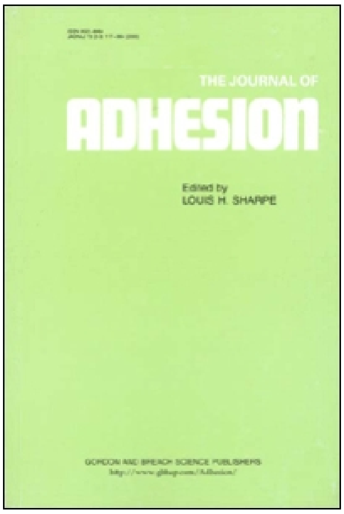

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

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To cite this Article Naderi, Mahmood(2008) 'Adhesion of Different Concrete Repair Systems Exposed to Different Environments', The Journal of Adhesion, 84: 1, 78 — 104

To link to this Article: DOI: 10.1080/00218460801888433

URL: http://dx.doi.org/10.1080/00218460801888433

The Journal of Adhesion, 84:78–104, 2008
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ISSN: 0021-8464 print/1545-5823 online
DOI: 10.1080/00218460801888433

Adhesion of Different Concrete Repair Systems Exposed to Different Environments

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This article presents the results of experiments conducted to assess the effects of aging under dry laboratory conditions, underwater storage, cyclic freeze-thaw, and temperature changes on the adhesion between the repair and the substrate concrete. The repair systems considered for these studies included ordinary sand/cement (S/C) mortar, with and without bonding agents, two polymer modified cementitious mortars, and two resinous mortars. The specimens were concrete slabs of 600 × 300 × 100 mm dimensions with saw cut face 600 × 300 mm on which a repair layer of 20 mm had been applied. In order to eliminate the effects of surface texture and surface strength of the concrete on the adhesion of repair systems, repair applied surfaces were all saw cut surfaces of concrete with 28-day design compressive strength of 65 MPa. Tensile bond strengths of these specimens were measured using a direct tensile test (pull-off) method. The results indicated that the tensile bond strengths of different repair systems under dry laboratory conditions, and stored underwater, ranged from 1.51 to 5.27 Mpa. Exposure to 300 cycles of freeze-thaw and to 200 cycles of temperature changes resulted in 6 to 100 percent reduction in their tensile bond strengths.

Keywords: Bond strength; Concrete repair; Cyclic temperature; Freeze-thaw

1. INTRODUCTION

The majority of concrete structures that require strengthening or rehabilitation are exposed to severe environmental conditions. Many of these severe circumstances are the result of cold climate conditions such as low temperature, freeze-thaw action, and exposure to hot and moist climates. Because of this, the environmental durability of the

Received 8 June 2007; in final form 29 December 2007.

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repair/concrete bond is of utmost importance, especially in aggressive climates.

In general, chemical, chemi-physical, or physical effects of the severe environmental conditions may cause the durability problems associated with repaired concrete structures. When diagnosing the causes of the problems that have come to light, it is almost impossible to differentiate between the chemical and physical effects. For example, if the causes are due to the rusting of the reinforcement, obviously the production of the rust is a chemical, while the actual spalling off the concrete is a physical process. Similarly, if a concrete has become soft in a marine environment, this is a chemical, while the damage due to an impact is a purely physical effect.

One of the greatest challenges facing the successful performance of repair materials under severe environmental conditions is their dimensional changes relative to the substrate. Relative dimensional changes cause interfacial stresses along the repair and substrate concrete. High interfacial stresses may result in loss of bond and delamination or deterioration. Particular attention is required to minimize these stresses and to select materials that properly address relative dimensional behavior [1]. However, more research is needed in evaluating the environmental durability of repair/concrete bond strength.

A limited amount of work has been done on the effects of freeze-thaw cycling on bonding of repair materials. Green *et al.* [2] conducted durability tests on the bond between Fiber Reinforced Polymer (FRP) and concrete, and found that the bond was not significantly damaged up to 300 freeze-thaw cycles. Experiments conducted by some researchers have compared the freeze-thaw effect on the repair/concrete bond strength [3], but due to the nature of the test method used,the results can not be related directly to the repair/concrete bond strength.

Therefore, not only short term and static bond strengths of a repair material are important but, also, studying the effects of cyclic freeze-thaw and temperature changes that could induce stresses along the concrete/repair interface would be useful, because these physical effects are those to which every repair system is exposed to during its life-long service.

When studying a parameter such as repair/concrete bond strength of a repair material, the test methods have to be designed in such a way that they facilitate not only the observation of the interfacial adhesion of the repair, but also shed light on the cause(s) of the undesired effects of the test conditions. Obviously the cost, the time, and more important than them all, the multidisciplinary nature of the repair/concrete interface problems exert limits and restrictions, which make the choice of proper bond tests much more difficult.

As explained by Austin *et al.* [4] see wide range of test methods has been proposed to evaluate bond strengths of repair materials in recent years. These include the tensile bond [5], slant shear [6–9], patch tests [10], flexural [9], the author's friction-transfer [10–12], and cylindrical shear methods [13].

Since the main aim was to study the effects of aging under dry laboratory conditions, underwater storage; cyclic freeze-thaw, and temperature changes on the adhesion between the repair and the substrate concrete, this article discusses the development of bond strengths of six different repair materials kept under dry laboratory conditions as well as stored underwater. Also discussed in this article are the effects of cyclic freeze-thaw and temperature changes which were obtained by using the direct tensile test (pull-off) method.

It should be noted that other methods, such as contact electrical resistance measurement [14], are also available for this purpose, but in the writer's view, occurrence of failure during the experiments can give more insight into the problem.

2. MATERIALS, SAMPLE PREPARATION AND TEST PROCEDURE

2.1. Materials

Engineers need information on the mechanical and physical characteristics of repair materials and the substrate concrete before selecting an appropriate repair system. Many proprietary systems for concrete repair are now available, making selection all the more difficult.

Emberson and Mays [15] have categorized repair systems into nine generic types. Some researchers [16] believe that all nine types have similar compressive strength, but the tensile strength of resinous materials and polymer-modified cementitious materials is significantly higher than those of cementitious materials, due to the polymer network. They also have indicated that cementitious-based repair materials have a higher modulus than pure resinous material because of the aggregate contribution and the ratio of the elastic modulus to that of an ordinary Portland cement (OPC) and sand mortar ranges from 0.67 for an acrylic mortar to 1.85 for a magnesium phosphate modified mortar. Poisson's Ratio was reported to be highest with the OPC/sand mortar (0.24) and lowest with the flowing concrete (0.08) and all cementitious-based materials are believed to have similar coefficients of thermal expansion (around 10×10^{-6}) but the resinous mortar has a much higher value (37×10^{-6}).

