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Superficial protection of concrete with epoxy resin impregnations: influence of the substrate roughness and moisture

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Abstract One of the possible strategies to protect concrete from aggressive agents consists of applying impregnation products on its surface. This type of strategy is relatively often used in both new and existing structures. However, there are still several aspects concerning impregnation products whose understanding is still rather limited, including the influence of the concrete substrate on their performance. This paper presents an experimental study on the influence of the roughness and the moisture content of concrete substrates in the performance of impregnation products used for superficial protection. For that purpose, two impregnations products based on epoxy resins were applied on concrete specimens with two different water/cement ratios (0.40 and 0.70). The concrete specimens were prepared according to different procedures, which created (i) three different surface roughnesses (no preparation, use of a 160 bar water jet and use of needle scalers) and (ii) three different moisture contents (3, 4.5 and 6 %). The performance of the protection systems was evaluated by means of the following tests suggested in EN 1504-2 standard: (i) product penetration depth; (ii) water absorption by immersion; (iii) abrasion resistance; (iv) impact resistance; and (v) bond strength. With the exception of the resistance to impact, the use of epoxy resins considerably improved the performance of the two types of concrete. Both surface roughness and moisture content proved to have a significant effect on the performance of the epoxy impregnations. However, such influence was different depending on the property at stake and the type of impregnation product.

Keywords Concrete · Surface protection · Impregnation · Epoxy resin · Surface preparation · Roughness · Moisture

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1 Introduction

The protection of concrete structures against aggressive agents is one of the possible intervention strategies, either for new structures or during rehabilitation works on existing constructions, in order to prevent defects that may lead to material degradation and reduction of service life. Such strategies can be implemented by many different ways based on the correspondent commercially available products, including acrylic and other dispersion polymermodified cementitious mortars, waterborne or solvent born epoxy resins, hydrophobic silane based products, organic coatings and many other options [1–7]. Each of the above mentioned protection systems confer a certain level of protection to concrete, depending on the aggressive agents it is subjected to.

The performance of the above mentioned surface treatment products can be evaluated by different test methods. Basheer et al. [6] presented a comprehensive literature review about the most useful techniques to evaluate the performance of surface treatments for concrete, including impregnations products.

In order to establish criteria for the use of such protection systems, EN 1504-2 standard [8] provides guidance on products selection, requirements for material properties and practical procedures for such type of intervention. Concerning surface protection of concrete, one of the procedures defined in the EN 1504-2 standard is the use of impregnation products that reduce the surface porosity, strengthen the surface and fill partially or totally the pores and capillaries usually leading to a discontinuous thin film on the concrete surface. They are also known as pore blockers and usually are of two main types [9, 10]: (i) compounds based on silicates, of which the most commonly used are sodium silicates and also fluorosilicates; and (ii) compounds based on synthetic resins, such as acrylic or epoxy, which harden by chemical reaction or drying inside the pores and capillaries of concrete, creating an appropriate barrier on the surface and preserving the initial alkaline environment of reinforced concrete.

There are several studies available in the literature on the performance of coatings and hydrophobic systems, in terms of both physical and durability properties. However, only a limited number of studies address impregnation systems. Almusallam et al. [2, 5] evaluated the performance of several types of concrete surface coatings under varying exposure conditions. In this research the following parameters were assessed: adhesion to concrete, crack-bridging ability, water absorption by immersion, chloride permeability, chloride diffusion, resistance to sulphuric acid and resistance to thermal variations. The results obtained indicated that epoxy and polyurethane resin coatings presented better overall performance than the remaining types of surface coatings that included acrylic, polymer emulsion, and chlorinated rubber coatings. Ku et al. [11] evaluated the performance of polymethyl-methacrylate (PMMA) resins as impregnations in cement mortars. Results of this study showed improvements in the concrete with the presence of PMMA impregnation, in terms of resistance to bending and compression, ultrasound velocity and several durability properties (water absorption, resistance to hydrochloric acid and sea water, and freeze thaw resistance). De Muynck et al. [12] evaluated the effectiveness of surface treatments and admixtures by means of accelerated chemical exposure and microbiological simulation cyclic tests. The chemical agent used was a 0.5 % acid sulphuric solution (simulating exposure in sewer systems) and the microbial action was simulated through exposure to cultures of sulphur oxidizing bacteria. The best protective performance was obtained with an epoxy coating, in which no degradation of the surface treated concrete was observed.

Although several studies were already performed to assess the ability of different types of surface treatments (only a few concern impregnations) in protecting concrete, there are still many aspects concerning concrete surface protection for which the understanding is still rather limited. Amongst those aspects, the influence of the concrete substrate, namely the type of concrete, its surface preparation and moisture content, is particularly relevant and according to the best of the authors' knowledge, it is still not reported in the literature.

The present work aims at contributing to a deeper understanding on the protection of concrete substrates by impregnation products. The main goals of this work are twofold: (i) to assess the performance of impregnation products based on epoxy resins; and (ii) to study the influence of the substrate condition in their performance, particularly the effects of (ii.1) the type of concrete, (ii.2) the substrate roughness [13] and (ii.3) the substrate moisture content at the moment of product application [14].

2 Materials and methods

2.1 Experimental programme

The experimental programme comprised the production of two concrete compositions, with water/cement (w/c) ratios of 0.40 and 0.70. Two different types of epoxy resins were used as impregnation products: a solvent based epoxy and a water based epoxy. The influence of the concrete substrate preparation was evaluated in terms of three different surface roughnesses (concrete series *R*), obtained by the following procedures: (i) no surface preparation, and surface roughening produced by either (ii) applying a 160 bar water jet or (iii) using a needle scaler. To evaluate the influence of the moisture content, three classes of moisture content were used (concrete series *H*): surface water saturated, and surface dried until two different levels of moisture content were attained. The performance of the impregnation products was assessed by means of the following tests indicated in EN 1504-2 [8]: (i) penetration depth; (ii) water permeability; (iii) abrasion resistance; (iv) impact resistance; and (v) bond strength.

2.2 Materials

Table 1 presents the composition of the two types of concrete produced in the experimental programme, with *w/c* ratios of 0.40 (MC40) and 0.70 (C70) and compositions defined in EN 1766 [15]. The difference in *w/c* ratio for the two different mixes is caused by the low binder content of the second mix. The cement used on both concrete compositions was type I/42.5R.

Concrete slabs with geometry of 300 × 300 × 40 mm^3, cubes with 150 × 150 × 150 mm^3 and cylinders with 300 mm of height and 150 mm of diameter were manufactured according to standard procedures and then cured in a moist chamber at (21 ± 2) °C for 28 days. After the curing period, the cubes and the cylinders were used to determine respectively the compressive strength and the splitting tensile strength—results are presented in Table 1.

