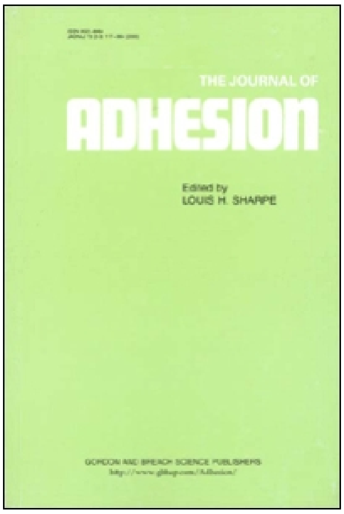

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Effects of Cyclic Loading, Freeze-Thaw and Temperature Changes on Shear Bond Strengths of Different Concrete Repair Systems

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An experimental study was performed to evaluate the residual shear bond strengths between different cementitious and resinous repair materials and substrate concrete after being subjected to cyclic loading, freeze-thaw, and temperature changes. In this paper, techniques and results of test methods that induce shear along the repair/concrete interface are discussed. In addition to the effect of surface preparation on the strength of the old concrete surface, which proved the saw cut surface as the most suitable substrate concrete for shear bond strength assessment, by means of cylindrical shear and friction-transfer methods, the effects of cyclic loading, freeze-thaw, and temperature changes on the shear bond strengths of six different repair systems are illustrated. Analysis of the results indicated that: in order to avoid fatigue failure, the maximum safe stress level to be applied should be between 20 to 40% of the original shear bond strength of the repair system, and the critical stress level differs for different repair materials; 300 freeze-thaw cycles can reduce the shear bond strength of a resin mortar by up to about 80%; and 200 cycles, of temperature changes can reduce the original shear bond strength of a cementitious mortar by up to about 90%.

Keywords: Bond strength; Concrete repair; Fatigue; Freezing and thawing; Mortar

1. INTRODUCTION

In the application and performance of concrete repairs, good adhesion of a repair material is of vital importance. In general, chemical, chemi-physical, or physical effects of the service conditions may cause the

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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 of 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.

Therefore, 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 most importantly, the multidisciplinary nature of the repair/concrete interface problems exert limits and restrictions, which make the choice of proper bond tests much more difficult.

Therefore, not only are short term and static bond strengths of a repair material important but, also, studying the effects of cyclic loading, freeze-thaw, and temperature changes that could induce stresses along the concrete/repair interface is useful, because these physical effects are those to which every repair system is exposed, during its life long service. As explained by Austin *et al.* [1] a wide range of test methods has been proposed to evaluate bond strengths of repair materials in recent years. These include the tensile bond [2], slant shear [2–6], patch tests [7], flexural [6], and the present author's friction-transfer [8–10] and cylindrical shear methods [11]. Since the main aim was to study the effects of induced shear strains and stresses along the repair/concrete interface (*e.g.*, shear stresses induced along the repair/concrete interface due to differential strains produced from different dimensional changes), this paper discusses the residual bond strengths of six different repair materials after being subjected to cyclic loading, freeze-thaw, and temperature changes which were obtained by using three types of bond tests that apply shear to the interface of a repair material and substrate, namely slant shear, cylindrical shear, and friction transfer test methods.

It should be noted that other methods such as contact electrical resistance measurement [12] 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. EXPERIMENTAL INVESTIGATION

2.1. Materials

There are many commercially available concrete repair systems for hand applications (including flowables) and these are categorized into nine generic types [13]. 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 project, 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; 7 μm silica (typically 5% of the OPC); admixtures such as styrene butadiene rubber (SBR); polypropylene fibers; and, sometimes, chemical shrinkage compensators.

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 to produce 28-day cube compressive strength of about 65 MPa. The mix design of this concrete is shown in Table 1.

In order to carry out the friction-transfer tests, 600 × 300 mm slabs were produced using concrete blocks with 600 × 300 × 150 mm dimensions which were cast vertically with the 600 × 150 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-day, 600 × 300 × 100 mm slabs were produced by cutting the 600 × 300 mm side of the cast slab, using a diamond tipped saw.