According to the information gathered from the suppliers, commercial considerations prevent the publication of the precise formulations of the pre-blended mortars used in this research, but they typically contain all or most of the following constituents: fine aggregates (75 μm to 2 mm); lightweight fillers (75 micro.m to 300 μm); ordinary Portland cement (OPC) in the ratio of 1.3–3.4:1; fumed silica (typically 5% of the OPC); admixtures such as styrene butadiene rubber (SBR); and sometimes chemical shrinkage compensators.

It might be of interest to mention that, except for the OPC which was produced in the country, the repair materials used in this research were mainly supplied by the Swiss-based Sika company.

2.1.1. Substrate Concrete

Concrete referred to as substrate (parent or old) concrete was made from ordinary Portland cement (binder), natural zone 2 sand (fine aggregate), and basalt aggregate with maximum size of 20 mm (coarse aggregate) mixed with sufficient drinking water. The mix proportions for 1 m^3 of concrete were as shown in Table 1.

Concrete blocks of 600 × 300 × 200 mm dimensions were cast vertically with the 600 × 200 mm face as the base. Casting was carried out in three equal layers and sufficient compaction was given to each layer using a vibrating rod. The top face was leveled using a trowel. At the age of 28 days, 600 × 300 × 100 mm slabs were produced by cutting the 600 × 300 mm side of the cast slab using a diamond-tipped saw.

2.1.2. Ordinary Sand/Cement (S/C) Mortar

The cement and sand were mixed in the ratio of 1:3 by volume. Water was added to achieve a reasonable consistency (about 40% of the cement content). Before application of this mortar, the surface was coated with a thick slurry (W/C = about 0.3) of cement grout.

2.1.3. SBR (Polymer)-Modified Cementitious Mortar

A polymer is a compound formed by the reaction of simple molecules that permit their combination to proceed to high molecular weights under suitable conditions.

TABLE 1 Mix Proportions for 1 m^3 Concrete

Water (liter)	Cement (kg)	Fine aggregate (kg)	Coarse aggregate (kg)
185	555	570	1290

TABLE 2 Mix Proportions for 1 m^3 SBR-Modified Cementitious Mortar

Water plus SBR latex (kg)	Cement (kg)	Sand (kg)
180	630	1570

The SBR latex containing 40% solids was mixed with water in the ratio of 2:1. The proportion of this mortar is shown in Table 2. Its basic constituents include Part A-SBR polymer latex; Part B-cement paste material (1 gal of Part A for 50 lb bag of Part B).

The surface of the substrate concrete was primed with a bonding grout, made up of latex, water, and cement in the volume proportions of 1:1:2, before the repair was applied.

2.1.4. Acrylic-Modified Cementitous Mortar

This is a pre-packed mortar in two components, one containing cements, aggregates, accelerators, and admixtures while the other contains the polymer and water, *i.e.* a two-component acrylic polymer-modified Portland cement, fast setting, non sag mortar; Part A: 1 gal of latex; Part B: 44 lb bag of cement paste material. According to the manufacturer, a bonding coat is not required unless the substrate concrete is particularly porous.

2.1.5. Epoxy Resin Mortar

Three different brands of epoxy resin mortars were tested. All contain aggregate as filler and achieve compressive strengths of 60–90 MPa after 24 hours. According to the supplier's information, these materials included a repair system for concrete repair that uses a radically structured polymeric repair compound: Part A-Epoxy Resin; Part B-Proprietary Accelerator; Part C-Mineral Aggregates (R:H:F: 2:1:2).

2.1.6. Epoxy Resin Bonding Agents

These bonding agents can be used with epoxy mortars or with ordinary cementitious mortars. The product used was a solvent-free, two component, 100% solids epoxy resin system.

2.1.7. Polyester Resin Mortar

The polyester resin used in this work was a styrene-diluted unsaturated polyester-based polymer concrete: Part A-1 gal of resin; Part B-3 oz of hardener (2% of the resin); Part C-0.5 ft^3 of filler.

2.2. Specimen Preparation

Samples used for these studies were 600 × 300 × 200 mm concrete blocks with design compressive strengths of about 65 MPa. This high strength was chosen to minimize the concrete failure during the testing process. After casting and initial curing, at the age of 28 days they were saw cut, to produce 600 × 300 × 100 mm slabs. The choice of these dimensions was to resemble the sizes of usual patch repairs on site. On the saw cut surfaces of these slabs, a 20-mm thick repair mortar was applied. At the time of testing, 25-mm deep partial cores were drilled on the repaired surface of each slab, using an ordinary diamond-tipped drill and direct tensile or pull-off [11] tests were carried out. For each condition in each group of testing, five pull-off tests were conducted under dry laboratory conditions, and the average of these results (*i.e.* bond strength and the percentage failures of bond, concrete, and repair) were calculated. Therefore, each value shown in the respective tables represents the average of five pull-off tests. It is worth mentioning that the coefficients of variation (C.V.) of the test results (for five tests) observed during these experiments ranged from 10.53 to 42.76%, with the average of 25.01%. The main reason for this high C.V. could be the mixed (bond, concrete, and repair) failures that were seen to occur during the testing process.

2.3. Test Procedure

The general procedure for performing the direct tensile test (pull-off) employed during this project can be summarized as follows:

(1) Abrade the surface of the concrete in the test area with a carbide stone or wire brush to remove any laitance[1] and deposits. This aids in achieving sufficient bond between the steel disk and the overlay surface.
(2) Advance a 50-mm diameter partial core through the overlay, and a minimum of 5 mm into the substrate concrete. Care should be taken to ensure that the core is advanced perpendicular to the overlay surface to minimize eccentricities during loading.
(3) After the top of the partial core has been cleaned and dried, bond a 50-mm diameter metal disk to the surface of the partial core with a fast-setting epoxy. Avoid applying too much epoxy, as excess will run down the sides of the core and possibly bond the core to the

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[1] Laitance is a soupy mixture of cement, fine sand, and water that accumulates on the surface when wet concrete mixes that bleed excessively are used.

sides of the core hole. Again, care should be taken to ensure that the disk is bonded to the middle of the partial core to minimize the potential for loading eccentricities.

