

An external surface coating to protect concrete and steel from aggressive environments

R. N. SWAMY*, S. TANIKAWA†

*Department of Mechanical and Process Engineering, The University of Sheffield, Mappin Street, Sheffield S1 3JD, UK

†Toagosei Chemical Industry Company Ltd., 1-1 Funami-cho, Minato-ku, Nagoya, Japan

Carbonation and chloride ions are known to be the two major factors responsible for the premature corrosion of steel reinforcement in concrete. Surface coatings on concrete can provide an effective and efficient protection for both concrete and the steel embedded in it, and can enhance the long-term durability of concrete materials and concrete structures exposed to aggressive environments. In practice, concrete is often cracked, and the crack-bridging ability of coatings is an important factor to be considered in evaluating their performance characteristics. Four different surface coatings were evaluated for their crack-bridging ability by tests of exposure to ozone and ultraviolet light, and for their ability to control chloride penetration and steel protection by accelerated wet-dry or continuous salt spray tests. From these results, a highly elastic acrylic rubber coating was chosen for further long-term stability tests. The data presented show conclusively that the acrylic rubber coating can prevent penetration of water, air and chloride ions, and ensure the long-term durability of steel embedded in concrete both when the concrete is free of chlorides and when it is contaminated with sodium chloride up to 1% of the mortar matrix. At high levels of chloride in the concrete, a high cover is also essential if the benefits of the surface coating are to be fully realized, and long-term serviceability of the concrete structure is to be ensured.

1. INTRODUCTION

By tradition and long experience concrete has come to be accepted as a reliable and durable construction material. It has an inherently high alkalinity, and provided reasonable care and control are exercised in the choice of materials, and in the fabrication, placement, compaction and curing of the final product, concrete has provided a safe and protective alkaline environment to the steel embedded in it. There is extensive evidence to show that in many environments, concrete has very satisfactorily and serenely withstood the effects of time, stress, unforeseen loads and unfavourable human operations. Indeed, with the passage of time, and due to no fault of the material, most people have come to treat concrete as a material that needs no maintenance, which will fulfil its function indefinitely, once the material is deposited in place.

In recent times, however, this real or imagined concept of concrete as an everlasting material has been shattered, partly due to widespread deficiencies in quality control and workmanship, but more importantly, due to the effects of aggressive agents to which it is, by necessity or otherwise, exposed, and in particular, due to the dramatic changes brought about by the industrial revolution and modern technology to the nature of our environment in which the material is constructed. Pollution of the environment has occurred progressively over several decades, and it has reached a critical stage where it is not only the serviceability of concrete construction but also the quality of human life that is being severely

impaired. When one considers the matter further, it is perhaps not that the quality of construction, *per se*, has deteriorated all that much, but that it has failed to meet the more stringent demands required of it if it is to survive, safely and economically, in the increasingly harsh urban and coastal environments.

Paradoxically, while being intrinsically protective to steel, it is the same concrete material that permits and controls the ingress of destructive agents that slowly but steadily destroy the stability of the concrete itself, and the protection it affords to the embedded steel. There are three major agents that influence the long-term performance characteristics of the concrete and lead to depassivation of the embedded steel – water, atmospheric pollutants and chloride ions. Water is probably the most critical agent, for either in liquid or crystalline form it is the common basis for many types of external and internal damage. It affects freeze-thaw durability, provides a means of transport for atmospheric pollutants and chloride ions, and establishes electrolytic continuity within the concrete material.

Concrete, like stone, is also a characteristically porous material. It is inherent in the nature of concrete construction that whatever improvements are made either to concrete itself or to the control of its quality, *per se*, they are not likely to completely prevent the ingress of potentially harmful agents into the material. Micro-cracks and micro-pores will always exist on the outer surfaces of concrete, and so long as these localized pockets of surface defects harbour as well as provide a transportation route to aggressive agents, it is only a matter of time

before atmospheric gases and chloride ions penetrate the concrete. This explains why there are at the moment a large number of concrete structures all over the world suffering from deterioration and structural distress [1,2]. This also explains why many concrete structures exposed to aggressive environmental or external agents have experienced unexpectedly earlier deterioration and loss of serviceable life than that predicted theoretically by reliability, stochastic or other models [1,2].

1.1 Surface coatings

The question that then arises is how can we protect and preserve our existing stock of structures so that they remain safe, serviceable and usable for many years to come? The obvious solution is to cut off the transportation path of these aggressive agents, and surface or barrier coatings on the concrete surface can do this efficiently, effectively and economically. There have, however, been difficulties of various kinds in their use, even though surface coatings of one kind or other, like linseed oil and epoxy resins, have been used for several years. To many engineers, the three broad categories of surface coatings, related to their diffusion characteristics, pose confusion of choice – should they use those that permit passage of gases and vapours but exclude liquids (vapour-permeable) or should they choose coatings that block passage of vapours and liquids alike (vapour barriers)? Or, would sealants that penetrate and seal the surface pores of the concrete be preferable? A similar uncertainty exists in the choice of protective systems for materials other than concrete, such as stone and marble monuments and buildings.

There also have been real technical problems in evaluating the performance characteristics of these coatings. The availability of a wide range of barrier coatings implies that there is a wide choice of coatings of similar generic type, and they are known to possess considerably different diffusion characteristics [3–10]. Further, many manufacturers and users seem to have ignored the engineering requirements of such coatings, so that many surface coatings have either failed to fulfil their intended functions or have lacked reasonable durability [11]. Whether the coatings are used on new or existing construction, concrete surfaces inevitably contain micro-pores and micro-voids which form sources of deterioration with time. More than that, all concrete surfaces are, by and large, in a cracked state, although the cracks may not always be readily visible to the naked eye. These cracks may arise from the inherent volume and thermal changes that occur during hydration of the cement, such as heat of hydration, plastic shrinkage, thermal/moisture movements or drying shrinkage, or they may be due entirely to applied stresses. Cracking may also originate from basic deteriorating processes such as freezing and thawing or alkali–aggregate reactions. It will be readily seen that the engineering requirements of surface coatings are just as important as their diffusion

characteristics, chemical resistance and weathering resistance.

This paper presents the development of a highly elastic surface coating to protect plain and reinforced concrete structures from external aggressive agents and environmental conditions. Test data are presented on the performance characteristics of the coating when subjected to a wide range of aggressive environments. It is shown that a well-designed and carefully formulated surface coating can effectively and efficiently enhance the long-term stability and serviceability of concrete structures and concrete monuments.

2. EXPERIMENTAL PROCEDURE

2.1 Acrylic rubber surface coating

The surface coating discussed here is a highly elastic acrylic rubber coating consisting of a primer, base coat and top coat [11]. The primer is a synthetic chlorinated resin with good temperature stability and bonding characteristics. The base coat is an acrylic rubber (water-type) viscous slurry material, the main component of which is 2-ethyl hexyl acrylate with excellent elasticity properties. The top coating can be of three types – the one used in the tests reported here is a two-component type, an acrylic urethane. The overall thickness of the coating is about 1100 μm .