For cylindrical and slant shear tests, 150 mm cubes and 100 × 100 × 500 mm beams were produced using the concrete mix proportions shown in Table 1.

2.1.2. Ordinary Cement 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

TABLE 1 Mix Proportions for 1 m^3 Substrate Concrete

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

the cement content). Before application of this mortar, the surface was coated with slurry of cement grout. The 28-day compressive strength of this mortar was measured as 71 MPa.

2.1.3. Styrene Butadiene Rubber (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.

The styrene butadiene rubber latex containing 40% solids was mixed with water in the ratio of 2:1. The mixing proportions of this mortar with 28-day compressive strength of 53 MPa are shown in Table 2. Its basic constituents include Part A: SBR Polymer latex (Sbd, division of Weber and Broutin, Belfast, UK); Part B: cement paste material; 1 gal of Part A for 50 lb bag.

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. Fiber Reinforced Acrylic Modified Cementitous Mortar

This is a pre-packed mortar in two components: one containing cements, aggregates, fibers, 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 plus fiber. According to the manufacturer, a bonding coat is not required unless the substrate concrete is particularly porous. The 28-day compressive strength of this system was 46 MPa.

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 N/mm^2 after 24 hours. According to the supplier's information, these materials included a repair system for concrete repair that uses radically structured polymeric repair compound; Part A: epoxy resin;

TABLE 2 Mix Proportions for 1 m^3 S.B.R. Modified Cementitious Mortar

Water plus S.B.R. latex (Kg)	Cement (Kg)	Sand (kg)
180	630	1570

Part B: proprietary accelerator; Part C: mineral aggregates; R:H:F (Resin: Hardner: Fine aggregate) = 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 solvent-free two component; 100% solids epoxy resin system with 28-day compressive strength of over 67 MPa.

2.1.7. Polyester Resin Mortar

The polyester resin used in this work was a styrene diluted unsaturated polyester-based polymer concrete with a 28-day compressive strength of 97 MPa.; Part A: 1 gal of resin; Part B: 3 oz of hardener (2% of the resin); Part C: $\frac{1}{2}$ cu. ft. of filler.

2.2. Test Methods

Testing of bond strength originates with adhesive testing. Numerous types of test methods exist for assessing the bond strength between adhesive and adherent, many of which relate to a particular application for the adhesive since it is possible to simulate both the size and stress condition which occur in practice.

Furthermore, since the application of most adhesives takes place under laboratory conditions (*e.g.*, in the aircraft industry) the results of laboratory test specimens are directly applicable. In the case of concrete repairs the situation is different in that:

(a) The loading condition in service may be varied and difficult to simulate in a test.

(b) The repair is usually carried out under conditions very different from those in a laboratory.

2.2.1. Slant Shear Test

This method, which puts the bond interface into a combined state of compression and shear, first appeared in the form of the Arizona slant-shear test [14] and was later modified using rectilinear prisms by Tabor [3]. It was adopted in BS6319: Part 4 [15] as a test method for evaluating repair materials. Some researchers claim the test represents stress states typical of real structures [4,16,17] and others claim this method is sensitive to variations in bond strength [4] and that it produces consistent results [5]. The test is still used by manufacturers and specifiers to characterize repair materials, but the test has some serious shortcomings. Failure is crucially dependent on the angle of the plane that is fixed in the standard test, precluding the possibility of obtaining a bond failure on a different plane (where there may be a critical combination of compressive and shear stresses). It is also relatively insensitive to surface roughness and condition, only producing bond failures with smooth surfaces [18]. Lastly, the test is sensitive to differences in elastic modulus of the repair and substrate concrete that cause stress concentration.

For the slant shear test, half prisms with cross sectional area of 100 × 100 mm were cut out from the 500 mm-long beams, using a concrete saw in such a way that the cut surface made 30° angles with the side of the original beam. The sloping sided prisms were placed in the oiled mould of the original beam and the other half was cast in repair material. After completion, composite prisms were produced, the components of which were two identical sloping faced prisms of concrete and repair. For every repair system and the related slant angle, three samples were prepared and the average of their ultimate strengths was calculated.

