

Durability of Concrete

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Aging Effect on the Properties of Flexible Surface Coating for Concrete Protection

by L. Coppola, C. Pistolesi, P. Zaffaroni
and M. Collepardi

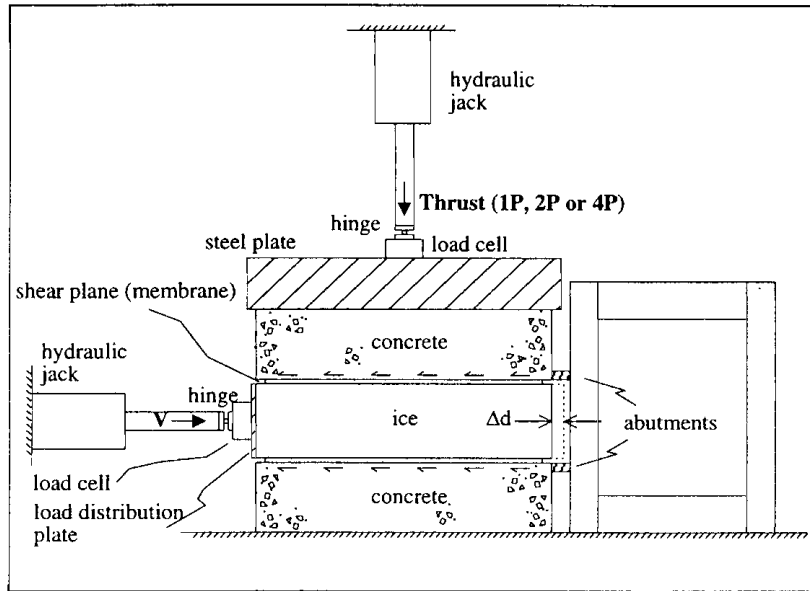


Fig. 6—Pull-off test setup

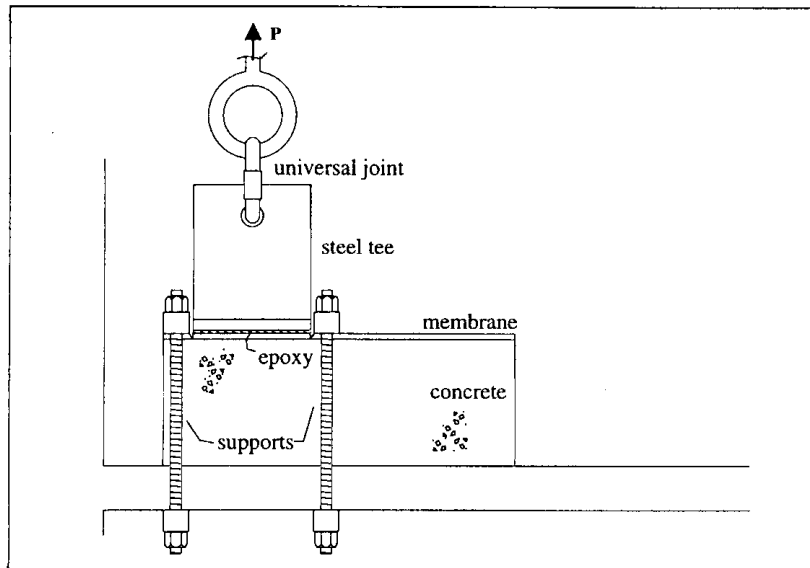


Fig. 7—Shear test setup

Synopsis: In the present work an acrylic polymer (based on 2-ethylhexyl acrylate) was mixed with cement and fine aggregate and was studied as rubber-like coating to protect reinforced concrete beam specimens. Two acrylic polymer-cement coatings (both with water-cement ratio of 0.50, polymer-cement ratio of 0.50 and fine aggregate-cement ratio of 2) were produced by changing the type of the cementitious component (portland cement or high alumina cement). The two coatings were applied to a porous concrete substrate with a water-cement ratio of 0.80.

Preliminary tests on the uncoated and coated concrete specimens were carried out to study the penetration of water, chloride, sulphate and carbon dioxide. The resistance to penetration of these aggressive agents was very poor in the uncoated specimens and became as good as that of a watertight and durable concrete in the coated specimens.

Then coated beam specimens have been kept for 1 year in three different environments (laboratory at 20°C and 65% R.H.; outdoors environment exposed to natural changes in temperature and relative humidity; under water) in order to examine the influence of the ageing on the bond strength as well as the flexibility and therefore the ability of the acrylic coatings to bridge the cracks of the concrete substrate.

The bond strength of the two coatings was substantially unchanged by the exposure to the three different environments. The flexibility of the polymer-cement coating remained substantially unchanged when portland cement was used independently of the exposure environment. On the other hand, when high-alumina cement was used there was a flexibility loss of the coating in humid environment, particularly in the underwater exposure.

Keywords: Coating durability; flexural strength.

Luigi Coppola, is a research civil engineer of Enco, Spresiano, Italy, which is engaged in consulting and research on cementitious materials. He has authored numerous papers on various aspects of concrete technology, durability and mix-design.

Carlo Pistolesi, is a research civil engineer, director of the Building Materials Laboratory of Mapei, Milan, Italy. He has authored several technical papers on concrete technology and durability.

Pasquale Zaffaroni, is the R&D manager of the Building Materials Division, Mapei, Milan, Italy. He has authored several technical papers on concrete technology.

Mario Collepari, is Professor of Materials Technology and Applied Chemistry at the Ancona University, Italy. He is author of numerous papers on concrete technology and cement chemistry.

INTRODUCTION

In contrast to what happens in the laboratory, real life concrete structures are subjected to static and dynamic loads. Moreover, the additional deterioration which is observed in real life structures exposed to aggressive environments, compared to that of the specimens stored in a laboratory room, is due to the following concrete "weak points":

- (i) poor tensile strength;
- (ii) high modulus of elasticity which is responsible for the transformation of thermal and hygrometric length changes in service into relative high tensile stresses;
- (iii) penetration of aggressive agents through the microcracks formed as a consequence of the properties (i) and (ii).

