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Evaluation Method on Bond Property of Concrete Surface Coating System

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ABSTRACT

Various repair methods have been recently applied to not a few concrete structures which had been degraded, in order to prolong the service life of infrastructures. We carried out by the systematic experiment with the common test procedure on the concrete surface coating systems/materials since 2006. In this study, the common test method was focused on the bond performance which has a great influence on the durability of concrete surface coating system. The bond test methods which enable to evaluate the peeling behavior were performed in addition to the popular bond test using uni-axial tension, which often resulted in the similar bond strength due to the fracture of the substrate. The common test results on the concrete surface coating system using both the uni-axial tensile and peeling bond test brought more practical and accurate evaluation for the bond performance of coating films.

Keywords. Concrete surface coating method, Durability, Adhesion property, Peeling property , Exposure test,

INTRODUCTION

Today when much deterioration and damage to concrete structures is being reported, various causes for the progression of the deterioration are being discussed. These causes include chlorine-induced corrosion, carbonation, alkali-aggregate reaction, and frost damage. As the deterioration progresses it is necessary to improve the durability of concrete structures and to repair and strengthen them. Various countermeasures have been proposed. Among them, the surface coating method for road bridges has been investigated from the early 1980s and has been used for concrete structures to improve durability. Based on follow-up studies conducted on many structures, a number of reports on their durability have been issued. Durability has been investigated on many structures, but in some cases, durability is not adequate, depending on the condition of the structures. Taking into account this background, and in order to establish better test methods for assessing performance, the results of trial application on actual structures as well as follow-up studies of exposure test pieces are being continually studied. Also to grasp the deterioration phenomena in a short time, several accelerated tests have been conducted. However, the correlation with outdoor exposure has not been clearly understood, and we have had to investigate the results of outdoor exposure tests over the long period.

With the recent trend of performance-specification and maintenance systems, evaluations of the performance of surface coating materials and coating systems are now required. The Subcommittee on Polymers for Repairing and Strengthening Concrete Structures has conducted common tests on the surface coating materials since 2006. The purposes of common tests are to verify the usefulness of surface coating materials when creating a barrier and for weather resistance, to demonstrate improved durability of concrete structures by using them to make repairs, and to propose test methods that can comprehensively evaluate performance under unified conditions. Under common conditions, the subcommittee has periodically conducted exposure tests on actual environments aiming at the longest period of 15 years, as well as conducting physical property tests after the exposure and evaluating the durability of various surface coating materials. This report describes the results of investigations into new evaluation methods adopted for the common tests in addition to conventional evaluation methods, paying attention to bonding performance, which is important for the durability of the surface coating methods.

PERFORMANCE EVALUATION OF COMMON TEST FOR SURFACE COATING MATERIALS

For surface coating materials used for repairing concrete structures, test items were used to evaluate performance from multiple angles. The evaluation methods themselves have been regularly investigated by referring to the results of follow-up studies of actual structures, including the test conditions. For the common tests conducted by the Subcommittee on Polymers for Repairing and Strengthening Concrete Structures, we decided to assess the durability of the surface coating materials by evaluating secondary properties with the coatings that had deteriorated during exposure tests. The evaluation items subject to investigation are an evaluation of the appearance of surface coating materials, and basic performance measures of the surface coating materials, such as bonding performance, crack follow-up performance, and water permeability resistance as a barrier property to prevent the penetration of foreign materials.

TEST OUTLINE

Outdoor exposure tests were conducted, where the test pieces to be used for durability testing are exposed at the exposure laboratory owned by Japan Weathering Test Center. At the same time, initial property evaluation was conducted with the test pieces for checking initial properties. Using exposure test pieces that had been subject to age deterioration, we investigated the evaluation methods used for assessing durability, paying close attention to bonding performance, an important item for the performance of surface coating methods.

Surface coating methods. The base coats of the surface coating method used for the tests were of several types: epoxy resin (including the flexible type), modified acrylic resin, chloroprene-rubber, urea-urethane resin, and polymer cement (including the flexible type). For the testing, 15 methods (shown in Table 1) were used. These were applied on concrete substrates (300 mm x 150 mm x 60 mm).