(4) After the epoxy has cured properly, attach the loading device to the metal disk. The loading device with its reaction frame should be adjusted to ensure that the load is applied parallel to the axis of the core. Some reaction frames have adjustable legs for this purpose.

(5) Apply the tensile load to the core at approximately 0.1 kN per second until the specimen fails. Record the failure load, as well as the failure mode and fracture location.

It should be noted that the direct tensile test method (pull-off) is covered by many standards such as ASTM C 1583 [17].

There are essentially four different modes of failure when applying load in this manner. These different failure modes provide valuable information about the overlay system. The magnitude and location of the fracture surface determines what conclusions may be drawn from the test. First, if the failure occurs at the bond surface, the tensile strength is in fact the tensile bond strength. In this case, the ultimate load is a direct measure of the adhesion between the overlay and the substrate concrete. Second, when the failure occurs between the disk and the overlay surface, there is an adhesive failure. In this case, the tensile strength of the overlay system is greater than the failure load, and a stronger adhesive is needed. Third, if the failure occurs in the overlay material, the repair material (overlay) is the weakest portion of the system, and we know the bond strength exceeds the ultimate stress applied. This can also be referred to as cohesive failure of the overlay. Finally, if the failure occurs in the substrate, or underlying concrete, the overlay (repair) concrete and the bond are stronger than the existing concrete, and the repair can be considered successful. This is, again, often referred to as cohesive failure of the substrate.

2.4. Conditions of Testing

Samples prepared for studying the effect of aging were kept under dry laboratory conditions at about 20°C after their initial curing. In order to study the effect of drinking water on the adhesion of repair/concrete interface repaired slabs prepared for this purpose, 24 hours after the completion of the repairs the specimens were transferred and kept in water tanks with temperature of 20°C. At intervals (indicated in the Section 3-Results and Discussion), the specimens were removed from the water tanks and the adhesions at their repair/concrete interface were determined in the dry condition.

To see the effects of freeze-thaw on the adhesion of different repair systems, the specimens prepared under dry laboratory conditions were transferred to the water tanks at the age of 7 days after measuring their tensile bond strength. The temperature inside the tank was 20°C. The measured adhesion is referred to as the adhesion at zero freeze-thaw cycle. After soaking the specimens for 7 days, they were subjected to freeze-thaw cycles each of which consisted of 17 hours in the freezer (-20°C) and 7 hours in the water tank (20°C). The freezing took place in air rather than in water. At different cycles, tensile bond strengths tests were carried out under dry laboratory conditions.

In order to study the effect of cyclic temperature changes on the bond strength of different repair materials, the samples were repaired initially under dry laboratory conditions. The range of the temperature for each cycle consisted of 80°C which was achieved by keeping the specimens inside an oven for six hours, and the cooling process was carried out by placing the specimens inside a freezer with temperature of 20 ± 1°C for 18 hours. To measure the temperature along the interface of the repair/concrete, thermocouples were inserted at the interface during the repairing process and the temperatures were monitored by means of a thermometer with a digital display. The initial ages of the specimens used for this part of the study-were 7 days. At the end of 25, 80, 150, and 200 cycles, direct tensile bond tests were carried out.

3. RESULTS AND DISCUSSION

In addition to the surface strengths of concrete with different surface textures, the relevant results of the effects of aging under dry laboratory conditions, underwater storage, cyclic freeze-thaw, and temperature changes on the adhesion of different repair systems applied to concrete surfaces are shown in Tables 3–7 and Figures 1–4.

3.1. Strength of Repair/Concrete Interface

It is believed that similar to the bond between the cement paste and the aggregate in a concrete [18–20], the main cause of adhesion between the hydration products of repair materials and the old concrete is the intermolecular force (van der Waals force); therefore, the specific surface of the old concrete has a significant influence on the bond strength. Unfortunately, many existing applications of

TABLE 3 Effect of Surface Treatment on Its Strength

Surface	Failure tensile stress (MPa)	Bond failure (%)	Concrete failure (%)
Cast face	4.78	0	100
Saw cut	4.45	62	38
Split (Brazilian method)	3.81	15	85
Split, grit blasted	3.28	16	84
Split, chiseled	3.23	11	89
Split, chiseled, grit blasted	2.67	12	88

concrete repairs were reported [21] not to be reliable although the necessary measures for roughing the old concrete surface (such as sand blasting, chipping with jack hammers, grinding, hydrodemolition, and needle gunning [22]) were used to obtain a specific surface, as large as possible.

Work by the author [23] has demonstrated that there are microcracks associated with naturally fractured, split, and chisel hammered surfaces, which not only reduce the ultimate bond strength but also makes the true assessment of the bonding properties of repair materials almost impossible [24,25]. Results published by some researchers [26] indicate that the non-metallic fiber reinforced High Performance Concrete (HPC) overlay has bonded sufficiently to the underlying concrete. However, all tensile failures had occurred in the substrate material within 8 mm of the bond interface, indicating that the existing concrete was the weakest portion of the system. It is suggested that the low tensile strength in the top portions of the concrete may be a result of existing delaminations or damage from milling and partial depth concrete removal during rehabilitation.

This bond is a function of surface preparation and the physical and chemical characteristics of the repair material and the substrate concrete. Therefore, in order to study the effect of different surface treatment, six different surfaces (cast face; saw cut; split using Brazilian method; split, grit blasted; split, chiseled; split, chiseled, grit blasted) were investigated. It should be noted that, while the cast surface represents the surface in contact with the mould, split surface represents the surfaces of concrete blocks obtained by applying compressive forces to a concrete block through two oppositely situated cylindrical metal rods. Chiseling was done by hand, using ordinary hammer and chisel, and grit blasting was carried out by shot blasting using steel grit (spherical, 1 mm diam) with pressurized air (60–80 psi). Although different strengths of these surfaces were of

TABLE 4 Average Tensile Bond Strengths of Different Repair Systems Under Dry Laboratory Conditions (MPa)

	Repair material					
Age of testing (days)	Epoxy resin mortar	Polyester resin mortar	SBR-modified cementitious mortar	Acrylic-modified cementitious mortar	S/C mortar + epoxy bonding agent	S/C mortar + cement bonding grout
10	4.31 (56,44,0)*	2.71 (43,45,2)	1.36 (88,4,8)	2.23 (58,7,35)	2.51 (91,3,6)	1.87 (87,2,1)
30	3.93 (59,41,0)	2.53 (92,8,0)	1.85 (76,12,12)	2.34 (4,11,85)	2.53 (87,3,10)	1.65 (98,1,1)
150	4.73 (53,47,0)	1.74 (86,14,0)	2.01 (35,18,47)	3.16 (27,15,58)	3.61 (68,7,25)	2.07 (23,17,60)
350	5.27 (51,49,0)	1.92 (90,10,0)	2.35 (19,25,56)	3.31 (55,20,25)	3.71 (51,1,48)	2.96 (25,55,20)

*Percentage failures of (bond, concrete, and repair).

