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Performance of concrete coatings under varying exposure conditions

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ABSTRACT

This paper reports the results of a study conducted to evaluate the performance of ten concrete coatings, representative of five generic types, under varying exposure conditions. The performance of selected coatings was assessed on laboratory specimens by testing their adhesion to concrete, crack-bridging ability, chloride permeability and resistance to moisture and thermal variations. The data indicate that the overall performance of epoxy resin and polyurethane coatings was better than that of other generic types of coatings depending on chemical formulations. Further, a variation in the performance of coatings of similar generic type was noted. The selected coating needs to be tested under conditions similar to the exposure environment. Guidelines for the selection of concrete coatings appropriate for the service conditions are presented along with the performance criteria.

RÉSUMÉ

Ce papier rapporte les résultats d'une étude qui a été conduite afin d'évaluer la performance d'une dizaine de revêtements en béton représentant cinq types génériques sous des conditions d'exposition variables. La performance des revêtements sélectionnés a été évaluée sur des échantillons de laboratoire en testant leur adhérence au béton, leur aptitude à émousser les fissures, la perméabilité des chlorures et la résistance à l'humidité et aux variations thermiques. Les données indiquent que la performance globale de la résine époxyde et des revêtements de polyuréthanne était meilleure que celle des autres types de revêtements en fonction de leurs formulations chimiques. De plus, une variation de la performance des revêtements de type générique similaire a été notée. Les revêtements sélectionnés doivent être testés sous des conditions similaires à celles de l'environnement d'exposition. Les règles de sélection des revêtements de béton appropriés pour les conditions de service sont présentées ainsi que les critères de performance.

1. INTRODUCTION

Concrete coatings can provide an effective and efficient protection to both concrete and steel embedded in it, and they can enhance the durability of reinforced concrete. A wide range of concrete coatings of varying generic type are now available for this purpose. However, many manufacturers and users seem to have ignored the engineering requirements of such coatings, as a result many concrete coatings have either failed to fulfill their intended functions or have lacked reasonable durability [1]. Swamy and Tanikawa [1] evaluated four different coatings for their crack-bridging ability, and 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 [1] show conclusively that the selected acrylic rubber coating was able to prevent penetration of water, air and chloride ions, and ensure the long-term durability of steel embedded in concrete both when the concrete was free of chlorides and when it was contaminated with sodium chloride, up to 1% of the mortar matrix.

The effect of organic coatings on water and chloride transport in reinforced concrete was studied by Fluckiger *et al.* [2]. They concluded that the concrete coatings strongly reduced the water and chloride uptake in concrete.

Swamy and Tanikawa [3] evaluated the effect of concrete coatings to preserve concrete durability, and concluded that the application of an impervious surface coating to concrete is a very attractive solution to protect new and existing concrete structures. In evaluating the performance characteristics of such coatings, they have shown that certain basic engineering requirements, such as crack-bridging ability, elasticity, strain capacity, adhesion and fatigue resistance are also essential for the successful protection of concrete [3]. A highly elastic acrylic rubber-type coating with an overall thickness of about 1000 μm was reported in that study [3] to exhibit excellent performance characteristics, and was found to be reliable in resisting the intrusion into concrete of a wide range of aggressive agents [3].

Saraswathy and Rangaswamy [4] investigated the influences of various characteristics of the concrete substrates on coating adhesion, and have shown that the adhesion strength of a coating on a concrete substrate depends on the substrate strength itself and that the adhesion strength of an acrylic coating was found to be slightly higher than the surface strength of the substrate.

Swamy and Tanikawa [5] also reported the development of an acrylic rubber coating possessing excellent elasticity, thermal stability and crack-bridging properties. They presented field data to show the outstanding performance of this coating in preventing, almost totally, diffusion of chloride ions and carbon dioxide. With time, coated concrete was able to cause realkalisation of the carbonated concrete.