These microcracks represent preferential paths for the penetration of aggressive environmental agents - such as air, water, sulphate, chloride, alkali ions - thanks to the mechanism of diffusion and capillary absorption through the cracks. This means that the concrete cover can be penetrated by the aggressive agents independently of the porosity of the cement matrix. This promotes the corrosion of the reinforcement and the deterioration of the cement matrix itself as well as that of the reactive aggregates, if any. Once any of these processes is initiated (all having an expansive-disruptive nature), the microcracks grow becoming macrocracks. After an initial induction period of a few years or more, the degradation process increases very rapidly (1, 2).

When service life of 20-30 years is considered to be acceptable for concrete structures exposed to aggressive environments, one can ignore the problems associated with the presence of microcracks and their transformation into macrocracks: it is sufficient to design the concrete structure following the European norms (3) or the American recommendations (4) for the durability of concrete structures. These regulations stress the importance of the water-cement ratio, which must not exceed a *maximum* value to guarantee the impermeability of the material and of the *minimum* volume of entrained air to prevent damage from the formation of ice.

However the required service life must be much longer, a minimum of 50 years and up to 200 years (5), when one considers structures of particular architectural interest (e.g. monumental works, churches, etc.) or structures of particular social importance which require great investments (e.g. underwater tunnels, long span bridges, highway viaducts, etc.). In designing these structures, one cannot ignore the mechanism of formation of microcracks described above and their subsequent transformation into macrocracks.

OBJECTIVES OF THE PRESENT WORK

The present work addresses the performances of protective flexible coatings to prevent the penetration of aggressive agents through the preferential paths offered by the microcracks even in a low porosity and well compacted cement matrix. The idea is to employ protective coatings which are resistant to the aggressive agents present in the environment, are sufficiently flexible so that they can deform and bridge the cracks in the rigid concrete substrate, and can maintain these characteristics in time, regardless of the environment in which they are placed. Swamy et al. (6-11) have pursued this approach and have designed a flexible coating combining an acrylic elastomer (2-ethylhexyl acrylate polymer) with mineral filler and inorganic pigments.

The present work discusses the performance (in terms of resistance to the penetration of aggressive agents) of two flexible coatings which are made from the same type of acrylic polymer employed by Swamy et al. (6-11), combined with cement and fine aggregates. Moreover, the ageing effect on the properties of these coatings (in terms of flexibility and bond strength to the concrete substrate) was examined in three different exposure conditions: laboratory room, underwater and outdoors natural environment.

EXPERIMENTAL PROGRAM

Materials

The experimental program was performed making use of a concrete substrate and two flexible polymer-cement coatings. The composition and the properties of the concrete are shown in Table 1. The water-cement ratio was chosen sufficiently high ($w/c = 0.80$) so that the concrete would be more easily penetrated by the aggressive agents and the effect of the coating would become more apparent. The same mix was employed to manufacture the specimens (250x250x300 mm) for the durability tests and the miniature beams (150x150x600 mm) for the flexibility and bond strength tests. The beams were reinforced with three steel rods (diameter = 8 mm) as indicated in Figure 1. The reinforcing steel was placed in the compression side of the concrete beams rather than in the tension side in order to control the crack opening easier on the bottom of the beams.

Table 2 summarizes the composition and the properties of the polymer-cement flexible coatings. While the composition was identical for both coatings (water-cement ratio = 0.50; polymer-cement ratio = 1 to 2), the cement used was different: portland cement for coating A, and high-alumina cement for coating B. The portland cement was a CE II/A-L 42.5 according to the EN197/1 European norm, whereas the high-alumina cement was characterized by an Al_2O_3 content of 50%. A rubber-like lattice was used which is a 50% aqueous emulsion of 2-ethylhexyl acrylate polymer.

In practice, the coatings were obtained by mixing 1 part of polymer lattice, with 1 part of cement (either portland or high-alumina), and 2 parts of ground limestone (0-0.2 mm).

Durability Tests

These tests were aimed to evaluate the ability of the cement coatings (2 mm thick) to prevent the penetration of water, carbon dioxide, chlorides, and sulphates. The experimental program included tests on both coated and uncoated specimens, so that the effectiveness of the coatings could be quantified in comparison with the results for the untreated concrete.

The concrete specimens were cured for 21 days at 100% R.H. Only the specimens employed to measure the penetration of CO_2 were stored at 60% R.H.

in order to dry them and favour the subsequent CO_2 penetration. After applying the coating on all the faces of the concrete prisms, the treated specimens were cured for additional 7 days at 60% R.H. The uncoated concrete specimens were cured as the corresponding treated specimens for a total of 28 days before the exposure to water penetration or aggressive agents (CO_2 , SO_4^{2-} , Cl^-).

A group of specimens was subjected to water penetration employing a maximum pressure of 7 bars, as described in ISO 7031 (12). The rest of the specimens was exposed to one of three different aggressive environments: air enriched with CO_2 (30% in volume), aqueous solution of NaCl (10% in mass), aqueous solution of $MgSO_4$ (10% in mass). The penetration of the three aggressive agents was measured at regular intervals employing the following Italian standard methods: UNI 9944, UNI 7928 and UNI 8019 for carbon dioxide, chloride and sulphate respectively (13-15).

Flexibility Tests

These tests were aimed to evaluate the flexibility of the polymer-cement coatings applied on concrete beams when exposed to three different environmental conditions: in the laboratory (20°C, 60% R.H.), under water (20°C) or in an outdoors natural environment characterized by thermal and hygrometric instability of the North Italy (Venice area).

The polymer-cement coating was applied after a preliminary curing of the concrete beams for three months in the laboratory room (R.H. = 60%). Then the coated specimens were cured for additional 7 days before the exposure to the above three different environmental conditions.

The coating (2 mm thick) was applied (Fig. 2) in form of a strip (45 mm wide and 600 mm long) only to the concrete face (150x600 mm) further from the steel reinforcement (Fig. 1) and subjected to the maximum tensile stress. The rest of this concrete surface was left bare, so that the appearance and the growth of the microcracks produced by the flexural loading were evaluated in the uncoated and coated areas of the same face.