Exposure test. The exposure tests were conducted at Choshi Exposure Laboratory (latitude 35°43'N and longitude 140°45'E) of the Japan Weathering Test Center, a standard exposure laboratory representing the climatic province of the Pacific side of Japan in the middle of Honshu (the main island of Japan) using test pieces prepared in accordance with the coating specifications of each manufacturer.

Test items. Using exposed test pieces recovered every year and at three years, the following two tests for bonding performance were carried out:

(1) uni-axial bond strength test
(2) peel-off resistance test

Table 1. List of concrete surface coating materials

Sign	Type of main coat (Film thickness：μm)	Type of top coat (Film thickness：μm)
E1	Epoxy resin (160)	Polyurethane [Flexible type] (30)
E2	Epoxy resin (186)	Fluorine (30)
E3	Epoxy resin (150)	Fluorine (40)
E4	Epoxy resin (320)	Fluorine [Flexible type] (30)
E5	Epoxy resin (1000)	Fluorine (38)
E6	Epoxy resin [Flexible type] (200)	Acrylic-urethane (30)
MA1	Acrylic (800)	Polyurethane (80)
MA2	Acrylic (800)	Fluorine (80)
R1	Polychloroprene (265)	Chlorosulfonated Polyethylene (70)
R2	Polychloroprene (465)	HALS-hybrid (60)
U1	Urea-urethane (2250)	Acrylic-urethane (80)
C1	Polymer cement	Polymer cement (1050)
C2	Polymer cement (660)	Acrylic-silicone (75)
C3	Polymer cement (660)	Acrylic-silicone (75)
C4	Polymer cement [Flexible type] (1950)	Acrylic- urethane (50)

TEST METHODS

Bond strength test (JSCE-K 531-2005). The coated film on each test piece (300 mm x 150 mm x 60 mm) was cut into a square 40 mm x 40 mm with a small diamond cutter to reach the concrete substrate. A pulling jig was bonded to the square of coated film with solvent-less epoxy resin adhesive. After 24 hours, a tensile force was applied vertically using a testing machine to the pulling jig at a loading rate of 1,500 to 2,000 N/min, and the maximum tensile load before detachment was sought. The maximum tensile load was divided by the jig adhesion area to calculate the bond strength. At the same time, each fracture position was evaluated. The test was conducted at three places and the measured values were averaged.

Peel-off resistance test. This test was introduced as a way to evaluate the work load of the bonding performance to consider the peeling phenomenon of the coating.
(a)Preparation of test pieces
The coated film of each test piece (300 mm x 150 mm x 60 mm) had two parallel cuts made 60 mm long at an interval of 50 mm with a small diamond cutter to reach the concrete substrate. A 10 mm area of the coated film (from one end of parallel cuts) was forcefully pulled up to separate it from the concrete substrate
As shown in Figure 1, adhesive cloth tape (equivalent to JIS Z 1524) 50 mm wide and 210 mm long was attached to the lower face of the raised coating (10 mm) and another cut adhesive cloth tape (equivalent to JIS Z 1524) 260 mm long was attached to the upper face. The coating was sandwiched between these two pieces of tape.
(b) Test method
As shown in Figure 2, the test piece was fixed to a stand and the coating was pulled in the 135°direction at the tensile speed of 100 mm/min. The peel force was then measured with the testing machine.
(c) Evaluation method
The work load (N・mm) required for peeling was divided by the peeling area (mm^2) to calculate the peel-off resistance. At the same time, the fracture positions were evaluated. This test was conducted at three places and the measured values were averaged.