Other organic and inorganic coatings that normally react with the hydration products of cement and penetrate and block the capillary pores of cement have been developed for application in the aggressive conditions [6-9]. Concrete coatings have the unique advantage that they can be applied to protect existing and new structures. However, with a wide range of coatings available in the market, it becomes extremely difficult to choose the right type of coating, since coatings of similar generic types are known to possess considerably different diffusion characteristics [10].

Al-Dulaijan *et al.* [11] evaluated the performance of cement-based coatings in protecting concrete. The results of the study [11] indicated that epoxy-modified cement-based coatings provide adequate protection to concrete. However, the crack-bridging ability of the polymer-modified cementitious coating was reported to be better than that of other cement-based coatings.

In another study, Al-Dulaijan *et al.* [12] evaluated the performance of five resin-based concrete coatings by ascertaining their adhesion to the concrete substrate, crack-bridging ability, chloride diffusion, moisture resistance, water permeability, carbonation, chloride permeability, and chemical resistance. They [12] found that adhesion of all the epoxy resin-based coatings, to the concrete substrates, was better than that of the acrylic resin-based concrete coatings. The water permeability in the concrete specimens coated with the selected resin-based surface coatings was very low, they exhibited good crack-bridging ability. Further, they [12] found that all the coatings considerably reduced the diffusion of carbon dioxide into the concrete matrix. However, not all the coatings were able to withstand acidic exposure. The chemical resistance of epoxy resin-based concrete coatings was reported to be better than that of acrylic resin-based coatings [12].

Several generic types of coatings are now marketed for application on concrete. The performance of the available generic types under varying service conditions, however, needs to be investigated. Also, there is a need to develop performance criteria for evaluation of concrete coatings. Guidelines for the selection of concrete coatings appropriate for various exposure conditions need also to be developed.

2. EXPERIMENTAL PROGRAM

2.1 Materials

ASTM C 150 Type V cement was used to prepare concrete and mortar specimens. Crushed limestone with a density of 2.42 g/cm^3, a water absorption of 2.5% and a maximum size of 12.5 mm was used as a coarse aggregate, while dune sand with a density of 2.64 g/cm^3 and a water absorption of 0.5% was used as a fine aggregate in the preparation of concrete or mortar specimens.

Concrete coatings were selected to represent the following five generic types:

i. Acrylic coatings (AC)
ii. Polymer emulsion coatings (PE)
iii. Epoxy resin coatings (EP)
iv. Polyurethane coatings (PU)
v. Chlorinated rubber coatings (CR).

Each generic type was represented by two coatings procured from different manufacturers. Table 1 shows the properties of the selected concrete coatings.

2.2 Preparation of specimens

Prismatic concrete specimens 100 × 62.5 × 300 mm were cast to evaluate the adhesion of concrete with the selected coatings. Disk concrete specimens 75 mm in diameter and 50 mm in thickness were cast for the determination of chloride permeability. Prismatic mortar specimens 25 × 25 × 250 mm were cast to evaluate the crack-bridging ability of the selected concrete coatings. The resistance of the selected concrete coatings to thermal and moisture variations was evaluated by coating them on 50 × 50 × 50 mm cement mortar specimens.

The concrete specimens were proportioned for an effec-

Table 1 – Description of the selected coating		
Coating type	Generic type	Coverage rate, m^2/l
Acrylic, AC1	Modified acrylic resin	8.6
Acrylic, AC2	Solvent-based acrylic resin	12.0
Polymer emulsion, PE1	Copolymer emulsion	12.0
Polymer emulsion, PE2	Copolymer emulsion	0.9
Epoxy resin, EP1	Two-component polyamide-cured epoxy resin	6.6
Epoxy resin, EP2	Two-component polyamide-cured epoxy resin	12.0
Polyurethane, PU1	Two-component polyurethane, isocyanate-cured acrylic resin	9.4
Polyurethane, PU2	Two-component polyurethane, isocyanate-cured acrylic resin	12.0
Chlorinated rubber, CR1	Chlorinated rubber	5.1
Chlorinated rubber, CR2	Chlorinated rubber	6.8

tive water-to-cementitious materials ratio of 0.45 and a cement content of 370 kg/m^3. The cement mortar specimens were prepared with a sand to cementitious materials ratio of 2.75, while in the concrete specimens the coarse aggregate constituted 62% of the total aggregate.