At regular intervals of exposure time in each of the environmental conditions, three point bending tests were performed on the beam specimen. The load was applied on the face of the beam closest to the steel reinforcement, and furthest

from the partly coated face (Fig. 1). Due to the application of a load, a crack formed in the uncoated region. A mirror positioned under the beam allowed to observe its formation and its growth (Fig. 3). As the load increased, the crack opening increased. The crack opening of the uncoated concrete face was measured by means of an electronic dial gauge mounted between two pins inserted on the bottom of the beam. Initially, the flexible coating remained intact. When the elastic coating started to break, the opening of the crack on the uncoated concrete surface was recorded.

The composition of the elastic coating (Table 2), and in particular the acrylic polymer-cement ratio, which is the parameter that most strongly affects its flexibility, was chosen so that the coating started to tear after the crack in the concrete substrate reached an opening of about 1 mm. A greater flexibility of the coating, due to a higher polymer-cement ratio, does not appear advisable. In these conditions, in fact, excessively large crack openings, related with dangerous concrete fractures (>2 mm), would remain invisible without any alert of the potential risk for the state of the structure.

Bond Strength Tests

The scope of these tests was to evaluate the effect of time and type of exposure (laboratory air environment at 20°C and R.H. of 60%; underwater environment at 20°C; outdoors environment with both thermal and hygrometric variations) on the bond strength of the coatings (2 mm thick) to the concrete substrate.

The tests were conducted on the same type of specimens employed for the flexibility tests described above. The bond strength of the coating to the concrete surface was evaluated at the end of every bending test using a dynamometer to measure the force necessary to debond the flexible coating from the concrete substrate.

RESULTS

This section presents and discusses the results of the durability, flexibility, and bond strength tests for coating A and B (Table 2).

Durability of the Polymer-Cement Coatings

Figure 4 indicates that the penetration of water under pressure (up to 7 bars)

is approximately 35 mm in the uncoated specimens, while it is undetectable when the concrete surface is protected by a coating. According to the European norms (1), concrete can be considered impermeable when the thickness penetrated by water is less than 20 mm according to this test method (16). The results shown in Fig. 4 indicate that the use of a polymer-cement coating allows to transform a permeable concrete (penetration = 35 mm) into an impermeable one.

Figure 5 shows the CO₂ penetration into uncoated and coated (A and B) specimens as a function of the exposure time in a 30% CO₂ enriched air. The use of these coatings completely blocks the penetration of CO₂, even when the concentration of this gas is as high as 30% by volume, about 1000 times higher than in a natural environment.

The results of the chloride penetration are shown in Fig. 6. Also in this case the two coatings are very effective in reducing the penetration of the aggressive agent into the concrete substrate, with respect to the uncoated control specimen.

Figure 7 shows the results for the sulphate penetration in concrete specimens exposed to a 10% aqueous solution of MgSO₄. The penetration of sulphate is completely inhibited when the concrete specimens are protected by the polymer-cement coatings examined in the present work.

All these results indicate that the polymer-cement coatings investigated in the present work are impermeable to water, and resistant to the diffusion of CO₂, Cl⁻ and SO₄²⁻. Not only are the coatings durable themselves but, most importantly, they can block the penetration of the aggressive agents inside the concrete, even when the cement matrix of the substrate is porous or, as might be the case under service loads, the concrete surface is cracked.

Flexibility of the Polymer-Cement Coatings

Figures 8 and 9 show the opening of the concrete surface crack, measured at the time when the polymer-cement coating is torn during the bending test, as a function of the exposure time in the three different environmental conditions (laboratory room, water, outdoors natural air).

Initially (7 days after the coating application) the concrete crack opening is approximately 1 mm. Subsequently, during the first year of exposure, the crack

opening does not vary significantly, except in the case of the beams stored permanently underwater (Fig. 8-9). The effect of water appears to be negligible if the coating is made with portland cement (product A): Fig. 8 shows that after 12 months of permanent immersion underwater, the crack opening decreases from 1 mm to 0.8 mm. On the other hand, when the acrylic polymer is combined with high-alumina cement (product B), the coating completely loses its initial flexibility after less than 3 months of exposure to water (Fig. 9): it breaks just when the first microcrack appears on the uncoated concrete surface of the beam. This indicates that the high-alumina cement coating has become as rigid as the concrete substrate and can no longer bridge the concrete surface microcracks when this coating is in contact with water for more than three months. This also means that, in the presence of water, this coating cannot protect the concrete in a reliable way from the penetration of the aggressive agents through the concrete microcracks. It is likely that the greater hydration of the high-alumina cement in a permanently wet environment (especially under water) is responsible for the stiffening of the coating in presence of water: the more rigid chemical bond of the inorganic hydrated cement prevails on the more flexible one due to the acrylic polymer. This stiffening of the high-alumina cement coating does not necessarily reduce the adhesion to the concrete substrate, as will be observed in the following section.

Bond Strength of the Polymer-Cement Coatings to Concrete

The bond strength of coatings A and B to concrete evaluated by means of debonding test was found to have in both cases an initial value of about 0.7 N/mm² (7 days after the coating application). The bond strength tended to stay constant, and in some cases improved with the exposure time, reaching a maximum value of 1 N/mm² (Fig. 10-11).

When portland cement was used for the coating A (Fig. 10), the bond strength improved as the underwater environment was replaced by a natural environment (where dry and wet conditions alternated) or even better by a permanently dry laboratory environment R.H. = 60%. When the high-alumina cement based coating was employed, the influence of humidity on the bond strength (Fig. 11) was opposite to the one described above.

It is likely that this different behaviour is related to the effect of the environment

humidity on the hydration of the residual anhydrous cement in the coating. It is possible that the completion of the hydration of the cement in the coating is more beneficial for the bond strength of coating B with high-alumina cement than for that of coating A with portland cement.

CONCLUSIONS

Coatings made from cement and aqueous emulsion of an acrylic polymer (based on 2-ethylhexyl acrylate) resist the penetration of water, carbon dioxide, chlorides and sulphate ions. This means that these coatings can be effective in the protection from the agents that normally attack concrete and rebars.

The flexibility of these polymer-cement coatings, that can bridge cracks as wide as 1 mm, remains unchanged in any environment for at least 1 year if the cement used in the coating is a portland type. On the other hand, when high-alumina cement is used, the coating loses its flexibility very rapidly under exposure to a very humid environment. Under water this type of coating becomes as rigid as the concrete substrate after only 3 months. This behaviour appears to be due to the hydration of the high-alumina cement present in the coating with a change in the proportion of inorganic (rigid) chemical bonds and polymeric (flexible) ones.