2.2 Test programme

The test data presented here were designed to evaluate the following performance characteristics of the coating:

- (i) crack-bridging ability
- (ii) durability of crack-bridging property,
- (iii) protective effect on reinforced concrete specimens and
- (iv) long-term stability of the coating.

As pointed out earlier, it is important to examine and evaluate the performance of surface coatings in both the *natural and extended states*. When protecting concrete, the surface coating has to be able to bridge existing cracks in concrete, and still prevent the penetration of agents that cause the deterioration. To examine the durability of the coating when bridging cracks, weathering resistance tests (first series) were carried out in which test specimens were exposed to ozone and ultraviolet radiation. To assess the ability of the coating to prevent penetration of chloride ions into concrete and protect the embedded steel, accelerated tests (second series) were carried out on coated and uncoated reinforced concrete specimens subjected to dry–wet cyclic as well as continuous salt spray cycles. In assessing the performance characteristics of the acrylic rubber coating, additional comparative tests were carried out in the first and second series using three other surface coatings. The additional coatings used in these two series were a highly elastic polyurethane rubber, a highly elastic polybutadiene

rubber and an epoxy resin. Thus four surface coatings were evaluated in the first two series.

From a critical analysis of the test results on crack-bridging ability and its durability (series 1 and 2), it was clear that the acrylic rubber surface coating gave the best performance characteristics required of a coating to protect concrete and the embedded steel from external aggressive agents. The further third series of tests were therefore confined only to the acrylic rubber coating. These tests were designed to establish the long-term stability of the coating when exposed to aggressive environments. In this series coated and uncoated reinforced concrete specimens were exposed for 5 years to a hot and humid coastal environment or soaked in seawater in hot and humid conditions. In these tests, the concrete in the test specimens was made both without or with additional chlorides which were added during mixing. Thus the test specimens in this series were additionally contaminated with sodium chloride prior to exposure to outside agents.

2.3 Tests for crack-bridging ability

If a surface coating exposed to a wide range of environments, movements and stresses is to retain its function effectively and satisfactorily, it is essential that it has the ability to accommodate movements in the underlying substrate, and allow, without fracturing, the opening and closing of cracks. The test devised to examine this property was to subject the coatings to tensile forces by mounting coatings of 100 mm × 200 mm in size on a slate board, 150 mm × 250 mm × 5 mm tested in tension, and determine the maximum crack width the coating was able to bridge prior to fracture. The variable in these tests was the thickness of the base coating, which was varied from 0.2 to 2.5 mm, whilst the primer and top-coating thicknesses were kept constant at 0.03 and 0.1 mm, respectively.

2.4 Weathering resistance tests – series 1

2.4.1 Ozone exposure test

The tests in this exposure regime were carried out both with the surface coatings in their natural unextended state and with the coatings bridging cracks of various widths. Only the three highly elastic coatings, namely acrylic rubber, polyurethane rubber and polybutadiene rubber, were used in these tests since the epoxy resin was of a brittle type and unable to remain uncracked. The tests were designed to evaluate the weathering resistance of the base coat without a top-coating protection as well as of the coating as a whole with the top coat. Each of the surface coatings was therefore used either as a primer + base coat with a total thickness of about 1030 µm or as primer + base + top coat (acrylic urethane) with a total thickness of about 1100 µm. The methodology of the tests was as follows. The coatings

were applied on flexible boards of slate, 150 mm × 70 mm × 3 mm, and the coated test pieces were then subjected to tensile forces in a holding device and cracked at the centre to crack widths of 0.1, 0.3, 1.0 and 3.0 mm. The coatings, stretching over the crack widths, were then exposed to an ozone concentration of 75 pphm for 168 h at 40°C. All the areas of the test specimens except the coated surface were protected against ozone penetration.

2.4.2 Ultraviolet ray exposure test

This test was also carried out on the three highly elastic surface coatings (i.e. acrylic rubber, polyurethane rubber and polybutadiene rubber), and as before, the coatings were used either as primer + base coat or primer + base + top coat, to evaluate the base coating on its own and the coating as a whole, respectively. The test specimens used were again similar to those used in the ozone exposure tests. The coatings, stretched over crack widths of 0.1 to 3.0 mm and held under tension, were then exposed to ultraviolet radiation in a special chamber for 1000 h. To simulate rain, the test specimens were sprayed at intervals with water for periods ranging from 18 min to 2 h.

After both these and the ozone exposure tests, the coating surfaces were examined for cracks, blisters, peeling and coating breakages around the cracks.

2.5 Chloride penetration tests – series 2

The protective effect of the coatings on reinforced concrete structures and the ability to prevent penetration of chloride ions were evaluated by accelerated laboratory tests in which reinforced concrete prisms were exposed to two types of salt spray regime. The specimens for these tests were concrete prisms 55 mm × 65 mm × 150 mm in size, with a 9 mm diameter reinforcing bar embedded in the middle. The concrete mix proportions used were 1.0:2.38:2.91:0.58 (cement:sand:coarse aggregate:w/c ratio), all by weight. Normal Portland cement and river aggregates were used. The maximum size of coarse aggregates in the concrete was 20 mm. A water-reducing agent was added, and the concrete had slumps of 200–210 mm.

Both coated and companion uncoated specimens were prepared for the tests. Four surface coatings were used – the three highly elastic surface coatings as for the weathering resistance tests, and in addition, an epoxy resin (primer + base + top acrylic urethane coat) coating, all with a total thickness of about 1100 µm.

The specimens were subjected to two salt exposure regimes. In the first, a wet–dry cycle was used – the specimens were initially sprayed with a 3% sodium chloride solution for 12 h at 30°C followed by drying for 12 h at 50°C. The test was continued for 100 cycles (i.e. over 100 days). In the second regime, the specimens were sprayed continuously with 3% NaCl in water for 5000 h

at 35°C (i.e. over 208 days). The aim of these test regimes was to simulate structural deterioration due to salt in hot and humid conditions.

2.6 Long-term stability of acrylic rubber coating – series 3

The results of the accelerated weathering and salt exposure tests described later showed that the best performance was given by the acrylic rubber coating, which was able to remain intact and maintain its continuity, integrity and adhesion, particularly when subjected to aggressive weathering exposures over cracked surfaces, and also able to prevent the penetration of chloride ions. The long-term tests described below were therefore carried out only on the acrylic rubber surface coating.

2.6.1 Test specimens

The specimens for these tests were reinforced concrete prisms 200 mm × 200 mm × 300 mm consisting of twelve 16 mm diameter bars with 9 mm diameter links as shown in Fig. 1. The rebars in the prisms were high tensile deformed bars which conformed to the Japanese Industrial Standards 'Steel Bars for Concrete Reinforcement'. The main steel had covers of 20 or 30 mm. The concrete mix proportions were the same as those used for the accelerated salt spray tests. However, in addition to the normal concrete test specimens, additional specimens were made with five levels of sodium chloride added to the concrete during the mixing stage. The NaCl was added at levels of 0.2, 0.4, 0.6, 0.8 and 1.0% by weight of mortar (i.e. cement and sand). Two exposure regimes were used, and both uncoated and coated specimens were tested. The acrylic rubber coating consisted, as before, of an overall thickness of about 1100 µm.