The slabs were used for the several tests aiming at assessing the performance of the impregnation products. Several parallelepiped test specimens were produced by cutting the slabs with a diamond blade into different dimensions, according to the test to be performed. In particular, the following concrete specimen geometries were used: geometry A—220 × 70 × 40 mm^3 (water permeability for series *R* and impact resistance); geometry B—110 × 110 × 15 mm^3 (abrasion resistance); geometry C—300 × 150 × 40 mm^3 (bond strength); and geometry D—70 × 50 × 40 mm^3 (water permeability for series *H*). It is worth mentioning that the corners of specimens used in the abrasion resistance tests had to be chamfered, so that they were compatible with the Taber abraser used (c.f. Sect. 2.5.3).

The two-component products used in this study, referred to in the technical sheets as impregnation treatments, were a solvent-based epoxy (product P1) and a water-based epoxy (product P2). Table 2 summarizes the following characteristics of those products, determined by the following identification tests referred in EN 1504-2 [8] and described on the normative documents indicated next: (i) chemical identification by means of Fourier transform infrared spectrophotometer (FTIR); (ii) density, ISO 2811-1 [16]; and (iii) non-volatile matter content, ISO 3251 [17]. Table 2 indicates also the pot life and the total curing period of both impregnation products, according to their technical sheets.

Table 1 Concrete compositions (in kg/m^3) and compressive and tensile strengths at 28 days of age (average ± standard deviation)

Materials	MC40	C70
Limestone coarse aggregate 1 (4–10 mm)	850	600
Limestone coarse aggregate 2 (20 mm)	–	400
Siliceous river sand	900	900
Cement	455	260
Water	182	182
Compressive strength (MPa)	56 ± 2	30 ± 2
Tensile strength (MPa)	4.2 ± 0.4	2.7 ± 0.2

2.3 Surface preparation and characterization

Regarding the type of surface preparation, the test specimens were grouped in the following two series: (i) series *R*, in which specimens exhibited different surface roughnesses, but similar moisture content prior to the application of the impregnation products; and (ii) series *H*, in which specimens had a similar surface roughness (*R*1 as explained in Sect. 2.3.1), but varying moisture content.

2.3.1 Series R (roughness)

The surface of the concrete slabs of series *R* was prepared by using different mechanical processes in order to obtain three roughness conditions: (i) concrete

Table 2 Characteristics of the impregnation products

Characteristic		Product P1	Product P2
Chemical identification	Component A	Solution of aromatic amine/amide	Emulsion of aromatic amine/amide
	Component B	Solution of epoxide polymer (bisphenol A and epichlorohydrin)	Emulsion of epoxide polymer (bisphenol A and epichlorohydrin)
Density, 20 °C (g/cm^3)		0.996	1.074
Non-volatile matter content at 125 °C (%)		62.4	52.0
Pot-life at 20 °C (min)[a]		60	60–90
Total curing period (h)[a]		36	72

[a] Manufacturers' technical sheets

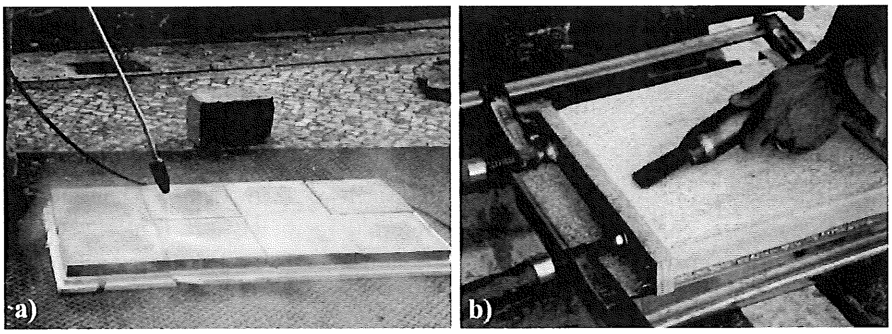


Fig. 1 Surface preparation using **a** water jet with 160 bar and **b** a needle scaler

surface without any preparation, i.e. a slab surface not in contact with the formwork (R0); (ii) concrete surface roughened by using a water jet with 160 bar (*R*1, Fig. 1a); and (iii) concrete surface subjected to a roughness modification by using a needle scaler (*R*2, Fig. 1b).

The surface roughness was evaluated using the following two alternative techniques: (i) surface texture determination, according to ISO 4287 [18], for which plasticine moulds were used to reproduce the surface of the concrete slabs (Fig. 2a); and (ii) roughness index determination by spreading sand, according to EN 1766 [15] (Fig. 2b). For the first method, the determination of the surface texture involved the following procedure: pressing plasticine moulds (4 × 4 cm^2) against the concrete surface; carefully cutting the moulded plasticine with a scalpel, thus producing several cross-sections; digitalizing the cross-sections with a high-precision scanner; and computing (with *BuildingsLife* software) the profiles coordinates and average roughness. For the second method, the following procedure was carried out: positioning 2.5 ml of sand in the centre of the test specimens; carefully spreading the sand with a disc, applying circular movements without pressure; measuring the diameter of the resulting circle.

A moisture content of about 5.0 ± 0.5 % (*H*2) was set for all specimens of series *R*, as suggested in EN 1504-2 [8] and estimated using the calculation procedure described in EN 13,579 [19]. Therefore, after the preparation of the concrete surface, the specimens were conditioned in a laboratory environment (temperature of 21 ± 2 °C and relative humidity of 60 ± 10 %) or placed in an oven at 60 °C, in order to stabilize the moisture content before applying the impregnation products.

2.3.2 Series H (moisture)

As already mentioned, in this series, prior to the application of the impregnation products, the moisture content of the concrete specimens was stabilized into three different levels: very dry (*H*1); water saturated (*H*3); and with an intermediate moisture level (*H*2). The experimental procedures for stabilizing the moisture content of the specimens were based on the

