution and cement content. The NA were used in oven-dried conditions. Table 1 presents a summary of the mixes' composition and Fig. 1 shows the Faury grading curve used in the concrete's production.

2.4. Curing conditions

After casting, all specimens were kept in the lab, for 24 h, until they had enough strength to be de-moulded and placed in their de-

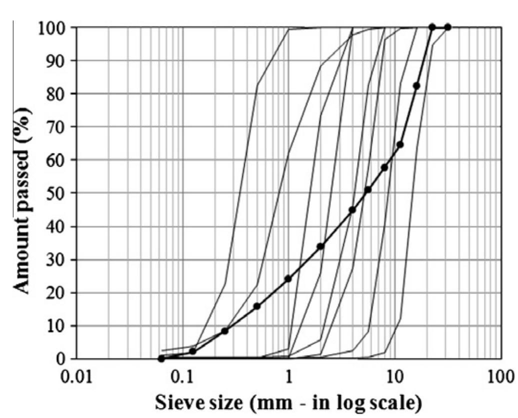

Fig. 1. Faury grading curve (with markers) along with the grading size curves of NA and PA.

Table 2
Natural and plastic aggregates' properties.

Aggregate	Fine sand	Coarse sand	"Rice grain"	Fine gravel	Coarse gravel	PCA	PPA	PFA
Particle dry density (kg/m^3)	2647	2717	2732	2665	2671	1302	1303	1280
Water absorption (%)	0.15	0.05	0.31	0.92	0.55	0.75	0.39	0.11
Bulk density (kg/dm^3)	1462	1461	1469	1420	1394	261	739	438
Los Angeles coefficient (%)	–	–	–	29.3	32.0	–	–	–
Shape index (%)	–	–	–	16.2	11.0	–	–	–

Table 3
Fresh concrete properties.

Mix code	W/C ratio	Slump (mm)	Density (kg/m^3)
RC	0.54	133	2361.8
C7.5PC	0.61	135	2215.0
C7.5PP	0.53	131	2300.9
C15PP	0.52	130	2222.9
C7.5PF	0.56	139	2235.8
C15PF	0.60	141	2089.2

Table 4
28-day compressive strength.

Mix code	Compressive strength at 28 days (MPa)		
	Outdoor environment	Laboratory environment	Wet chamber
RC	36.6	36.7	39.0
C7.5PC	21.2	19.7	23.8
C7.5PP	32.2	35.3	37.0
C15PP	33.1	31.9	34.7
C7.5PF	26.1	24.4	29.6
C15PF	21.2	19.7	22.7

sign environment. Three sets of the six mixes were produced, each one placed in different curing conditions: outdoor environment; laboratory environment; and wet chamber. For the first two, temperature and relative humidity reading devices were placed near the concrete specimens, so as to ascertain the effect of these properties on those of the hardened concrete. The average temperature and relative humidity for the outdoor and laboratory environment were 20 °C, 55% and 22 °C, 46%, respectively. The specimens placed in the wet chamber were at constant temperature and relative humidity of 20 °C and 100%, respectively.

2.5. Tests on concrete mixes

The test methods specified in standards NP EN 12350-2 [24] and NP EN 12350-6 [25] were used to determine the slump and fresh density of all concrete mixes.

The test method specified in NP EN 12390-3 [26] was used to determine the compressive strength. Tests were performed on eleven 150 × 150 × 150 mm cubic specimens, per concrete mix.

The method described by Portuguese specification LNEC E-398 [27] was used to measure the concrete's drying shrinkage, using two 150 × 150 × 600 mm prismatic specimens per mix. This test began immediately after the specimens were de-moulded and placed in their design curing environment.

The determination of the water absorption by immersion followed the test method specified in Portuguese standard LNEC E-394 [28]. Four 100 × 100 × 100 mm cubic specimens were tested per concrete mix.