2.2.2. Cylindrical Shear Test Method

In this method, which was developed by the author [11], a 60 mm diameter cylindrical void is created along the center of a 150 mm concrete cube by means of a coring drill [see Fig. 1(b)]. A 5 mm cut is made along one of the sides of the cube running parallel to the cylindrical void (this cut is to overcome the restraining effect of the lateral expansion of the material under compression and to ensure that no cylindrical hoop stresses are developed). Then, by sealing this cut using expanded polystyrene, the cylindrical void is partially filled (140 mm out of 150 mm cube height) with the repair material. The necessary compaction is provided by the use of a steel rod and different specified curing regimes were applied for cementitious and resinous systems. To assess the bond strength between the repair and its surrounding concrete, at the age of 28-day, [Fig. 1(b)], the repair is pushed out of the cube and the ultimate shear bond strength is calculated by dividing the failure load by the bond area.

This test method appeared to be very suitable because:

- The preparation of the specimen is very simple.
- The pieces of apparatus used for the manufacture of the specimen are all available in a normal concrete laboratory.
- The compaction and curing process can be carried out under better-controlled conditions.

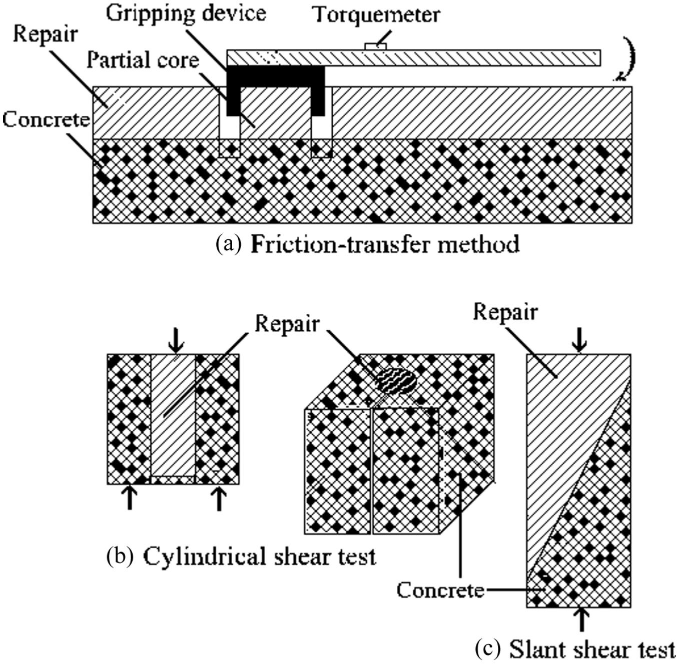

FIGURE 1 (a) Friction-transfer, (b) cylindrical shear, and (c) slant shear methods.

- No flash drying of the bonding grout takes place.
- No extra precautions (such as capping, etc.) are required prior to testing.
- Since the nature of failure is almost 100% bond failure, it provides more reliable results for measuring the true bond strength and for comparison of different repair systems.

In addition to the above-mentioned advantages, it was found that this method could easily show the curing shrinkage, if it is associated with the repair system.

At the age of 28-day, for each repair system three specimens were tested to failure and the average ultimate bond strength, were calculated. Then, for the application of the cyclic loads, sinusoidal pulsating loads varying between a minimum load of 10% and maximum load of 80, 60, and 40% of the ultimate strength were applied at the rate of 30 cycles per minute and the number of cycles at failure for each stress level was recorded.

2.2.3. In-Situ Friction-Transfer Shear Test

The friction-transfer test method [8] involves cutting a 50 mm partial core by means of coring drill [Fig. 1(a)]. The depth of the core for assessing the bond strength between a repair and the substrate concrete should be deep enough to penetrate about 5 mm into the substrate concrete. The gripping device fits on top of the partial core and after tightening the pressure bolts a torque is applied to the gripping device using the torque-applying unit, by fitting it into the square space provided at the top of the device. The torque is then gradually increased manually until the partial core is fractured and maximum torsional shear stress at failure is calculated.

In order to assess the bond strengths of different repair materials under cyclic freeze-thaw and temperature changes, 600 × 300 m sawn surfaces of the concrete slabs were repaired using different repair systems. The curing process was carried out according to the manufacturer's specifications, which included 7 days under wet hessian and polyethylene sheets for cementitious materials and dry conditions for resinous systems. The thickness of the repair layer was 20 mm for all the systems considered.