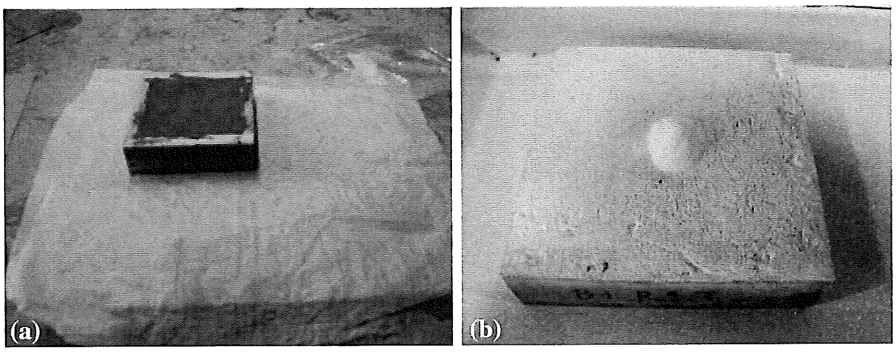


Fig. 2 Surface roughness measurement using two alternative techniques: **a** pressing a plasticine mould against the concrete surface (ISO 4287); **b** spreading sand over the concrete surface (EN 1766)

recommendations of the standard EN 13579 [19], which describes a methodology to obtain a moisture value of 5 % in concrete slabs for testing impregnation products, by drying the slabs in the laboratory environment and comparing their weight with the weight of specimens with the same dimensions dried in an oven at 105 °C until constant mass. That methodology was duly adjusted to the need of increasing the moisture content to that corresponding to a saturated condition (corresponding to a value of 6 % calculated according to EN 13579, *H*3) or decreasing the moisture content by drying in an oven or in the laboratory environment until obtaining a value next to 5 % (*H*2) or even lower (3 %, *H*1). Thereby, specimens with moisture content below the intended value were immersed in water or placed in a humidity chamber until their mass increased up to the target value. In opposition, specimens that needed to dry were placed in an oven at 60 °C or in a conditioned room at (21 ± 2) °C and (60 ± 10) % (depending on the magnitude of the mass decrease envisaged) until their mass matched the target values corresponding to the intended moisture content (the option for a 60 °C temperature instead of ambient temperature was set in order to attain the lower and intermediate target moistures in due time). During this process, the surface moisture content of the specimens was controlled with a *Protimeter* moisture meter. In average, following the procedure indicated in EN 13579 the specimens from *H*1, *H*2 and *H*3 groups had moisture contents of about 3, 4, 5 and 6 %, respectively.

Prior to the moisture content stabilization procedure, the concrete specimens were subjected to a surface preparation by using a water jet with 160 bar, one of the techniques used in series *R* (roughness *R*1).

2.4 Application of impregnation products

After preparing the concrete specimens as described above they were treated with the impregnation products P1 and P2. These products were applied with a brush in the prepared surface of the test specimens, taking into account the quantities recommended by the manufactures technical sheets, 150–250 g/m^2. During application it was noticed that the viscosity of both products was relatively high, thus creating a film at the concrete surfaces.

After applying the impregnation products, all specimens were kept in a conditioned room to ensure their drying in a controlled environment. By observation of the specimens after the drying period it was possible to confirm the presence of a transparent thin film over the concrete surface, characteristic of the impregnation type used—polymer based products.

2.5 Tests to assess the performance of the impregnation products

2.5.1 Product penetration depth

The penetration depth was first evaluated following the description in the test standard EN 1504-2 [8]. According to that standard, the specimens treated with impregnation products were fractured in two halves and the fracture surfaces were sprayed with water. The depth of the dry zone was taken as the effective depth of impregnation of the products (Fig. 3a).

In a second stage, because the above mentioned procedure described in the standard EN 1504-2 [8] proved to be ineffective in evaluating the penetration depth of the impregnation products studied, the

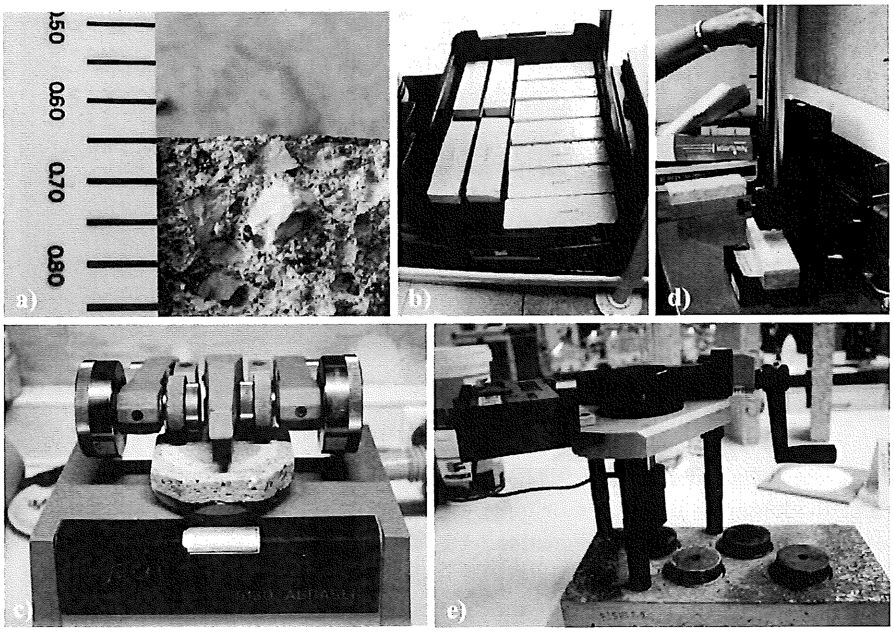


Fig. 3 Tests to assess the performance of the impregnation products: **a** product penetration test; **b** water absorption by capillary test (immersion); **c** abrasion resistance test; **d** impact resistance test; and **e** pull-off test

authors decided to use an alternative test. A small quantity of a red pigment (*KVK Aquadisperse FG–EP*) soluble in water was mixed with the impregnation products, which were then applied based on the manufacturer's specifications, as referred in Sect. 2.4. These tests were performed for specimens of series H, with a moisture content of about 5 %, as specified in EN 13579 [19]. According to EN 1504-2 [8], the penetration depth of the impregnation products applied in concrete C70 should be at least 5 mm.

2.5.2 *Water permeability*

The water permeability test was carried out in accordance with the standard EN 1062-3 [20]. The specimens used in the tests were previously sealed with an epoxy coating in all the faces, except the one in which the product had been applied. The test consisted of immersing in demineralised water the tested surface of the specimens (previously sealed), about 10 mm below the surface of the water. After predefined periods of time (10, 30 min, 1, 2, 3, 6, 24, 30, 48, 72 h and then every 2 days until attaining a saturation tendency, Fig. 3b), the specimens were surface dried with an absorbent cloth and weighed.

The water transmissibility coefficient of the specimens after the first 24 h (w_{24}) was calculated using Eq. (1) and the results obtained for the specimens protected with surface impregnations were compared with those of the non-treated specimens,

$$w_{24} = \frac{\Delta m_{24}}{\sqrt{24} \times A} [\mathrm{kg}/(\mathrm{m}^2 \cdot \mathrm{h}^{0.5})], \tag{1}$$

where Δm_{24} is the mass difference of the specimens between 0 and 24 h of immersion (kg), and A is the specimen area (m^2).

2.5.3 *Abrasion resistance*

The abrasion resistance test was carried out only in specimens from series H according to the experimental procedure described in the standard EN ISO 5470-1 [21]. A Taber abraser was used and, according to the EN 1504-2 [8] standard, masses of 1 kg were attached on each arm of the abraser (Fig. 3c) and type H22 abrasive wheels were used.