The test method specified in LNEC E-393 [29] was used to determine the water absorption by capillarity. Tests were performed on

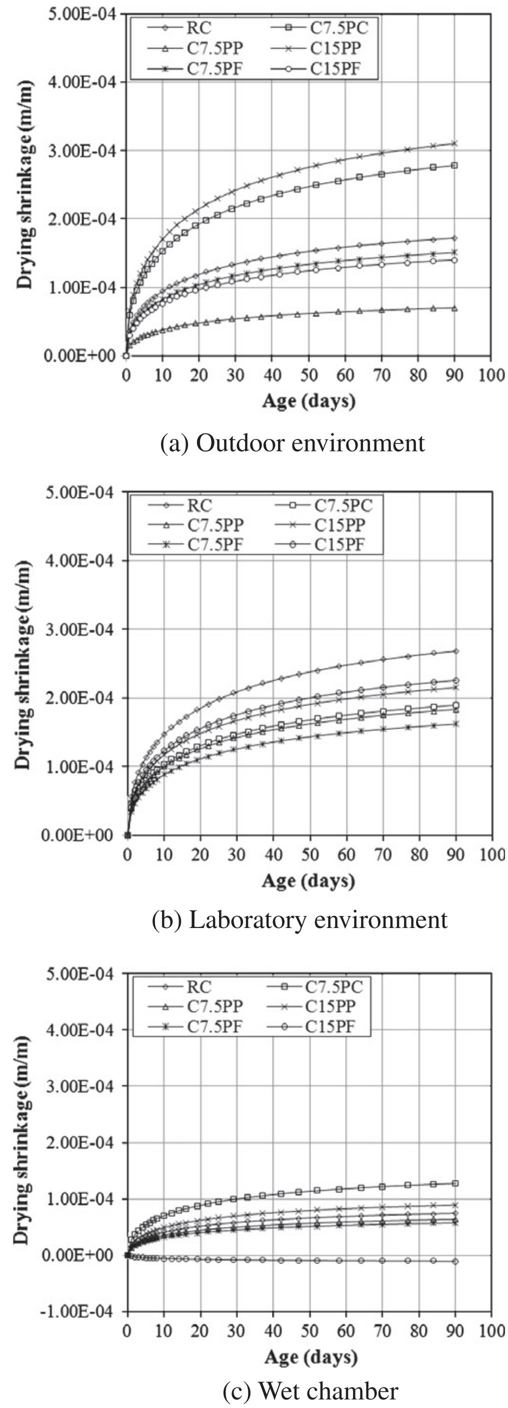

Fig. 2. Drying shrinkage of concrete mixes cured in the: (a) outdoor environment; (b) laboratory environment and (c) wet chamber.

four 100 × 100 × 500 mm prismatic specimens to measure water absorption by capillarity, per concrete mix.

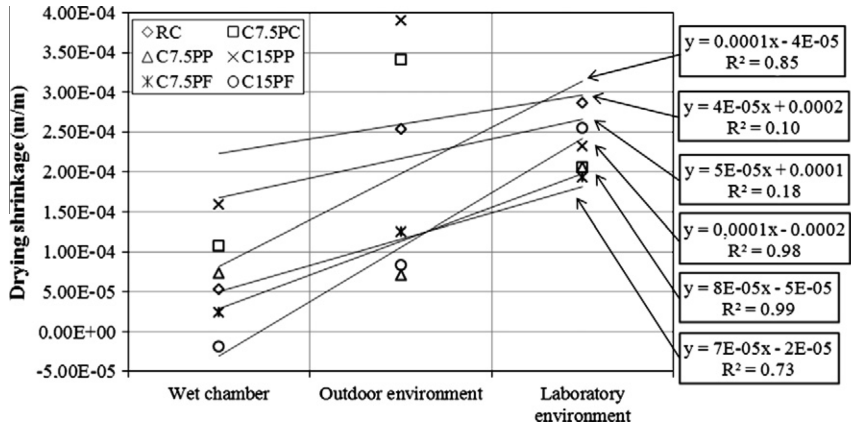

Fig. 3. Relative drying shrinkage of concrete mixes cured in the three curing conditions at 90 days.

Table 5
28-day water absorption by immersion.