The bond strength of these coatings to the concrete substrate remains substantially unchanged with time (about 0.7 N/mm²) in most cases. However, it increases in dry environments if the coating contains portland cement, and increases in wet environments if the coating contains high-alumina cement.

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15. UNI 8019, "Determination of Sulphate Ion Penetration" (in Italian).

TABLE 1—COMPOSITION AND PROPERTIES OF THE CONCRETE

Cement	Sand	Gravel	Water	w/c	slump	Compr. Strength
CE II/A-L 42.5	(FM=2.6)	(5-20 mm)				at 28 days
310 kg/m ³	710 kg/m ³	1060 kg/m ³	215 kg/m ³	0.80	215 mm	25 N/mm ²

TABLE 2—COMPOSITION AND PROPERTIES OF THE POLYMER-CEMENT COATINGS

Ingredients:	Coating A	Coating B
Polymeric Lattice (50% 2-ethylhexyl acrylate)	25%	25%
Portland Cement CE I 32.5 R	25%	-
High-Alumina Cement (50% Al ₂ O ₃)	-	25%
Limestone (0-0.2 mm)	50%	50%
water-cement ratio*	0.50	0.50
modulus of elasticity** (N/mm ²)	228	280
strain at stress failure** (%)	24.2	23.1

* the water comes from the polymeric lattice (50%)

** measured after 28 days on specimens stored at 20°C and 60% R.H.

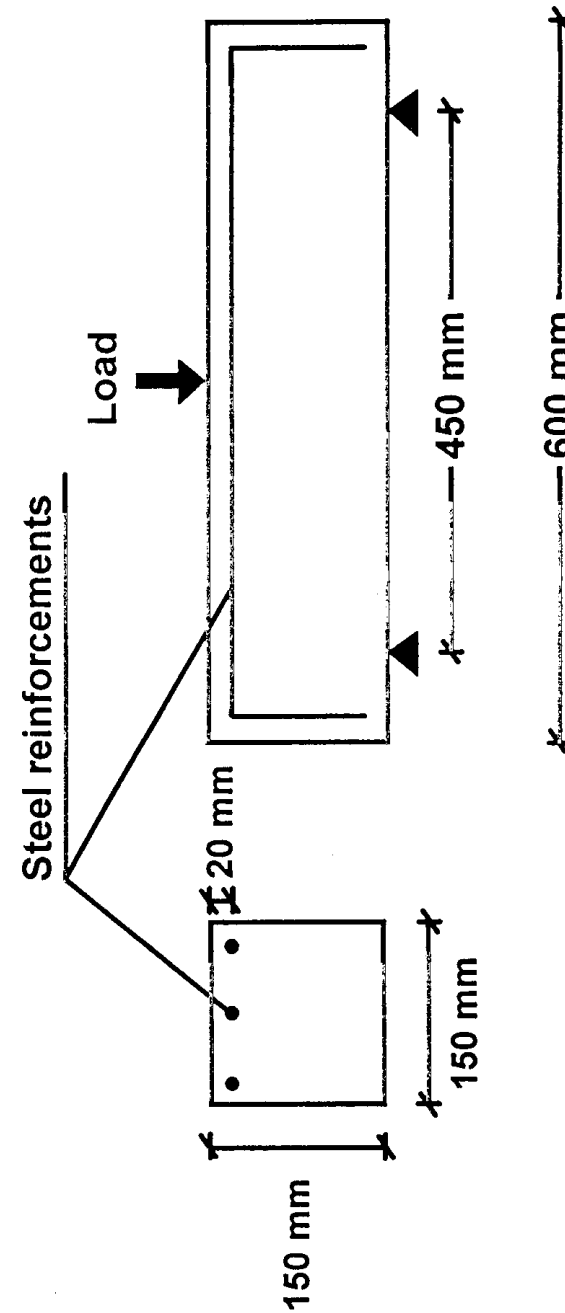


Fig. 1—Reinforced beam (150 x 150 x 600 mm)

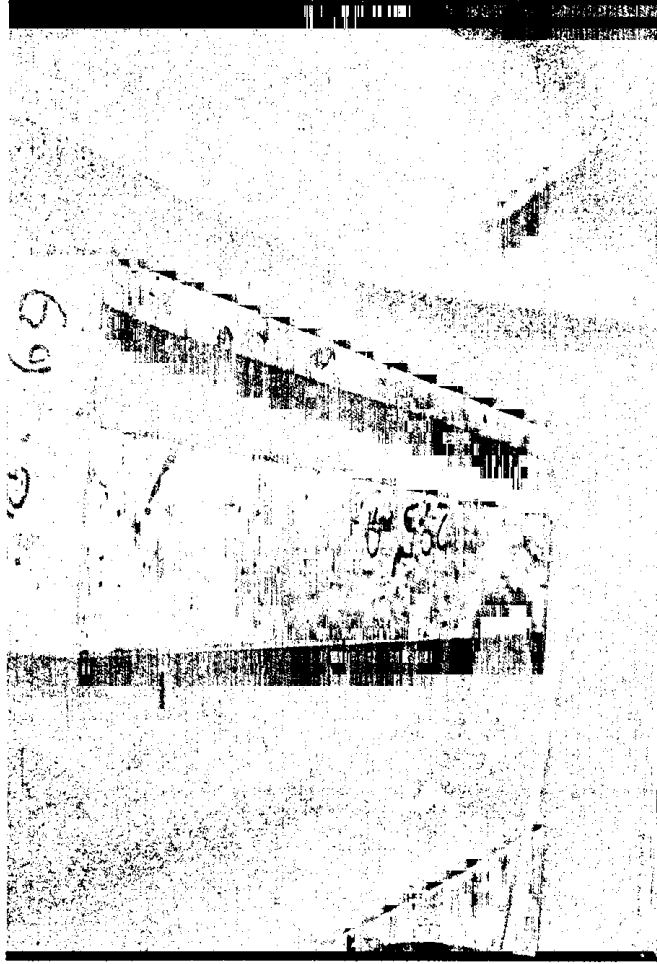


Fig. 2—Photograph of a concrete beam only partially protected by a strip (45 mm wide) of polymer-cement coating

