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Strength degradation of polymer concrete in acidic environments

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Abstract

This paper presents an assessment of the chemical resistance of eight different compositions of polymeric mortars using four different concentrations of filler, fly ash, and two types of unsaturated polyester resins, namely isophtalic polyester and orthophtalic polyester. The samples were exposed to seven different acid environments that represent those that often account for corrosive processes in industrial environments. None of the compositions in the study showed evidence of physical surface changes nor weight loss. There was a decrease in the flexural strength of the samples exposed to corrosive agents and this effect was more pronounced in the compositions with lower filler concentrations. However, even in those samples, the remaining flexural strength values remained far higher than those found in mortars prepared with Portland cement, an inorganic binder. Statistical analysis showed that the type of resin, the concentration of filler and the type of corrosive solution used have a significant effect on the chemical resistance of the polymeric mortars investigated in this study. SEM analyses also showed that the chemical attack occurred in the polymer matrix–aggregate interface.

Keywords: Polyester; Isophtalic; Orthophtalic; Fly ash; Flexural strength; Chemical resistance

1. Introduction

In the last few decades, polymers have been used in the production of concrete and mortar with improved mechanical strength and durability. The resulting compound is known as polymer concrete. The binder in polymer concrete is a resin that polymerizes with the aid of additives, namely an initiator and a catalyst [1,2]. Polymer concrete (PC) displays high compressive and flexural strength values, as well as improved chemical resistance to acid environments, particularly when compared with Portland cement concrete [3].

The hydration products of Portland cement concrete are alkaline and therefore react with acid environments. Over time, if exposed to acid environments, this type of concrete will show signs of wear [4]. However, in the case of PC, the polyester, epoxy, vinyl, phenol and methylmetacrylate resins that are often used as binders show good chemical resistance to acid environments and the concrete prepared with these polymers tends to replicate the inherent characteristics of the binders used [3].

Gorninski et al. [5] believe polymer concrete is an example of a relatively new high performance material. Its excellent mechanical strength and durability reduce the need for maintenance and frequent repairs required by conventional concrete. Other advantages observed in the use of PC include its fast curing time, which greatly facilitates the production of precast members because the cast parts can be removed from their molds in a matter of hours. When PC is used in coatings or repairs, the structure involved can be back into service overnight [6,7]. These characteristics of PC are a result of the substitution of a polymeric material for the cement binder [8].

For Rebeiz and Fowler [9], PC is the material of choice for coatings because of its strong bonding with Portland

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cement concrete, its resistance to abrasion and weathering, its impermeability and the low weight resulting from the small layer thicknesses used. PC also shows good sound and thermal insulation properties because of its low thermal conductivity and good dampening characteristics. In hydraulic structures such as dams, dikes, reservoirs and piers, PC creates a highly abrasion-resistant surface [10].

Fowler [1] observed that in the United States, the most common applications of PC are found in highway surfaces and bridge decks as well as in the petrochemical industry. In Canada and Japan, PC is often used in underground constructions and road surfaces, mainly because of severe weather conditions. In Europe, however, a large share of the applications is represented by precast materials for the civil construction sector, in the metal-mechanical industry as a replacement for cast metals and in the construction of reservoirs and coating materials in the chemical and food industry.

Judging from the improved properties and flexibility of these materials, one would expect to find a vast field of applications for PC. However, the cost of the resins, which is far higher than that of cement, results in a more expensive final product when compared with conventional concrete and this limits the scope of applications of PC compounds, particularly in developing countries, as discussed by Gorninski [3] and Czarnecki [11]. At the same time, it is important to remember that PC compounds compare favorably in terms of costs when durable materials with reduced maintenance is required [5]. In addition, in most cases, because of their higher strength lower amounts of PC compounds are needed when compared with the amounts of Portland cement concrete needed to obtain materials with the same strength levels [9].

To address the questions above, a previous study of PC compositions was carried out in order to define the compositions used here. That first study provided optimal cost/performance compositions with better packing of aggregate materials. The performance of the different compositions tested in that study was evaluated by means of a mechanical property (i.e., compressive strength) and a property related to durability (water absorption) [3]. Two different polymers were tested: isophtalic polyester, the most common PC polymer, and orthophtalic polyester, which has a much lower cost but has seen limited use in PC compositions used in aggressive environments. Strength and water absorption were assessed in samples with four different filler (fly ash) concentrations and two different binders, resulting in eight different compositions.