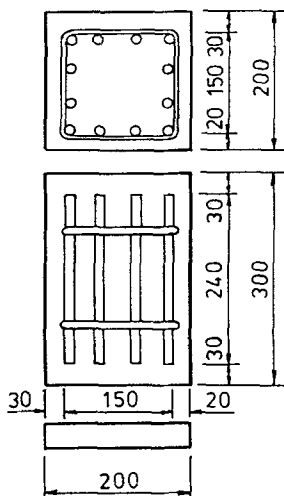


Fig. 1 Test specimens and reinforcing bar arrangement for long-term stability test (dimensions in mm).

2.6.2 Outdoor exposure test

In the outdoor test only two levels of NaCl were used, namely, 0 and 1.0%. The specimens were exposed to a hot and humid regime: they were exposed 20 m above ground and 2 km from the sea for 5 years.

2.6.3 Sea water soaking test

In this test, the coated and uncoated specimens were soaked in sea water for 5 years at six levels of NaCl, namely 0, 0.2, 0.4, 0.6, 0.8 and 1.0% (all by weight of mortar). The specimens were placed half immersed in a clear plastic vessel and covered with a clear lid to prevent vaporization and maintain high humidity.

2.6.4 Test measurements

Extensive test measurements were made as follows:

(a) Surface appearance: the specimen surfaces were inspected for blisters, rust and visible cracks, and the crack widths measured.

(b) Adhesion strength: the strength of adhesion of the coating to the concrete surface was measured in a vertical position using a tensile testing rig.

(c) Carbonation depth: the carbonation depth was measured by spraying a 1% phenolphthalein ethanol solution (containing 10% water).

(d) Corrosion damage: the corrosion damage suffered by the reinforcing bars was estimated by measuring the corroded areas and corrosion thickness.

(e) Chloride penetration: the amount of soluble chloride in the concrete was determined by a potential difference titration method using a chloride-selective electrode. About 60% of the salt content is detected as soluble chloride by this test. The test method consists of crushing the concrete matrix (particle size below 149 µm) followed by salt extraction by shaking the crushed material in hot water at 50°C for 30 min. The potential difference titration method is then used according to the JCI-SC method to quantify the soluble chloride.

3. RESULTS AND DISCUSSION

3.1 Crack-bridging ability

It was found that at a base coating thickness of 0.5 and 1.0 mm, the crack width bridged was about 2.0 and 3.5 mm, respectively, whilst at a base coating thickness of 2.5 mm, the maximum crack width bridged was over 10 mm [11].

To examine the stability of this property at various temperatures, coatings with a total thickness of about 1 mm (i.e. including primer + base coat + top coat) were tested in tension at various temperatures, and the maximum width of base coat bridging a crack at failure was determined. The results are shown in Table 1. These, and the previous data, show conclusively that the acrylic rubber coating developed in this study has the ability to

Table 1 Maximum crack width bridged at base coat failure

Temperature (°C)	Maximum crack width (mm)
-20	2.3
-10	2.7
20	3.8
60	5.2

bridge the range of cracks that normally occur and are observed in deteriorating structures.

3.2 Weathering resistance tests – series 1

The results of the exposure tests for ozone and ultraviolet radiation are shown in Table 2. In the ozone exposure test

the polyurethane rubber coating performed quite well except that at a substrate crack width of 3.0 mm, breaks and pinholes were observed in the top coat, but no cracks were found in the base coat. The polybutadiene coating performed badly – cracks and breaks appeared both in the base coat and the top coat around the centre of the specimens and at right-angles to the tensile stress direction. The top coat was only about 100 µm thick and was not expected to resist ozone penetration, but it was clear that ozone had penetrated the base coating of the polybutadiene rubber.

The ultraviolet radiation was much more aggressive to both the polyurethane and polybutadiene rubber coatings. The base coat without the top coating in both cases showed quite extensive cracking – these cracks were shaped like tortoise-shells in the polyurethane rubber whilst they appeared like stars and pinholes in the polybutadiene rubber. It was obvious that in both cases

Table 2 Degradation of surface coatings by ozone and ultraviolet light

		Highly elastic coatings					
		Acrylic rubber-type		Polyurethane rubber type		Polybutadiene rubber type	
Test	Crack width	Primer + base coat*	Base + top coat**	Primer + base coat	Base + top coat	Primer + base coat	Base + top coat
Exposed in ozone (75 ppm × 168 h)	0.1 mm					crack in base coat	
	0.3 mm						break in top and base coat
	1.0 mm						
	3.0 mm				break in top coat	break	
Irradiated with ultraviolet rays (1,000 h)	0.1 mm			cracks like a tortoise shell		cracks like stars	cracks in top coat
	0.3 mm				cracks in top coat		
	1.0 mm					cracks like stars	
	3.0 mm			breaks in base coat	holes in base coat	breaks in top coat	pinpoint hole

* Primer + base coat, no top coat. ** Primer + base + top coat. Top coat acrylic urethane in all cases.

the base coat was unable to resist ultraviolet radiation. The top coatings also cracked in the case of the polyurethane and polybutadiene rubber – as expected to some extent, since the base coats themselves were unable to withstand the ultraviolet radiation. Overall, both the polyurethane and polybutadiene rubber coatings performed worse under ultraviolet radiation than under ozone penetration. These results indicate very strongly that both these coatings are unlikely to give long-term stability and protection to a concrete surface exposed to natural weathering.

The acrylic rubber coating, on the other hand, showed excellent performance under both ozone exposure and ultraviolet radiation. No changes were observed in the coating system. The results confirm that this coating has very good crack-bridging ability, and that the coating is able to maintain its continuity, adhesion and integrity when stretched over cracked substrates and exposed to aggressive environmental attack.

The results of accelerated tests of this kind are always difficult to interpret in real-life terms. The ozone exposure test reported here represents an equivalent life of 4.4 months of continued and intense oxidation attack, whereas the ultraviolet radiation test represents about 4 years of continued exposure to sun and rain. These are sufficiently long-term, bearing in mind the difference in severity of accelerated tests and intermittent exposure in real life, to give confidence in the ability of the acrylic rubber coating to resist aggressive natural environments without suffering any damage itself. The long-term tests reported later in this paper confirm this conclusion.

3.3 Chloride penetration tests – series 2

3.3.1 Appearance and adhesion of coatings

The results of the surface inspection of the coatings and their adhesion strength after the accelerated salt spray tests are shown in Table 3. In the wet-dry cyclic test, the uncoated specimens developed cracks of 0.1 mm width. No blisters or cracks appeared in any of the coated specimens, except that the polybutadiene rubber underwent some chemical changes and turned yellow in colour. In the continuous salt spray test, both the uncoated and coated specimens showed no surface deterioration, except that the polybutadiene rubber coating again showed slight discoloration to yellow.