After exposing the repaired 600 × 300 mm concrete slabs to different cycles of freeze-thaw and temperature changes, the friction-transfer test method was used to obtain the concrete/repair interfacial bond strength. For every measurement, five friction transfer tests were carried out and the observed values were averaged.

3. RESULTS AND DISCUSSION

3.1. Strength of Repair/Concrete Interface

Surface roughness and surface strength have a profound effect on the test results. Work by the author [19] has demonstrated that there are micro cracks 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 [20,17].

Therefore, in order to study the effect of different surface treatments, eight different surfaces were investigated. The tensile strengths of these surfaces are shown in Table 3. It is worth mentioning that the 28-day strength of the concrete used for surface strength studies was 68 N/mm^2.

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

TABLE 3 Effect of Surface Treatment on its Strength

Surface	Failure tensile stress (N/mm^2)	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

during testing, because 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 in order 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. Slant Shear Test Results

According to the recorded 30° axial failure stresses plotted in Figure 2, the acrylic modified cementitious mortar would appear to have the lowest bond strength among the materials tested. It is also apparent from this figure that the fiber reinforced acrylic modified cementitious mortar and acrylic modified bonding grout seem to have produced the lowest 30° axial failure stresses. It can also be seen from this figure that the highest respective value recorded, belongs to the epoxy mortar tested.

In order to assess the suitability of the slant shear method for measuring the adhesion of a repair material, respective results of this method along with those of direct tensile, friction-transfer, and

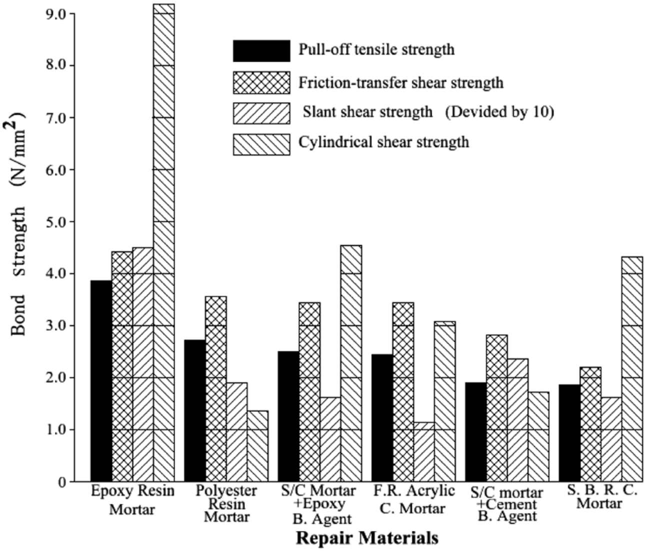

FIGURE 2 Bond strengths of different repair systems measured by different test methods.

cylindrical shear methods are plotted in Figure 2. This figure shows that, despite the fact that very good correlation seems to exist between the comparative results of the pull-off tensile and friction transfer methods, results obtained from cylindrical and slant shear methods do not show the same trend. This finding agrees well with the results of some researchers who believe that when using this method a bond failure envelope should be constructed that covers the full range of normal/shear stress combinations that can arise in practice [1]. Therefore, it was decided to look for a more suitable test method for the application of cyclic shear stresses, which result from cyclic loading, freeze-thaw, and temperature changes.

3.3. Results of Cylindrical Shear Test Method Used for Cyclic Load Tests

Having realized the independency of the measured bond strength from the repair depth, it was found that the repeatability and coefficient of variation of the results (less than 10%) of the cylindrical shear method was within acceptable limits and with the limitations of the slant shear method in mind, this method was used to examine the effect(s) of cyclic loading on the shear bond strengths of six different repair systems.