2. Experimental program

2.1. Materials

2.1.1. Resins

Unsaturated polyester resins were used as binders. Polyester is one of the most common polymers used in the production of PC because of its high performance, which results in durable PC with low permeability and fast cure [7,2]. In addition, polyester has a lower cost than epoxy resins and is readily available commercially. This study investigated PC compositions with isophtalic or orthophtalic polyester dissolved in styrene.

Isophtalic and orthophtalic polyester are produced using different reactants. Polyesters are produced through polycondensation reactions of dicarboxylic acids with dihidroxy alcohols. Isophtalic polyester (isopolyester) is produced using isophtalic acid while orthophtalic polyester is the result of a reaction with phtalic acid [12,13].

It is difficult to obtain high molecular weight orthophtalic polyester and for this reason, the chemical and mechanical properties of this material are inferior to those of isophtalic polyester. Phtalic anhydride shows a strong tendency to regenerate from the ester medium of the phtalic acid (reversible reaction), which increases the amount of low molecular weight chains (more susceptible to chemical attack) [13,14].

As isophtalic acid does not form cyclic anhydrides in isophtalic resins, regeneration does not occur and high molecular weight polyester (with longer chains) can be obtained. The carboxyl groups of isophtalic polyester are more widely spaced (meta position) and for this reason do not greatly affect the growth of the molecular chain of the polymer. As a result, the synthesis of long chains is possible and the final product shows increased mechanical strength [3,14,15]. Table 1 lists the main properties of the binders used in this study.

2.1.2. Filler and aggregate

Fly ash was chosen as a filler material because of the wide availability of this material in the state of Rio Grande do Sul, where it is a by-product of the burning of coal used

Table 1
Properties of unsaturated isophtalic and orthophtalic polyester

Property	Unsaturated isophtalic polyester (33–411)	Unsaturated orthophtalic polyester (10–228)
Brookfield viscosity @ 25 °C, 60 rpm (cp)[a]	400–650	250–350
Acid index (mg KOH/g)[a]	9–15	30 max
Tensile modulus (MPa)[a]	3200 min	2400 min
Flexural modulus (MPa)[a]	3500 min	3800 min
Linear shrinkage (%)[a]	2.0	1.0 max
Specific gravity (g/cm^3) – ASTM D 1475[b]	1.0968	1.0955
Axial compressive strength (MPa) – ABNT 5738[b]	117.31	91.44
Flexural strength (MPa) – ABNT 12142[b]	29.45	17.23

[a] Manufacturer data (Reichhold do Brasil).
[b] Determined in this study.

in local power plants. Rio Grande do Sul (RS) holds 89% of Brazil's coal deposits, or some 28.8 billion metric tones. Rohde [16] states that the thermoelectric power plants located in this state generated approximately 1.1 metric tones of fly ash in 1996, of which only 337.000 metric tones (31%) found commercial use. Ten years later, in 2006, the local power plants generated 2 million metric tones of fly ash. Although fly ash is basically non-toxic material, these large amounts generated by local power plants pose a potential environmental hazard because they require huge landfill sites. Unfortunately, fly ash still finds limited use in industrial processes. One possible destination to this by-product is its use as an aggregate in concrete. The effectiveness of fly ash in PC is well-known. Varuguese and Chaturvedi [17] used fly ash as fine aggregate and observed an improvement in mechanical properties and a reduction in water absorption, with good compatibility between sand and ash [17]. Fly ash improves the workability of fresh PC mortar and the resulting concrete shows excellent surface finish [18]. The small size of spherical fly ash particles also contributes to a better packing of the aggregate materials, which reduces porosity and hinders the penetration of aggressive agents, thus considerably improving the chemical resistance of PC [3].

The chemical composition and physical properties of the ash are related to the type of coal that was used as its source, its particle size distribution and the filtering process used. Fly ash for PC use must show rather uniform properties from batch to batch and low moisture content [18]. The specific mass of fly ash is 2.16 g/cm^3 and was determined according to Brazilian Standard NBR 6474 (Brazilian Association of Technical Standards, 1984) [19].

After a particle size analysis of five different aggregate samples available in the area of Porto Alegre, a choice was made for river sand with continuous particle size distribution, medium particle size, maximum diameter 4.8 mm, fineness modulus 3.73 and specific mass 2.65 g/cm^3 according to Brazilian Standard NBR 9776 [20].