Regarding the number of cycles, the standard EN 1504-2 [8] refers that 1,000 cycles of abrasive wear must be carried out on each specimen. However, after a much lower number of cycles it was observed that in most specimens the surface protection had been completely abraded. In average, this occurred after about 100–200 cycles. Therefore, additional cycles on protected specimens provided only the abrasion resistance of the concrete itself. This procedure is in agreement with recommendations defined in ISO 5470-1 [21].

The abrasion resistance tests were carried out in sets of 100 cycles, after which the specimens were weighed. Based on the mass values measured, the percentage reductions of mass loss (R) of protected specimens were computed with respect to the non-treated specimens. A total of 400 cycles were completed. However, due to reasons stated above, only the results correspondent to the first set of 100 cycles are presented.

According to EN 1504-2 [8], an improvement of at least 30 % in the abrasion resistance should be expected due to the application of impregnation products in comparison with a non-impregnated sample (using concrete type C70).

2.5.4 *Impact resistance*

The impact resistance before and after the application of the products under study were evaluated based on EN ISO 6272-1 [22] standard. A test device was used to drop a mass of 1973.28 g with a sphere of 20 mm diameter at the end (Fig. 3d). The test was performed with a load corresponding to class II (10 N m) according to EN 1504-2 [8]; preliminary tests were also performed for classes I (4 N m) and III (20 N m)—the latter class caused the fracture of the concrete specimens. The drop height of the mass was set as 51.7 cm based on the gravitational potential energy Eq. (2)

$$U = m \times g \times h[N \cdot m], \tag{2}$$

where U is the potential energy ($N{\cdot}m$), m is the mass (g), g is the gravity acceleration (m/s^2) and h is the height (m).

After dropping the mass, the impact locations were assessed using a magnifying lens in order to detect cracks or delamination. In particular, the diameter and the depth of the cavities were measured using respectively a metallic ruler and a calliper.

2.5.5 *Bond strength*

The bond strength adhesion between the concrete substrate and the epoxy impregnated layers was determined by means of pull-off tests according to the standard EN 1542 [23].

Drills with 50 mm of diameter and 15 mm of depth were first performed on each specimen using a core drilling machine. Subsequently, metallic dollies (50 mm of diameter) were bonded to the surface of the concrete specimens using an epoxy adhesive. The dollies were then attached to the pull-off equipment with a screw and finally a tensile load was applied until failure (Fig. 3e).

The tensile load required to separate the dolly was measured and the type of failure was classified according to EN 1542 [23] standard. The bond strength, σ, was calculated from the following Eq. (3),

$$\sigma = \frac{F_{\max}}{A_{\text{dolly}}}, \tag{3}$$

where $F_{\max}$ is the maximum normal load and A_{dolly} is the dolly's cross-section area.

EN 1504-2 [8] specifies that for concrete type C70 the bond strength adhesion of impregnations to the support must be higher than 1.5 or 1.0 MPa for horizontal substrates subjected or not subjected to road traffic, respectively.

3 Results and discussion

3.1 Characterization of surface roughness

Table 3 shows the results of the surface roughness test. It can be seen that the two methods used to assess the surface roughness provided very consistent results. Despite some small differences, arising from the different nature of the two tests, the roughness measurements follow the same variation trend, with a relatively high coefficient of determination of $R^2 = 0.986$ (Fig. 4).

Table 3 Characterization of surface roughness based on test procedures defined in ISO 4287 and EN 1766 (in mm, average ± standard deviation)

Type of concrete	Plasticine casts, ISO 4287 [18] (–)	Sand test, EN 1766 [15] (–)
MC40·R_0	0.014 ± 0.003	0.096 ± 0.003
MC40·R_1	0.020 ± 0.008	0.154 ± 0.001
MC40·R_2	0.022 ± 0.003	0.164 ± 0.008
C70·R_0	0.017 ± 0.006	0.133 ± 0.007
C70·R_1	0.024 ± 0.013	0.181 ± 0.006
C70·R_2	0.027 ± 0.005	0.207 ± 0.020

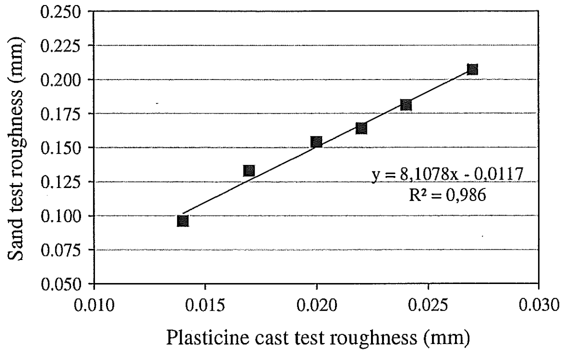


Fig. 4 Comparison between the experimental procedures defined in ISO 4287 and EN 1766 to measure the surface roughness

As expected, for the same type of surface preparation, concrete type C70 presents higher roughness due to its higher *w*/*c* ratio and therefore the lower resistance of its superficial layer to the abrasive action of either the water jet or the needle scaler. For both types of concrete, the roughness is higher when the surface is prepared with the needle scaler (*R*2) than when the water jet at 160 bar (*R*1) is used. This result stems from the higher abrasive power of the needle scaler, when compared to the water jet. Both techniques provided considerable roughness increase compared to specimens with no surface preparation (*R*0), as expected.

3.2 Product penetration

The visual procedure recommended in standard EN 1504-2 [8] did not allow detecting the penetration depth of products P1 and P2. Apparently, none of the products significantly penetrated the concrete substrates, forming only a surface film. This surface film was clearly thicker in concrete type MC40 than in concrete type C70, due the fact that the latter concrete is more porous and thereby facilitates the slight penetration of the products.

The inefficiency of the procedure indicated in the standard EN 1504-2 [8] may be due to the following aspects: (i) the main function of impregnation products is the hardening of concrete surfaces and not the water repellence (which is the case of the hydrophobic products); (ii) therefore, as these products do not have such repellence effect, it is difficult to detect the dry zone of the concrete surface when sprayed with water; (iii) the absence of colour of the products used in this study, after contacting with the concrete, also did not facilitate distinguishing the penetration depth.