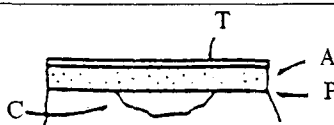
All the coatings showed good adhesion strength after both types of accelerated tests. The epoxy resin had the highest adhesion strength of 2.52 and 2.81 MPa, respectively, in both the accelerated tests. This was followed by polybutadiene rubber (2.2 and 1.62 MPa) and the acrylic rubber coating (1.63 and 1.18 MPa), respectively. The polyurethane rubber had the least adhesion strength of 0.94 and 0.63 MPa, respectively. The nature of the coating failure during the adhesion strength test is also shown in Table 3. With its very high adhesion strength, the failure with the epoxy resin coating occurred in the concrete, whilst with the other three highly elastic coatings failure occurred at various points and interfaces depending on the nature of the coating and the exposure. It is, however, to be emphasized that all the surface coatings had adequate adhesion strength, and there was no degradation of adhesion by exposure to salt sprays.

Table 3 Appearance and adhesion strength after accelerated salt spray tests ($1 \text{ N/mm}^2 = 9.81 \text{ kgf/cm}^2$)

	Accelerated test						
	(A) Dry-wet cycle 100 cycles (over 100 days)			(B) Salt spraying test 5000 h (over 208 days)			
	Appearance	Adhesion strength		Appearance	Adhesion strength		
Strength (kgf/cm ²)		Peeling point	Strength (kgf/cm ²)		Peeling point		
Non-coated specimen	△ 0.1 mm cracks	—	—	○ no change	—	—	
Coated specimen	Acrylic rubber	○ no change	16.3	A	○ no change	11.8	T
	Polyurethane rubber	○ no change	9.4	T	○ no change	6.3	T
	Polybutadiene rubber	△ coloured in yellow	21.9	A	○-△ slight coloured in yellow	16.2	P
	Epoxy resin	○ no change	25.2	C	○ no change	28.1	C

Note:
Peeling point

C; break of
surface
concrete



T; Peeling between top and base coat
A; breakage of base coat
P; Peeling between base coat and primer

Further, the acrylic, polyurethane and polybutadiene rubber coatings maintained good residual elasticity properties.

3.3.2 Chloride penetration and rebar corrosion

Figure 2 shows the chloride penetration profile in the uncoated and coated specimens after the two accelerated salt exposure tests. The results show that all the surface coatings were extremely effective in preventing penetration of chlorides into the concrete. There are minor differences between the coatings in the amount of salt penetrating the concrete, but these are sufficiently small to be negligible and to emphasize the high ability of these coatings in protecting concrete when exposed to salt-laden environments.

The chloride penetration tests were followed by evaluation of the extent of corroded areas in the rebars embedded in the concrete prisms in the two types of salt exposure tests. These results are presented in Table 4. The uncoated prisms showed corroded areas of 85 and 61% in the cyclic and continuous spray tests, respectively. The epoxy resin coating showed the best performance, whilst the acrylic rubber coating showed small corroded areas of 3 and 7%, respectively. The polyurethane and polybutadiene surface coatings were also very effective, showing corroded areas of 5 to 10% in the two salt exposure regimes. In general, the data on corroded areas in Table 4 follow the same pattern as the data on chloride penetration profiles shown in Fig. 2. There is thus a close

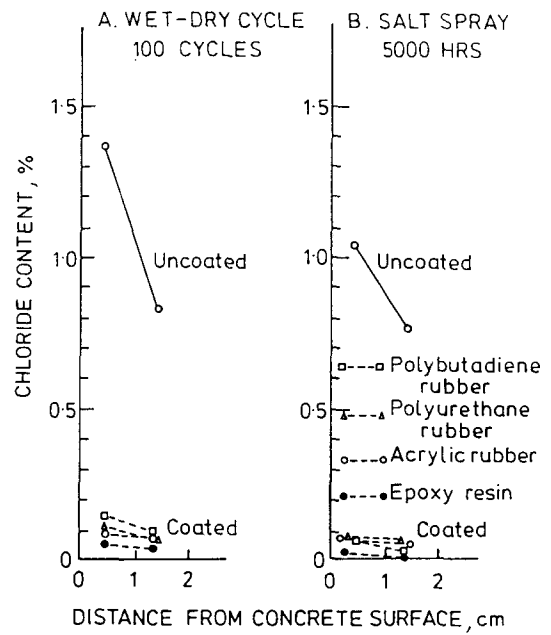


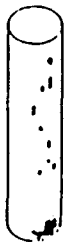





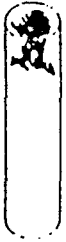
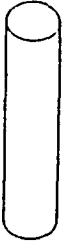


Fig. 2 Chloride penetration profile in uncoated and coated specimens after accelerated salt spray tests.

interrelationship between chloride penetration and rebar corrosion.

The accelerated salt exposure tests confirm that surface coatings on concrete have a very important role in resisting chloride penetration into concrete from outside, and in protecting the embedded rebars from corrosion. The wet-dry cyclic test was generally found to be more

Table 4 Corrosion of reinforcement after accelerated salt spray tests

		Specimens				
		Non-coated	Acrylic rubber coating	Polyurethane rubber coating	Polybutadiene rubber coating	Epoxy resin coating
Accelerated test						
	Dry-wet cycle test 100 cycles (100 days)					
	Appearance					
	Corroded area (%)	85	3	10	5	1
Salt spraying test 5000 h (208 days)						
	Appearance					
	Corroded area (%)	61	7	10	10	0

stringent and rigorous in evaluating the coatings – it caused 0.1 mm wide cracks in concrete, corroded the reinforcing bars about 1.4 times faster, and let the chlorides penetrate about 1.3 times faster in half the continuous spraying time.

The accelerated weathering and salt spray tests indicated the following performance characteristics of the surface coatings tested in this study. The epoxy resin coating had excellent resistance to salt penetration and protected the embedded steel extremely well. It had also very good adhesion strength to concrete, but it is brittle in nature and unable to bridge wide cracks in the concrete substrate. The polyurethane and polybutadiene coatings were also good in preventing chloride penetration and protecting the embedded steel, and they had good adhesion properties to concrete. However, they had relatively poor resistance to oxidation, sunshine and rain, and are likely to fail under continued exposure to natural environments. The acrylic rubber coating showed very good resistance to natural weathering and chloride penetration, and also had sufficiently high elasticity and adhesion strength to give durable long-term performance.