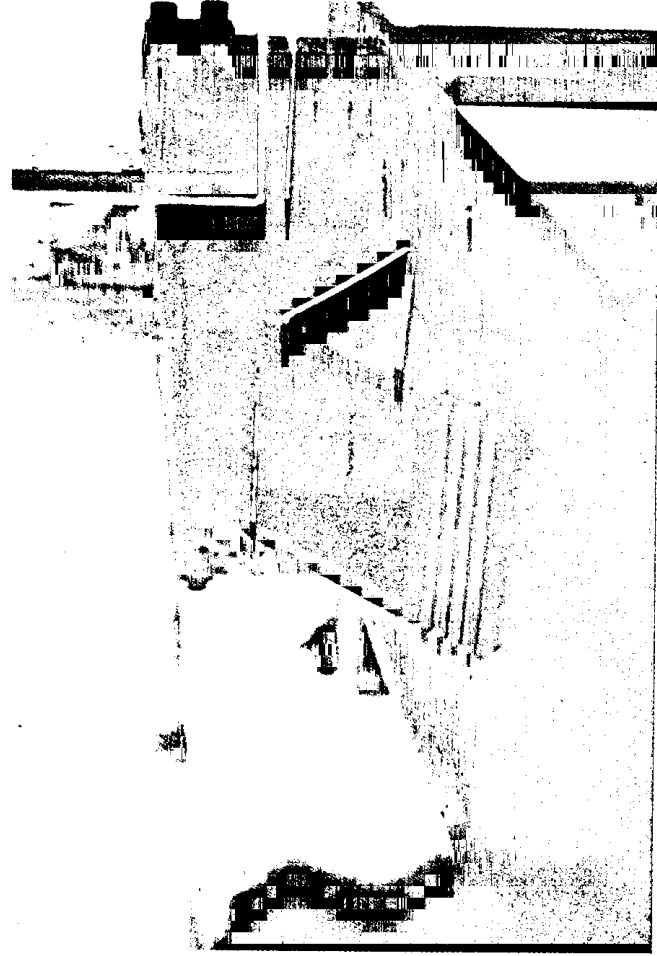
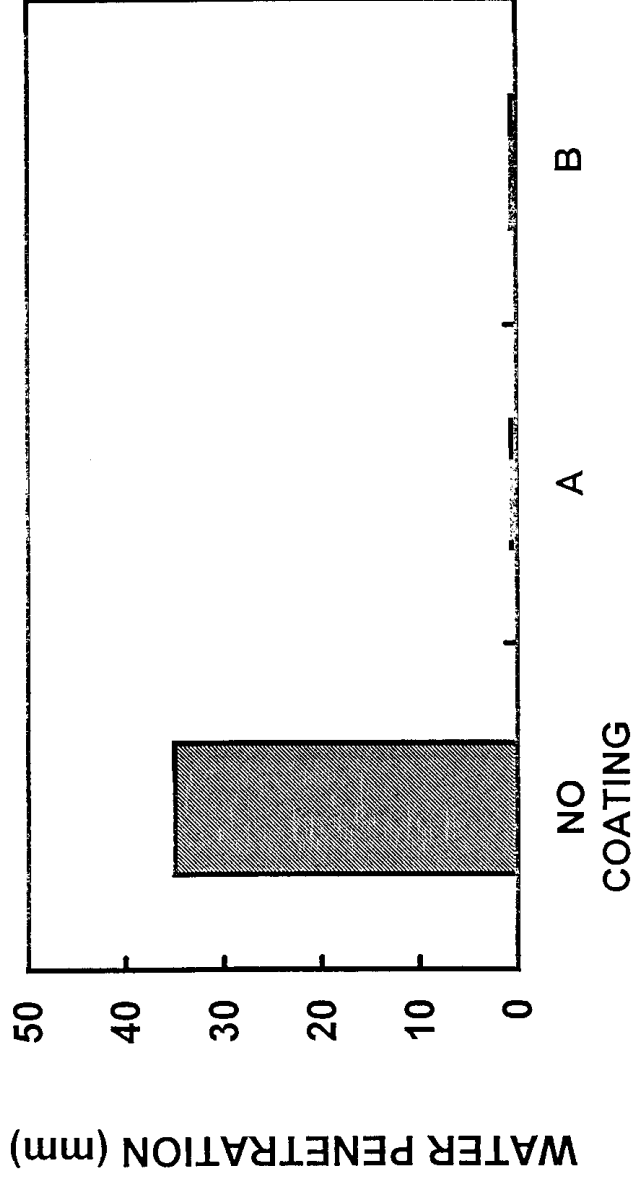


Fig. 3—Photograph of a beam during a bending test. The mirror placed under the beam allows to determine the onset of the cracking process and of the breakage of the flexible coating



FLEXIBLE COATING

Fig. 4—Penetration of water under pressure in both uncoated and coated (A or B) concrete specimens (w/c = 0.80)

