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Cost efficiency and resistance to chemical attack of a fly ash geopolymeric mortar versus epoxy resin and acrylic paint coatings

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This article presents results of an experimental investigation on the resistance to chemical attack (with sulphuric, hydrochloric and nitric acid) of several materials: OPC concrete, high-performance concrete, epoxy resin, acrylic painting and a fly ash-based geopolymeric mortar). Three types of acids with three high concentrations (10, 20 and 30%) were used to simulate long-term degradation. A cost analysis was also performed. The results show that the epoxy resin has the best resistance to chemical attack independently of the acid type and the acid concentration. However, the cost analysis shows that the epoxy resin-based solution is the least cost-efficient solution being 70% above the cost efficiency of the fly ash-based geopolymeric mortar.

Keywords: concrete infrastructures; Portland cement; geopolymers; coatings; acid attack

1. Introduction

Premature degradation of OPC concrete infrastructures is a current and serious problem related to the fact that OPC concrete presents a higher permeability that allows water and other aggressive elements to enter, leading to carbonation and chloride ion attack resulting in corrosion problems (Glasser, Marchand, & Samson, 2008).

Pacheco-Torgal, Gomes, and Jalali (2008a) mentioned the case of a tunnel in Dubai, which has been concluded in 1975 and needed to be completely repaired just after 11 years, a case of pile foundations disintegrated just after 12 years, and also a study on Norway OPC concrete bridges which indicate that several presented corrosion problems 24 years after they were built. As a consequence, worldwide concrete infrastructure rehabilitation costs are staggering. For example, in the USA, the needs are estimated to be over 1.6 trillion dollars over the next 5 years, where about 27% of all highway bridges are in need of repair or replacement, and the corrosion deterioration cost due to deicing and sea salt effects are estimated at over 150 billion dollars. In the European Union, nearly 84,000 reinforced and prestressed concrete bridges require maintenance, repair and strengthening with an annual budget of £215M, and that estimate does not include traffic management cost (Pacheco-Torgal, Abdollahnejad, Miraldo, Baklouti, & Ding, 2012).

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Many of the degraded concrete structures were built decades ago when little attention was given to durability issues. Concrete durability means above all minimising the possibility of aggressive elements to enter the concrete, under certain environmental conditions for any of the following transport mechanisms: permeability, diffusion or capillarity. The use of concrete surface treatments with waterproofing materials (also known as sealers) to prevent the access of aggressive substances is an important way of contributing to concrete durability. Almusallam, Khan, Dulaijan, and Al-Amoudi (2003) studied several concrete coatings concluding that epoxy and polyurethane coatings performed better than acrylic, polymer and chlorinated rubber coatings.

Other authors (Aguiar, Camões, & Moreira, 2008; Moreira, 2006) showed that although some waterproof materials are effective for a particular transport mechanism (diffusion, capillarity, permeability), but cannot be for another. They compared the waterproofing capacity of concrete with three polymeric resins (epoxy, silicone, acrylic) and mentioned that the silicone based is more effective (99.2%) in reducing water absorption by capillarity than the epoxy resin (93.6%), but in terms of chloride diffusion the epoxy resin is 100% effective, while the silicone varnish does not go beyond 67.5%. Epoxy coatings exhibited excellent durability under the laboratory and field test conditions and are recommended for protecting concrete in cooling tower basins against sulphur-oxidising or other acid-producing bacteria (Berndt, 2011).

Medeiros and Helene (2008) used a water-repellent material based on silane-siloxane noticing that although it is effective to reduce the water absorption by capillarity of concrete (reduced from 2 to 7 times), it only managed to achieve a reduction of the chloride diffusion from 11 to 17% and also failed to prevent the access of water by permeability.

Pacheco-Torgal and Jalali (2009) confirm that the surface treatment of concrete with a water-repellent material is effective, but above all more cost effective when compared with the alternative of using a polymer additive in the composition of concrete.

Recently, Brenna, Bolzoni, Beretta, and Ormellese (2013) studied the efficiency of four commercial concrete coatings (a polymer-modified cementitious mortar and three elastomeric coatings) against chloride-induced corrosion concluding that the polymer containing mortar shows the best effect on delay chlorides penetration in concrete. In summary, the most common surface treatments use polymeric resins based on epoxy, silicone (siloxane), acrylics, chlorinated rubber, polyurethanes or polymethacrylate.

Bijen (2000) mentioned that the epoxy resins have low resistance to ultraviolet radiation and polyurethanes are sensitive to high alkalinity environments. Polyurethane is obtained from the isocyanates, known worldwide for its tragic association with the Bhopal disaster. As for chlorinated rubber, it is derived from reacting butyl rubber with chlorine and it is important to remember that chlorine is associated with the production of dioxins and furans that are extremely toxic and also biocumulative. Several scientist groups already suggest that chlorine industrial-based products should be prohibited (Pacheco Torgal & Jalali, 2011).

Besides, recently, the European Union recently approved the Regulation (EU) 305/2011 related to the Construction Products Regulation (CPR) that will replace the current Directive 89/106/CEE, already amended by Directive 1993/68/EEC, known as the Construction Products Directive (CPD). A crucial aspect of the new regulation relates to the information regarding hazardous substances (Pacheco-Torgal, Jalali, & Fucic, 2012).