3.4 Long-term stability of acrylic rubber coating – series 3

3.4.1 Appearance and adhesion

The results of the surface inspection of the coatings, together with the adhesion strength tests after 5 years of outdoor exposure or sea water soaking, are shown in Table 5. The uncoated specimens without added chlorides in concrete and exposed outside showed no cracking, whereas those soaked in sea water showed some cracking. Uncoated specimens with chlorides in the concrete mix showed (with one exception, Table 5) various degrees of cracking. Most of these cracks occurred along the 16 mm diameter main reinforcement, but in many cases additional random cracking also occurred. The reinforcement cover had a clear and distinct effect on these surface cracks, the intensity and width of cracks being generally lower for the 30 mm cover than for the 20 mm cover. At 20 mm cover, the crack widths ranged from 0.3 to 1.5 mm, and at 30 mm cover, the crack widths ranged from 0.4 to 1.2 mm after 5 years' exposure to sea water. Specimens exposed outside showed crack widths of 0.8 and 0.4 mm, respectively, for 20 and 30 mm cover.

Table 5 Appearance, carbonation depth and adhesion strength of acrylic rubber coating after 5-year exposure tests

		Soaking test in sea water						Exposure outdoors (Nagoya)	
		Content of NaCl (%)							
Concrete cover (mm)		0	0.2	0.4	0.6	0.8	1.0	0	1.0
Non-coated RC(II) specimens	20								
	Crack width (mm)	0.4 ~ 1.2	0.8	0.5 ~ 1.2	0.3 ~ 1.2	0.6 ~ 0.7	1.0 ~ 1.5	no change	0.8
	30								
	Crack width (mm)	1.0	0.4	1.2	0.5	no change	0.5	no change	0.4
	Carbonation thickness (mm)	5.3	4.7	4.9	7.2	4.5	6.9	7.6	8.9
Acrylic rubber coated RC(II) specimens	Appearance	○	○	○	○	○	○	○	○
	Carbonated thickness (mm)	0	0	0	0	0	0	0	0
	Adhesion strength (kgf/cm ²)	15.9	16.2	15.8	15.1	15.5	15.2	16.6	17.1

The quantity of salt present in the concrete mix prior to exposure had also a distinct effect on the degree and intensity of cracking. Increased salt content increased the extent of cracking, although because of the random nature of cracking, there can be no quantitative relationship between the two. There was, however, clear evidence that chlorides already present in the concrete prior to exposure can have a more devastating effect on the integrity of the concrete than when it is uncontaminated by chlorides.

The acrylic rubber coating showed no blisters, peeling or cracking after 5 years of severe exposure conditions, even when the concrete contained up to 1.0% NaCl, and the specimens were soaked in sea water (Table 5). This result is very significant in two respects – firstly, the coating prevented the ingress of water, chloride ions and oxygen into the concrete after 5 years' exposure, and secondly, the coating restricted and contained, without any external visible distress, any corrosion activity that might have occurred within the concrete specimens containing chlorides. As shown later in this paper, various degrees of internal corrosion activity did indeed occur in specimens containing high chloride contents (0.8 to 1.0%); but in spite of this, the coating was able to contain and restrict this activity without external visible surface damage in both the external exposure and sea water soaking regimes. Another important aspect was that no cracks were observed on the concrete surface itself of the coated specimens when examined after the tests.

The adhesion strength of the coating to the concrete substrate was measured after 5 years' exposure to both regimes (Table 5). The average adhesion strength varied from 1.51 to 1.62 MPa in the soaked specimens and from 1.66 to 1.71 MPa in the outdoor exposure specimens. Previous data [11] confirmed that these are high values, and the fact that the surface of the coating showed no adverse effects of exposure such as blisters, cracking or peeling emphasized the integrity, excellent adhesion and film continuity of the coating under severe exposure conditions.

3.4.2 Resistance to carbonation

The resistance to carbonation of surface coatings applied to concrete has been investigated both by outside exposure tests in the Gulf area [8] and by accelerated laboratory tests [7,9]. Carbonation is a slow process, and when concrete is exposed to real natural environments it takes several years for the carbonation front to penetrate even a few millimetres [8,12]. Accelerated carbonation tests on fresh coatings where exposure of the concrete or mortar is limited to 12 to 14 days only [7,9] can then be misleading, because such an accelerated test does not take into account the damage which some surface coatings may suffer by prolonged exposure to natural weathering as shown in this study.

The effectiveness of the acrylic rubber surface coating in controlling the ingress of the carbonation front was

therefore evaluated from the 5-year exposure tests. The results are shown in Table 5. During this period the uncoated specimens partially soaked in sea water showed carbonation thicknesses of 4.5 to 7.2 mm whereas those exposed outside showed carbonation depths of 7.6 to 8.9 mm. The progress of carbonated thickness in the outdoor exposure test was faster, as would be expected, than that in the soaking test. The coating, on the other hand, completely prevented the penetration of carbonation into concrete in both exposure regimes: the coated specimens showed no carbonated thickness in any of the specimens, without or with added chlorides.