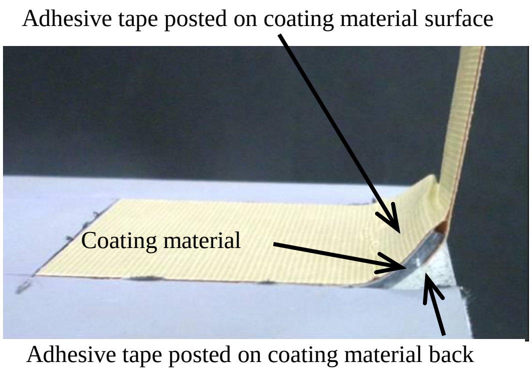

Figure 1. Method of attaching tape

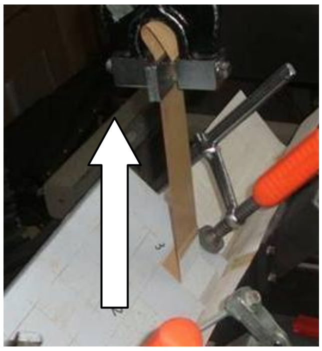

Figure 2. Condition of peel-off resistance

TEST RESULTS AND DISCUSSION

Bond strength test. The initial bond strength of surface coating methods, except C3 of polymer cement, showed 1.0 N/ mm^2 as a standard value by many organizations. The C3 increased in bond strength as the exposure period elapsed and became the same strength without any problems. This was similar to other methods, showing the same tendency as existing research (Figure 3). For the fracture positions (Table 2), most surface coating methods, except polymer cements and some chloroprene rubber types, showed substrate fractures and no changes in fracture positions occurred even after an exposure of three years.

Table 2. Fracture position of adhesion performance

Sign	Position of fracture*					
	Uni-axial bond strength			Peel-off resistance		
	initial	1year	3years	initial	1year	3years
E1	A	A	A	AB	AB	AB
E2	A	A	A	BK	BK	BK
E3	A	A	A	—	BK	BK
E4	A	A	A	AB	AB	AB
E5	A	A	A	BK	BK	BK
E6	A	A	A	—	—	A
MA1	A	A	A	BK	BK	BK
MA2	A	A	A	BK	—	BK
R1	BK	A	A	BG	BG	BG
R2	A	A	A	BK	BK	BK
U1	A	A	A	A	A	AB
C1	A	A	BG	—	—	—
C2	BG	A	A	—	—	A
C3	BG	BG	BG	—	—	AB
C4	A	A,BG	A	BK	BK	BK

*—: Break down of coating before peeling off
A : Fracture of substrate (included vulnerable part)
AB: Fracture between substrate and coating material
BG: Fracture of coating material
BK: Fracture between coating materials

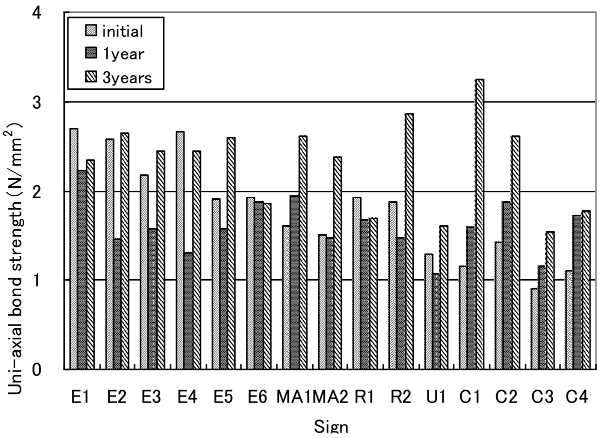

Figure 3. Uni-axial bond strength

Even those showing fractures between coating materials (chloroprene rubber type) and cohesion fracture (polymer cement) in the initial stages showed substrate fractures after an exposure of one year. At this moment, no methods causing interfacial fractures between substrate and coating material were recognized, showing no tendency to deteriorate.