2.3 Test procedures for evaluation of concrete coatings

The selected concrete coatings were applied to concrete or mortar specimens. The coverage rate is shown in Table 1. The coated specimens were tested for adhesion to concrete, crack-bridging ability, chloride permeability and resistance to thermal and moisture variations.

Adhesion to concrete: The selected concrete coatings were applied to prismatic concrete specimens measuring 100 × 62.5 × 300 mm. After two weeks of application, three aluminum dollies were fixed on the coated surface of the specimen with a strong epoxy glue to ensure that the strength of the bond between the dolly and concrete coating was much higher than the adhesive strength of the coating with concrete. Upon drying, the dollies were pulled off the coated surface using a pull-off tester as per the procedure outlined in ASTM D 4541, and the pull-off load recorded. The average of three pull-off readings was recorded as the adhesive strength of the concrete coating with the concrete substrate.

Crack-bridging ability: Cement mortar specimens, measuring 25 × 25 × 250 mm, with a notch in the center were coated with the selected concrete coatings, and two steel plates were fixed on the uncoated surface using an epoxy glue as schematically shown in Fig. 1. A tensile load was applied on the mortar specimen through the steel plates. A very low rate of loading was utilized to ensure a gradual failure of the specimen. As the load was applied, the width of the crack was carefully noted, and the crack width at the time of coating failure was recorded as the crack bridging ability of the concrete coating [11, 13, 14]. Three specimens were tested, and the average crack width was recorded.

Chloride permeability: The selected concrete coatings were applied on the two faces of 75 mm diameter and 50 mm thick concrete specimens. A rapid-set epoxy resin coating was applied to the curved surfaces of the concrete specimens. The specimens were then saturated with water under vacuum, and the chloride permeability was determined as per the procedures outlined in ASTM C 1202.

Resistance to thermal variations: Concrete structures are normally exposed to thermal variations in the hot and arid areas of the world. The thermal variations may cause failure of coatings. Under such circumstances, it is essential to evaluate the performance of concrete coatings under thermal variations with a view to select the most suitable coatings.

The selected concrete coatings were applied to all the faces of mortar specimens measuring 50 × 50 × 50 mm. These cubes, upon drying, were placed in an oven where they were exposed to 70°C for 8 h and to 25°C for 16 h. This completed one thermal cycle. The performance of

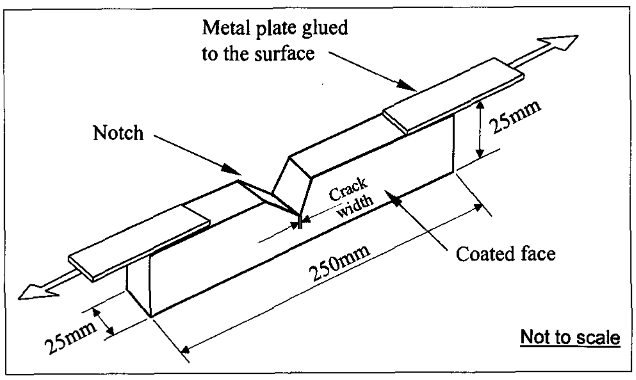

Fig. 1 – Specimen for crack-bridging ability of coating.