Recent investigations on the geopolymer field (Pacheco-Torgal, Gomes, & Jalali, 2008b) reveal a third category of mortars with high potential to enhance the durability

of concrete structures. Investigations in the field of geopolymers had an exponential increase after the research results of Davidovits (1979), who developed and patented binders obtained from the alkali activation of metakaolin, having named it after the term “geopolymer” in 1978. The technology of alkali activation however predates this terminology by several decades (Pacheco-Torgal, Labrincha, Leonelli, Palomo, & Chindapasirt, 2014).

For the chemical designation of the geopolymer, Davidovits suggested the name “polysialates” in which Sialate is an abbreviation for aluminosilicate oxide. The sialate network is composed of tetrahedral anions $[\text{SiO}_4]^{4-}$ and $[\text{AlO}_4]^{5-}$, sharing the oxygen, which need positive ions such as (Na^+ , K^+ , Li^+ , Ca^{++} , Na^+ , Ba^{++} , NH_4^+ , H_3O^+) to compensate the electric charge of Al^{3+} in tetrahedral coordination (after dehydroxilation, the aluminium changes from coordination six (octahedral) to coordination four (tetrahedral)). However, Provis and Van Deventer (2009) mentioned that the sialate nomenclature “implies certain aspects of the geopolymer gel structure which do not correspond to reality”.

Provis (2014) has recently presented a rigorous and useful definition of these materials:

alkali-activated materials are produced through the reaction of an aluminosilicate – normally supplied in powder form as an industrial by-product or other inexpensive material – with an alkaline activator, which is usually a concentrated aqueous solution of alkali hydroxide, silicate, carbonate or sulfate.

Over the last years, several authors have reported research in a large number of aspects related to geopolymers.

However, very few studies (Papakonstantinou & Balaguru, 2007; Zhang, Yao, & Zhu, 2010a, 2010b) have addressed the use of geopolymers for enhancement of concrete structures durability. Since geopolymer performance concerning the resistance to acid attack is far better than that of Portland cement (Pacheco-Torgal et al., 2014), this means that these materials could be an alternative low toxicity, coating material.

This paper presents results of an experimental investigation on the resistance to chemical attack (with sulphuric, hydrochloric and nitric acid) of several materials: OPC concrete, high-performance concrete (HPC), epoxy resin, acrylic painting and a fly ash-based geopolymeric mortar.

2. Experimental work

2.1. Materials, mix design, mortar and concrete mixing and concrete coating

The characteristics of the aggregates (coarse and sand) used are shown in Table 1 and in Figure 1. The fly ash used in the geopolymeric mortars was supplied by Sines-EDP and according to the NP EN 450-1, it belongs to B class and has an N-class fineness modulus. Geopolymeric mortars were a mixture of aggregates, fly ash, calcium

Table 1. Characteristics of the aggregates.

| | Max dimension | Fine content | Density (kg/m^3) | Water absorption |
|-------------------|---------------|--------------|-----------------------------|------------------|
| Sand | 4.0 | ≤ 3 | 2660 | .2 |
| Coarse aggregates | 8.0 | ≤ 1.5 | 2620 | .6 |

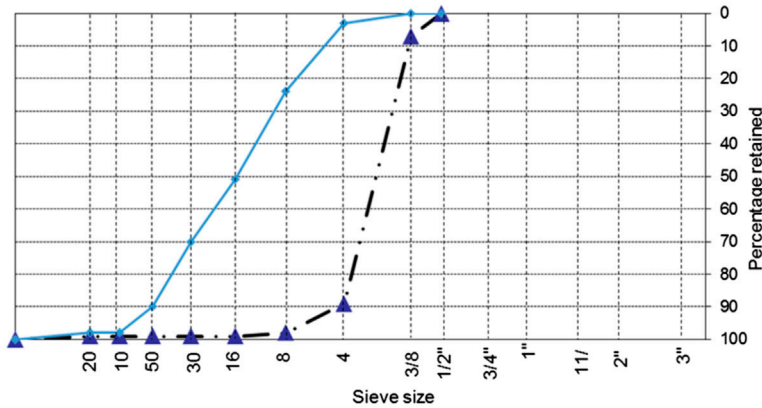


Figure 1. Aggregate particle size distribution of the sand and the coarse aggregate.