Mix code	Outdoor environment		Laboratory environment		Wet chamber	
	Water absorption (%)	Variation (%)	Water absorption (%)	Variation (%)	Water absorption (%)	Variation (%)
RC	12.94	0.00	13.28	0.00	13.76	0.00
C7.5PC	15.73	21.55	16.17	21.78	16.21	17.86
C7.5PP	13.91	7.49	12.86	−3.12	13.10	−4.74
C15PP	13.30	2.79	13.49	1.56	13.19	−4.10
C7.5PF	14.22	9.90	12.82	−3.43	12.76	−7.27
C15PF	16.41	26.85	16.06	20.96	14.08	2.35

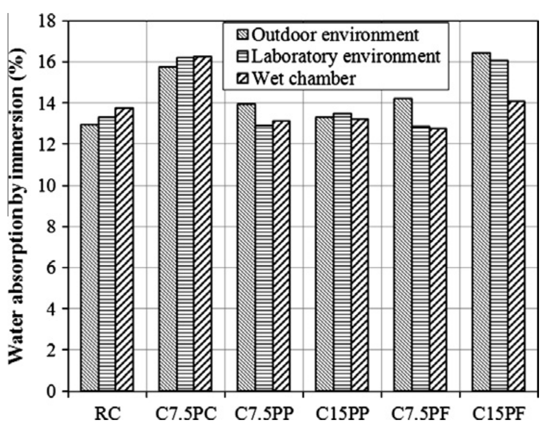

Fig. 4. Water absorption by immersion at 28 days.

The test to determine the carbonation depth was conducted according to specification LNEC E-391 [30]. Eight Ø100 × 50 mm cylindrical specimens were tested per concrete mix.

The determination of chloride ion penetration followed the test method specified in standard Nordtest NT Build 492 [31]. Six Ø100 × 50 mm cylindrical specimens were tested per concrete mix.

3. Results and discussion

3.1. Properties of aggregates

The aggregate's physical and mechanical properties are shown in Table 2. The particle dry density of PA is significantly lower than that of NA. The same result was obtained for the bulk density. There is a remarkable difference between the bulk density values

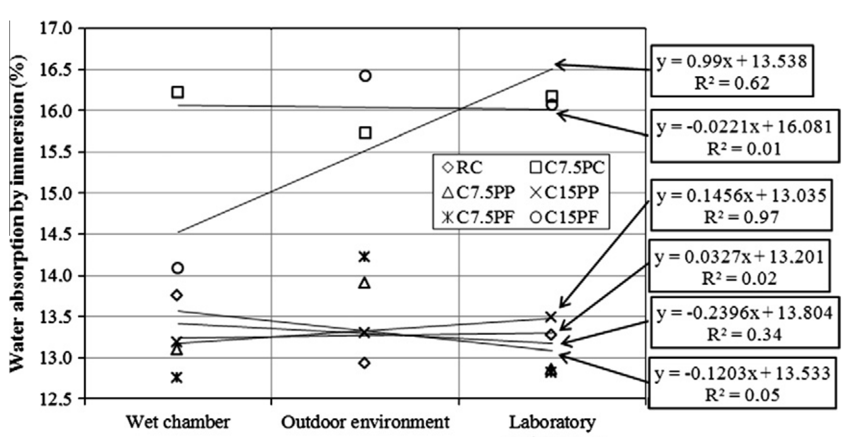

Fig. 5. Relative water absorption by immersion of concrete mixes cured in the three curing conditions.

Table 6
Water absorption by capillarity at 72 h.

Mix code	Outdoor environment		Laboratory environment		Wet chamber	
	Absorption by capillarity at 72 h (g/mm^2 $\times$ 10^{-3})	Variation (%)	Absorption by capillarity at 72 h (g/mm^2 $\times$ 10^{-3})	Variation (%)	Absorption by capillarity at 72 h (g/mm^2 $\times$ 10^{-3})	Variation (%)
RC	3.46	0.00	9.68	0.00	1.10	0.00
C7.5PC	9.87	184.98	12.48	28.93	1.74	57.95
C7.5PP	3.72	7.51	8.03	−17.07	1.41	28.64
C15PP	3.82	10.25	7.84	−18.98	1.36	23.18
C7.5PF	3.72	7.44	8.99	−7.13	1.27	15.68
C15PF	4.54	31.05	10.98	13.46	1.67	52.05