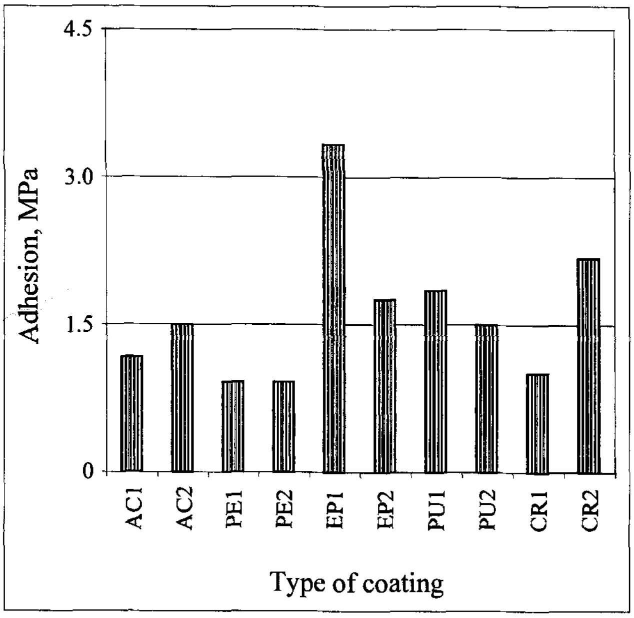

Fig. 2 – Adhesion of the selected coatings to concrete.

the selected coatings under thermal variations was evaluated after 30, 60 and 90 thermal cycles by: (i) visual inspection of the specimens for cracking and blistering of the coatings, and (ii) water absorption of the coated mortar specimens according to ASTM C 642.

Resistance to moisture variations: To investigate the effect of moisture variations, the selected concrete coatings were applied to all the faces of mortar specimens measuring 50 × 50 × 50 mm. After oven drying at 70°C for three days, the specimens were weighed, and then exposed to wet and dry cycles. They were submerged in a chloride-sulfate solution for 4 h and dried in air for 8 h. After 60, 120 and 180 wet-dry cycles, the specimens were examined for coating deterioration and loss in mass.

3. TEST RESULTS AND DISCUSSION

3.1 Adhesion to concrete

Fig. 2 shows the adhesive strength of the selected concrete coatings. The highest value of adhesive strength, 3.3 MPa, was noted in the epoxy resin coating EP1. Further, failure was noted in the concrete indicating that the adhesive strength of coating was higher than the tensile strength of concrete. The chlorinated rubber coating, CR2, was the next best in adhesion as it failed at 2.2 MPa, but CR1 gave low readings due to inter-layer failure of the coating. The polyurethane coatings also performed well with coating failures occurring between 1.5 to 1.8 MPa. The adhesive strength of the acrylic coatings was in the range of 1.2 to 1.5 MPa, while it was 0.9 MPa for the polymer emulsion coatings. The superior performance of the epoxy resin coatings in adhesion with concrete could be attributed to their chemical formulation. Based on the results, a threshold adhesive strength of 1.5 MPa can be specified for concrete coatings.

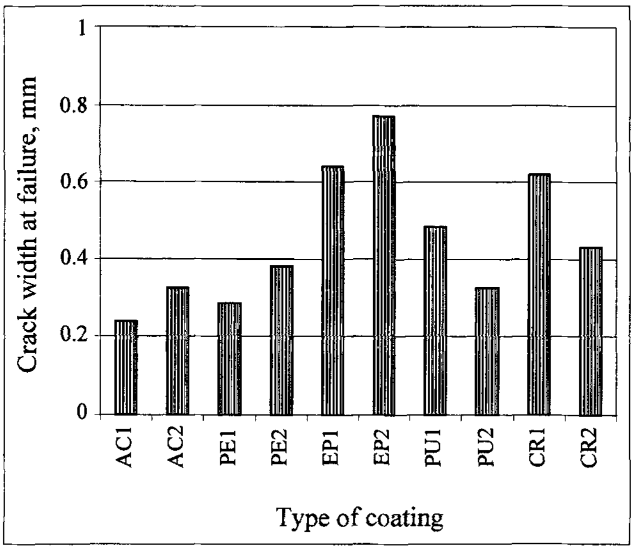

Fig. 3 – Crack-bridging ability of the selected coatings.