Of the 15 methods, 12 caused substrate fractures in the initial stage and 13 methods did the same after exposures of one year and three years. For the methods (E1, E2, E3, E4, E5, E6, MA1, MA2, R2, U1 and C4) which caused the substrate fractures in the first stage and after one year and three years, we investigated statistically if any difference was recognized due to aging or if there was a difference between methods. We recognized a significant difference in the change due to aging, at a risk rate of 5%, with the variance ratio of 10.624 and boundary value of 3.493. However, between the methods, we recognized no significant difference with a variance ratio of 2.184 and boundary value of 2.348. Generally, it is considered that the coating becomes strong as the reaction advances with time. While the adhesion of the coating is maintained, the fraction condition is the substrate fracture, and the bonding strength in this case is considered stronger than the breaking strength of the substrate itself. That is, if the condition is the cohesion failure within the coating material or interfacial fracture between coating materials, the comparative investigation between methods is made possible by the bonding strength and the fracture condition. Even if the reference value is exceeded, it is clear that a method showing the substrate fracture maintains the substrate strength or higher, and the bonding strength depends on the strength of the substrate. A direct comparison of the bonding performance is considered difficult. In the case of the substrate fracture in the bonding strength testing, therefore, the comparison of performance differences is difficult, and it is considered that an investigation by other methods is required. If the bonding strength decreases in the substrate interface, no integration with the concrete structure can be expected, and in due course, coating delamination tends to occur, and eventually the barrier property may decrease. This means that the effectiveness of the surface coating method will be gradually lost. For future exposure investigations, it will be necessary to pay close attention to changes in fracture positions.

Peel-off resistance test. In the bonding strength tests by uni-axial tension, most methods showed 1.0 N/mm^2 or higher and most fraction positions clearly showed the substrate fracture, indicating that the bonding strength was higher than the substrate strength. However, a comparison of the bonding performance was difficult. For performance comparisons of these methods, we investigated the bonding performance from different angles.

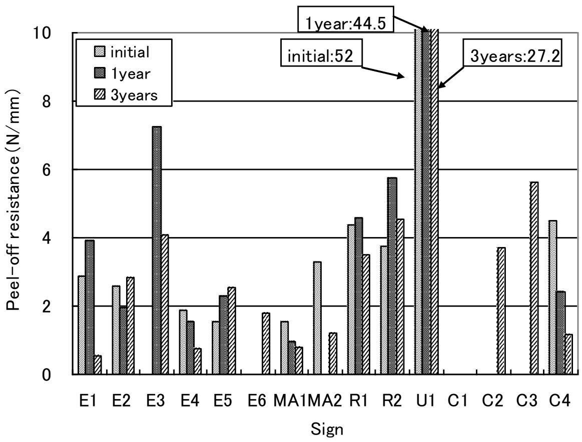

Figure 4. Peel-off resistance

In this test (paying attention to the delamination phenomenon of the coating), five (E3, E6, C1, C2 and C3) of the 15 methods resulted in a breakdown of the coating before peel off test in the initial stages, as shown in Table 2. Therefore, an evaluation was impossible. However, after an exposure of three years, a breakdown of the coating occurred only with one method (C1). As for the peel-off resistance of 10 methods for which aging can be compared, 8 methods (E1, E4, MA1, MA2, R1, R2, U1 and C4)—including E1, R1 and R2 where it increased after the exposure of one year and decreased after an exposure of three years in comparison with the initial stage—showed a decreasing tendency. On the other hand, E2 and E5 (epoxy type) showed an increasing tendency after an exposure of three years in comparison with the initial stage (Figure 4). This peel-off resistance was obtained by dividing the work load (N・mm) produced when the coating was peeled off by the actual delaminated area (mm^2). This work load for peeling includes the peel-off strength of the coating and the tensile strength of the coating itself. If the peel-off resistance is high, it can be said that the coating is difficult to be peeled. But, as in the case of the bonding strength by the uni-axial tension showing the bonding force in the vertical direction, it is necessary to pay close attention to changes in fracture positions to assess peel-off conditions. For most methods, there is no substantial change in the fraction positions (Table 2), but the epoxy type (E6), which caused a breakdown in the coating before testing, showed the substrate fracture after three years. Especially with the E3, which caused a breakdown of coating before testing, the fracture changed to an interfacial fracture between coating materials after an exposure of one year and the peel-off resistance also showed a decreasing tendency after an exposure of three years. The urea-urethane type (U1) caused a breakdown of the coating before testing after an exposure of one year, but the fracture changed to an interfacial fracture between the substrate and coating material after three years of exposure. From this observation, it is supposed that this coating, though initially hard and strong, is gradually changing something in the substrate interface.