hydroxide and alkaline silicate solution. The mass ratio for aggregates/fly ash and activator was 2/1/6. A 10% percentage substitution of fly ash by calcium hydroxide in the mixture was also used. This is because, the use of minor calcium hydroxide percentages is pivotal for the strength and durability of geopolymers (Van Deventer, Provis, & Duxson, 2012; Yip, Lukey, & Deventer, 2005). The alkaline activator was prepared prior to use. An activator with sodium hydroxide and sodium silicate solution ($\text{Na}_2\text{O} = 13.5\%$, $\text{SiO}_2 = 58.7\%$, and water = 45.2%) was used with a mass ratio of 1:2.5. Previous investigations showed that this ratio lead to the highest compressive strength results in geopolymeric mortars (Pacheco-Torgal et al., 2008b). The sand, fly ash and calcium hydroxide were dry mixed before being added to the activator. Three different sodium hydroxide concentrations (10, 14, 18 M) were used. The fresh mortar was cast and allowed to set at room temperature for 24 h before being removed from the moulds and kept at room temperature (20 °C) until tested in compression and flexural strength. An ordinary Portland cement (CEM I 42.5 N) was used to prepare the concrete mixtures. Two concrete mixes (normal and HPC) were designed using the Faury concrete mix design method (Table 2). The concrete mixing starts with the introduction of the coarse aggregates in the mixer, followed by the sand during two minutes, then OPC is introduced and mixed to the aggregates during two more minutes. Then, 70% of the water is introduced in the mixer and all the ingredients are mixed during two minutes. Finally, the remaining water is added during two minutes and all are mixed during two more minutes. The concrete specimens were conditioned at a temperature equal to 21 ± 2 °C cured in a moist chamber until they have reached 28 days. An epoxy resin often used as concrete coating protection against acid attack with a commercial reference Sikagard 62 PT was used for coating of the two concrete mixtures. The epoxy adhesive is a two-component system (resin and hardener) with a bulk density

Table 2. Concrete mix proportions per cubic metre of concrete.

| | Cement (kg) | Sand (kg) | Coarse aggregates (kg) | Water | W/C |
|-----|-------------|-----------|------------------------|-------|-----|
| NC | 270 | 1135 | 732 | 182 | .65 |
| BED | 442 | 876 | 782 | 205 | .45 |

of 1.35 kg/dm^3 . After mixing, the two components, the mixtures remain workable during 20 min at 20°C or just a 0 min at 30°C . An acrylic paint often used as concrete coating protection to prevent the access of aggressive substances with a commercial reference Sikagard – 660 ES was also used for coating of the two concrete mixtures. This material has a bulk density of 1.30 kg/dm^3 and is provided by the manufacturer as ready to be used.

3. Experimental procedures

3.1. Compressive strength

The compressive strength was performed under NP EN 206-1. Tests were performed on $100 \times 100 \times 100 \text{ mm}^3$ concrete specimens. The compressive and flexural strength data of geopolymeric mortars were obtained using $160 \times 40 \times 40 \text{ mm}^3$ cubic specimens according to EN 1015-11. Compressive strength for each mixture was obtained from an average of 3 cubic specimens determined at the age of 28 days of curing.

3.2. Water absorption by immersion

Tests were performed on $40 \times 400 \times 80 \text{ mm}^3$ specimens. Specimens were tested with 28 days curing. The specimens were immersed in water at room temperature for 24 h. First, the weight of the specimens while suspended by a thin wire and completely submerged in water is recorded as W_{im} (immersed weight). After that, the specimens were removed from water and placed for 1 min on a wire mesh allowing water to drain, then visible surface water is removed with a damp cloth and weight is recorded as W_{sat} (saturated weight). All specimens were placed in a ventilated oven at 105°C for not less than 24 h and allowing that two successive weightings at intervals of 2 h show an increment of loss not greater than .1% of the last previously determined weight of the specimen. The weight of the dried specimens is recorded as W_{dry} (oven-dry weight). Absorption coefficient is determined as following equation:

$$A(\%) = \frac{W_{sat} - W_{dry}}{W_{sat} - W_{im}} \times 100 \quad (1)$$

3.3. Capillary water absorption

Capillary water absorption was carried out using $40 \times 400 \times 80 \text{ mm}^3$ specimens in the case of geopolymeric mortars and $100 \times 100 \times 100 \text{ mm}^3$ specimens for concrete. After 28 days in a moist chamber, the specimens were placed in an oven 105°C for 24 h. The test consists in placing the specimens in a container with enough water to maintain the immersion of one of the sides of the sample. This test is carried out according to Standard LNEC E393. Water absorption has been measured after 5, 10, 20, 30, 60, 90, 120, 180, 240, 300, 360, 420, 480 min. Capillarity water absorption was obtained from an average of three specimens.

3.4. Resistance to chemical attack

The resistance to chemical attack followed a variation of the ASTM C-267 (Standard test methods for chemical resistance of mortars, grouts, and monolithic surfacing's and polymer concretes).

The test used in the present investigation consists in the immersion of $100 \times 100 \times 100 \text{ mm}^3$ concrete (NC, HPC, coated concrete specimens) and fly ash geopolymeric mortar specimens with 28 days curing in acid solution during 28 days. Three different acids were used (sulphuric, hydrochloric and nitric). Three acid concentrations were used (10, 20 and 30%) to simulate long-time exposure at lower concentrations. Other authors used 5% Na_2SO_4 concentrations and immersion during 12 months (Bakharev, Sanjayan, & Cheng, 2002). The resistance to acid attack was assessed by the differences in weight of dry specimens before and after acid attack at 1, 7, 14, 28 and 56 days. The chemical resistance was assessed by the differences in weight of dry specimens before and after acid attack, since compressive strength of specimens immersed in acid media could not be evaluated. The fly ash-based geopolymeric mortar used in the resistance to acid attack was the one associated with the highest compressive strength and low water absorption.