3.2 Crack-bridging ability

Fig. 3 summarizes the crack-bridging ability, *i.e.*, the crack width at the time of coating failure, of the selected coatings. The higher the width of crack at coating failure the better the crack-bridging ability of the coating would be. The crack-bridging ability of the epoxy resin coatings was better than that of the other coatings, being in the range of 0.64 to 0.77 mm. The chlorinated rubber coatings failed at crack widths ranging from 0.43 to 0.63 mm, followed by the polyurethane coatings, which failed at widths of 0.32 to 0.48 mm. The crack-bridging ability of the acrylic coatings was in the range of 0.24 to 0.33 mm, while it was in the range of 0.33 to 0.48 mm in the polymer emulsion coatings.

The crack-bridging ability of any coating depends primarily on its flexibility, adhesion and cohesiveness. The crack widths at failure for all the coatings tested were found to be less than 0.5 mm, and cracks of this size are very common in concrete structures. These could be shrinkage cracks, structural cracks or thermal expansion cracks. Therefore, concrete surface treatments would be more effective in bridging such cracks. The epoxy resin and chlorinated rubber coatings were able to bridge cracks wider than 0.5 mm. Hence, they can be utilized on substrates that are prone to cracking. However, the polymer emulsion and acrylic coatings should be used only in situations where wider cracks are not expected.

Table 2 – Chloride permeability of coated and uncoated concretes		
Coating type	Charge passed, Coulombs	ASTM C 1202 classification
Acrylic, AC1	164	Very low
Acrylic, AC2	70	Negligible
Polymer emulsion, PE1	703	Very low
Polymer emulsion, PE2	515	Very low
Epoxy resin, EP1	7	Negligible
Epoxy resin, EP2	160	Very low
Polyurethane, PU1	39	Negligible
Polyurethane, PU2	6	Negligible
Chlorinated rubber, CR1	50	Negligible
Chlorinated rubber, CR2	39	Negligible
Uncoated	975	Very low

3.3 Chloride permeability

Table 2 shows the total charge passed through the coated and uncoated concrete specimens. It also shows the ASTM C 1202 classification on chloride permeability. The chloride permeability of the concretes coated with the chlorinated rubber coatings was in the range of 39 to 50 Coulombs, while it was in the range of 6 to 40 Coulombs in the concretes coated with polyurethane coatings. In the concretes coated with epoxy resin, the total charge passed varied from 7 to 160 Coulombs, whereas in the concretes coated with acrylic coatings the total charge passed varied from 70 to 164 Coulombs. The total charge passed in the concretes coated with the polymer emulsion coatings was in the range of 515 to 713 Coulombs, whereas the total charge passed in the uncoated concrete was 975 Coulombs.

According to the ASTM C 1202 classification, the chloride permeability of all the coated concretes was 'negligible' except in the concrete coated with coatings AC1, PE1, PE2 and EP2, in which the chloride permeability was 'very low'. The chloride permeability of the uncoated concrete was 'very low' according to the ASTM C 1202 classification.

The chloride permeability of the concretes coated with polyurethane, chlorinated rubber, epoxy resin and acrylic coatings was almost one-tenth of that of the uncoated concrete and one-fifth of the concretes coated with polymer emulsion coatings.

The chloride permeability of coated concretes depends primarily on the porosity of the coating film. The lower the porosity of the film, the lower the charge passing through the film will be. The porosity, in turn, depends on the volume of solids, dry film thickness and the type of binder used in the coatings. The polyurethane and epoxy resin coatings offer better resistance to the diffusion of the aggressive ions, since they are solvent-based and as the coating cures, it leaves behind a tough film with low porosity.

Another point to be noted is that the chloride permeability values indirectly represent the electrical resistivity of concrete. Lower chloride permeability, therefore, indicates that the rate of reinforcement corrosion will be low.