For some of the polymer cements (mostly with a breakdown of coating before testing), the fracture changed to a substrate fracture for C2 and an interfacial fracture between the substrate and coating material for C3 after an exposure of three years. This also indicated that some change was occurring in the substrate interface.

In the tests of peel-off resistance, some of the evaluation could not be made depending on the material quality of the coating, but out of 13 methods (after an exposure of three years) that showed the substrate fracture in the bonding strength by the uni-axial tension, 11 methods in the peel-off resistance showed cohesion failure within the coating material, interfacial fractures between coating materials, and interfacial fractures between the substrate and coating material. This clearly showed the differences among the methods.

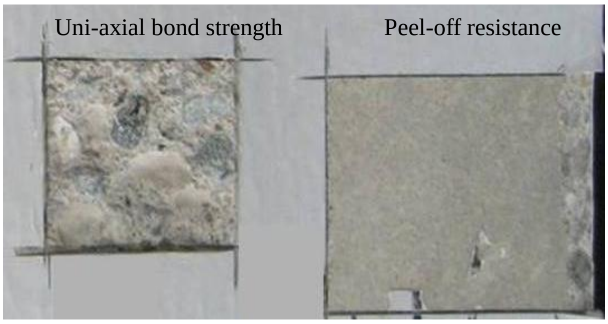

Figure 5. Difference in fracture position between uni-axial bond strength and peel-off resistance tests

It seems that as the deterioration of the coating progresses, cohesion failure occurs at a weak/vulnerable part of the coating system or at an interface where adhesion is not good. Of the 11 methods that showed cohesion or interfacial fractures, there were 7 methods where the peel-off resistance after three years became lower than that in the initial stage and 8 methods where it decreased after an exposure of one year. For those where the substrate fracture occurred in the bonding strength test and differences in characteristics were not clear, we could find in the peel off resistance test, weak points (points where delamination of the coating material might occur) for the individual methods, and some methods which clearly showed the aging tendency of degradation. And we also found that it is possible to compare durability among the methods showing a decreasing tendency for peel off resistance, even if they showed the same fraction part. For those results that were different for fracture positions depending on the test method adopted, Figure 5 shows an example of substrate fractures for the bonding strength and interfacial fractures between the substrate and the coating material for the peel-off resistance.

Correlation between test methods. We investigated the correlation between test methods looking for peel-off resistance imaging of the delamination phenomenon of the coating film and the bonding strength by uni-axial tension as well as adhesion in the vertical direction for conventionally implemented tests.

Figure 6 shows a scatter diagram that expresses the relationship between the bonding strength test and the peel-off resistance test using the test results in the initial stage, after exposures of one year and after three years. In the peel-off resistance test, a method where the breakdown of coating film before testing occurred was excluded because no digitalization can be made. Method (U1) was extremely high in comparison with other methods, and was also excluded. The correlation coefficient between these two methods is r = -0.247, and no correlation was recognized.