4. Results and discussion

4.1. Compressive strength

Figure 2 shows the results of the compressive strength of the fly ash-based geopolymeric mortars after 28 days curing as well as of the two concrete mixtures. The results show that the compressive strength of geopolymeric mortars is very dependent on the molarity of the sodium hydroxide. Increasing the molarity from 10 to 14 M leads to a relevant compressive strength loss. However, further increase from 14 to 18 M shows no noticeable effects. Previous investigations (Lee & van Deventer, 2002) have shown that although a high alkali content favours the dissolution of Al and Si species of fly ash, but can also negatively affect its strength. Pacheco-Torgal, Gomes, and Jalali (2008c) that studied the geopolymerisation of mine wastes noticed the opposite phenomenon. Other authors (Somna, Jaturapitakkul, Kajitvichyanukul, & Chindaprasirt, 2011) mentioned that when OH^- concentration was high enough, dissolution of fly ash was accelerated but polycondensation was hindered. Normal concrete (NC) has a compressive strength around 30 MPa, while HPC compressive strength slightly exceeds

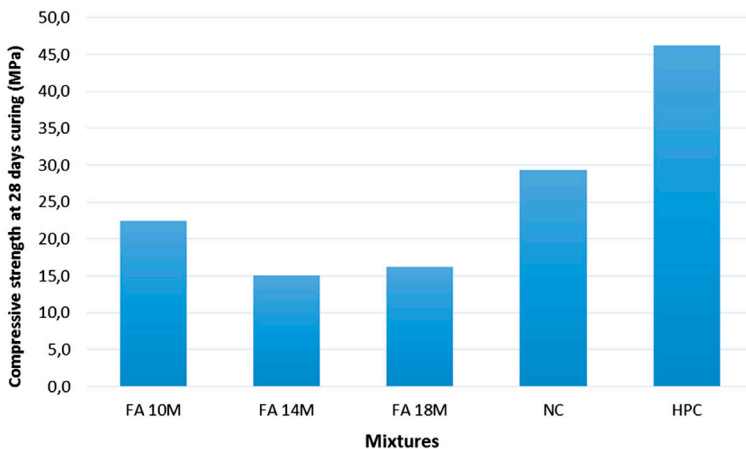


Figure 2. Compressive strength.

45 MPa. The standard deviation was low and the coefficient of variation does not exceed 12% meaning that the results were statistically relevant.

4.2. Water absorption by immersion

The results of water absorption by immersion are shown in Figure 3. These results are aligned with compressive strength performance. The fly ash geopolymeric mortar with the least water absorption by immersion is the one with the highest compressive strength. The geopolymeric mortars with a sodium hydroxide molarity of 14 and 18 M show a water absorption around 20%. This means that compressive strength is directly influenced by open porosity. However, previous investigations (Granizo, Blanco-Varela, & Martínez-Ramírez, 2007) on the field of geopolymers showed that low porosity does not always mean high compressive strength; being that compressive strength is more influenced by NaOH concentration than it is from porosity. Both NC and HPC show a water absorption around 15%. This falls in the current water absorption by immersion range of current OPC concretes used by construction industry (compressive strength at 28 days curing between 25 and 45 MPa), of 12 to 16%.

4.3. Capillary water absorption

Figure 4 shows the capillary water absorption coefficients. While the fly ash geopolymeric mortars with a sodium hydroxide molarity of 14 and 18 M show a capillary water absorption around $.45 \text{ kg/m}^2 \text{ h}^{-5}$, the geopolymeric mortar with the lowest open porosity and the highest compressive strength has a $.1 \text{ kg/m}^2 \text{ h}^{-5}$ capillary water absorption coefficient. The capillary water absorption of the two concrete mixes used in this investigation is very low around $.15 \text{ kg/m}^2 \text{ h}^{-5}$. As a comparison, a plain C30/37 strength class concrete has a capillary coefficient of $.251 \text{ kg/m}^2 \text{ h}^{-5}$ for 28 days curing (Ferreira, 2000), while a plain C20/25 strength class concrete (the most used strength class in Europe (ERMCO, 2014)) has capillary coefficients between $.85$ and $2.6 \text{ kg/m}^2 \text{ h}^{-5}$ (Pacheco-Torgal & Castro-Gomes, 2006).

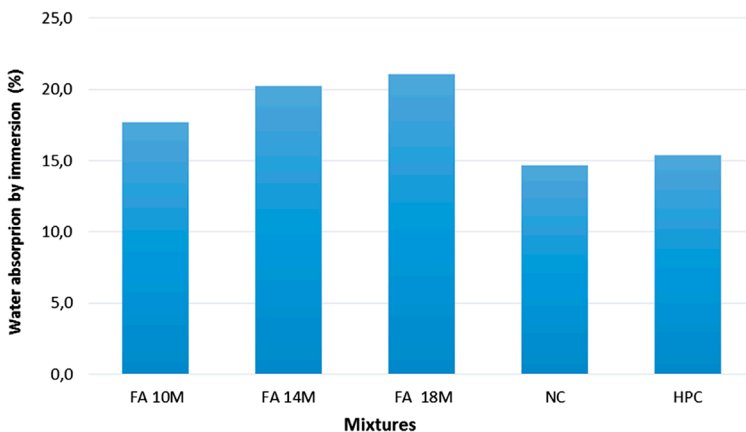


Figure 3. Water absorption by immersion.