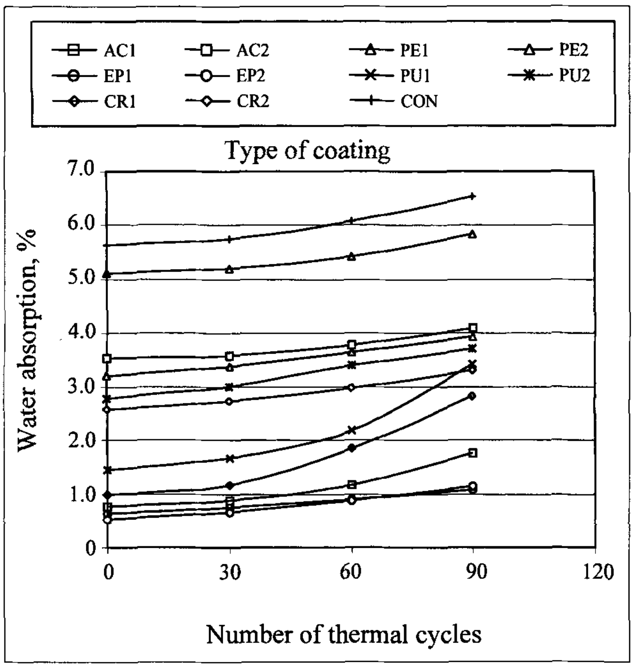

Fig. 4 – Variation of water absorption in the coated and uncoated concretes exposed to head-cool cycles.

3.4 Performance under thermal variations

No visible signs of coating deterioration were noted in any of the coated specimens after 90 heat-cool cycles. The changes in the water absorption of the coated and uncoated mortars after exposure to 30, 60, and 90 thermal cycles are plotted in Fig. 4. Fig. 5 shows the water absorption of all the coated and uncoated mortars after 90 heat-cool cycles.

The water absorption in both coated and uncoated mortars increased with the number of thermal cycles. The increase in the water absorption of the uncoated mortars may be attributed to the formation of microcracks in the mortar. In the coated mortars, the increase in the water absorption may be attributed to the conjoint effect of coating damage and formation of microcracks in the mortars. After 90 thermal cycles, the water absorption of the mortars coated with polymer emulsion coatings was in the range of 4.0 to 5.8%, while in the mortars

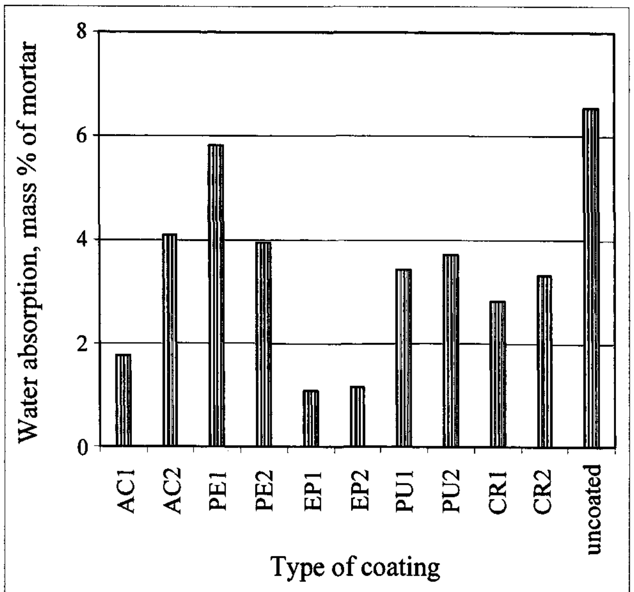

Fig. 5 – Water absorption in the coated and uncoated mortars after exposure to 90 heat-cool cycles.