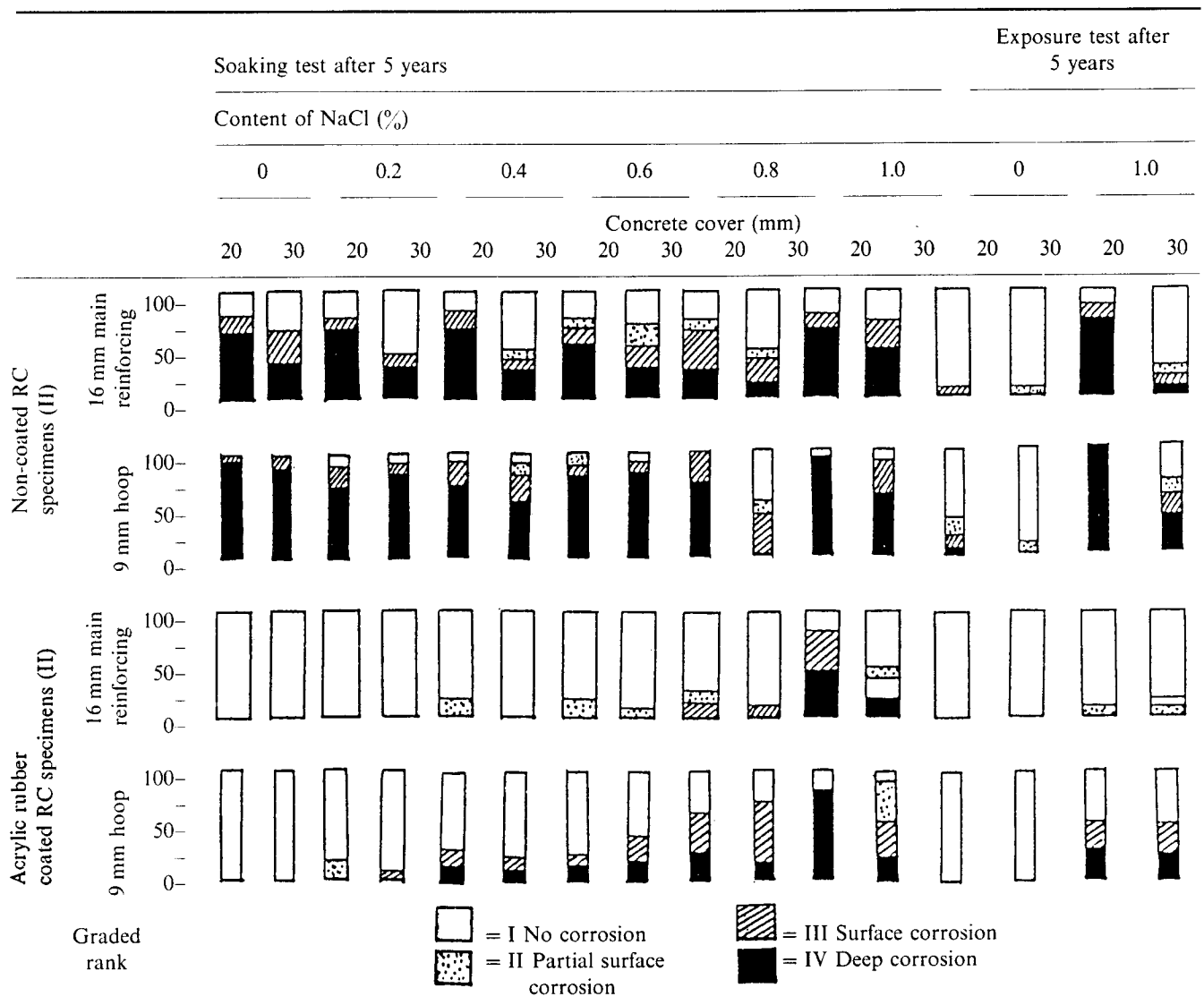
3.4.3 Rebar corrosion

The status of the rebar corrosion was carefully and extensively assessed in all the exposed specimens. To have some quantitative evaluation of the extent and degree of corrosion, both the main rebars and the links were graded into four categories from 'no corrosion' to 'deep corrosion'. The data obtained from this analysis on all exposed uncoated and coated specimens with different concrete covers are summarised in Table 6.

In the outdoor exposure test, the uncoated specimens without added chlorides showed very little corrosion, the corroded area being about 5% of the total area. The presence of 1% added chloride in the concrete during mixing, on the other hand, led to extensive corrosion on the rebars – about 85 and 25% corroded areas were observed on specimens with covers of 20 and 30 mm, respectively. These data are very significant from the point of view of general corrosion of inshore concrete structures. The presence of chlorides in the concrete has an undoubted accelerating effect on rebar corrosion. Further, the cover to steel has also an equally important influence. These results show that even a 30 mm cover is inadequate to protect the steel in concretes uncontaminated by salts but exposed to a salt-laden environment.

In the sea water soaking test, the uncoated specimens without added chlorides performed no better than those with added chlorides, implying that whether the concrete is initially contaminated with chlorides or not, the continuous availability of water-borne chlorides in the immediate vicinity of concrete would in time result in the penetration of chlorides into concrete and cause rebar corrosion (Table 6). The corroded areas in the uncoated specimens both without and with 0.2 to 1.0% added chloride were more than 70% where the cover to steel was restricted to 20 mm, but this was substantially reduced to about 40% when the cover was increased to 30 mm. Analysis of data at intermediate stages during the 5 year exposure life, but not reported here, showed that although the specimens with added chlorides exhibited increased rates of corrosion during early stages, in proportion to the amount of salt added, this influence became less apparent with the passage of time. Thus with continued exposure, and after long-term soaking, the rebar corrosion in the specimens without chlorides progressed in a very similar manner to that in specimens

Table 6 Extent of corrosion of reinforcement in uncoated and coated specimens after 5 years' exposure



with added chlorides. These data have profound significance for our understanding of the diffusion rate of chlorides in concrete, and this will be discussed elsewhere.

It was reported earlier in this paper that uncoated specimens soaked in sea water had shown various degrees of cracking. These cracks in the concrete were obviously the result of expansion of the corroded steel as discussed above.

The coated specimens without chlorides exposed to either regime for 5 years showed no corrosion of the rebars. Specimens with up to 0.8% added chloride showed little corrosion in the main reinforcement, whereas the links (which had 21 and 11 mm covers, respectively) showed some grade IV corrosion. At 1% chloride, the observed corroded area in the main rebars amounted to some 15%. The links showed much higher corrosion.

The diagrammatic representation of the degree of corrosion in the main bars and links of the exposed prisms shown in Table 6 is clear evidence of the excellent protection given by the acrylic rubber surface coating to rebar corrosion. At very high levels of chloride con-

tamination of 0.8 and 1% NaCl, however, rebar corrosion cannot be expected to be prevented by the provision of a surface coating to the concrete. Nevertheless, the results of Table 6 indicate that even in such cases, the coating can act as an effective controller of corrosion by limiting the ingress of water and oxygen, and provided adequate covers exist, the acrylic rubber surface coating applied to an existing salt-contaminated concrete structure can bring advantages by limiting and slowing down the progress of rebar corrosion. This is confirmed by the results of the chloride profile discussed below.

3.4.4 Chloride distribution in concrete

3.4.4.1 Outdoor exposure tests

Figure 3 shows the chloride profile after 5 years' exposure to outdoor environments. The diffusion of chlorides through the different layers of concrete shown in Fig. 3 was quantified by sampling the concrete at different depths, and determining the amount of soluble chloride

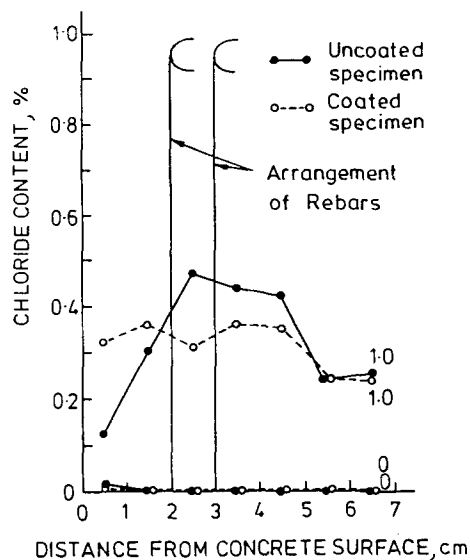


Fig. 3 Chloride distribution profile in uncoated and coated specimens after 5 years' outdoor exposure (numbers refer to % of NaCl).

by the titration test described earlier. The results show that there was little or no penetration of chloride during this period in both uncoated and coated specimens without chlorides. These specimens were located at a distance of 2 km from the sea, and it was obvious that at this distance there was little water- or air-borne chloride to penetrate concrete during the 5-year exposure period. For the uncoated specimens containing chlorides added during mixing, the distribution of chlorides within the body of the concrete was non-uniform: there was a reduction in the concentration of chlorides immediately behind the external surface, but there was increased concentration at the level of the rebars 20 to 30 mm from the surface. Obviously there has been some leaching of chloride ions towards the external surface, and being exposed to outside environment, there has also been some washing out of the chlorides by rain, causing a reduction in chloride concentration near the boundaries.