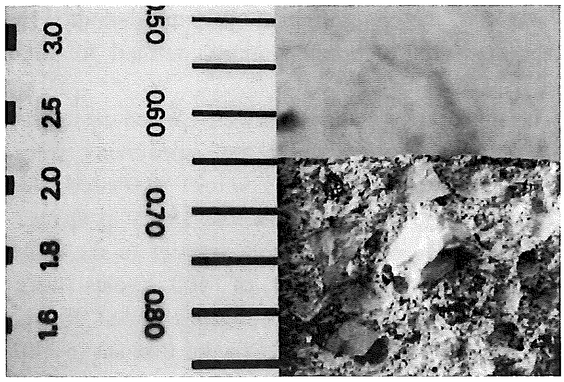


Fig. 5 Measurement of the impregnation depth (specimen C70, product P1)

Table 4 Penetration depth (in mm)

Product	MC40	C70
P1	0.40	0.65
P2	0.10	0.20

However, with the alternative procedure (cf. Sect. 2.5.1), in which a red pigment was added to the products, it was much easier to distinguish the impregnated depth (Fig. 5)—the average values listed in Table 4 were obtained for specimens of series *H* (with a moisture content of about 5 %, H_2) based on three measurements performed on each specimen. In all specimens, the penetration was very uniform.

As expected, the products achieved higher penetration depths in the more porous concrete, C70. However, those penetrations were much lower than the minimum value of 5.0 mm specified in EN 1504-2. On the other hand, product P1 (solvent-based) presented a higher penetration depth compared to product P2 (water-based). The overall results obtained in this test, namely the very limited penetration achieved is deemed to be due to the relatively high viscosity of both impregnation products.

3.3 Water permeability

3.3.1 Influence of the surface roughness

Figure 6 plots the curves for the water absorption as a function of the square root of time of representative

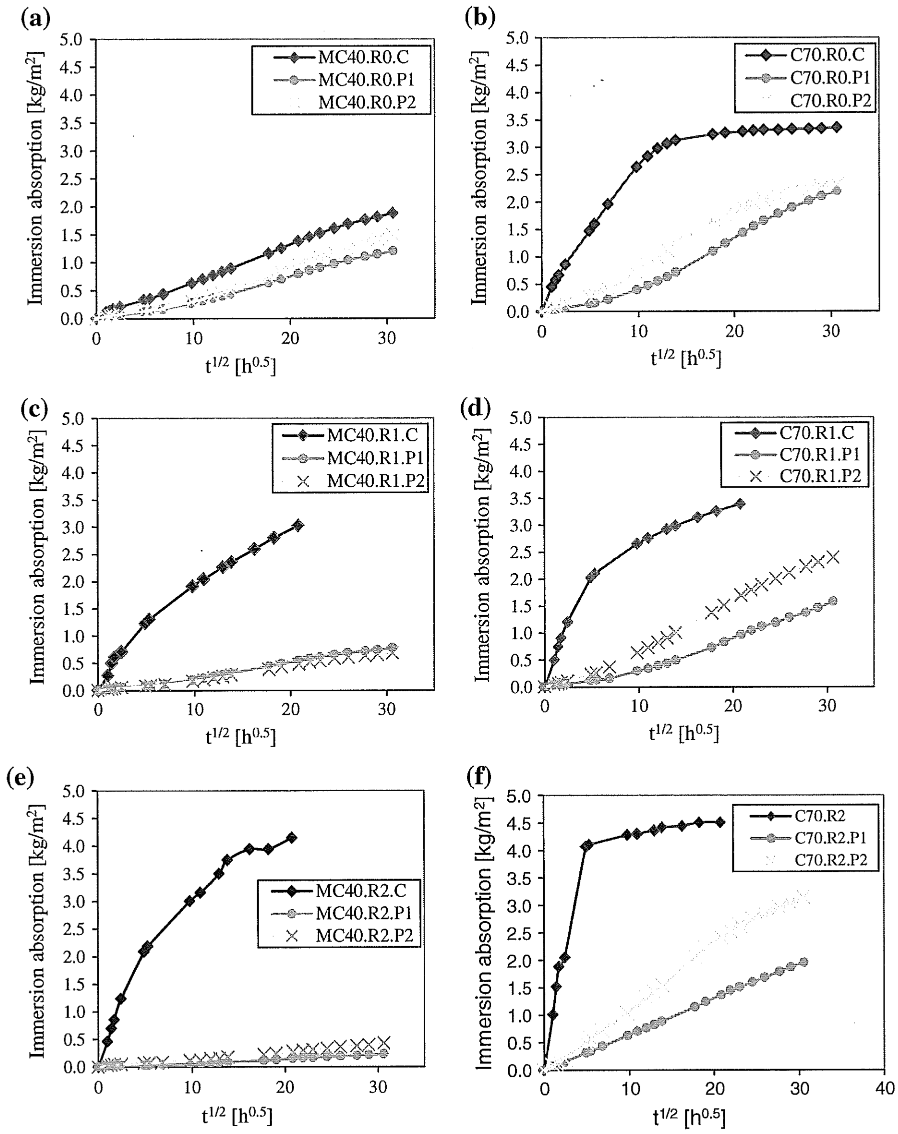


Fig. 6 Water transmissibility in **a** MC40·R0, **b** C70·R0, **c** MC40·R1, **d** C70·R1, **e** MC40·R2 and **f** C70·R2

test specimens from series *R*, comprising the two types of concrete (MC40 and C70), with three different surface roughnesses (*R*0, *R*1 and *R*2) and the two impregnation products analysed (P1 and P2). The values of the water transmissibility coefficient after the first 24 h of immersion are reported in Table 5. For each type of concrete, the percentage reduction (*R*) compared to control specimens (i.e., without any surface protection) is also listed in Table 5.

As expected, the concrete MC40 presented much better performance in terms of water permeability than concrete C70—this result stems from the lower *w*/*c* ratio of the former type of concrete and, thus, its lower porosity. With the exception of the concrete MC40·R0, in all of the reference concrete specimens, the water transmissibility coefficient is higher than 0.1 kg/m^2 h$^{0.5}$, the maximum value required by EN 1504-2 (Table 5).

Specimens protected with products P1 and P2 provided significant water transmission reductions compared with the unprotected reference specimens (Table 5). In fact, both products form a film on the concrete surface creating a protection against the ingress of water. The better performance of product P1 most likely stems from its solvent based nature, which improves the ability to create a waterproof film;

Table 5 Water transmissibility coefficient after 24 h of immersion (w) of series R and percentage reduction compared to control specimens (C)

Identification	MC40		C70	
	w (kg/m^2 h$^{0.5}$)	R (%)	w (kg/m^2 h$^{0.5}$)	R (%)
R0·C	0.068 ± 0.013	–	0.301 ± 0.082	–
R0·P1	0.024 ± 0.006	65.1	0.030 ± 0.008	90.3
R0·P2	0.027 ± 0.004	61.0	0.044 ± 0.028	85.5
R1·C	0.252	–	0.415	–
R1·P1	0.015 ± 0.006	94.3	0.024 ± 0.007	94.3
R1·P2	0.016 ± 0.002	93.7	0.047 ± 0.015	88.7
R2·C	0.426	–	0.831	–
R2·P1	0.007 ± 0.001	98.5	0.065 ± 0.003	92.3
R2·P2	0.013 ± 0.006	97.2	0.082 ± 0.031	90.2

product P2, being water-based, is probably less efficient in avoiding water ingress, namely in the concrete series C70 (Fig. 6 and Table 5).