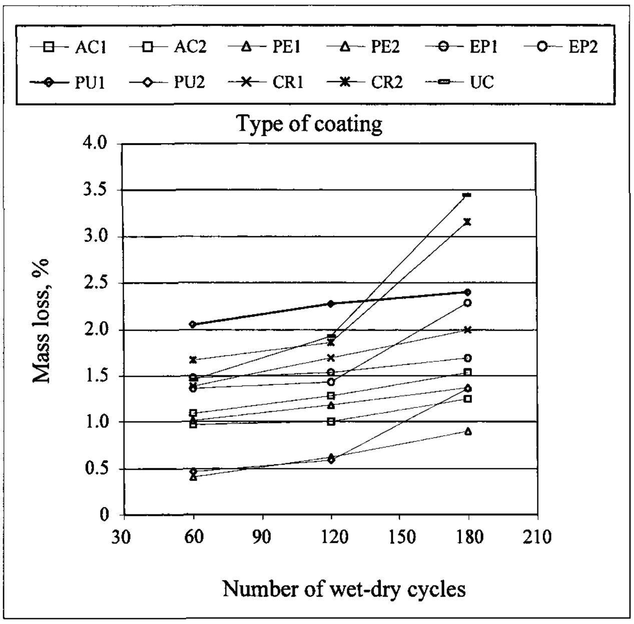

Fig. 6 – Mass loss in the coated and uncoated exposed to wet-dry cycles.

coated with acrylic coatings it was in the range of 1.8 to 4.1%. The mortars coated with chlorinated rubber coatings absorbed 2.8 to 3.3% water after exposure to 90 thermal cycles, whereas the mortars coated with polyurethane coatings absorbed 3.4 to 3.7% water. The lowest water absorption of 1.1%, after 90 heat-cool cycles, was noted in the mortars coated with the epoxy resin coatings.

The German Committee for reinforced concrete [15, 16] specifies a limiting water absorption of 2.5% and a reduction in water absorption of at least 50% compared to the untreated substrate. According to the data in Fig. 5, all the coatings fail to meet the water absorption criterion of 2.5%, after 90 thermal cycles, except the epoxy resin coatings and one of the acrylic coatings.

3.5 Performance under moisture variations

The average mass loss in the coated and uncoated mortars exposed to moisture variations is plotted against the number of wet-dry cycles in Fig. 6. Both coated and uncoated cement mortars continued to lose mass with increasing number of wet-dry cycles. The mass loss after 180 wet-dry cycles was 3.5% in the uncoated mortar and in the range of 1.7 to 2.3% in the mortars coated with the epoxy resin coatings. The mass loss in the mortars coated with polyurethane coatings was in the range of 1.4 to 2.4%, whereas in the mortars coated with chlorinated rubber coatings it was in the range of 2.0 to 3.2%. The mass loss in the mortars coated with acrylic coatings was 1.3 to 1.5%, while it was in the range of 0.9 to 1.4% in the mortars coated with polymer emulsion coatings, after exposure to 180 wet-dry cycles. The mass loss in the coated and uncoated mortars could be attributed to the damage caused by the alternate wetting and drying.

Most of the coated mortars lost less than 2% mass due to exposure to 180 wet-dry cycles, and there were no visible signs of coating deterioration. Some of the epoxy resin and chlorinated rubber coatings lost more than 2% of their mass after 180 wet-dry cycles. Thus, exposure to moisture variations has not affected the performance of the selected coatings, within the duration of the study.

4. PERFORMANCE RANKING OF CONCRETE COATINGS

The performance of the selected concrete coatings under the test regimes investigated in this study is summarized in Table 3. The performance of the selected concrete coatings varies with the exposure conditions. For example, the adhesion and crack-bridging ability of the epoxy resin coatings was better than that of other coatings. The chloride permeability of one of the polyurethane coatings was lower than that of other coatings. This was followed by one

Table 3 – Performance ranking of selected coatings

Test	Performance ranking									
	1	2	3	4	5	6	7	8	9	10
Crack bridging	EP2	EP1	CR1	PU1	CR2	PE2	PU2	AC2	PE1	AC1
Chloride permeability	PU2	EP1	CR2	PU1	CR1	AC2	EP2	AC1	PE2	PE1
Thermal variations	EP1	EP2	AC1	CR1	CR2	PU1	PU2	PE2	AC2	PE1
Moisture variations	PE2	AC2	PU2	PE1	AC1	EP1	CR1	PU1	EP2	CR2

of the epoxy resin coatings. Epoxy resin coatings have also shown better performance when exposed to thermal variations, while one of the polymer emulsion and acrylic coatings have shown improved performance when exposed to moisture variations compared to the other coatings.