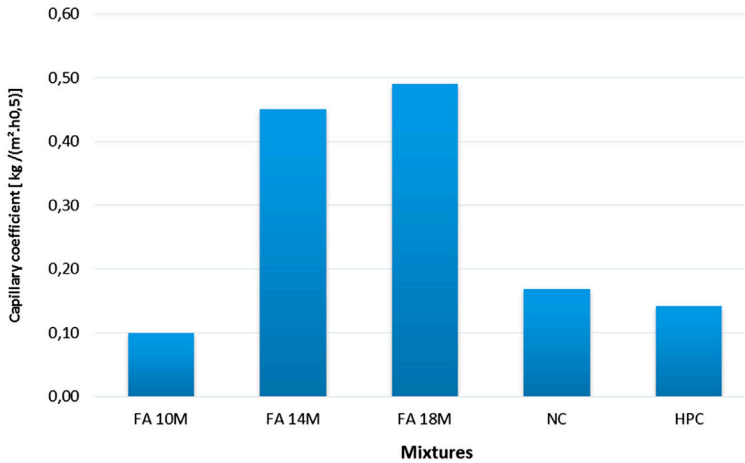
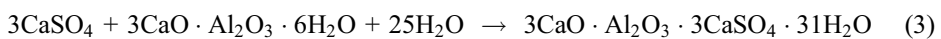
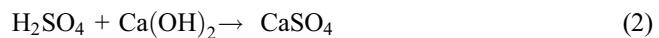


Figure 4. Water absorption capillary coefficients.

4.4. Resistance to chemical attack

4.4.1. Resistance to sulphuric acid attack

Figure 5 shows the weight loss after sulphuric acid attack for the different acid concentrations. NC coated with epoxy resin shows the most stable performance for all three acid concentrations conforming previous investigations. The fly ash geopolymeric mortar shows a good performance for both 10 and 20% sulphuric acid concentration. Figure 6 shows photos of the different specimens after immersion on a 20% sulphuric acid concentration. Even for a 30% sulphuric acid concentration, this mortar shows a good acid resistance for immersion until 14 days. HPC specimens show the third best performance. It shows a minor weight loss after 56 days in a 10% sulphuric acid concentration. For a 20% sulphuric acid concentration, the weight loss is clear beyond 14 days reaching a maximum of 9%. When the concentration increases to 30%, the weight loss starts after 7 days immersion and reaches a maximum of 20% after 56 days. Specimens of NC coated with acrylic paint show the same performance of uncoated concrete specimens for both 10 and 20% sulphuric acid concentrations. Only for the 30% acid concentration and long-time immersion can this coat be of some use. Since NC and HPC have almost similar capillary water absorption, then the differences in acid resistance lie in the leaching of calcium hydroxide ($\text{Ca}(\text{OH})_2$) from the pore solution and decalcification of CSH that must be lower in the latter case due to a much higher Portland cement content. In sulphuric acid attack, sulphate ions react with calcium hydroxide forming calcium sulphate dihydrate gypsum (2) and with aluminate hydrates forming ettringite (3).



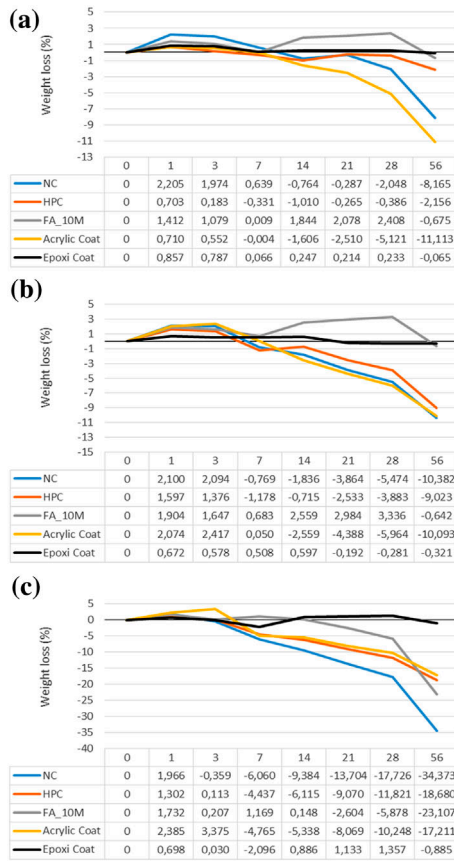


Figure 5. Weight loss due to sulphuric acid attack: (a) 10% acid concentration; (b) 20% acid concentration; (c) 30% acid concentration.