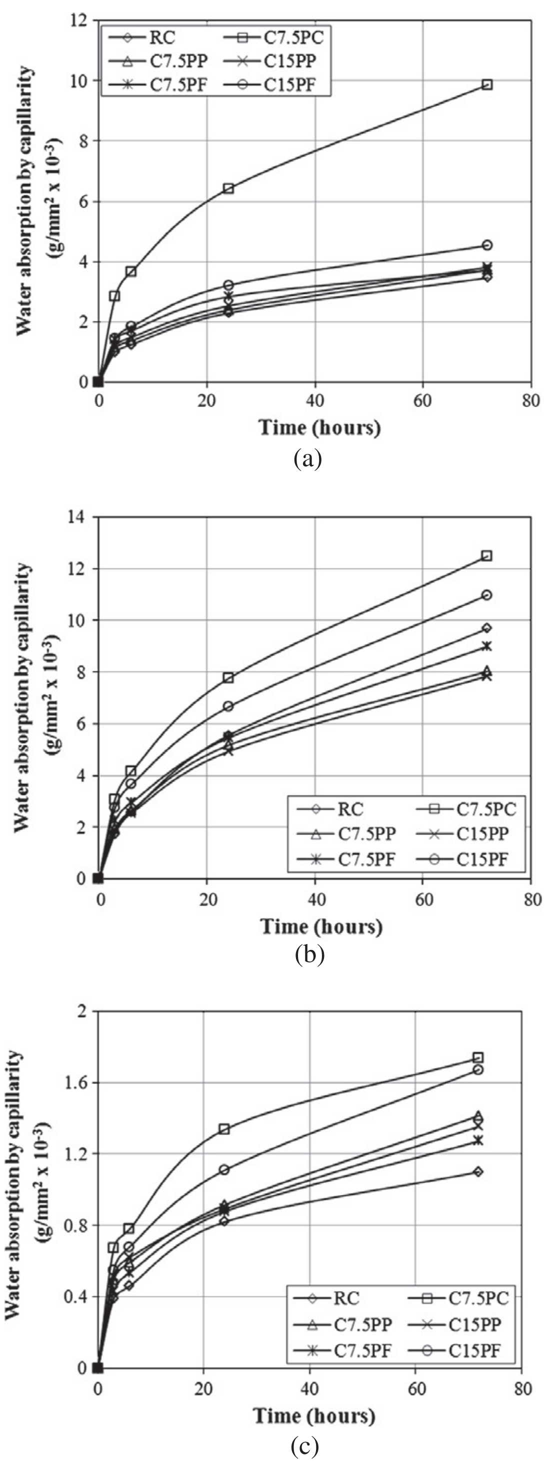

Fig. 6. Water absorption by capillarity in concrete mixes cured in the: (a) outdoor environment; (b) laboratory environment and (c) wet chamber.

of PP and PC aggregates (739 kg/m^3 and 261 kg/m^3, respectively). This is due to the PC aggregate's flake shape which, by using space less efficiently, led to a lower bulk density. The water absorption results show a similarity between PA and NA. However, in previous studies [9,12,32], PA exhibited an impermeable nature. The results obtained in this study are a little higher than expected due to a difficulty in drying the aggregate's surface.

3.2. Workability

The slump value for each mix is shown in Table 3. All mixes fell within the 130 ± 15 mm range. To maintain the workability, it was necessary to adjust the w/c ratio of each concrete mix. The w/c ratio was increased in the C7.5PC, C7.5PF and C15PF mixes to 0.61, 0.56 and 0.60, respectively. This was because of the PCA's and PFA's flake shape, which impaired the fresh concrete's fluidity. Ismail and Al-Hashmi [32], Albano et al. [8] and Kou et al. [14] report similar results with concrete containing aggregates with similar shapes. But the w/c ratio was reduced to 0.53 for C7.5PP and 0.52 for C15PP. This was because of the PPA's regular shape, smooth texture and impermeable nature. Choi et al. [10] obtained higher slumps than for conventional concrete when increasing amounts of smooth and regular shaped plastic aggregates were added to the concrete mix.

3.3. Fresh density

The density of each fresh concrete mix is shown in Table 3. The concrete with plastic aggregates' (CPAs) wet density is significantly lower than that of RC, due to the PA's lower density. The loss in density was greater when progressively bigger and flakier PA was incorporated.