TABLE 4 Results of Cyclic Loading on Different Repair Systems

Repair material	Max. applied stress/bond strength	Number of cycles at failure
Epoxy resin mortar	0.8	276
	0.6	531
	0.4	>50000
Polyester resin mortar	0.8	681
	0.6	>50000
	0.4	>50000
Styrene butadiene rubber modified cementitious mortar	0.8	6
	0.6	78
	0.4	32108
Fiber reinforced acrylic modified cementitous mortar	0.8	41
	0.6	1638
	0.4	4903
Sand/cement mortar + epoxy bonding agent	0.8	18
	0.6	271
	0.4	7209
Sand/cement mortar + cement bonding grout	0.8	4
	0.6	44
	0.4	>50000

Examination of Figure 2, which depicts the bond strengths of six different repair systems obtained using cylindrical shear, pull-off, and friction-transfer methods, indicates that, due to the confinement of the repair material within a prefixed cylindrical volume, repair materials with high shrinkage properties, such as polyester resin mortar, show lower bond strength. Therefore, it was anticipated that the cylindrical shear method could be used to study the shrinkages of different repair systems. It should be noted that, for the purpose of cyclic load testing, the effect of shrinkage does not affect the results because a percentage of the ultimate bond strength is employed.

Results of cyclic load tests are shown in Table 4. Every reading shown in Table 4 is the average of three test results. It should be noted that when a repair system reached over 50,000 cycles without any failure, the test was terminated and the results were recorded as such.

The first point that can be seen from Table 4 is that as the ratio of maximum applied stress to ultimate bond strength decreases from unity to about 0.5, a small increase in the number of failure cycles is observed and when this ratio is reduced from 0.5 to about 0.4, a large increase in the number of failure cycles can be seen. It is also clear that, as the above-mentioned ratio employed for sand/cement mortar + cement bonding grout decreases from unity to 0.4, the number of failure cycles exceeds 50,000, indicating an almost sudden change in the adhesion behaviour of this system. At first instance it might be seen necessary to carry out more tests in the transitional region, *i.e.*, between the stress ratios of 0.6 and 0.4, in order to achieve better classification of the curve in this region. However, with the very high variations that are common in fatigue testing of even homogenous materials, this would require a large number of specimens [21].

The relatively low number of failure cycles, at the stress ratios of more than 0.5, may be better explained if the internal cracks within an ordinary concrete cube are examined. In this respect, it is believed that some cracks would be present within the concrete along the aggregate/paste interface. These cracks are said to be due to shrinkage effects, which occur during the setting and hardening process of the concrete. It is also reported that when an ordinary concrete is subjected to loading, at a low stress level of about 30% of its ultimate strength, new cracks develop within the matrix. As the intensity of the applied load increases, so will the initiation of new cracks and the propagation of, and linking between, cracks. At a stage when the cracks within the paste and along the aggregate-paste interface join, the failure takes place [22].

So, appreciation of the effects of the cracks along the aggregate/paste interface on the strength of the ordinary concrete, plus the fact that, depending on the rate of loading and the creep, the concrete strength can vary by up to 30%, fatigue behaviour of repaired concrete shown in Table 4 does not appear to be unexpected.

Examination of the results recorded for the SBR modified cementitious and F. R. acrylic mortars reveals that as the ratio of maximum applied stress/bond strength decreases from unity to 0.4, the number of cycles at failure becomes alarmingly low. Examination of the number of cycles at failure recorded for sand/cement mortar + epoxy bonding agent and s/c mortar plus cement bonding grout shows an inferior behaviour for the latter. Results recorded in Table 4 for the epoxy mortar tend to indicate a better performance for this system when compared with epoxy bonding agent used with s/c mortar.

Comparison of the low bond strength of polyester resin mortar measured by the cylindrical shear test with its shear bond strength obtained using the friction-transfer method shows significant difference between the two, which can be attributed to the high shrinkage of this material. It is worth mentioning that during study of the temperature effect on the adhesion of repair materials, a very high shrinkage was observed for this repair system. Therefore, it can be said that the cylindrical shear test method can also be used to study the shrinkage of a repair material and its effects on the resulting bond strength.

Comprehensive examination of the results shown in Table 4 shows that the safe bond stress for the repair systems investigated-lies within 20 to 50% of the original bond strengths of cementitious and resinous repair systems. Therefore, considering the specified bond strength by different sources [23], it should be emphasized that when opting for a repair system, in addition to the ultimate bond strength of the system, its shrinkage as well as its safe applicable stress level must be given serious thought.