2.2. Methods

The test method for chemical attack follows the procedure presented by Camps et al. [21]. Test specimens (TS) measuring 4 × 4 × 16 cm were molded for the test. They were cured and then the 14-day exposure cycles started. Each exposure cycle consisted of immersing the samples for 7 days in a chemical solution and then allowing them to dry for 7 days. The TS were weighed before the beginning of each test cycle. After the immersion cycle, the TS were washed with pressurized water in order to simulate the effect of mechanical abrasion and to remove any corrosion products from their surface. The TS were then allowed to dry in a controlled laboratory atmosphere for 7 days. At the end of the drying cycle, the TS were again weighed thus completing the 14-day cycle. After each new cycle, the aggressive agent solution was replaced with fresh solution. The pH of the solutions was measured before immersing the TS and after they were removed. The aggressive agents used were acetic acid, citric acid, formic acid, lactic acid, sulfuric acid, cola soft drink and distilled water. All acids were diluted to 5%.

Five exposure cycles were scheduled. The volume of aggressive solutions amounted to 4 times the volume of the TS. After the final exposure cycle, the TS were tested for flexural strength according to ASTM C78-02 [22]. For this test, three TS measuring 4 × 4 × 16 cm were molded. The results shown are the mean of the three individual value for these TS. All TS used in the tests were cured in an oven at 30 °C for 7 days.

All data underwent statistical analysis using the SPSS statistical software application with the Tukey HSD (honest significant differences) method for analysis of variance (ANOVA). The data were treated for three fixed factors and three repetitions for each combination of levels. The factors are: type of resin (isophtalic polyester or orthophtalic polyester), concentration of fly ash (8, 12, 16 and 20%) and type of acidic solution (acetic acid, citric acid, formic acid, lactic acid, sulfuric acid, cola soft drink and distilled water). The response or analysis variable is flexural strength.

ANOVA was used to check for significant differences between the mean values of flexural strength within the levels of each of the factors. After that, the Tukey test was used in each factor to define the homogeneous subgroups, i.e., which levels of each factor show significant differences in the response variable. A level of significance of 5% was used in the tests.

Table 2
PC Compositions used in this study

Polymer matrix components	Composition	Mass (%)
(a) Polyester		
Resin 1	Unsaturated isophtalic polyester 33411(Reichhold)	12[a]
Resin 2	Unsaturated orthophtalic polyester 10228 (Reichhold)	13[a]
Catalyst	Cobalt naphthenate 3%	1.0[b]
Initiator	Methyl ethyl ketone peroxide (MEKP)	1.0[b]
(b) Aggregates		
Sand	River sand, medium particle size	(70.4–1.0)[d] for 12% resin (69.6–80.0)[d] for 13% resin
Filler	Fly ash	(8% 12% 16% and 20%)[c] (7.0–17.6)[d] for 12% resin (7.0–17.4)[d] for 13% resin

[a] Percentage by weight of ash + sand.
[b] Percentage by weight of binder.
[c] Percentage by weight of sand.
[d] Range (grams) for each 100 g of PC.

2.3. PC compositions

The PC compositions used in the present study are listed in Table 2. These were selected from a study of different concentrations of resin used in the production of PC in order to determine the lowest binder concentration that would deliver an optimal cost/performance ratio [3]. It should be noted that the polymer accounts for the biggest share of the cost of PC, while the cost of inert materials is almost negligible by comparison [2]. The polymer concentrations selected were 12% of orthophtalic polyester and 13% of isophtalic polyester by weight of aggregate.

After the binder concentrations were determined, the next step was to investigate the effect of filler concentration on PC. A filler concentration of 12% was used as reference for maximum capacity and different percentages representing a study of the behavior of the filler below and above maximum capacity were selected. Table 2 shows the compositions used in this study.

3. Results and discussion

The results and statistical analysis of the flexural strength and chemical resistance tests of isophtalic polyester PC and orthophtalic polyester PC using 8, 12, 16 and 20% of fly ash are presented and discussed in this section. In Tables 3 and 4, the sample type is represented by a four-character code in which the first entry indicates solution type (A = acetic acid, C = citric acid, F = formic acid, L = lactic acid, S = sulfuric acid, R = cola soft drink, H = distilled water); the second entry indicates the polyester type (I = Samples prepared with unsaturated isophtalic polyester, O = Samples prepared with unsaturated orthophtalic polyester); and the last two entries indicate the percentage of fly ash by weight of sand used as a filler.