3.4. Compressive strength

The compressive strength of each concrete mix cured in different conditions is shown in Table 4. The compressive strength decreased as the PA content increased. For C7.5PP, C15PP, C7.5PF, C15PF and C7.5PC, the compressive strength was respectively 5.1%, 11.0%, 28.7%, 42.1% and 42.1% lower than that of RC. This strength reduction can be explained by: low bonding strength between the PET aggregates and the cement paste due to the PA's impermeable nature; the coarser particle size of the PA leading to a reduction in the level of packing of concrete; the water that had not been absorbed by the PA surrounded these aggregates leading to poorer bond. Compressive strength declined in all mixes, as the specimens were cured in progressively drier environments.

3.5. Drying shrinkage

The drying shrinkage results of the concrete mixes are shown in Fig. 2. With the exception of the C7.5PC and C15PP mixes, the CPA's

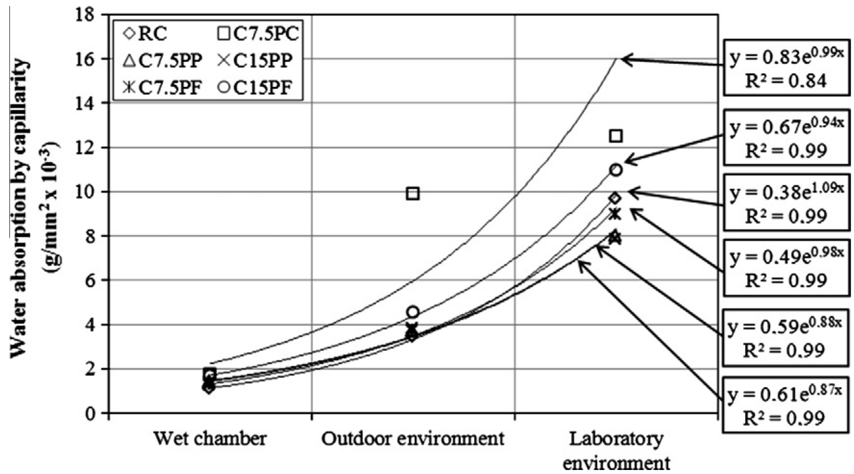

Fig. 7. Relative water absorption by capillarity of concrete mixes cured in the three curing conditions at 72 h.

drying shrinkage is lower than that of the RC. These results agree with the findings of Soroushian [15], who suggested that the drying shrinkage cracking of concrete can be controlled by adding plastic flakes. Kou et al. [14] obtained similar results by incorporating PVC aggregates into the mix. Drying shrinkage occurs due to the capillary tensile force induced as a result of water loss from the concrete. The PA's impervious nature reduces the quantity of water absorbed by the aggregates, leaving more free water to hydrate the cement, thereby leading to lower shrinkage values.

With the exception of the C7.5PC and C15PP mixes, which were cured in the outdoor environment, the concrete's drying shrinkage was progressively higher the drier the curing environment. These findings agree with those of Türkmen and Kantarci [33] and Amorim et al. [34].

In Fig. 3 and the matching ones for the following properties, the differences between CPA and RC in terms of the influence of curing conditions are analysed by means of a sensitivity analysis of a fictional regression line slope of concrete specimens cured in progressively drier environments. With the exception of the C15PF mix, CPA cured in progressively drier environments have a lower increment in drying shrinkage than that of RC. The lower increment in this property and in the next ones may be due to the PA's impermeable nature. Kou et al. [14] stated that if there was more PA in the mix there would be less water absorption by the aggregates,