4.4.2. Resistance to nitric acid attack

Weight loss after nitric acid attack is shown in Figure 7. Again NC coated with epoxy resin shows the most stable performance for all three acid concentrations. Nitric acid attack at 10% concentrations is especially destructive for NC even after just 7 days immersion. Nitric acid reacts with calcium compounds forming calcium nitrate which has a solubility (56%). All the other mixtures show a weight loss not exceeding 2% even after 56 days immersion. The behaviour for a 20% nitric acid concentration is almost the same. The difference being that NC shows a higher weight loss. When the acid concentration is increased to 30%, NC does not show an increase in the weight loss. For this very high acid concentration, the geopolymeric mortar shows a disappointing performance. Allahverdi and Škvára (2001a, 2001b) suggested that the electrophilic attack of nitric acid protons results in the ejection of tetrahedral aluminium from the aluminosilicate framework and in the formation of an imperfect highly siliceous framework. Other authors (Fernandez-Jimenez, García-Lodeiro, & Palomo, 2007) also suggested this aluminosilicate depolymerisation.

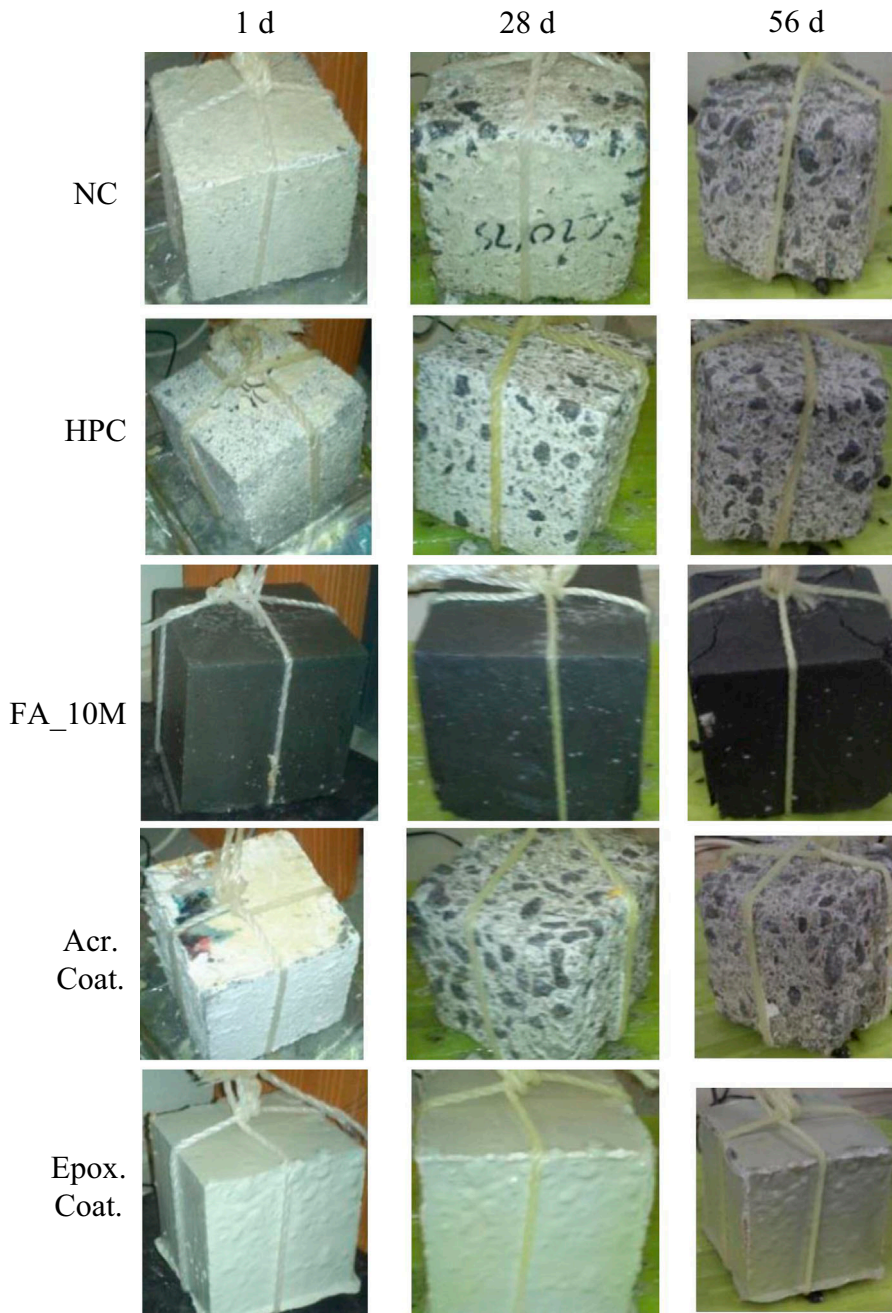


Figure 6. Specimens after immersion in a 20% sulphuric acid solution.