Regarding the influence of the surface preparation on protected specimens, the results obtained show that for concrete type MC40, the speed of transmission of liquid water decreases with the increase of the surface roughness. For concrete type C70, such influence is less clear and furthermore water absorption results obtained with surface preparation $R2$ (higher roughness) are worse than those obtained with surface preparation $R1$. This result may indicate that as far as water absorption is concerned, a higher degree of surface roughness can be favourable to a better behaviour of the impregnation product on concrete type MC40 but not on concrete type C70. It is very likely that the needle scaler surface treatment ($R2$) was too aggressive for the less compact concrete C70, increasing excessively its surface porosity. It is interesting to note that in unprotected specimens, the increase of surface roughness caused an increase of the water transmissibility. This result is naturally due to the fact that in this type of specimens, the surface treatment not only opened the superficial pores, but it also removed the slurry laitance of the concrete at the surface, which generally provides some protection against water ingress.

3.3.2 *Influence of moisture content*

Figure 7 plots the water transmissibility of representative test specimens from series H made of concrete type MC40 (results for concrete C70 are not shown as they were not consistent, eventually due to the higher heterogeneity of these particular concrete samples), with surfaces prepared by water jet to obtain a roughness $R1$ and impregnation products (P1 and P2), now with three different moisture contents ($H1$, $H2$ and $H3$) of the substrate at the moment of application of the superficial protections. The water transmissibility coefficients after the first 24 h of immersion of those specimens are listed in Table 6, together with the percentage reduction compared to the control specimens (C).

The application of impregnation products in concrete MC40 caused, in most cases, reductions in the coefficient of water transmission higher than 90 % after 24 h of immersion (Table 6). In what concerns the influence of the moisture content in the performance of the impregnations products, for concrete MC40, it was found that such influence was reduced for both P1 and P2 products, probably due to the general stagnation of the products in the surface, because of the low porosity of the support. However, product P2 obtained a better performance with moisture $H3$, possibly because this product, being water based, is less affected by the water present in the saturated support.

3.4 Abrasion resistance

Figure 8 presents the results of the abrasion resistance tests for specimens from series H, after being subjected to 100 cycles in the Taber abrader. Results are plotted in terms of mass loss exhibited by protected specimens compared to unprotected specimens. As

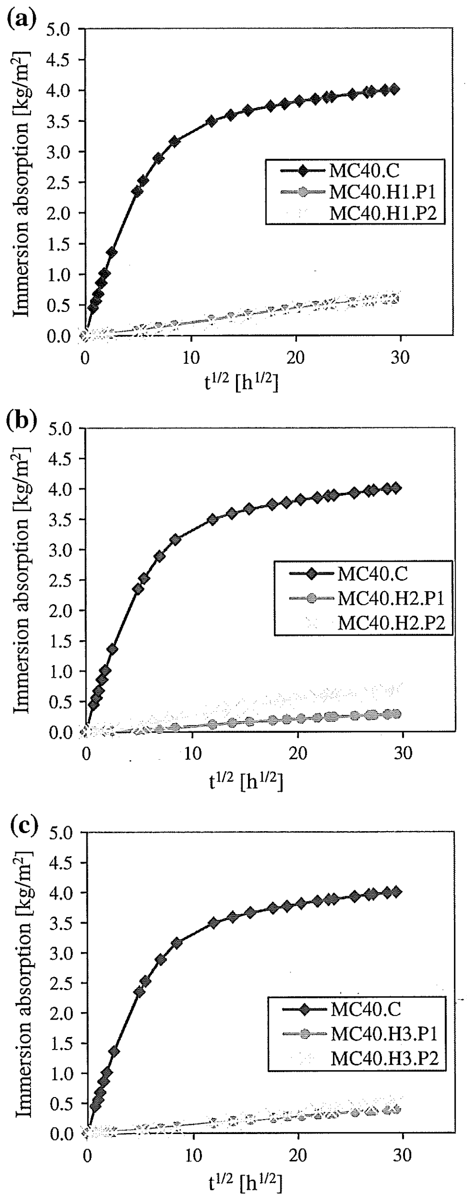


Fig. 7 Water transmissibility in **a** MC40·H1, **b** MC40·H2 and **c** MC40·H3

already mentioned, after about 200 cycles the impregnation products were generally no longer visible.

The results obtained show that up to 100 abrasion cycles both products provided a relatively high degree of abrasion resistance, reducing the mass loss more than 70 % compared with the unprotected concrete. Since the studied products could not penetrate deep enough to strengthen also the inner concrete, the minimum value required by the standard EN 1504-2 [8] for concrete type C70 of 30 % after 1,000 abrasion cycles could not be attained. However, the results obtained show that as long as these impregnation products remain at the concrete surface, they provide a high level of abrasion resistance.

Table 6 Water transmissibility coefficient after 24 h of immersion (w) of series H and percentage reduction compared to control specimens (C), for concrete MC40

Identification	MC40	
	w (kg/m^2 h$^{0.5}$)	R (%)
H2·C	0.252 ± 0.121	–
H1·P1	0.014 ± 0.010	94.7
H1·P2	0.010 ± 0.001	96.2
H2·P1	0.005 ± 0.002	98.1
H2·P2	0.015 ± 0.005	94.2
H3·P1	0.010 ± 0.002	96.4
H3·P2	0.006 ± 0.001	97.8

Product P2 presented slightly better performance than product P1, for both types of concrete and all moisture contents. However, the performance exhibited by both products was very similar, which may stem from the fact that they both form a film in the concrete surface.

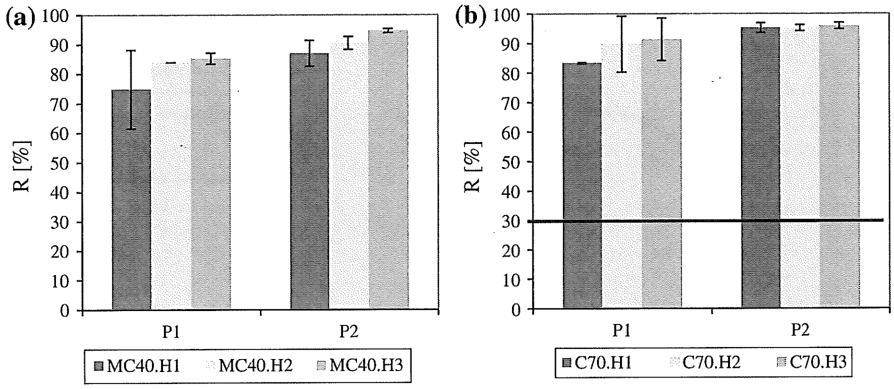
Regarding the influence of the moisture content, both products P1 and P2 present a slight tendency to improve their behaviour with the increase of the moisture content. This is possibly due to the fact that the presence of water in the pores hinders the penetration of the products, forcing them to be retained in the surface. In any case, results obtained show that the presence of water in the substrate does not seem to influence considerably the resistance to abrasion provided by the impregnation products. These results are in agreement with those obtained in the water absorption test, in which the transport properties of the film were not significantly affected by the moisture content.