Figure 3 also shows that for the coated specimens with 1% added NaCl, there was a more uniform distribution of chlorides within the body of the concrete. There was also no evidence of chloride concentration in the vicinity of the rebars. Exposure to an outside environment with little water- or air-borne chloride cannot obviously show the effectiveness of the coating in preventing salt penetration. In such an environment, the contribution of the coating as shown in Fig. 3 is that it prevents the salt concentration from peaking around the reinforcement by excluding the effects of rain-wash at the surface and salt condensation on the inside.

3.4.4.2 Sea-water soaking tests

Figure 4 shows the distribution of chlorides in the uncoated and coated specimens partially soaked in sea water. In the uncoated specimens with no added chlorides during mixing, there has clearly been penetration of

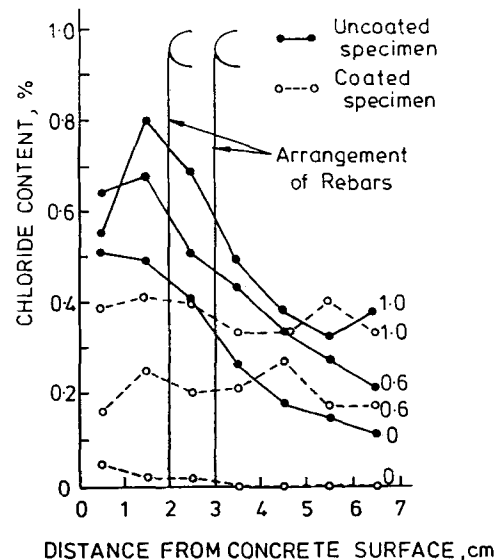


Fig. 4 Chloride concentration profile in uncoated and coated specimens after 5 years' exposure to salt environment (numbers refer to % of NaCl).

chloride ions, and the chloride profile largely follows the diffusion process. In concretes with 0.6 and 1% NaCl, there was chloride concentration in the vicinity of the rebars, partly due to salt penetration from outside, and partly due to inner transport of the chloride ions already contained in the concrete mix. The peak concentration of chloride ions occurred not at the external surface, but at some 15–18 mm from the surface.

In the coated specimens with no added chlorides, the salt content beyond 10 mm from the surface was practically nil, confirming that the acrylic rubber surface was able to prevent the transport of chlorides into the concrete from the surrounding sea water. In concretes containing 0.6 and 1.0% added NaCl, on the other hand, there was a more uniform distribution of chlorides within the body of the concrete, and there was no concentration of chlorides at the rebar level, as found in specimens subjected to outside exposure. From the quantitative values of chlorides in these two sets of specimens, it is also clear that the coating has also prevented the ingress of chlorides from the surrounding sea water. A comparison of the chloride profiles in the coated specimens containing 1.0% salt in the concrete mix, and subjected to the two exposure regimes shown in Figs 3 and 4, indicates the same order of chloride content in both cases, emphasizing the effectiveness of the coating as a barrier to the infiltration of chloride ions into concrete from outside.

Figures 3 and 4 thus provide excellent evidence of the effectiveness of the acrylic rubber surface coating in preventing chloride penetration into concrete. The results in these two figures show two distinct roles of this surface coating. Firstly, it acts as an efficient and effective barrier preventing the penetration of chlorides into concrete. Secondly, the coating also enables and permits a more uniform distribution of chloride ions in concrete already contaminated by chlorides. By encouraging this internal

Table 7 Comparison of chloride ion intrusion from outside uncoated and coated concrete specimens after 5 years' exposure to salt environment

Depth (mm)	Chloride ion concentration (%)		Chloride penetration ratio (uncoated/coated)
	Uncoated	Coated	
0-10	0.52	0.05	10.4/1.0
10-20	0.49	0.02	24.5/1.0
20-30	0.41	0.02	20.5/1.0
30-40	0.27	0.00	0.27/0.0
40-50	0.18	0.00	0.18/0.0
50-60	0.15	0.00	0.15/0.0
60-70	0.12	0.00	0.12/0.0

movement of chlorides, any concentration in the vicinity of the rebars has been prevented.

The data in Figs 3 and 4 highlight one of the outstanding properties of the surface coating reported here. The uniqueness of this coating is that it contains a lot of acrylic resin rubber which has a very low chloride ion diffusion coefficient [11], enough to prevent the intrusion of chlorides into concrete. To clarify this property, values of the percentage chloride distribution in the uncoated and coated specimens without added salt in the concrete, and exposed to a high salt environment (such as sea water), are extracted from Fig. 4 and collated in Table 7. The ratio of the salt penetration in the uncoated to that in the coated specimens is a measure of the intrusion of chlorides into concrete from an outside environment, and the data in Table 7 show the outstanding resistance of the acrylic rubber coating to chloride penetration.

3.4.5 Cover depth to rebar

Cover depths of 20 and 30 mm to main steel, and of 11 and 21 mm to links, are blatantly inadequate for reinforced concrete specimens exposed to aggressive environments like those used in this study. These cover depths were nevertheless knowingly adopted in this investigation to assess the relationship between the acrylic rubber coating developed here and an acceptable concrete cover to steel. The data presented in Table 6 and Figs 3 and 4 show that in spite of the very small covers, the acrylic coating was fully and completely effective in preventing chloride penetration from outside and protecting the embedded steel after 5 years of exposure in those specimens which had no added salt in the concrete mix. This was also true even where the concrete was initially contaminated with small amounts of chloride of the order of 0.2 to 0.4%.

However, at higher levels of salt in the concrete mix, of 0.6 and 1.0%, there was unacceptable corrosion in the rebars – in the main steel at 1.0% salt content and in the links at 0.4 to 1.0% salt. A critical analysis of data such

as those given in Figs 3 and 4 and Table 6 leads to the conclusion that this high degree of corrosion in embedded steel was caused not by the lack of effectiveness of the coating, but by the presence of chlorides and the lack of adequate cover to the steel. This is further confirmed by the data in Table 6 which show that in almost all cases, with either type of exposure, steel with the higher cover performed far better and suffered much less corrosion than steel with the lower cover.

It is thus concluded that the acrylic rubber coating described in these tests can effectively protect reinforced concrete structures having low covers to steel and exposed to aggressive environments, provided the concrete is not initially contaminated by salt or where such contamination is low. When the concrete is likely to contain high levels of chloride at the fabrication stage, of the order of 1.0%, a coating can still be very effective not only in preventing penetration of chlorides into concrete, but also in preventing high concentrations of chlorides in the vicinity of the rebars, and achieving a more uniform distribution of chlorides already present in the concrete.