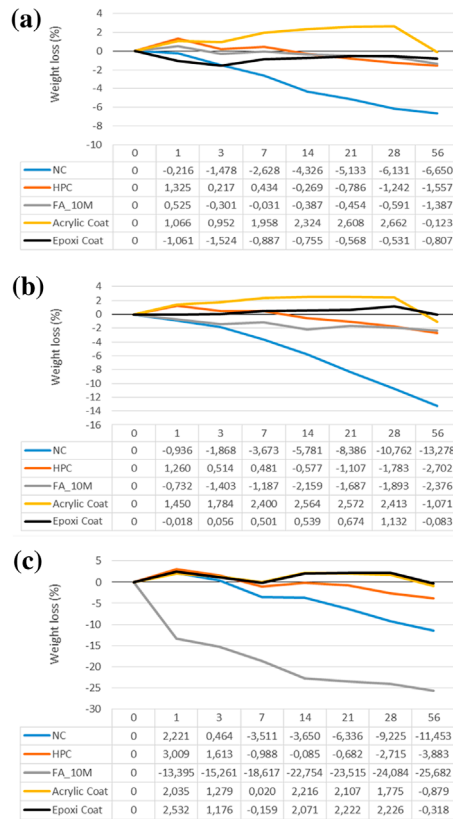


Figure 7. Weight loss due to nitric acid attack: (a)10% acid concentration; (b) 20% acid concentration; (c) 30% acid concentration.

4.4.3. Resistance to hydrochloric acid attack

Figure 8 shows the weight loss after hydrochloric acid attack for the different acid concentrations. The results are very similar to the ones of nitric acid attack. A 10% hydrochloric acid concentrations is responsible for a relevant NC weight loss even after just 7 days immersion. This type of acid reacts with calcium compounds leading to the formation of calcium chloride which has extremely high solubility (46.1 wt. %) (Zivica & Bazja, 2001). The behaviour for a 20% nitric acid concentration is almost the same. The difference being that NC shows a higher weight loss. All the other mixtures show a weight loss not exceeding 2% even after 56 days immersion. When the hydrochloric acid concentration is increased to 30%, NC does not show a relevant increase in the weight loss. However, the geopolymeric mortar shows a high weight loss. Davidovits, Comrie, Paterson, and Ritcey (1990) reported a 78% weight loss for OPC concrete specimens immersed during 4 weeks in a 5% hydrochloric acid solution which is much higher than the weight loss of NC after immersion during 56 days in a 30% hydrochloric acid solution which was lower than 10%. This difference is so high that it cannot be explained in specimen's geometry or OPC concrete composition. A possible explanation could be related to the periodic replacement of the acid solution by Davidovits study. Just because pH is raising with time, for instance, a solution of sulphuric acid at 5% concentration evolves from a pH = 1.05 to 6.95 after 28 days (Roy, Arjunan, & Silsbee, 2001).

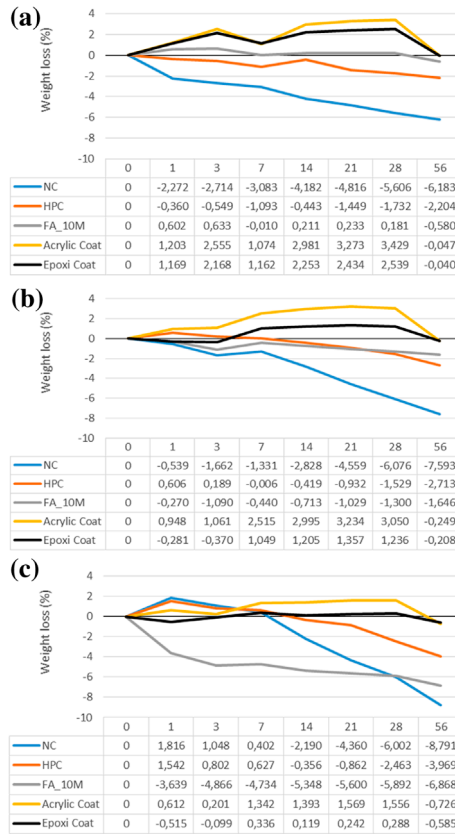


Figure 8. Weight loss due to hydrochloric acid attack: (a) 10% acid concentration; (b) 20% acid concentration; (c) 30% acid concentration.

5. Cost analysis

In order to evaluate the economic efficiency of several structural solutions, comparisons between the costs of materials were made. The cost calculations were related to 1 m² of concrete pavement with .3-m thickness. Two non-coated solutions (NC, HPC), one with .275-m NC thickness coated with .025-m fly ash geopolymer and other coated with acrylic paint and epoxy resin were analysed. Figure 9 shows the costs of the different solutions. The concrete pavement coated by epoxy resin is by far the most costly solution. Epoxy coating costs exceed the NC solution costs by as much as 100%. Figure 10 shows the cost to remaining mass (after acid attack) ratio according to acid concentration. The results show that for 10 and even 20% acid concentrations, NC shows the best cost efficiency. The cost efficiency of HPC-based solution is similar to the fly ash-based geopolymeric mortar except for a 30% acid concentration. The results also show that no matter how well epoxy resin performs under acid attack, its economic efficiency is the worst between all the 5 solutions being 70% above the cost efficiency of the fly ash-based geopolymeric mortar. Only for a 30% acid concentration, the epoxy-based solution is gaining some interest. It is important to remember that the cost of the fly ash-based geopolymeric mortar is very dependent on the cost of sodium silicate (Figure 11). Figure 12 shows a simulation of the cost to remaining mass (after acid

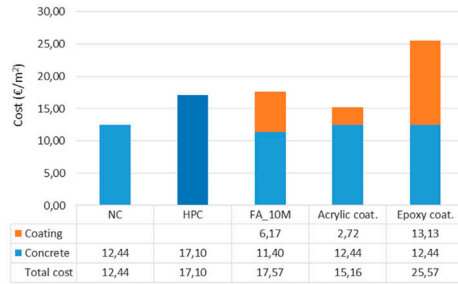


Figure 9. Costs of the different concrete pavement solutions.