3.1. Flexural strength

Fig. 1 shows how the type of resin and the concentration of ash affect flexural strength.

The values obtained here (Fig. 1) are similar to those reported in the literature and show that PC has excellent flexural strength. The values observed in this study are quite high if compared with Portland cement concrete, including high-strength types. Sensale [23], in his study of cement concrete, found a mean of 7.60 MPa for flexural strength with an addition of 20% of rice husk ash and a w/b ratio of 0.25. Silveira et al. [24], however, obtained compressive strength values of 90 MPa in a sample with flexural strength of 4.06 MPa. In the same study, the highest flexural strength value obtained was 5.51 MPa and in this mix compressive strength was 53.7 MPa. That study used two different types of cement, a mix of crushed rock and granite with the addition of silica fume and w/c ratio of 0.26 and 0.49, respectively. Another difference between PC and cement concrete is the ratio of flexural strength to compressive strength. In Portland cement concrete, flexural strength values correspond to approximately 10% of those of compressive strength. In the case of the PC in the current study, flexural strength values correspond to 22.2–25% of those found for compressive strength. It was also observed that both PC compositions showed an increase in flexural strength as the concentration of fly ash increased.

Fig. 1 shows that flexural strength values in isophtalic polyester PC were higher than those of orthophtalic polyester PC. It also shows that the PC with 8% fly ash has the lowest strength of all compositions. This is probably due to the fact that the concentration of filler is below the value of maximum compactness of the sand and fly ash mixture.

Table 3
Flexural strength of TS after chemical attack

Solution type; resin; % ash; sample	Mean (MPa)	Solution type; resin; % ash; sample	Mean (MPa)	Solution type; resin; % ash; sample	Mean (MPa)	Solution type; resin; % ash; sample	Mean (MPa)	Solution type
A-O08	8.28	F-O08	11.83	R-O08	11.32	L-O08	11.66	A = acetic acid
A-O12	12.76	F-O12	18.08	R-O12	16.64	L-O12	16.52	
A-O16	14.99	F-O16	16.01	R-O16	18.11	L-O16	17.60	F = formic acid
A-O20	19.63	F-O20	18.40	R-O20	19.20	L-O20	18.16	
A-I08	10.58	F-I08	10.41	R-I08	11.18	L-I08	11.82	C = citric acid
A-I12	16.16	F-I12	14.61	R-I12	15.75	L-I12	12.81	
A-I16	16.30	F-I16	15.61	R-I16	19.17	L-I16	15.63	L = lactic acid
A-I20	18.52	F-I20	15.65	R-I20	19.64	L-I20	17.92	
C-O08	15.16	S-O08	13.33	H-O08	13.51	P-O08	18.00	H = water
C-O12	17.25	S-O12	17.35	H-O12	17.22	P-O12	20.03	
C-O16	18.87	S-O16	19.79	H-O16	18.74	P-O16	19.77	R = soft drink
C-O20	17.35	S-O20	19.48	H-O20	17.98	P-O20	20.47	
C-I08	11.20	S-I08	11.74	H-I08	7.55	P-I08	17.90	P = reference sample
C-I12	10.73	S-I12	16.71	H-I12	9.26	P-I12	20.44	
C-I16	18.03	S-I16	16.49	H-I16	15.13	P-I16	22.23	S = sulfuric acid
C-I20	17.97	S-I20	20.61	H-I20	16.03	P-I20	22.75	

Table 4
Flexural strength of isophtalic polyester PC and orthophtalic polyester PC with 8% and 20% of fly ash after chemical attack

Isophtalic PC	Mean strength after attack (MPa)	% Strength loss[a]	Orthophtalic PC	Mean strength after attack (MPa)	% Strength loss[a]
A-I08	10.58	40.9	A-O08	8.28	54.0
A-I20	18.52	18.6	A-O20	19.63	4.1
C-I08	11.20	37.4	C-O08	15.16	15.8
C-I20	17.97	21.0	C-O20	17.35	15.2
F-I08	10.41	41.8	F-O08	11.83	34.3
F-I20	15.65	31.2	F-O20	18.40	10.1
S-I08	11.74	34.4	S-O08	13.33	25.9
S-I20	20.61	9.4	S-O20	19.48	4.8
R-I08	11.18	37.5	R-O08	11.32	37.1
R-I20	19.64	13.7	R-O20	19.20	6.2
H-I08	7.55	57.8	H-O08	13.51	25.0
H-I20	16.03	29.5	H-O20	17.98	12.2
L-I08	11.82	34.0	L-O08	11.66	35.2
L-I20	17.92	21.2	L-O20	18.16	11.3