Based on the data developed in this study the overall ranking of the performance of the selected concrete coatings in the descending order of importance is as shown below:

i) Epoxy resin coatings
ii) Polyurethane coatings
iii) Acrylic coatings
iv) Chlorinated rubber coatings
v) Polymer emulsion coatings.

The data developed in this study have also indicated that there is a variation in the performance of coatings of similar generic types. It is, therefore, recommended that whenever a coating is selected for use in aggressive environments, it should be tested under conditions similar to those it will be exposed to during its service life.

Table 4 – Generic type of concrete coatings recommended for various exposure conditions

Conditions	Generic type of coating, recommended in descending order of preference
Cracked substrate	Epoxy resin, Chlorinated rubber, Polyurethane
Exposure to chlorides	Polyurethane, Chlorinated Rubber, Epoxy resin
Exposure to thermal variations	Epoxy resin, Chlorinated rubber, Polyurethane
Exposure to moisture variations	Acrylic, Polyurethane, Polymer emulsion

5. CONCLUSIONS

The epoxy resin coatings exhibited the highest adhesion to concrete, followed by chlorinated rubber and polyurethane coatings. The acrylic and polymer emulsion coatings were poor in adhesion, and should be utilized only in situations where adhesion is not the basic requirement.

The crack-bridging ability of the epoxy resin coatings was better than that of chlorinated rubber and polyurethane coatings. The acrylic and polymer emulsion coatings were not so effective in bridging the cracks.

The polyurethane coatings were highly effective in reducing the electrical resistivity of concrete, measured in terms of chloride permeability. The chloride permeability of the epoxy resin and chlorinated rubber coatings was negligible, while it was very low in the acrylic and polymer emulsion coatings.

The epoxy resin coatings were the most effective in reducing water absorption in the coated specimens exposed to thermal cycles. The chlorinated rubber coatings performed better than the polyurethane coatings in resisting deterioration due to thermal variations. One of the acrylic coatings was efficient in limiting the increase in water absorption due to exposure to thermal variations, whereas the other acrylic coating was not that effective. Both polymer emulsion coatings were ineffective in controlling concrete deterioration due to thermal variations.

All the selected coatings were effective in reducing the damage to the mortar specimens due to moisture variations. The least mass loss was noted in the specimens coated with polymer emulsion and acrylic coatings. All the other coatings also prevented any significant loss in mass of mortar due to moisture variations. Maximum mass loss was noted in the specimens coated with one of the chlorinated rubber coatings.

As an overall evaluation, the performance of epoxy resin and polyurethane coatings was better than that of other concrete coatings investigated in this study.

6. GUIDANCE FOR SELECTION OF CONCRETE COATINGS

The data developed in this study have indicated that the performance of coatings varies with the exposure conditions. While the performance of a certain coating is better under certain exposure conditions, it does not perform better than others in another environment. Therefore, the selection of the coatings should be case specific.

Guidelines for the selection of concrete coatings for various exposure conditions are summarized in Table 4.

7. PERFORMANCE CRITERIA

Based on the results of this study, performance criteria for the selection of concrete coatings, summarized in Table 5, are suggested. However, it is recommended to test the selected coatings particularly under the expected exposure conditions prior to their selection.

Table 5 – Performance criteria recommended for the selection of coatings

Test item	Performance criteria
Adhesion to concrete	> 1.5 MPa
Crack-bridging ability	> 0.5 mm
Chloride permeability of coated concrete	< 500 Coulombs

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