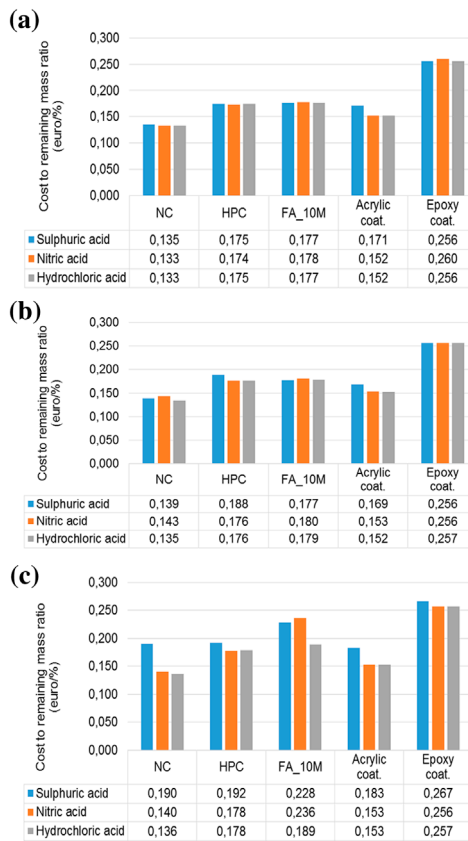


Figure 10. Cost to remaining mass ratio (euro/%) : (a)10% acid concentration; (b) 20% acid concentration; (c) 30% acid concentration.

attack) ratio according to acid concentration when sodium silicate cost is around 30% of its current cost. This means that current investigations aiming to replace sodium silicate by low-cost waste glass (Puertas, Torres-Carrasco, & Alonso, 2014) will increase the cost efficiency of the fly ash-based geopolymeric mortar as coating material of OPC

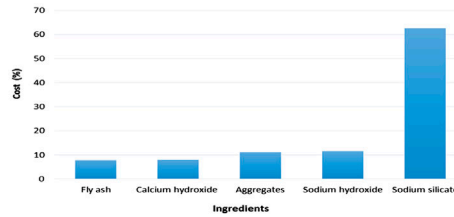


Figure 11. Cost percentage of fly ash geopolymeric mortar ingredients.

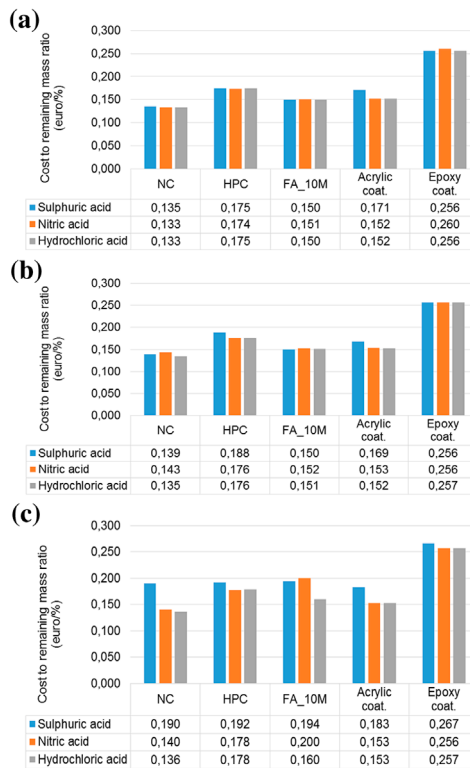


Figure 12. Cost to remaining mass ratio (euro/%) for a low-cost waste glass sodium silicate replacement simulation: (a) 10% acid concentration; (b) 20% acid concentration; (c) 30% acid concentration.

concrete infrastructures exposed to harsh chemical environments. Furthermore, the future use of waste glass as sodium silicate replacement fits the European zero waste program COM 398 (2014).

6. Conclusions

Worldwide infrastructure rehabilitation costs are staggering. Premature degradation of OPC concrete infrastructures is a current and serious problem related to the fact that OPC concrete presents a higher permeability that allows water and other aggressive

elements to enter, leading to carbonation and chloride ion attack resulting in corrosion problems. This article presents results of an experimental investigation on the resistance to chemical attack of several materials. NC coated with epoxy resin shows the most stable performance for all three acid types and acid concentrations. For a very high nitric acid concentration, the geopolymeric mortar shows a disappointing performance that could be due to the ejection of tetrahedral aluminium from the aluminosilicate framework and in the formation of an imperfect highly siliceous framework. The results show that no matter how well epoxy resin performs under acid attack, its economic efficiency is the worst between all the 5 solutions being 70% above the cost efficiency of the fly ash-based geopolymeric mortar. Current investigations aiming to replace sodium silicate by low-cost waste glass will increase the cost efficiency of the fly ash-based geopolymeric mortar as coating material of OPC concrete infrastructures exposed to harsh chemical environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

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