*I08 = 17.90 MPa.
I20 = 22.75 MPa.
*O08 = 18.00 MPa.
O20 = 20.47 MPa.
[a] The percentage was calculated by comparison with flexural strength values in the control sample, i.e., the PC sample that did not undergo chemical attack.

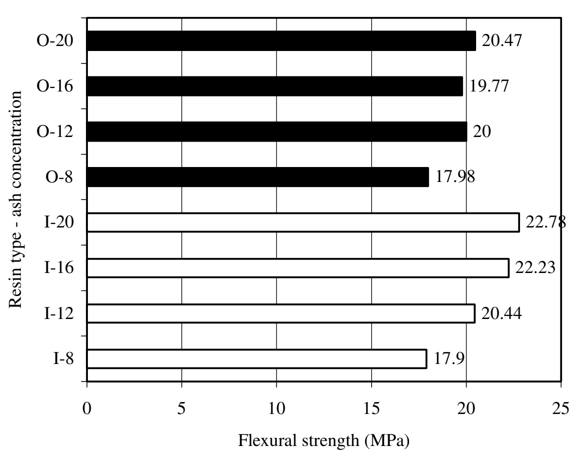

Fig. 1. Effect of the type of resin and the concentration of fly ash on flexural strength.

3.2. Chemical attack

Table 3 shows the mean results calculated from three separate flexural strength test results of the TS after chemical attack and also of control samples not exposed to chemical agents (standard samples).

3.2.1. Discussion of results

First of all, it is important to highlight that TS that were exposed to one of the seven solutions used in this study showed no weight loss nor surface changes after the fifth exposure cycle, when their weights were recorded. Portland cement concrete, on the other hand, usually shows great weight loss in these conditions. Kulakowski et al. [25] investigated the chemical strength of concrete compositions using CP III ASTM C150 cement with 9% silica fume and a w/b ratio of 0.59 and reported a weight loss of 32%.

The flexural strength values in Table 3 show that all TS prepared with isophtalic and orthophtalic polyester PC lose strength to some degree after exposed to a chemical agent. This was more evident in those compositions with lower silica fume concentrations.

Table 4 lists the percentage loss of strength in the compositions with 8% and 20% fly ash. The table entries show that higher fly ash concentrations resulted in increased chemical resistance in both isophtalic polyester PC and orthophtalic PC for all compositions.

When the loss of strength in PC is compared with the losses observed in cement concrete, it becomes clear that large percentage losses in the latter mean that very low strength values are retained. This can be seen in Table 5, which shows the results of a study by Kulakowski et al. in samples of cement concrete with 9% silica fume and w/b ratio of 0.59 exposed to formic and acetic acids [26]. In the case of PC, however, even in more aggressive

Table 5
Flexural strength of cement concrete after chemical attack [25]

Solution type	Mean strength after attack (MPa)	% Strength loss*
Acetic acid	1.09	72.3
Formic acid	0.90	77.2
Lactic acid	3.86	2.4
Sulfuric acid	2.8	29.2
Distilled water	5.56	29.0 (increased ft)
Soft drink	5.27	25.0 (increased ft)

The percentage was calculated by comparison with flexural strength values in the control sample (3.95 MPa), i.e., the PC sample. The Kulakowski study used the same methodology used in the present study, which allows results to be compared.

environments (e.g., isophtalic polyester PC with 8% fly ash in water and orthophtalic polyester PC in acetic acid), the remaining strength level *after* chemical attack is higher than the values observed in cement concrete with no chemical attack.

The loss of strength in PC is probably due to the degradation of the -sand interface. Mebarkia and Vipulanandan [26] published results of several studies on the behavior of PC in aggressive environments. They reported that PC samples prepared with a coupling agent to increase the strength of the aggregate-resin bond showed a reduction in the loss of strength in tests using water as a chemical agent. These authors also observed flexural strength losses of 17% in the samples of isophtalic polyester PC immersed in 5% sulfuric acid and of 20% in the samples immersed in water (one-month exposure). After the test, the total organic carbon content in the water used in the immersion was measured and a value of 50 ppm was found. This indicated that there was no reaction or significant dissolution of the polymer in water.