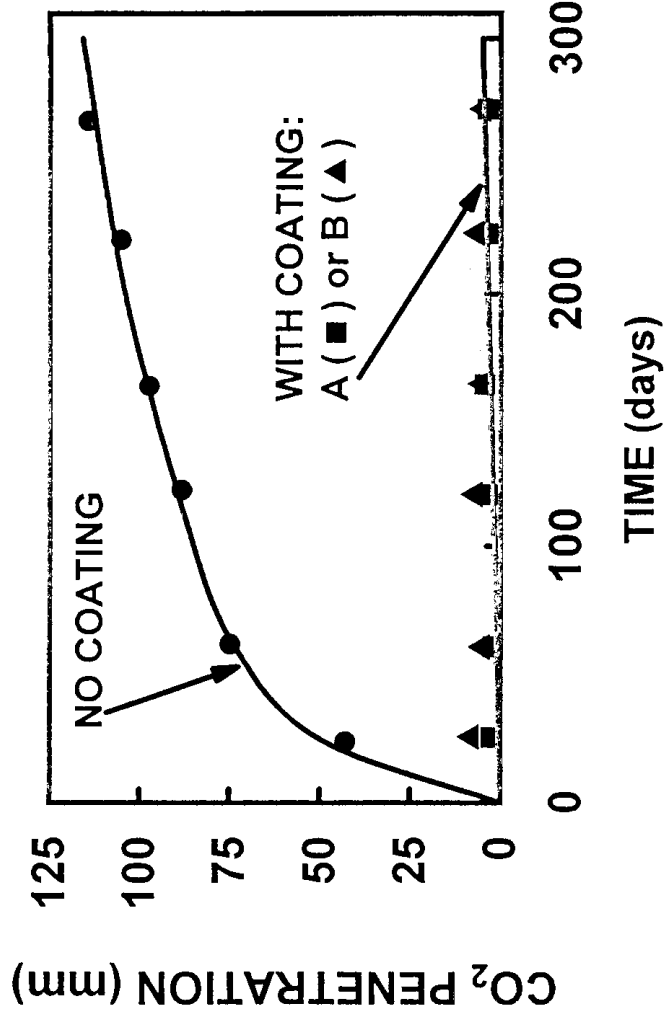


Fig. 5—Penetration of CO₂ in uncoated and coated (A or B) concrete specimens (w/c = 0.80)

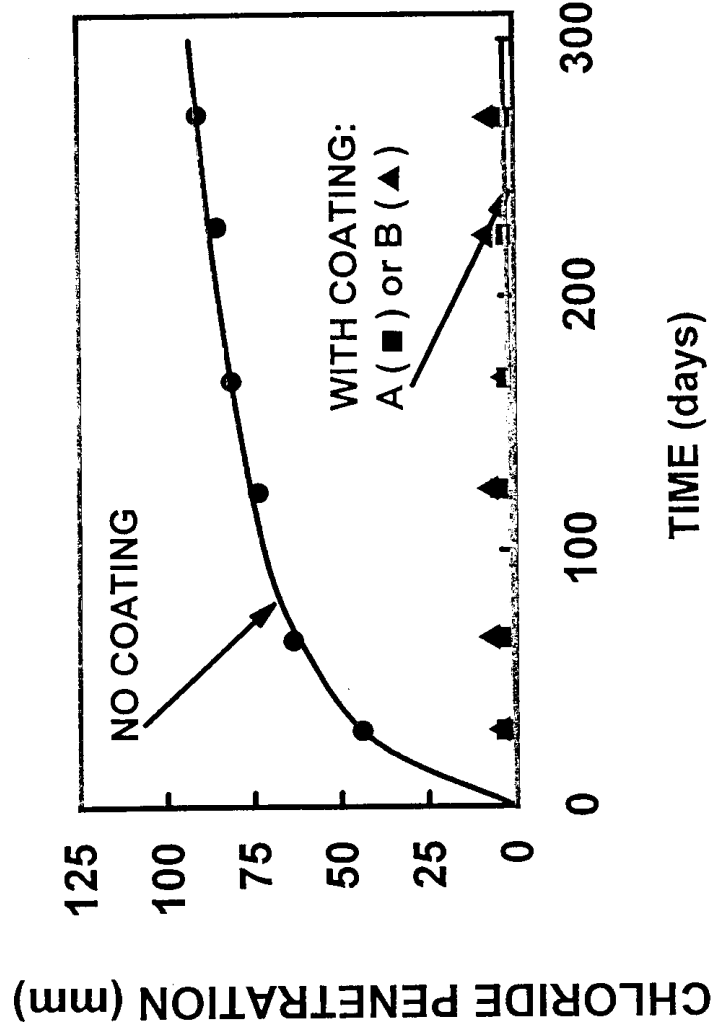


Fig. 6—Penetration of chloride in uncoated and coated (A o B) concrete specimens (w/c = 0.80)