Examination of Poisson's ratios of the different repair materials indicated that, as was anticipated (by cutting a slot along the longitudinal direction of the cylindrical test), the Poisson's ratios of the repair materials tested did not have a significant effect on the measured bond strengths.

3.4. Cyclic Freezing and Thawing

In order to study the effect of freeze-thaw cycles on the bond strengths of the different repair materials, the specimens prepared under dry laboratory conditions were transferred into a water tank at the age of 28-day, after measuring their shear bond strengths by means of the friction-transfer method. The temperature inside the tanks was 20°C. These measured shear bond strengths are referred to as the bond strengths at zero freeze-thaw cycle. After soaking the specimens for 48 hours, 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. At different cycles, the shear bond strengths of the samples were measured under dry conditions.

Examination of the results of freeze-thaw tests shown in Table 5 indicates that the highest loss in shear bond strength (77%) after 300 freeze-thaw cycles belongs to polyester resin mortar. Polyesters are subject to deterioration on exposure to weathering, with resulting embrittlement, shrinkage, yellowing, crazing, and failure of adhesion. Their common usage warrants the continual comparative studies of their properties and degradation [24].

From the same results it can be seen that, after exposing to 300 freeze-thaw cycles, SBR. added cementitious mortar shows a shear bond loss of 63%. It can also be seen from the results shown in Table 5 that the losses in shear bond strengths of epoxy resin mortar and s/c mortar plus epoxy bonding grout after 300 cycles appear to be the same (33%) but s/c mortar plus cement bonding grout shows a

TABLE 5 Effect of Cyclic Freeze-Thaw on the Shear Bond Strength of Different Repair Systems

Repair material	Number of cycles	Changes in shear bond strength (%)
Epoxy resin mortar	0	0
	33	−6.58
	100	−11.56
	200	−21.09
	300	−32.88
Polyester resin mortar	0	0
	33	−13.73
	100	−26.33
	200	−49.86
	300	−62.73
Styrene butadiene rubber modified cementitious mortar	0	0
	33	+17.73
	100	−32.27
	200	−48.56
	300	−62.73
Fiber reinforced acrylic modified cementitous mortar	0	0
	33	+14.62
	100	+10.53
	200	−3.80
	300	−25.15
Sand/cement mortar + epoxy bonding agent	0	0
	33	−4.06
	100	−27.25
	200	−21.74
	300	−32.75
Sand/cement mortar + cement bonding grout	0	0
	33	+23.67
	100	+33.22
	200	+10.60
	300	+30.39

gain of about 30% in its bond strength. These findings seem to agree well with the findings of other researchers who stated that high surface moisture content, extreme humidity, and extreme low temperature can be detrimental to bond strength of epoxy adhesives used for strengthening of concrete structures [25]. One possible reason for inferior bond performance of resinous systems, *i.e.*, polyester and epoxy resin mortars, subjected to freeze-thaw cycles, could be the water vapor flow through the existing concrete in a humid environment. This water vapor transmission is very important in areas that experience numerous freeze-thaw cycles because, if an impermeable repair material is used, it is possible that the water vapor can become trapped under the repair in the existing concrete substrate. Once the entrapped water vapor freezes, a hydraulic pressure builds up which could possibly cause a failure in the bond. It is also possible that the water vapor could gradually build up causing the concrete substrate to become critically saturated. This build up could very likely cause the substrate to experience freeze-thaw deterioration. For these reasons, impermeable repair materials are not recommended for large repairs or thin patches. Since the bond strength is the primary requirement in order to achieve a successful repair, emphasizing the superior freeze-thaw resistance of resinous repair mortars over cementitous mortars [26] without paying enough attention to their bond performance can be very misleading because interfacial bond failure, if present, occurs before the full strength capacity of the repair layer can be achieved.

It should also be noted that according to some findings [27,28] the bonding between epoxy and old concrete is affected by the thermal history of the joint and the joint temperature during the test. The bond is also affected by the moist or dry condition history of the joint; cycles of wet and dry conditions indicated a reduction in bond strength [27,28]. Therefore, it may be deduced that the wetting and drying processes involved in these experiments could have a deteriorating effect on the original bond strengths of the resinous systems tested.