In the present study, the fact that the samples of PC with higher concentrations of fly ash display higher chemical resistance than those samples with lower concentrations of fly ash is probably related to the filler effect, i.e., the number of voids in the mix is reduced and therefore the diffusion of aggressive solutions is also reduced. Norwood [27] studied the behavior of filler-added resins and showed that the introduction of fillers in polyester resins has the advantage of reducing shrinkage and increasing the elasticity modulus, but chemical resistance and flexibility are also reduced in this process. According to the Norwood study, when fillers are added (inert or otherwise) to a polymer, a reduction in the bond between the filler and the polymer matrix is observed and this translates as a loss of strength. However, his study did not include PC. In PC, lower chemical resistance is associated with increases in porosity, which results in increased diffusion of aggressive agents. Norwood [27] studied the behavior of resins with filler. In PC, the addition of a filler reduces the number of voids in the material. Therefore, the fact that PC compositions with higher concentrations of fly ash (such as 20%) are more resistant to chemical attack can be attributed to these compositions being more compact than those with lower filler concentrations. SEM analysis reveals that the ash is made up by very small round particles. This allows a denser packing of the mixture; the number of pores is therefore reduced and diffusion of aggressive solutions is hampered.

Norwood [27] also analyzed the behavior of isophtalic neopentylglycol polyester immersed in acidic solutions for three months. He observed that the degree of strength loss is affected by both the concentration and the temperature of aggressive solutions. When the concentration or the temperature of a solution increases, chemical resistance tends to drop. According to the results of the study, in 50% acetic acid (CH_3COOH) at 20 °C, the resin retained 100% of its flexural strength. The samples placed in 30% hydrochloric acid (HCl) at 50 °C retained 99% of their original strength and in 30% sulfuric acid (H_2SO_4) at 10 °C, polyester retained 94% of its initial strength.

All aggressive solutions in the present study were used in 5% concentrations. Therefore, according to the results of Norwood, it seems reasonable to believe that the polyester resins used in the production of PC did not suffer significant strength losses. The loss of strength in PC can be attributed to an increase in porosity of the PC samples with increased capillary diffusion of the solutions, which weakens the bond between the aggregate and the polymer matrix [27,28].

All the data above indicate that a good packing of aggregate materials, the mixing method used (which can cause air to become trapped in the mix) and even the consolidation of the mix should be taken into consideration as factors that can affect the chemical resistance of PC because a more or less porous material may result depending on how these factors are controlled.

To make comparisons with the results of this study possible, flexural strength values were measured in isophtalic and orthophtalic polyester without aggregate or filler, and without exposure to chemical attack (reference or standard sample). All procedures of the chemical attack tests used in PC were followed with the samples of isophtalic and orthophtalic polyester without aggregate or filler. The samples were exposed to acetic and sulfuric acids as well as a cola soft drink and water.

The results in Table 6 show a small reduction in strength in all samples that may be due to the solution of small resin molecules. An analysis of these results and a comparison with data published by other authors who investigated this area indicates that the loss of strength in PC is associated mainly to attack in the interface, one of the major mechanisms of degradation of the mechanical properties of fiber-added polyester composites when in contact with aggressive environments [15]. In addition, microstructural SEM analysis shows that the mixtures with 8% fly ash have a greater number of voids and a weakening of the resin-aggregate bond when compared with the samples containing 20% fly ash. This can be seen in Figs. 2–4, which show samples with 8% fly ash exposed to acetic and sulfuric acids.

Figs. 2–4 show images of concrete with 8% fly ash, where the weakening of the bond between the polymer matrix and the aggregate is clearly visible.