TABLE 5 Average Tensile Bond Strengths of Different Repair Systems Stored Underwater (MPa)

	Repair material					
Age of testing (days)	Epoxy resin mortar	Polyester resin mortar	SBR-modified cementitious mortar	Acrylic-modified cementitious mortar	S/C mortar + epoxy bonding agent	S/C mortar + cement bonding grout
14	3.22 (56,44,0)*	1.73 (84,11,5)	2.51 (50,6,44)	1.61 (77,11,12)	2.32 (41,2,57)	1.51 (56,43,1)
28	3.08 (61,29,10)	1.75 (62,1,37)	2.53 (47,35,18)	1.65 (63,28,09)	2.81 (50,48,2)	1.63 (43,55,2)
90	3.11 (42,57,1)	2.05 (47,20,33)	2.78 (30,28,42)	1.53 (71,19,10)	3.51 (51,29,20)	2.13 (45,36,19)
250	3.10 (19,52,9)*	2.15 (70,15,25)	3.02 (14,86,10)	1.51 (53,20,27)	3.11 (24,61,15)	2.19 (33,67,0)

*Percentage failures of (bond, concrete, and repair).

TABLE 6 Average Tensile Bond Strengths of Different Repair Systems After Being Exposed to Different Cycles of Freezing and Thawing (MPa)

	Repair material					
Number of cycles	Epoxy resin mortar	Polyester resin mortar	SBR-modified cementitious mortar	Acrylic-modified cementitious mortar	S/C mortar + epoxy bonding agent	S/C mortar + cement bonding grout
0	4.31 (54,46,0)*	2.71 (46,44,0)	1.36 (88,1,11)	2.23 (55,10,35)	2.51 (87,3,10)	1.87 (85,0,5)
33	2.73 (67,33,0)	1.81 (65,23,11)	1.25 (86,14,0)	2.57 (32,14,54)	1.58 (95,0,5)	2.11 (65,35,5)
100	2.38 (76,24,0)	1.35 (61,39,0)	0.95 (95,5,0)	2.47 (24,2,74)	1.19 (99,1,0)	2.75 (48,33,29)
200	2.02 (48,52,0)	0.48 (48,52,0)	0.45 (98,2,0)	1.88 (96,0,4)	1.14 (90,3,6)	1.77 (75,4,21)
300	1.86 (50,50,0)	0.41 (73,27,0)	R separation	1.51 (96,4,0)	1.16 (94,2,3)	1.97 (14,81,5)

*Percentage failures of (bond, concrete, and repair).

TABLE 7 Average Tensile Bond Strengths of Different Repair Systems After Being Exposed to Different Cycles of Temperature Changes (MPa)

	Repair material					
Number of cycles	Epoxy resin mortar	Polyester resin mortar	SBR-modified cementitious mortar	Acrylic-modified cementitious mortar	S/C mortar + epoxy bonding agent	S/C mortar + cement bonding grout
0	4.31 (67,33,0)*	2.71 (100,0,0)	1.36 (63,30,7)	2.23 (94,7,0)	2.51 (45,52,3)	1.87 (70,28,2)
30	3.23 (4,96,0)	1.03 (31,18,51)	1.45 (40,60,0)	2.41 (85,15,0)	2.52 (14,55,31)	1.91(98,2,0)
90	2.45 (45,55,0)	0.74 (75,15,10)	1.74 (7,93,0)	2.31 (51,49,0)	2.42 (34,41,25)	0.61 (99,1,0)
150	1.62 (15,85,0)	0.87 (60,40,0)	1.43 (24,76,0)	1.85 (91,4,5)	1.99 (32,68,0)	R. separation
200	1.12 (5,85,0)	0.79 (51,28,21)	1.28 (65,35,0)	1.15 (77,23,0)	1.63 (40,60,0)	R. separation

*Percentage failures of (bond, concrete, and repair).

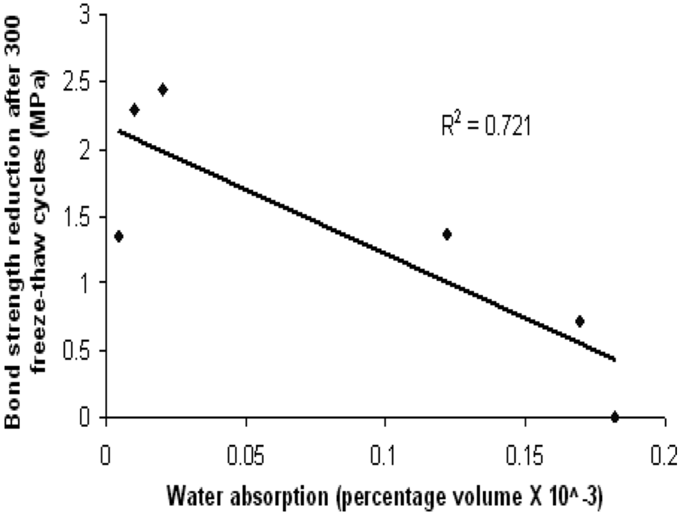

FIGURE 1 Bond strength reduction and water absorption relationship of tested repair materials.

interest to us, the natural occurrence and the expenses associated with each surface preparation should be kept in mind when opting for a particular surface treatment on site. The tensile strengths of