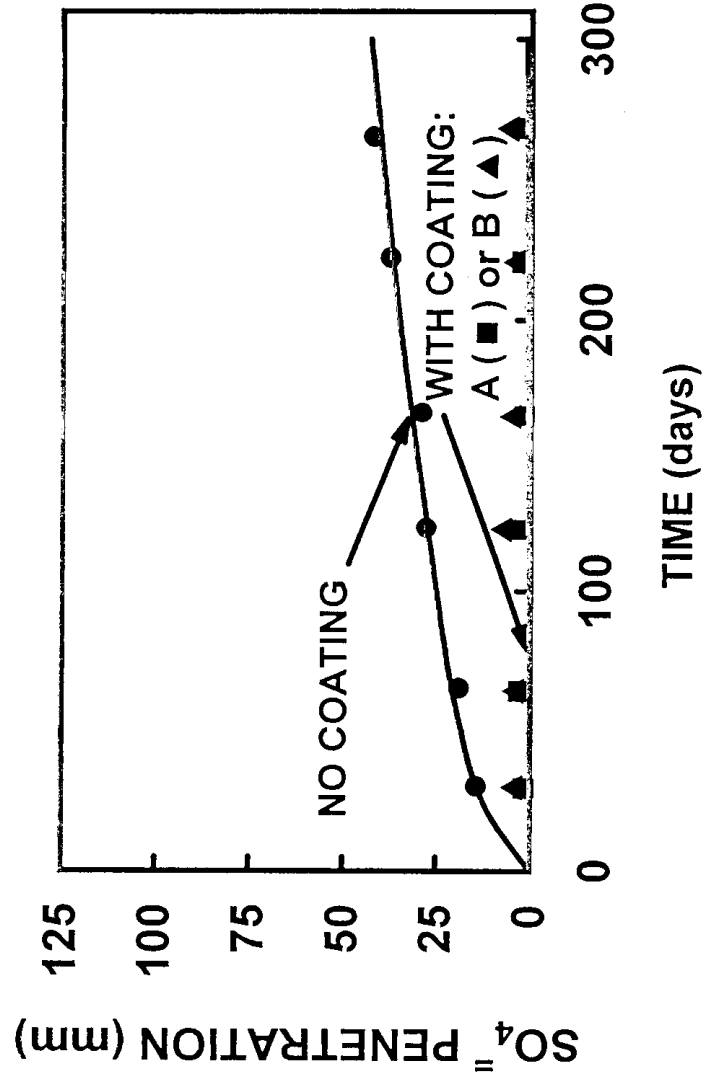
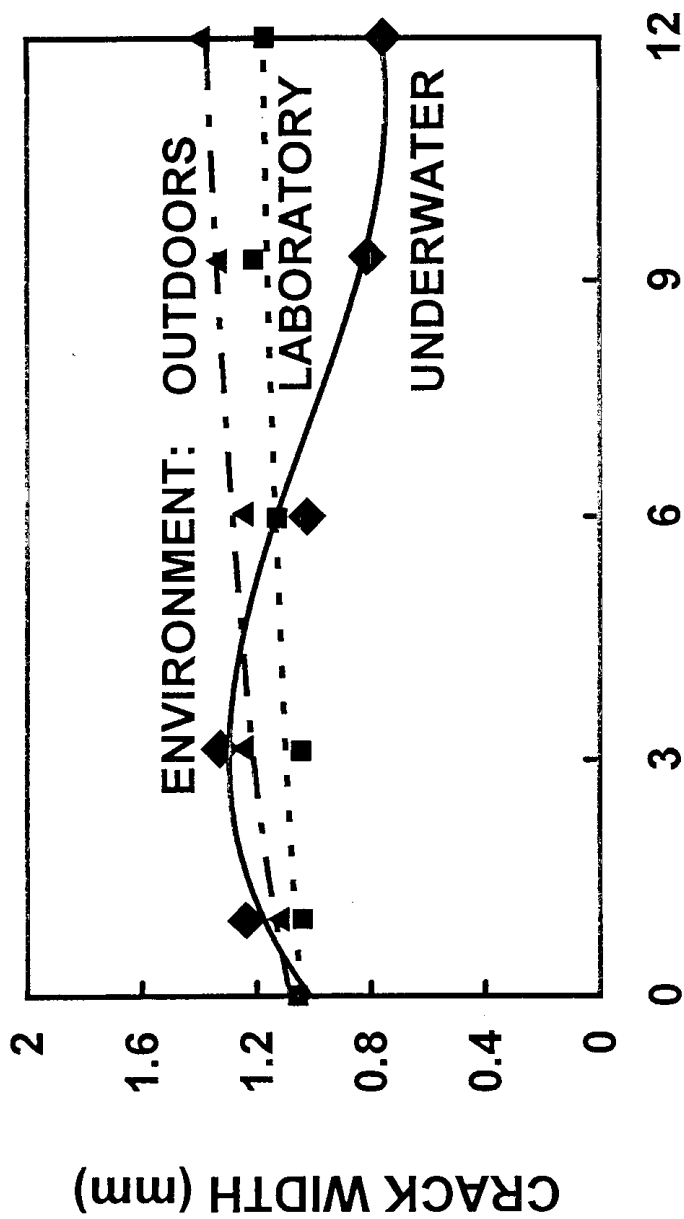
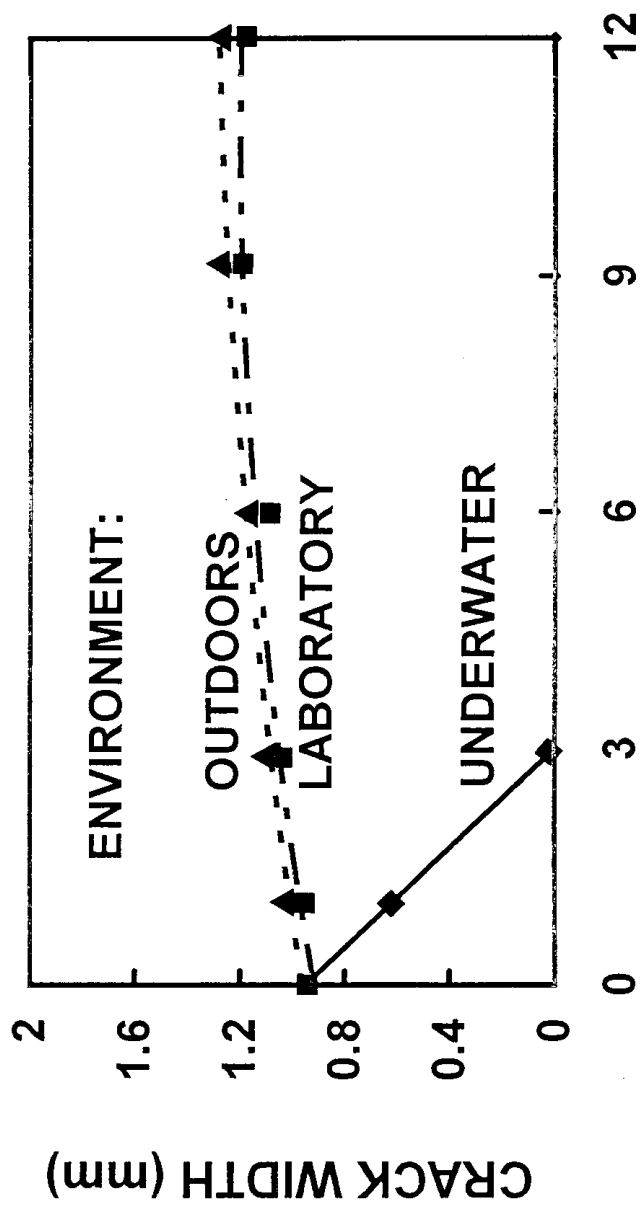


Fig. 7—Penetration of sulphate in uncoated and coated (A o B) concrete specimens (w/c = 0.80)



EXPOSURE TIME (months)

Fig. 8—Variation with exposure time of the concrete crack opening by flexural loading at the moment of breakage of the flexible coating with portland cement



EXPOSURE TIME (months)

Fig. 9—Variation with exposure time of the concrete crack opening by flexural loading at the moment of breakage of the flexible coating with high-alumina cement