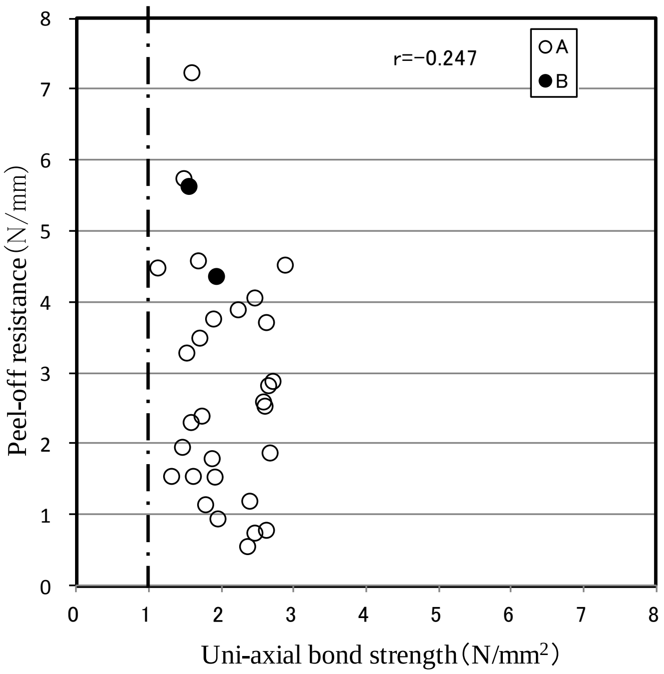

Figure 6. Relation among adhesive test methods

From the above data, the bonding strength test by uni-axial tension in the vertical direction and the peel-off resistance test imaging the delamination phenomenon of the coating showed respectively different phenomena, almost the same tendency as that of the existing research results.

Comparison of performance values by test methods reveals that the values for bonding strength are distributed in the range of 1 to 3 N/mm^2 and those for the peel-off resistance were in a wide range: 0.56 to 7.24 N/mm (Figure 6). The circle ○ in the figure indicates samples which showed a substrate fracture in the bonding strength test and the mark ● indicates others than a substrate fracture.

For the samples (marked ○), which showed the substrate fracture in the bonding strength test by uni-axial tension, the performance values depended on the substrate strength. As well, though they maintain higher performance values than the substrate strength, it is difficult to evaluate performance values for the coating itself in some samples. In the peel-off resistance test imaging the peel-off phenomenon, on the other hand, the fraction positions were different, and it is considered possible to compare the performance values between methods.

The peel-off resistance used to quantitatively grasp the delamination phenomenon of the coating film, which was adopted this time, cannot be measured with a brittle coating which tends to cause a breakdown of the coating film before testing. However, it is possible to evaluate/consider the delamination phenomenon of these coatings from a different angle, and it is considered an effective means to contribute to evaluating the bonding behavior more accurately, in addition to the bonding strength test by uni-axial tension.

CONCLUSIONS

Of the common tests on surface coating materials implemented by the Subcommittee on Polymers for Repairing and Strengthening Concrete Structures, the following summarizes the results obtained on the bonding performance up to the third year of outdoor exposure and the evaluation method.

(1) For the bonding strength tests by uni-axial tension with the emphasis placed on force in the vertical direction, most methods looked for a substrate fracture, and it was difficult to compare the performance differences between the methods. This is similar to existing investigation results.

(2) In the peel-off resistance test adopted to quantitatively assess the peel-off phenomenon, we could confirm the peel-off phenomenon by 14 of the 15 methods after an exposure of three years. In some cases, an evaluation could not be made depending on the coating material. However, from the fact that those which caused the substrate fracture in the bonding strength by uni-axial tension showed different fracture forms in the peel-off resistance test differences between methods were clear. As for those where the fracture positions are the same over time and the peel-off resistance showed a decreasing tendency, it became possible to evaluate durability.

(3) We investigated the correlation between the bonding strength and the peel-off resistance, recognizing that the correlation between test methods is low. This showed the same tendency as existing research results, and it was found that different bonding performance has been evaluated.

(4) When the bonding performance is to be evaluated, the comparison has so far been difficult due to the substrate fraction in the bonding strength test. Nonetheless, we think that a combination of the peel-off resistance (considering the delamination phenomenon of the coating) with a conventional bonding strength test by uni-axial tension will contribute to evaluating/considering the differences.

The exposure tests of 15 methods implemented by the Subcommittee on Polymers for Repairing and Strengthening Concrete Structures are being continued. In the future, we intend to continue the investigation from various angles by further accumulating data. As well, we intend to improve the reliability for the “peel-off resistance test” as a new evaluation method. Even for difficult-to-apply materials (because the coating is brittle and fragile), we intend to establish testing conditions for a proper evaluation and plan to establish the evaluation method to contribute to the development of highly durable surface coating materials.

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