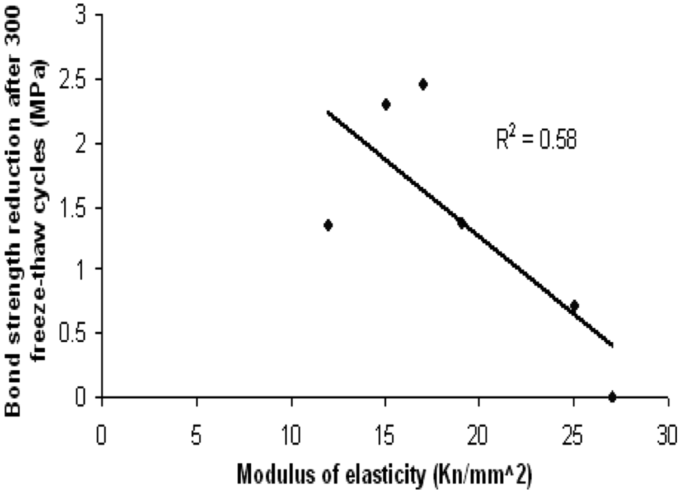

FIGURE 2 Bond strength reduction and modulus of elasticity relationship of tested repair materials.

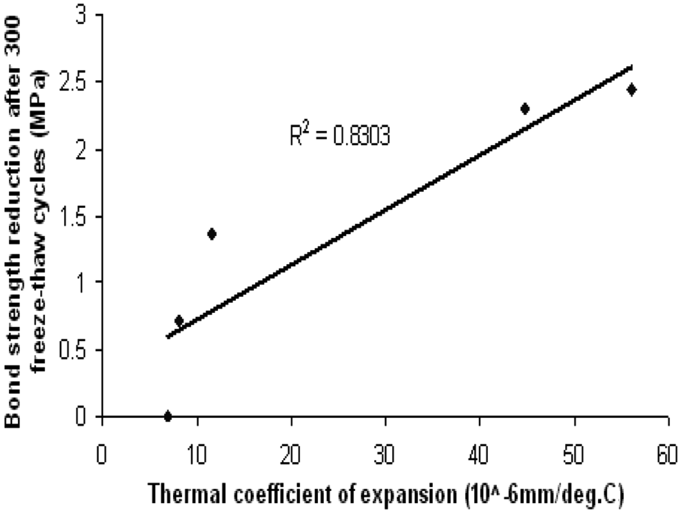

FIGURE 3 Bond strength reduction and thermal coefficient of expansion relationship of tested repair materials.

these surfaces are shown in Table 3. It is worth mentioning that the 28-day design strength of the concrete used for surface strength studies was 65 MPa.

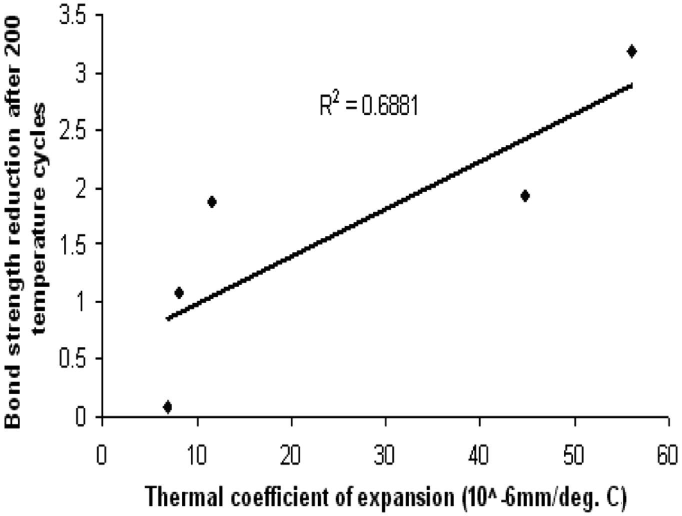

FIGURE 4 Bond strength reduction and thermal coefficient of expansion relationship of tested repair materials.

In order to measure the true adhesion at a repair/concrete interface as accurately as possible, it is very important to avoid the fracture starting at or running into any of the repair or substrate concrete during testing, because otherwise the measured value will be contaminated by the strengths of the repair or substrate concrete. Therefore, when assessing the repair/concrete bond strength, the chosen substrate concrete surface should be strong enough to have the fracture take place along the repair/concrete interface. With this in mind, as can be seen from Table 3, although the highest tensile strength belongs to the cast face, in order to have the bared aggregates as well as cement paste and to assess their bonding properties with different repair materials, the most suitable surface appears to be the saw cut surface because, in addition to the high strength, this surface produces a good proportion of bond failure that is necessary for a better bond assessment of any repair system. Furthermore, if a strong and representative substrate concrete surface is employed for the repair/concrete bond assessment, then, for practical purposes, the effect(s) of any surface preparation system can be studied independently, without facing possible complicated interactions of the adhesion of a repair system and the strength of the substrate concrete.

3.2. Acrylic-Modified Cementitious Mortar

The adhesion-age relationship for the acrylic-modified cementitious mortar kept in dry laboratory conditions is shown in Table 4. Examination of this table shows that, by day 350, when the bond strength reaches about 3.31 Mpa, the increase in adhesion becomes almost negligible. The observation of relatively equal percentage repair failure at early ages during the testing tends to indicate that the adhesion is almost the same as the repair strength but, with the passage of time, the repair strength tends to exceed the value of the adhesion, because the percentage repair failure at the age of 350 days is seen to be less than that of the bond failure. With regard to the concrete failure, it was seen that, when the adhesion reached about 3 MPa, the percentage concrete failure became noticeable.

The results of the effects of underwater storage on acrylic-modified cementitious mortar are shown in Table 5. Examination of this table shows that despite the increase in the bond strength of this system up to 28 days, it shows a decrease between the ages of 14 and 90 days and then remains almost constant at 1.51 MPa, up to the final day of testing (250 days). Since the percentage bond failure recorded for the age of 14 days was relatively high (85%), no apparent reason could be identified for the drop in the bond strength between the ages of 14 and 90 days.

The results of freeze-thaw tests on acrylic-modified cementitious mortar are given in Table 6. This table shows that during the initial stages of freeze-thaw cycles, *i.e.* up to 33 cycles, the adhesion of this system tends to increase. However, after the 33rd freeze-thaw cycle its adhesion decreases with increasing number of cycles. This decrease in the residual adhesion would appear to continue until the last cycle of the test, causing the primary adhesion of 2.23 MPa to reduce to about 1.51 MPa at the end of the 300th freeze-thaw cycle. Despite the low percentage bond failures and high percentage repair failures during the 33rd and 100th cycles, the situation was almost completely reversed after the 100th cycle. From this it could be inferred that the real adhesion losses appear to be even higher than those that can be observed from Table 6, because low percentage bond failures during the early numbers of freeze-thaw cycles would indicate higher adhesion than those recorded for the early stages. Furthermore, it could be said that at the early stages of freeze-thaw cycles, the strength of the repair itself is lower than its adhesion to substrate concrete.