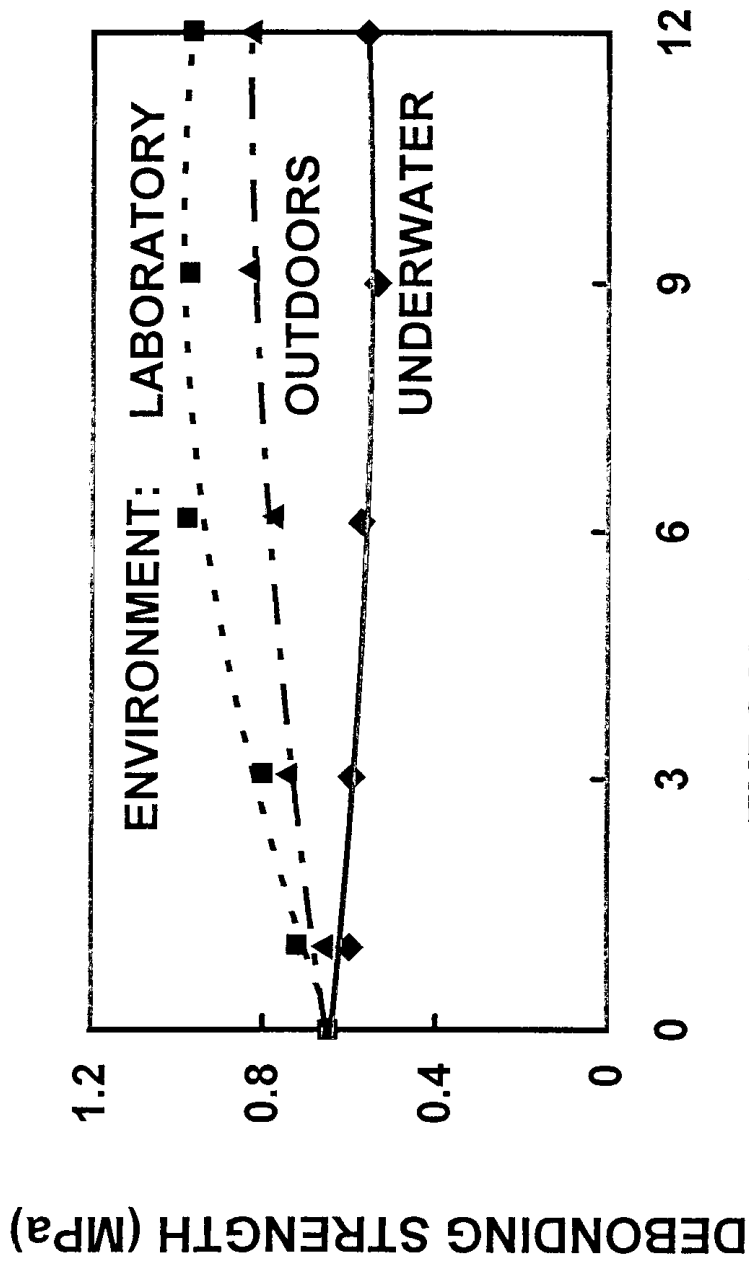


Fig. 10—Variation with exposure time of the debonding strength of coating A (portland cement) to the concrete substrate

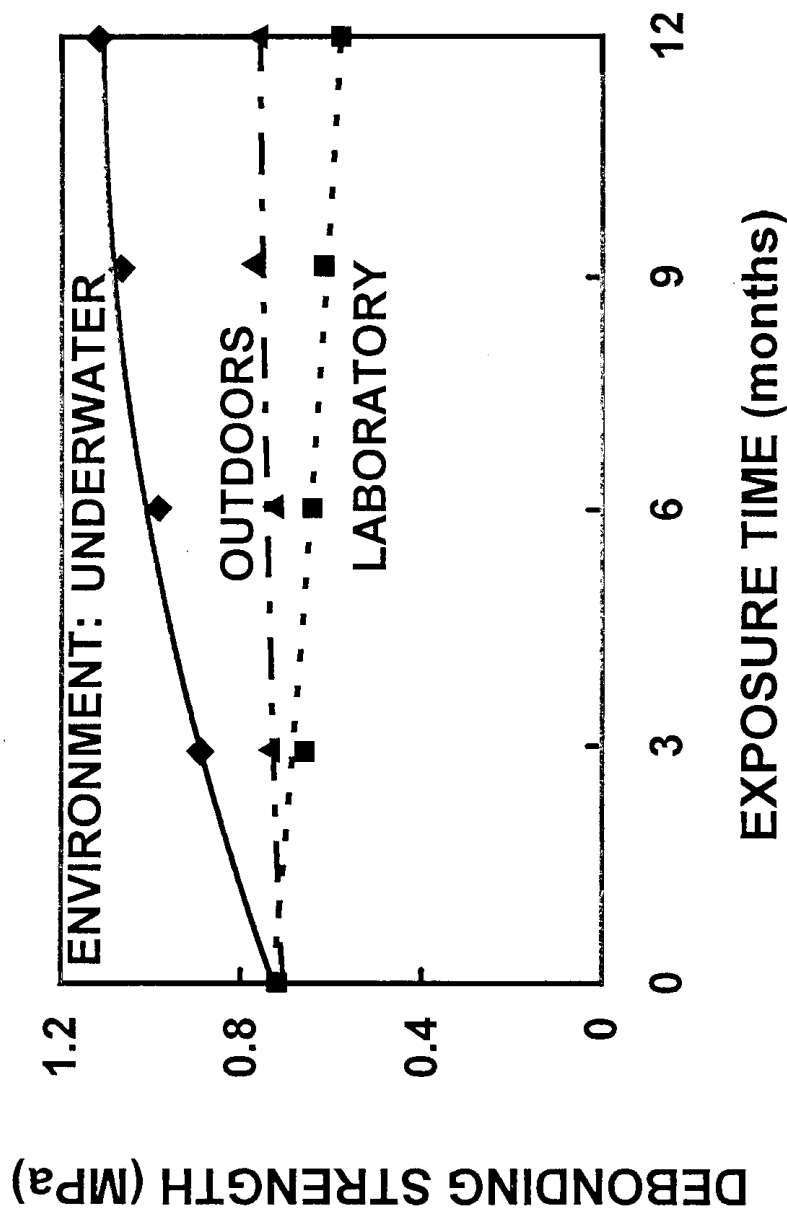


Fig. 11—Variation with exposure time of the debonding strength of coating B (High-alumina cement) to the concrete substrate