3.2.2. Statistical analysis

The response in the chemical attack test is the measurement of flexural strength. The test of flexural strength was selected for statistical analysis because its results showed considerable variation in relation to the reference sample (flexural strength of PC not exposed to chemical agents). The individual values that are listed in Table 3 (flexural strength values of TS after chemical attack by one of seven different chemical agents) were used for statistical analysis. The analysis aims to check for the individual effect of the concentration of fly ash, the type of resin and the type of

Table 6
Flexural strength of isophtalic and orthophtalic polyester after chemical attack

Resin – solution	Flexural strength (MPa)			Mean	% Strength loss
Isophtalic – reference	26.29	23.73	24.83	24.95	–
Orthophtalic – reference	17.01	16.73	17.94	17.23	–
Isophtalic – acetic acid	25.37	24.02	23.32	24.24	2.9
Orthophtalic – acetic acid	17.56	15.06	16.63	16.41	4.7
Isophtalic – sulfuric acid	24.26	23.06	25.44	24.25	2.8
Orthophtalic – sulfuric acid	17.16	15.17	16.05	16.13	6.4
Isophtalic – cola soft drink	23.09	24.53	22.97	23.89	4.2
Orthophtalic – cola soft drink	16.27	17.99	16.10	16.79	2.6
Isophtalic – distilled water.	26.01	23.05	22.09	23.71	4.9
Orthophtalic – distilled drink	16.74	17.28	16.02	16.68	3.2

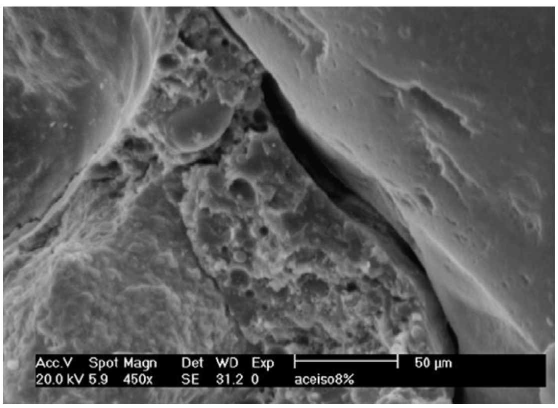

Fig. 2. SEM image, 450× magnification, isophtalic PC with 8% ash in acetic acid.

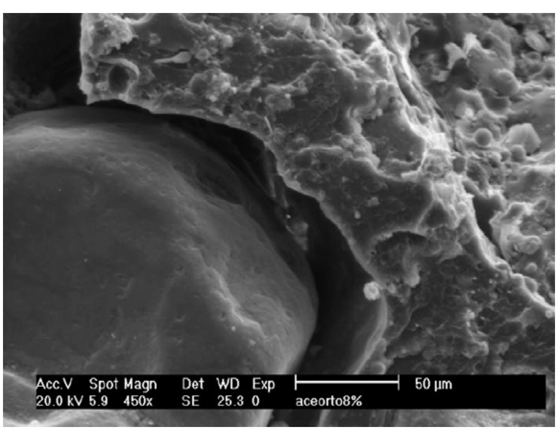

Fig. 3. SEM image, 450× magnification, orthophtalic PC with 8% ash in acetic acid.

solution as well as any interactions between type of resin and type of solution, type of solution and concentration of fly ash, type of resin and concentration of fly ash and a combination of these three factors. The results of this analysis are summarized in Table 7. Tables 8 and 9 show the homogeneous subgroups generated by a multiple comparison of mean values of the type of aggressive solution and of the concentration of fly ash, respectively, in the composition of PC.

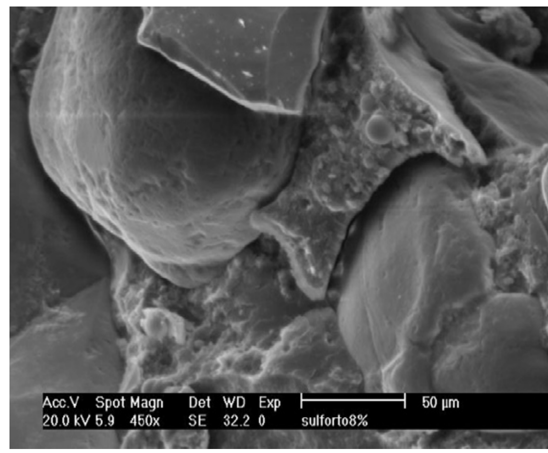

Fig. 4. SEM image, 450× magnification, orthophtalic PC with 8% ash in sulfuric acid.

The statistical analysis (ANOVA) results shown in Table 7 clearly indicate that the following individual factors have a significant effect on the flexural strength of PC after chemical attack: type of resin, type of aggressive solution, concentration of fly ash in the composition of concrete.