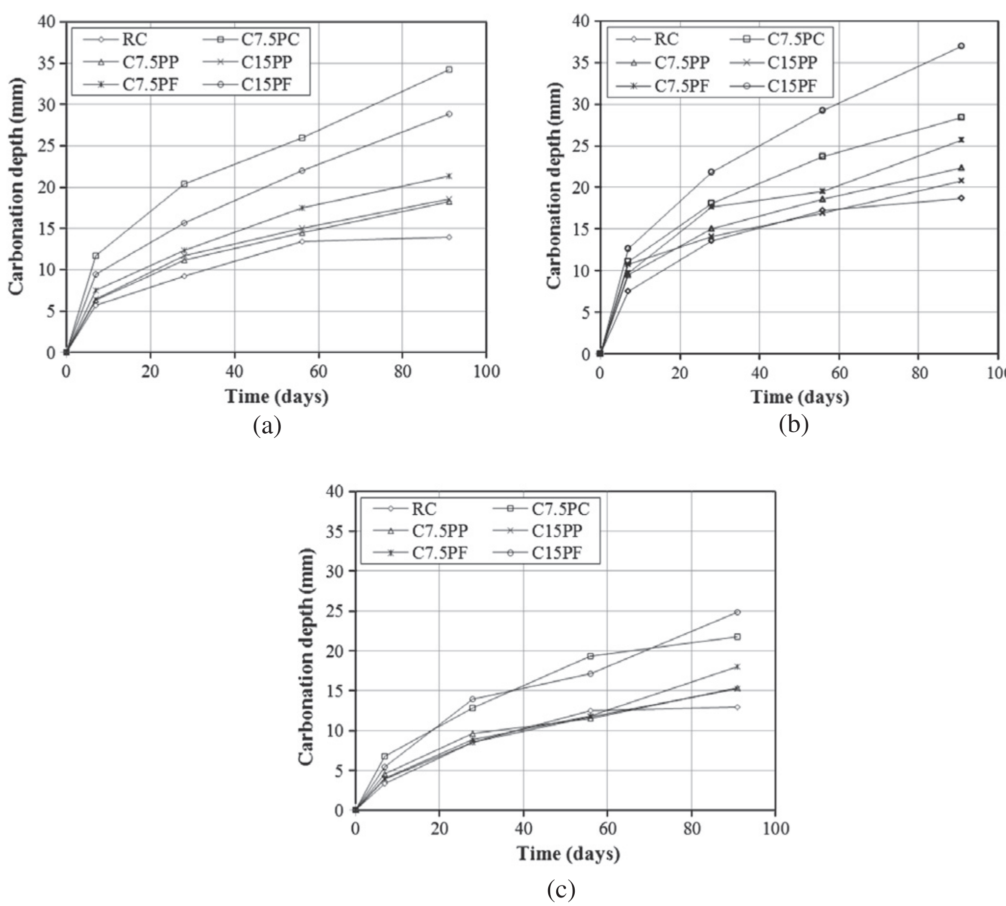

Fig. 8. Carbonation depth of specimens cured in the: (a) outdoor environment; (b) laboratory environment and (c) wet chamber.

Table 7
Carbonation depth at 91 days.

Mix code	Outdoor environment		Laboratory environment		Wet chamber	
	Carbonation depth at 91 days (mm)	Variation (%)	Carbonation depth at 91 days (mm)	Variation (%)	Carbonation depth at 91 days (mm)	Variation (%)
RC	14.0	0.0	18.7	0.0	12.9	0.0
C7.5PC	34.2	144.2	28.4	52.2	21.8	68.1
C7.5PP	18.3	30.4	22.4	19.7	15.4	18.8
C15PP	18.6	32.6	20.8	11.0	15.3	17.9
C7.5PF	21.3	52.2	25.7	37.5	18.1	39.6
C15PF	28.8	105.8	36.9	97.7	24.9	92.3

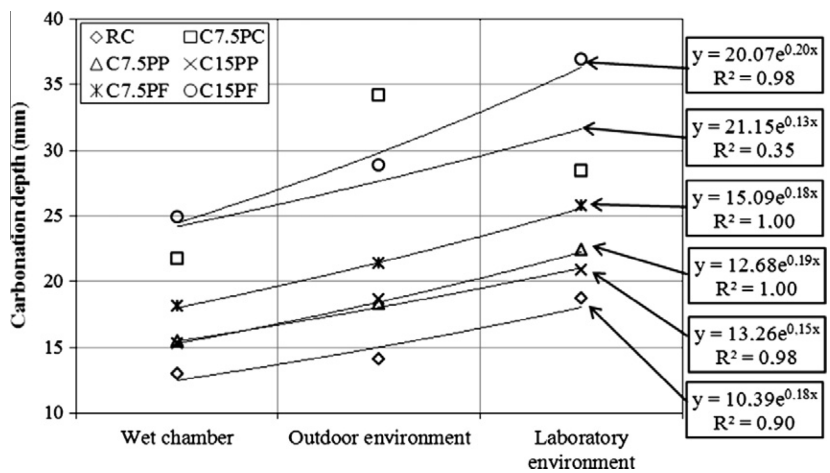

Fig. 9. Relative carbonation depth at 91 days of concrete mixes cured in the three curing conditions.