The results of the effects of cyclic temperature on the acrylic-modified cementitious mortar are shown in Table 7. According to this table the adhesion of this system to concrete has increased during the first 30 cycles, by reaching 2.41 MPa. After the 30th cycle, the bond strength appears to decrease and reach the value of 1.15 MPa at the end of the 200th cycle.

Comparison of the SBR and acrylic systems examined would indicate a better overall performance for the acrylic than for the SBR system. It should be noted that this finding agrees with the findings based on the experiments with the polymers alone. According to some researchers [27], the polymethylmethacrylate which is generally referred to by the term “acrylics’ is reported to be more durable than its counterpart SBR system. It should be noted that according to [28] the bond strength of this material appears to be higher than that of ordinary portland cement mortar.

3.3. Sand/Cement (S/C) Mortar + Epoxy Bonding Agent

The effects of aging on the adhesion of S/C mortar plus epoxy bonding agent kept under dry laboratory conditions are shown in Table 4. This table shows that, despite the constant adhesion recorded between the ages of 10 and 30 days, the adhesion has increased from 2.51 to

3.71 MPa at the age of 350 days. Therefore, from Table 4 it may be inferred that, when S/C mortar plus epoxy bonding agent is used as a concrete repair system which is designed to stay under dry conditions, about 5 months is needed for the repair to develop its full bond strength. Examination of percentage repair failures reveals that the bond strength of this system is actually higher than the values recorded, because the percentage bond failure is seen to be lower than that recorded for repair failure. Comparison of the results of S/C mortar + epoxy bonding agent with those of the S/C mortar + cement bonding grout-tends to suggest that, despite the high adhesion of the former system during the early ages, the adhesion of the two systems would appear to differ slightly at the age of about 350 days, if they are kept under dry conditions. Considering the high cost and the differences in the engineering properties of epoxy, this finding is very important when choosing a repair system.

The results of the effects of underwater storage on sand/cement mortar + epoxy bonding agent are shown in Table 5. These results show that the adhesion of this repair system increases up to the age of 90 days, reaching the value of about 3.51 MPa and then reduces to about 3.11 MPa . Examination of the percentage repair, bond and concrete failures indicated that the strength of the repair material was higher than that of the parent concrete.

The results of the effects of freeze-thaw cycles on the adhesion of S/C mortar + epoxy bonding agent are shown in Table 6. According to this table, as the number of freeze-thaw cycles increases the residual adhesion decreases up to 100 cycles but it remains almost constant at about 1.18 MPa during the rest of the exposure to freeze-thaw cycles. It can also be seen that the rate of decrease in the adhesion would appear to be higher during the first 33 cycles. It is also apparent from Table 6 that, after 300 cycles, this repair system has lost more than 50% of its original tensile bond strength.

The results of the effects of cyclic temperature on S/C mortar + epoxy bonding agent are shown in Table 7. According to these results, although during the first 30 cycles little increase is observed in the bond strength of this repair material, after that a drop of about 30% can be seen in the bond strength at the end of 200th cycle. It is worth mentioning that after 70 temperature cycles, extensive cracking of the parent concrete was observed which had certainly affected the bond strengths measured afterwards. Therefore, it is advised that when considering this repair system for situations in which large temperature changes are present, the effect of cyclic temperature on the strength of the parent concrete should also be paid attention to, for proper assessment of the bond deterioration.

3.4. SBR-Modified Cementitious Mortar

The age-adhesion relationship for this repair system is shown in Table 4. This table shows that the bond strength of this repair material tends to increase steadily, and reaches the value of about 2.35 MPa at the age of 350 days. One point of significant importance noted with this repair system was the presence of a weak bond between the repair mortar and the bonding slurry which made the identification of the true nature of the failure patterns more difficult. Because, to be consistent, the term "bond failure" has been meant to indicate the failure along the surface of the substrate concrete and the repair. The low adhesion between the repair and the bonding slurry would appear to have influenced the overall adhesion property of this system because the mutual penetration of the repair and the bonding slurry results in mechanical interlocking, offering more resistant axce to de-bonding.

The results of the effects of underwater storage on the bond strength of SBR-modified cementitious mortar are shown in Table 5. These results show that the adhesion of this repair system increases with time and reaches about 3.02 MPa at the age of 250 days.

Examination of percentage concrete failures of this material revealed that when the adhesion reached about 3 MPa, the percentage concrete failures reached about 86%, indicating the importance of the concrete surface strength for repair/concrete adhesion studies.

The results of freeze-thaw tests on SBR-modified cementitious mortar are presented in Table 6. It is apparent from Table 6 that as the number of freeze-thaw cycles increases, the residual adhesion decreases and it becomes almost zero after 300 freeze-thaw cycles. The term "almost" is used because after the 300th cycles of freeze-thaw, the repair layer separated from the substrate concrete during the coring process of testing. The percentage failures recorded for this material indicates a significant decrease in adhesion of this system because the percentage bond failure is sufficiently high to support this. Possible reasons for the separation of the repair layer could be the accumulation of water along the interface between the repair material and the bonding slurry, and exertion of high pressure due to the frozen water. It is worth mentioning that some cracks were visible along the perimeter of the slab between the repair and substrate concrete before the separation. Considering the decrease in adhesion per cycle of freeze-thaw for this repair system, and the average number of freeze-thaw cycle/year, it would be possible to estimate the life span of a repair system. However, for doing so, the conditions of freezing and thawing have to be considered carefully. In this respect, it should be noted that if, for example, the freezing and thawing takes place underwater or under partially dry conditions, the end effects may differ significantly. Ohama [29] has also observed that the bond strength of mortars containing SBR decreases over time and with every freezing and thawing cycle.