3.5 Impact resistance

3.5.1 Influence of surface roughness

The results of the impact resistance test are shown in Fig. 9, in terms of the diameter of the impact zone. By comparing the diameter of the impact zone for the specimens with and without protection, one can

Fig. 8 Influence of the substrate moisture content in reduction of mass loss (after 100 abrasion cycles) for concretes **a** MC40 and **b** C70 (average ± standard deviation, the *horizontalline* represents the limit specified in EN 1504-2)



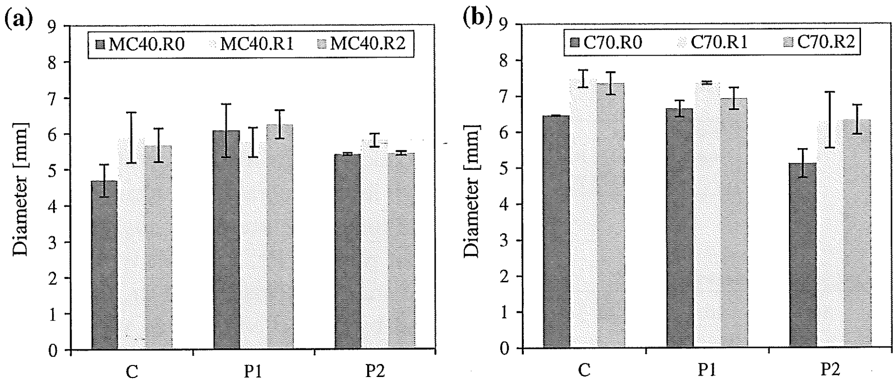


Fig. 9 Influence of the substrate roughness in the impact resistance for concretes **a** MC40 and **b** C70 (average ± standard deviation)

conclude that no significant improvements were achieved with the impregnation products, particularly with product P1. However, to some point, these results may be affected by the deformation capacity of the products, considering the tendency of epoxy resins to form a film in the concrete surface.

For control specimens (C), roughness type *R*0 (for which specimens still have the slurry laitance of the concrete) provided better performance to impact. Between roughnesses *R*1 and *R*2 (with surface preparation), the difference is not statistically relevant (taking into account the mean and standard deviation values), although the average diameter of the impact zones of specimens with roughness *R*1 is higher than that of specimens with roughness *R*2.

Concerning the surface protection products, for product P1 no significant differences were observed between roughnesses *R*0, *R*1 and *R*2. For product P2, increasing the roughness of the surface had no influence for both types of concrete (the slight detrimental effect observed in C70 specimens is not statistically relevant).

As expected, the type of concrete had a remarkable effect in the impact resistance. Concrete C70, with the higher *w*/*c* ratio, presented a lower performance, with a diameter of the impact zone that was in average about 2 mm higher than that of concrete MC40.

3.5.2 Influence of moisture content

Figure 10 plots the diameter of the impact sites for series *H*. Again, one can conclude that in general the application of the impregnation products did not cause a considerable improvement of the impact resistance of MC40 and C70 concrete specimens.

By comparing the performance of both products P1 and P2 in the two types of concrete, it can be seen that for concrete type C70, unlike concrete type MC40, the protected specimens presented slightly better performance than the untreated (C) specimens. This

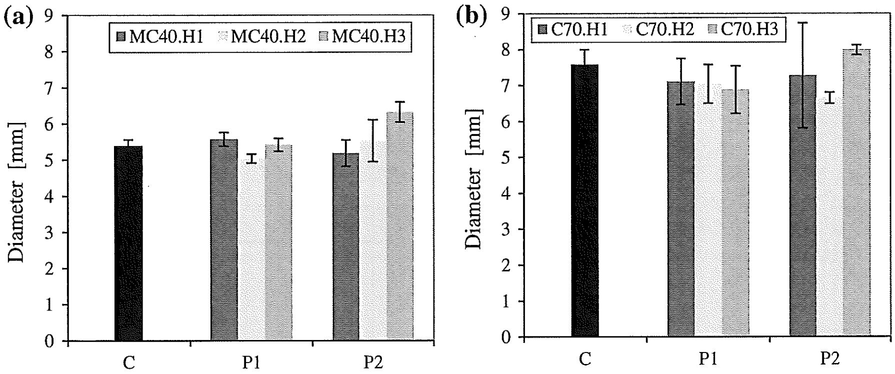


Fig. 10 Influence of the substrate moisture content in the impact resistance for concretes **a** MC40 and **b** MC70 (average ± standard deviation)

difference may be due to the higher penetration of the products in the more porous concrete. Therefore, the cavities formed by the impacts depend less on the deformation capacity of the products.

In what concerns the influence of the moisture content of the substrate in the performance of the products, the results obtained and their scatter do not allow identifying any clear tendency. In any case, it seems that the influence of the moisture content is not significant for product P1, but for product P2 the higher level of humidity H3 causes a slight increase in the impact diameter, once more due to the reason previously stated for the abrasion resistance—the presence of water in the pores forces the product to be retained at the surface.

3.6 Bond strength by pull-off

3.6.1 Influence of surface roughness

Figure 11 presents the results of bond strength (or direct tensile strength in unprotected specimens) measurements corresponding only to valid failure modes (all specimens in which bonding problems with the adhesive were found were excluded from the analysis).

In unprotected (C) specimens, failure occurred always in the concrete. In the protected specimens, debonding failure occurred mostly at the interface between the concrete substrate and the impregnation products. In a limited number of specimens protected with product P1, failure was observed within the concrete substrate.

Bond strength results, although exhibiting relatively high scatter, show that the adhesion between both products and the concrete substrate generally improves when surface preparation is applied—minimum bond strength corresponds to roughness *R*0. With the exception of product P1 in concrete type MC40 (for which a particularly high scatter was obtained), the best performance in terms of adhesion between the substrate and the impregnation products is obtained for roughness *R*1. In what concerns the type of concrete, as expected, the pull-off strength was considerably higher for specimens made of concrete type MC40. Such result stems from the lower *w*/*c* ratio of this type of concrete, which promotes a higher mechanical strength and adhesion to the impregnation products.