Table 8
Chloride migration coefficients at 91 days.

Mix code	Outdoor environment		Laboratory environment		Wet chamber	
	Chloride migration coefficient at 91 days ($\times 10^{-2}$ m^2/s)	Variation (%)	Chloride migration coefficient at 91 days ($\times 10^{-2}$ m^2/s)	Variation (%)	Chloride migration coefficient at 91 days ($\times 10^{-2}$ m^2/s)	Variation (%)
RC	12.2	0.0	24.3	0.0	10.1	0.0
C7.5PC	27.2	122.6	30.1	24.2	12.7	24.9
C7.5PP	16.0	31.0	25.5	4.9	11.9	16.9
C15PP	17.4	42.0	28.7	18.5	11.3	11.2
C7.5PF	16.1	31.6	32.2	32.8	13.9	36.5
C15PF	19.2	57.1	38.0	56.4	16.0	57.7

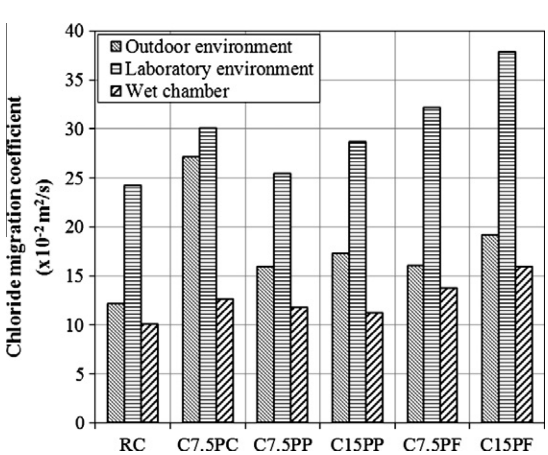

Fig. 10. Chloride migration coefficient at 91 days.

leaving more water to hydrate the cement during the curing process. This would lead to a slower evaporation of the free water, which would consequently reduce the shrinkage values of CPA.

3.6. Water absorption by immersion

Water absorption by immersion of the concrete mixes is shown in Table 5. Adding PA to the concrete mixes cured in the outdoor environment has increased the water absorption by immersion when compared to the RC (which is corroborated by the studies of Akçaözoglu et al. [7] and Albano et al. [8]).

Fig. 4 analyses the influence of curing conditions on mixes with the same volumetric proportions. According to Toutanji and Bayasi [35] and Safiuddin et al. [36] the higher the environment's relative humidity, the greater the amount of water in the pores of the cement matrix will be. The cement's continuing hydration will optimize the concrete's packing level and porosity, leading to lower water absorption [37].

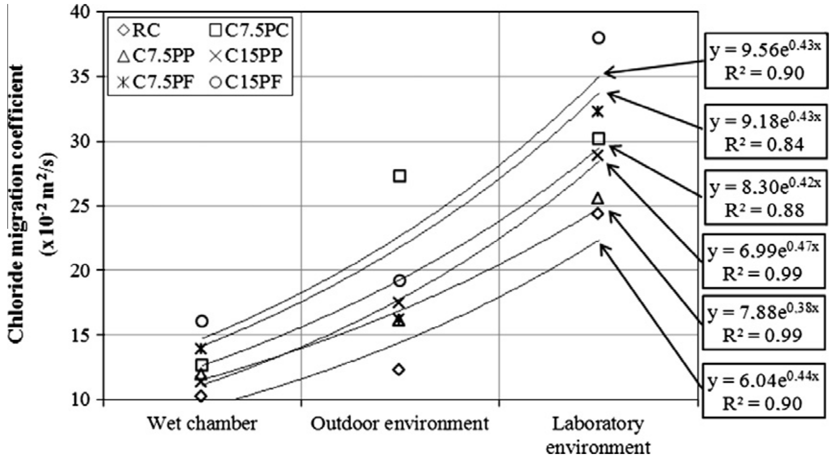

Fig. 11. Relative chloride migration coefficient at 91 days of concrete mixes cured in the three curing conditions.