The results of the effects of the temperature changes on the adhesion of SBR-modified cementitious mortar are shown in Table 7. This table shows that the bond strength of this system appears to have increased during the first 90 cycles and then decreased continuously until the 200th cycle. The percentage concrete failure recorded for this repair system revealed that, as the number of temperature change cycles increased, the strength of substrate concrete also decreased relative to its bond strength. The average percentage concrete failures were relatively high giving the effect of underestimating the true bond strength of the repair system.

3.5. Epoxy Resin Mortar

The changes in the adhesion of the epoxy resin mortar during aging under dry laboratory conditions are shown in Table 4. According to this table, adhesion of this system appears to increase with time except between the ages of 10 and 30 days, during which it decreases from 4.31 to 3.93 MPa. It also appears from Table 4 that, the rate of gain in the adhesion is slightly higher during the time from 30 to 150 days, than between the ages of 150 and 350 days. Comparing the 10-day adhesion recorded as 4.30 MPa with that of 350 days (5.27 MPa), it would appear that this repair system achieves about 80% of its long term adhesion in about 10 days from its application. It should be noted that the rapid setting and hardening repair systems are of significant importance in areas where restrictions are faced with regard to the repair time. Examination of the type of failure recorded for this repair material indicated that the strength of the repair mortar itself was higher than the strengths of both the adhesion and substrate concrete, because no repair failure was observed during the testing process of this system. These records also showed that in almost 50% of the partial cores tested, the concrete strength was lower than the adhesion of this repair system.

The results of the effects of underwater storage on epoxy resin mortar are shown in Table 5. This table shows an almost constant adhesion of about 3.10 MPa between the ages of 14 and 250 days.

The results of exposing this repair system to cyclic freezing and thawing are shown in Table 6. One apparent point from this table is the loss of its adhesion to substrate concrete throughout the freeze-thaw tests. The rates of bond losses during the first 30 cycles appear to be higher than those observed for the later cycles. It can also be seen that, during the 300 cycles of freeze-thaw, the bond strength of this repair system is reduced by about 60%. The observed percentage concrete failures indicate that the freeze-thaw action tends to reduce the strength of the parent concrete as well. This reduction after about 300 freeze-thaw cycles seems to be higher than that of the reduction in bond strength.

The results of the adhesion of the epoxy resin mortar under cyclic temperatures are shown in Table 7. According to this table, cyclic temperature changes affect the bond strength of this repair system adversely, reducing its original bond strength by more than 3 MPa at the end of the 200th cycle. However, because of low percentage bond failure, the bond strength is thought to be higher than the recorded values. The effect of thermal movement is similar to that of shrinkage in terms of generating stresses at the interface when the repair and substrate have different coefficients of thermal expansion. Results published by some researchers [30] indicate that the epoxy resin mortars, in general, did not perform well because they were not thermally compatible with the base concrete. Tests carried out by Emberson and Mays [15] showed that resinous materials have much higher coefficients of thermal expansion than non-resinous materials, but polymer-modified cementitious materials tend to have values approximately equal to that of a typical substrate concrete. The latter systems are, therefore, less likely to be subject to thermally induced stresses which can cause or precipitate bond failure.

3.6. Polyester Resin Mortar

The bond strengths of this repair system kept under dry laboratory conditions are presented in Table 4. Examination of this table shows that the 10-day adhesion of 2.71 MPa has dropped to 1.92 MPa at the age of 350 days. According to Table 4, the lowest adhesion would appear to have occurred at the age of 150 days. The main reason for this was the presence of cracks in the substrate concrete which caused more concrete failures, resulting in an underestimated adhesion for this repair system. The occurrence of the cracks in the concrete seemed to be due to the excessive shrinkage within the repair material, indicating that the adhesion would be more influenced by the substrate concrete cracks.

The results of the effects of underwater storage on the adhesion of polyester resin mortar are shown in Table 5. According to this table, adhesion of this system increases with time up to the age of 90 days. During the experiments with this system it was observed that almost always a thin layer of repair mortar remained on the bond area after testing, which made the true assessment of the adhesion more difficult. Furthermore, the mixed failures involved with this system did not allow the accurate assessment of the percentage failure to take place.

The results of the effect of freeze-thaw cycles on the adhesion of this repair system to substrate concrete are given in Table 6. According to this table, the rate of the reduction in the adhesion of this repair material under the freeze-thaw cycles appears to be higher than in the later cycles. Although according to Table 6, it can be seen that the rate of the adhesion reduction of this repair system tends to decrease as the number of cycles increases but reference to percentage failures of this system indicates that, because of a relatively high percentage concrete failures, this reduction might be doubtful. The percentage concrete failures recorded were mainly due to the excessive shrinkage of the polyester mortar which had caused flexural cracks along the back side of the substrate concrete. Further examination of these results shows a reduction of about 85% in the tensile bond strength of this repair material after being exposed to 300 freeze-thaw cycles.

The results of bond strength of polyester resin mortar applied to substrate concrete exposed to cyclic temperature changes are shown in Table 7. This table reveals that the cyclic temperature has had a deterioration effect on the bond strength of this repair material during the first 90 cycles. This reduction is seen to be about 75%. A point worth mentioning is that between the 90th and 150th cycles, the bond strength tends to have increased by about 20%. It should also be noted that when experimenting with this material, due to its high shrinkage which caused bending and flexural cracking in the middle part of the substrate concrete, the true bond strength assessment was very difficult and, therefore, the readings are not as accurate as they should be. The results also tend to show that the strength of polyester resin mortar also seems to have been adversely affected by the cyclic temperature, because for relatively low tensile stresses of less than 1 MPa a high percentage of repair failures were seen.

Working on the shrinkage of repair mortars, Emberson and Mays [15] have shown that the first 2-hour shrinkage of the polyester resin mortar was 4000 microstrain (parts per million) with little change afterwards; this may explain the high early bond strength losses under cyclic temperature changes.