Excessive damage to the structure from the embedded salt can thus be prevented, provided there is adequate cover to the steel, but the long-term serviceable life of such a structure will be dictated by the cover to the steel and the level of chlorides already in the concrete. Concrete cover to steel is thus an important factor in the corrosion process of steel in concrete, and cannot be treated as an irrelevant parameter even where the concrete or steel itself is protected with a surface coating [13].

4. CONCLUSIONS

From the extensive test results presented here, the following conclusions can be drawn.

1. The crack-bridging ability of surface coatings for applications on concrete surfaces is an important engineering requirement. Natural exposure tests need therefore be carried out with the coatings stretched over cracks.
2. The polyurethane rubber coating under these conditions withstood exposure to ozone quite well but suffered extensive cracking when exposed to ultraviolet radiation. The polybutadiene rubber coating performed very badly under both exposures. These results indicate strongly that these surface coatings do not possess adequate crack-bridging ability, and are unlikely to give long-term stability and protection to concrete exposed to natural weathering.
3. The acrylic rubber coating showed excellent performance and crack-bridging ability under exposure to both ozone and ultraviolet radiation. The coating maintained its continuity, adhesion and integrity when stretched over cracked substrates (bridging cracks up to 3 mm) and when exposed to accelerated natural weathering.

4. The accelerated exposure tests represent a sufficiently long-term equivalent life in real exposure conditions to give confidence in their long-term performance.

5. Under accelerated salt spray tests, all the surface coatings remained intact without blisters and cracks, except that the polybutadiene rubber suffered some chemical changes and showed slight yellow discoloration.

6. All the coatings maintained very good adhesion to concrete after accelerated wet-dry cyclic or continuous salt spray tests. There was no degradation of adhesion by exposure to salt spray tests.

7. All the highly elastic rubber coatings and the epoxy resin were extremely effective in preventing penetration of chlorides into concrete when subjected to accelerated salt spray tests.

8. Measurement of corroded areas in the rebars embedded in the concrete prisms showed that with all the surface coatings, the extent of corroded area after the salt spray tests was 10% or less. Both the epoxy resin and the acrylic rubber coating showed excellent performance, slightly superior to that of the polyurethane and polybutadiene rubber coatings.

9. Uncoated specimens exposed for 5 years to a coastal environment or soaking in sea water under hot and humid conditions, and containing added chlorides in the concrete mix prior to exposure, showed various degrees of cracking. Both the cover to the steel and the amount of chloride in the concrete had a distinct effect on the intensity of cracking.

10. The acrylic rubber coating showed no blisters, peeling or cracking after 5 years' exposure under these conditions, even when the concrete contained up to 1% NaCl by weight of mortar.

11. The adhesion strength of the acrylic rubber coating to the concrete substrate after 5 years' exposure varied from 1.5 to 1.7 MPa. There was evidence of excellent adhesion, integrity and film continuity after exposure to an aggressive environment.

12. Uncoated concrete prisms exposed for 5 years to these environments showed carbonation depths of 4.5 to 9.0 mm. Specimens coated with acrylic rubber showed no carbonated thickness, and the coating was able to prevent the penetration of carbonation into concrete containing chlorides up to 1%.

13. In uncoated concrete prisms exposed to outdoor environments, the presence of chlorides in the concrete had an undoubted accelerating effect on rebar corrosion. In uncoated prisms soaked in sea water, whether the concrete was initially contaminated with chlorides or not, the continuous availability of water-borne chlorides caused extensive rebar corrosion. In both cases the cover to the steel had a significant effect on the extent of corrosion.

14. Specimens coated with acrylic rubber coating and exposed to either regime for 5 years showed negligible corrosion in the main reinforcement. Even at very high levels of chloride content of 0.8 to 1.0% NaCl, the acrylic rubber coating can act as an effective controller of corrosion by limiting the ingress of water and oxygen.

15. An acrylic rubber surface coating applied to an existing salt-contaminated concrete structure can limit and slow down the progress of rebar corrosion. This was confirmed by the measured chloride profiles reported below.

16. Uncoated concrete prisms containing no chlorides and subjected to outside exposure showed little or no penetration of chlorides during the 5 years. Specimens containing chlorides, on the other hand, showed a non-uniform distribution of chlorides in the body of the concrete, with the peak concentration in the vicinity of the rebars.

17. In prisms coated with acrylic rubber coating and containing 1% NaCl, there was a more uniform distribution of chlorides within the concrete, and there was no evidence of chloride concentration in the vicinity of the rebars.

18. In uncoated specimens with no chlorides and soaked in sea water, there was clear evidence of chloride penetration into concrete. In specimens containing chlorides, there was chloride concentration in the vicinity of the rebars.

19. In coated prisms with no added chlorides, and exposed to sea water, the salt content beyond 10 mm from the surface was practically nil. In coated prisms containing up to 1% chlorides and exposed to sea water, the acrylic rubber coating not only effectively prevented the penetration of chlorides into concrete, but also achieved a more uniform distribution of existing chlorides, thus preventing their concentration at the level of the rebars.

20. The 5-year exposure studies with acrylic rubber surface coatings reported here point to two distinct roles of the coating. Firstly, the coating acts as an efficient and effective barrier to the penetration of chlorides, water and air into concrete. Secondly, where the concrete is already contaminated by chlorides, even at high levels, the barrier action of the coating enables internal movement of chloride ions resulting in their more uniform distribution within, and preventing chloride concentration at the level of, the rebars.

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RESUME

Un traitement de surface pour protéger le béton et l'acier des milieux agressifs

La carbonatation et les ions chlorures sont connus comme les deux principaux facteurs de corrosion prématurée de l'armature d'acier du béton. Des revêtements de surface peuvent assurer une protection réelle et efficace à la fois du béton et de l'acier noyé dans le béton, et améliorer la durabilité à long terme des matériaux du béton et des ouvrages exposés à des milieux agressifs. Dans la pratique, le béton est souvent fissuré et il convient de considérer la capacité de reprise de fissuration des revêtements comme un élément important de l'évaluation de la performance. Cette capacité a été évaluée pour quatre revêtements de surface différents par des expositions à l'ozone et aux

ultraviolets. On a aussi déterminé l'aptitude à contrôler la pénétration de chlorure et la protection de l'acier par des essais accélérés secs/humides et l'essai continu au brouillard salin. Sur la base de ces résultats, on a choisi un revêtement de caoutchouc acrylique très élastique pour des essais ultérieurs de stabilité à long terme. En conclusion, les données présentées montrent que le revêtement de caoutchouc acrylique peut empêcher la pénétration d'eau, d'air et d'ions chlorures, et assurer une durabilité à long terme de l'acier noyé dans le béton, à la fois quand le béton est exempt de chlorures et quand il est contaminé par des chlorures de sodium jusqu'à un taux de 1% de la matrice de mortier. Pour des niveaux élevés de chlorure, il est aussi essentiel que l'épaisseur d'enrobage soit élevée si l'on veut que les avantages du revêtement de surface soient pleinement réalisés et la durée de vie à long terme de la structure en béton assurée.