The concrete specimens cured in the laboratory environment should have presented the highest water absorptions because of its lower relative humidity, followed by those cured in the outdoor environment and finally those cured in the wet chamber. This anomaly can be explained by the carbonation of specimens cured in the uncontrolled environments, which created a thin layer on the exposed surface and made it less permeable to water penetration. Should this carbonated layer be removed, the water absorption values would most likely be closer to those expected.

The test results in Fig. 5 suggest that either this test method does not allow an effective analysis of the differences in the influence of the curing conditions between the CPA and the RC or that the influence on this property is inconclusive. The authors believe that to fully assess the water absorption by immersion of all specimens this test should be carried out under vacuum conditions, or that all exposed surfaces should be removed before this test.

3.7. Water absorption by capillarity

Table 6 shows the water absorption by capillarity results for the three curing conditions at 72 h. Generally the CPA's water absorption by capillarity is greater than that of RC (Choi et al. [10] obtained similar results). The C7.5PC mix cured in the outdoor environment had a wide variation in this property and in the subsequent ones, due to a higher than required w/c ratio, which led to a slump value of 150 mm. The evaporation of the excess free water led to greater porosity and so to higher water absorption. Fig. 6 shows an intense water absorption by capillarity in the first few hours that stabilized by the end of the test.

Fig. 7 shows that specimens cured in drier environments had higher water absorption, since the presence of water in hydrated cement pores is essential to the optimization of concrete's density and porosity levels. However, the sensitivity analysis on the fictional regression slopes indicates that CPA have lower increments than RC, when cured in progressively drier environments. This can be attributed to the PA's impermeable nature, which means less water is absorbed by the aggregates, leaving more water to hydrate the cement during the curing process.

3.8. Carbonation

The carbonation depth of the concrete mixes at 91 days is seen in Table 7. CPA had higher carbonation depths than RC. Fig. 8 shows a high increase in the carbonation depth in the first 7 days, gradually stabilizing by the end of the test.

The carbonation reached higher depths in specimens cured in the laboratory environment as opposed to those cured in the wet chamber, which had the lowest values. This trend agrees with the findings of Lo and Lee [38] and Güneyisi et al. [39].

Carbonation depth increases when concrete is cured in progressively drier environments, as shown in Fig. 9. With the exception of C15PF, all mixes have almost the same fictional slope. Thus, it is considered that there is almost no difference in the influence of curing conditions between CPA and RC.

3.9. Chloride ion penetration

The chloride migration coefficients are shown in Table 8. They were higher for CPA than for RC. Fig. 10 shows that chloride ion penetration was higher in concrete specimens cured in the laboratory environment, followed by those cured in the outdoor environment and finally those in the wet chamber.

The analysis performed on the difference between CPA and RC in the influence of curing conditions in Fig. 11 shows that the fictional slopes are very similar. This suggests that there is almost no differentiated influence of the curing conditions, between CPA and RC, on this property.

4. Conclusions

Some conclusions can be drawn from this experimental programme in terms of the influence of curing conditions on the durability-related performance of concrete mixes containing selected plastic waste aggregates. CPA show worse durability performances in some properties than the corresponding RC. But it can be said that, in all the situations analysed, their quality was good enough for ordinary non-structural and structural uses. The following conclusions are based on the experimental results:

- Workability decreases with increasing amount of coarser, flakier and irregular shaped PA; these properties also affect the concrete's density (the lower the PA's bulk density, the lower the concrete mixes' density).
- CPA have lower drying shrinkage values than those of RC. The gap between these values widened as all concrete specimens were cured in progressively drier environments, with reductions varying between 11.1% and 28.3% of CPA specimens cured in the laboratory environment.
- Increasing the substitution rate of NA with PA increases the water absorption by immersion and by capillarity; however, RC cured in progressively drier environments showed a more

rapid increase in the latter property (some CPA mixes, cured in the laboratory environment, saw reductions between 7.1% and 17.1%, compared with the water absorption values of RC specimens cured in the same environment);

- All CPA exhibited greater carbonation depths and chloride migration coefficients than those of RC; there was no significant difference in the effect of curing conditions between CPA and RC.
- Generally, concrete mixes with increasing amount of coarser, flakier and irregular-shaped PA had worse durability-related performance than concrete mixes with finer, smoother and regular shaped PA, irrespective of their curing regime.

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