The data in Table 7 also show that the factors type of resin and type of solution, the factors type of resin and concentration of fly ash and the factors type of solution and concentration of fly ash, in combination, have a significant effect n the flexural strength of the test specimens after chemical attack.

Tables 8 and 9 were also a result of the multiple comparison of mean values through statistical analysis. The data in Table 8 shows that the flexural strength in the samples exposed to acetic acid 5% was considerably different from the results for all other solutions. The difference in strength values for the samples exposed to distilled water, formic acid, lactic acid and citric acid was not significant. These samples showed a significant difference in strength when compared to the other samples. The samples exposed to a cola soft drink and to sulfuric acid showed no significant difference when compared to one another but the difference was significant when compared to the other 5 solutions. In all cases, there was a significant difference between the

Table 7
Analysis of variance for the chemical attack test

Source	SQ	GLD	MQ	Fcal
Resin type (A)	78.677	1	78.677	113.634[a]
Solution (B)	458.224	7	65.461	94.546[a]
Fly ash concentration (C)	819.032	3	273.011	394.314[a]
Interaction AB	110.959	7	15.851	22.894[a]
Interaction AC	15.971	3	5.324	7.689[a]
Interaction BC	119.256	21	5.679	8.202[a]
Interaction ABC	94.753	21	4.512	6.517[a]
Error	65.775	95	0.692	
Total	1762.647	158		

SQ = Squared sum; GLD = Degrees of Freedom; MQ = Squared mean = SQ/GDL; F = MQ/MQ Error.
[a] Indicates a significant difference in the mean of the response variable in the chemical attack test.

Table 8
Homogeneous subgroups of flexural strength of samples after chemical attack in different solutions

Solutions	*N*	Subgroups			
		1	2	3	4
Acetic acid	22	14.3591			
Distilled water	17		15.2941		
Formic acid	20		15.3975		
Lactic acid	17		15.7035		
Citric acid	20		15.7080		
Coca-Cola®	20			16.7790	
Sulfuric acid	23			17.1635	
Reference	20				20.3045

N = number of samples.

Table 9
Homogeneous subgroups in relation of the concentration of fly ash for the chemical attack tests

Fly ash concentration (%)	*N*	Subgroups			
		1	2	3	4
8	35	12.2951			
12	41		15.9746		
16	42			17.7850	
20	41				18.7595

N = number of samples.

samples exposed to the aggressive agents when compared with the reference samples (no exposure).

Table 9 shows a significant difference in flexural strength for the test specimens that were exposed to a chemical agent for all concentrations of fly ash used. It can be observed that no other property investigated in this study showed a significant difference in all concentrations of fly ash. This attests that the concentration of fly ash affects the strength of PC.

4. Conclusion

The present study aimed to investigate the influence of the type of resin and the concentration of fly ash on the strength of polymer concrete. This was done by means of a chemical test in samples of polymer concrete exposed to six different aggressive agents (plus distilled water) commonly found in industrial environments. The following conclusions refer to the data generated in the present study and are valid for the materials, methods and compositions studied here.

- The values of flexural strength were quite high for both isophtalic polyester PC (18–23 MPa) and orthophtalic polyester PC (18–20 MPa) when compared with the typical values of high-strength cement concrete.
- The values of flexural strength in the samples with 8% fly ash were considerably lower than the values found in the other compositions.
- Unlike what is observed in Portland cement compounds, there was no weight loss nor visible surface changes after chemical attack in PC.
- There was a loss of flexural strength in the samples of PC exposed to aggressive solutions. The compositions of orthophtalic polyester PC with the lowest concentrations of fly ash showed the lowest resistance to chemical agents. The loss of strength was lower in both isophtalic and orthophtalic polyester PC for higher concentrations of fly ash.
- The study revealed that the different degree of strength loss is possibly related with the number of pores of PC compounds, i.e., as the concentration of fly ash increased, the PC composition showed better "packing", which slowed the diffusion of aggressive agents. This was evident in the SEM analysis, where it was seen that the compositions with 8% fly ash (higher porosity) suffered more intense chemical attack because the aggressive solutions penetrated through the pore network more easily and reached the binder–aggregate interface.
- Statistical analysis showed that the factors type of resin, concentration of fly ash, type of solution and interaction between these factors significantly affected flexural strength results of all samples exposed to chemical attack.

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