3.7. S/C Mortar + Cement Bonding Grout

Examination of the bond strength of S/C mortar + cement bonding grout, kept under dry laboratory conditions, which is shown in Table 4, suggests that the adhesion of this system has increased from 1.87 to 2.96 MPa within the period of 10 to 350 days. It was also seen from the recorded percentage failures of this system that, as the adhesion increases, so does the percentage concrete failure. In this respect, it was evident that, while the concrete failure had been absent during the 10 and 30 day tests, it reached 30% at the age of 350 days. One possible reason for the increase in the adhesion due to aging could be the increase in the gel volume due to the continuing hydration process, which in turn increases the contact area between the repair mortar and the substrate concrete. Another reason could be the fact that, as the age increases, so does the crystalline growth along the repair/concrete interface which, in turn, enhances the interfacial mechanical interlocking. The effect of the crystalline growth on the adhesion could be enhanced if reactive aggregates are present at the repair/concrete interface. There is also the possibility that, due to the presence of a complex solution of calcium, silica, aluminum, and sulfur at the interface, the crystalline growth could be higher at the interface than within the mortar matrix. However, it should be noted that the crystalline growth is a two-way process within the repair matrix compared with almost a one-way process along the interface. This is because within the matrix every individual particle contributes to the crystalline growth while, along the interface, no crystalline contribution is expected from the surface of the substrate concrete, unless its aggregates are of a reactive nature.

The results of the effect of underwater storage on the adhesion of S/C mortar + cement bonding grout are shown in Table 5. According to this table, up to the age of 90 days, as the time of submergence increases, so does the adhesion but it remains almost constant until the end of testing which terminated at the age of 250 days.

The results of effects of freeze-thaw cycles on the bond strength of S/C mortar + cement bonding grout are plotted in Table 6. This table shows that the adhesion of this system to substrate concrete increases up to about 100 cycles, then it decreases to less than its original value at 200 cycles, after which it tends to rise again. No possible explanation is found for this behavior except to say that as the number of cycles increased, the percentage bond failures decreased which could give underestimated results for the measured bond strengths. This point was more pronounced at the 300th cycle, the percentage bond failure of which was about 15% for the tensile stress of about 2 MPa. Considering tensile bond strength (adhesion) of about 2 MPa recorded after 300 freeze-thaw cycles, it appears that the freeze-thaw performance of this repair system is satisfactory. Noting the percentage concrete failures recorded after 300 freeze-thaw cycles, it is possible to say that the parent concrete had also been degrading under freeze-thaw action.

The results of the effects of cyclic temperature changes on the adhesion of S/C mortar + cement bonding grout are Shown in Table 7. These results show that during the first 30 cycles the bond strength increases slightly, then it falls significantly as the number of cycles increases. This increase could be due to the better hydration of the S/C mortar under higher temperatures. Table 7 also shows that, at the end of the 90th cycle, about 60% of the bond strength appears to have been lost. Then, as the number of temperature cycles reaches 150, the bond strength of this system is reduced to a negligible value because the repair layer had separated from the substrate concrete during the coring process of testing.

3.8. Studying the Relationship Between the Adhesion Losses Under Freeze-Thaw and Temperature Change Cycles With Some Properties of the Repair Materials

As is shown in Figure 1, examination of the material properties tested showed an average correlation coefficient of -0.70 between the bond losses and the water absorption of the repair systems. This may be due to two factors: one could be the presence of pores which could accommodate the pressure exerted by the frozen water: the other could be the better drainage associated with the porous systems which leads to a lesser water freeze and, consequently, less pressure because, as stated earlier, the freezing process was taking place in the air rather than in water.

The other significant correlation coefficient (-0.58) was spotted between the modulus of elasticity (E) of the repair systems and their bond losses during the freeze-thaw tests (Fig. 2). The negative sign of this correlation coefficient tends to indicate that, as E increases the bond losses decrease. It should be noted that, since the E values of the resinous systems are lower than those of the cementitious systems and concrete, the bond losses for resinous systems would be higher than for the cementitious ones.

After neglecting the data belonging to the epoxy adhesive used as the bonding agent, due to its very thin layer that could not play any significant role in accommodating the stresses freely, as is shown in Figure 3, a correlation coefficient of 0.8303 was found to exist between the bond losses under freeze-thaw tests and the thermal coefficient of expansion of different repair systems. This could suggest that the build up of stresses due to differential shrinkages may also be responsible for the bond losses. A difference in elastic modulus influences the stress distribution in the substrate and repair. Stress concentration is the case with epoxy bonded plates where, despite a very large modulus mismatch between the steel and epoxy resin/concrete (and, hence, very high stress concentrations) this system can still generate high bond strengths. In the specific case of concrete patch repairs, engineers should be aware of the influence of modulus mismatch on stresses, not only in a simple tensile test but also in repairs subject to compressive and shear stresses, as we have seen elsewhere [31].

As is depicted in Figure 4, examination of bond losses of different repair systems exposed to 200 temperature cycles and their respective thermal coefficients of expansion showed a correlation coefficient of 0.6881 between the two, which is an indication of the effect of dimensional changes and the fact that the consequent residual stresses are also responsible for bond deterioration. It should be noted that when studying this relationship, the data related to S/C mortar + epoxy bonding agent was not taken into account, because the epoxy adhesive layer was very thin and sandwiched between the repair and substrate concrete and, therefore, was not able to move freely under temperature changes.

4. CONCLUSIONS

From the results presented and discussed in this article the following conclusions can be made:

(1) For 350 days under dry laboratory conditions, while the lowest adhesion was seen to belong to polyester resin mortar (about 1.92 MPa), the epoxy resin mortar with about 5.27 MPa adhesion, showed the highest value. The bond strengths for other repair systems were recorded as 2.35, 3.31, 3.71, and 2.96 for SBR modified mortar, acrylic-modified mortar, S/C mortar + epoxy bonding agent, and S/C mortar + cement bonding grout, respectively.
(2) For 250-day underwater storage of different repair systems, the bond strengths of 3.10, 2.15, 3.02, 1.51, 3.11, and 2.19 MPa were recorded for epoxy resin mortar, polyester resin mortar, SBR mortar, acrylic mortar, S/C mortar + epoxy bonding agent, and S/C mortar + cement bonding grout, respectively.
(3) While the percentage reduction of the tensile bond strengths of different repair systems after 300 freeze-thaw cycles were seen to be 57, 85, 100, 32, and 54 for epoxy resin mortar, polyester resin mortar, SBR mortar, acrylic mortar, and S/C mortar + epoxy bonding agent, respectively, the tensile bond strength of S/C mortar + cement bonding grout showed an increase of about 5%.

(4) Exposure of different repair systems to cyclic temperature changes caused the reduction of 74, 71, 6, 48, 35, and 100% on the tensile bond strengths of epoxy resin mortar, polyester resin mortar, SBR mortar, acrylic mortar, S/C mortar + epoxy bonding agent, and S/C mortar + cement bonding grout, respectively.

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