Regarding the comparison between products P1 and P2, given the scatter of the results, it is not possible to identify which one performs best in terms of adhesion to the concrete substrate. In this respect, it is worth mentioning that all protected specimens presented a bond strength adhesion above the minimum value of 1.5 MPa specified in EN 1504-2 for concrete type C70.

3.6.2 Influence of moisture content

Figure 12 illustrates the influence of the moisture content on the bond strength. For specimens protected with product P1, failure occurred within the concrete substrate for moisture levels *H*1 and *H*2, while for moisture level *H*3 failure was observed at the concrete-substrate interface. Therefore, for the two lower moisture contents, the actual bond strength was

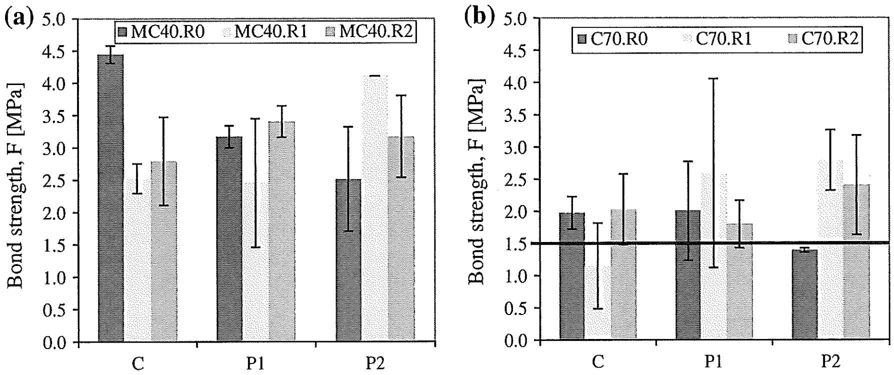


Fig. 11 Influence of the substrate roughness in the bond strength by pull-off test for concretes **a** MC40 and **b** C70 (average ± standard deviation, the *horizontal line* represents thelimit specified in EN 1504-2)

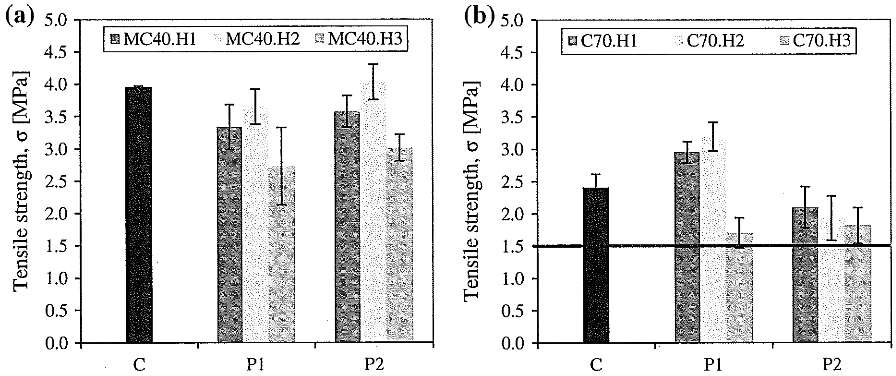


Fig. 12 Influence of the substrate moisture content in the bond strength by pull-off test for concretes **a** MC40 and **b** C70 (the *horizontal line* represents the limit specified in EN 1504-2)

higher than the cohesion strength of the concrete. For specimens protected with product P2, for moisture levels *H*1 and *H*2 failure occurred at the concrete-impregnation product interface. For moisture level *H*3, part of the specimens failed within the concrete core, whereas the other part failed at the concrete-product interface (as for the other moisture contents).

Results obtained show that for both products a substantial pull-off strength reduction occurred for moisture level *H*3. For concrete type C70 and product P1, this reduction was particularly high when compared to moisture levels *H*1 and *H*2. This behaviour indicates that moisture level *H*3 prevented the proper penetration of the impregnation products in the saturated concrete substrate. For product P1, this performance reduction is clearly associated with a change in the failure mode, i.e. from cohesive (within the concrete) to adhesive (at the concrete-impregnation product interface).

4 Conclusions

This paper presented an experimental study about the influence of the concrete substrate on the performance of epoxy based impregnation protections. In particular, the influence of the type of concrete together with the type of roughness and the moisture content at the moment of the application of the impregnations was assessed. Based on the results obtained, the following main conclusions are drawn:

1. With the exception of the resistance to impact, in all of the remaining tests the use of epoxy resins

improved the behaviour of both types of concrete. This fact is related with the intrinsic characteristics of these resins, namely their ability to form a film in the concrete surface, thereby providing a protection barrier between the concrete and the surrounding environment. For the impact resistance, results were inconclusive, as they were influenced by the deformation capacity of the impregnation products.

2. The procedure for evaluating the penetration depth described in the standard EN 1504-2 [8] is inadequate for the type of impregnation products analysed in this study. The alternative procedure tested, which consisted of adding a pigment to the impregnation products, appeared to be feasible. The reduced penetration depth attained by the two impregnation products should be due to their relatively high viscosity.
3. As expected, the several tests performed with the concrete type MC40 presented better performance when compared to concrete type C70. Such difference stems from the dissimilar *w*/*c* ratios of both concrete compositions, which considerably influence their porosity, mechanical performance and adhesion to impregnation products.
4. The concrete roughness influences the performance of the products, but such influence acts differently, depending on the parameter under study. In the case of water permeability, the higher roughness (*R*2) allowed for a more effective performance of the impregnation products. In terms of bond strength, roughnesses *R*1 and *R*2 both provided better results compared to *R*0. However, regarding the resistance to impact, the substrate roughness did not have a beneficial effect.
5. The influence of the moisture content is also different depending on the type of impregnation product and property at stake. In the test of water permeability, the saturated condition of the support (*H*3) promoted a better performance of product P2 (water-based), mainly because the product retention at the concrete surface helped forming a more efficient barrier; however, for product P1 (solvent-based), the increment of humidity of the support proved to be detrimental to the transport properties of the protection film, most likely due to the incompatibility of the water with a solvent based product. In terms of adhesion to the support, the saturated condition considerably reduced the bond strength and this may have negative consequences regarding the medium and long-term durability of these superficial protection systems.
6. For most parameters evaluated, the performance of the impregnation products when applied in concrete type MC40 was less influenced by the moisture content when compared to concrete C70. This result stems from the lower porosity of the former concrete, which allowed increasing the concentration of the impregnation products at the surface of the specimens.

It is likely that the findings reported in this paper, namely the influence of the roughness and moisture content of the substrate on the performance of epoxy based impregnations, are valid for other types of resin based formulations. Future investigations should address this issue.

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