Studying of shear bond losses of six different repair systems with their water absorption characteristics showed a correlation coefficient of -0.69 between the two. 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 system which leads to less water to freeze and, consequently, less pressure because, as stated earlier, the freezing process took place in the air rather than in the water.

3.5. Effect of Cyclic Temperature Changes on the Bond Strengths of Different Repair Systems

When repair is carried out by reinstatement of the section after removing the deteriorated concrete, the compatibility between the repair materials and the parent concrete becomes a major general concern. The concern is, however, greatly magnified in climatic conditions where large fluctuations of temperatures and, thus, of thermal expansions of repair material and parent concrete, would cause differential thermal strains at the repair material-concrete interface resulting in possible damage to the bond or adhesion at the repair joint.

In order to study the bond performance of repair materials under thermal cycles, using six different materials, 12 slabs were repaired under dry conditions and at the age of 28-day they were subjected to cyclic temperature changes which ranged from -20 ± 2°C to 80°C. Each cycle of temperature variation consisted of 6 hours inside an oven at 80 ± 2°C and 18 hours inside a freezer at -20°C.

To measure the temperature along the interface between the repair and the parent concrete, thermocouples were inserted at the interface and the temperature was monitored by means of a digital thermometer.

Examination of the results in Table 6 shows that at the end of 200 cycles of temperature changes the ordinary sand/cement mortar plus cement bonding grout encountered a bond loss of 89% of its shear bond strength. This shows that when applying conventional sand/cement repair mortar, the bond is often a problem, in particular where the repairs are to be exposed to high ambient temperatures. It can also be said that drying shrinkage is of more concern when using ordinary sand/cement mortar as a repair material. This is because cement-based materials typically have larger volume changes during drying. Furthermore, many times more water is added than needed for hydration and as soon as the repair material adjusts to the humidity of the new environment the repair material will shrink in volume. This shrinkage volume change can cause many problems, especially when dealing with an older substrate that has already reached a stable shrinkage volume. This volume change of the repair material will cause new internal forces at the bond interface, which could lead to failure.

It can also be seen from Table 6 that after 200 cycles of temperature changes, the two polymer modified cementitious mortars, *i.e.*, styrene butadiene rubber and fiber reinforced acrylic modified cementitous mortars, have suffered 3.29 and 2.54% losses in their bond strengths, respectively. The reason for the observed slightly better adhesion of the fiber reinforced acrylic modified cementitous mortar over SBR modified cementitous mortar can be attributed to a better performance of acrylic polymer compared with SBR polymer and its fiber constituents. The superior bond performance of these polymer modified cementitious mortars over ordinary s/c mortar plus cement bonding grout is said to be due to the reduced shrinkage involved with the polymer added mortars [29,30]. With regard to the bond performance of the polymer modified cementitous mortars, using the slant shear test method, it is reported that the cement based materials that have a strong bond between repair materials and concrete at room temperature failed at significantly lower strength than the control specimens

TABLE 6 Effect of Cyclic Temperature Change on the Shear Bond Strength of Different Repair Systems

Repair material	Number of cycles	Changes in shear bond strength (%)
Epoxy resin mortar	0	0
	30	+17.23
	90	−0.45
	150	−0.23
	200	−21.09
Polyester resin mortar	0	3.57
	30	−26.05
	90	−27.09
	150	−30.53
	200	−37.25
Styrene butadiene rubber modified cementitious mortar	0	0
	30	+13.15
	90	+34.25
	150	−8.49
	200	−3.29
Fiber reinforced acrylic modified cementitous mortar	0	0
	30	+28.65
	90	+13.74
	150	+0.88
	200	−2.54
Sand/cement mortar + epoxy bonding agent	0	0
	30	+31.30
	90	+6.67
	150	+9.56
	200	+7.54
Sand/cement mortar + cement bonding grout	0	0
	30	+40.28
	90	−4.88
	150	−60.42
	200	−89.05

with a reduction in slant shear strength that ranged from 19.2 to 40% when subjected to 60 thermal cycles [31].

It is also clear from Table 6 that after 200 cycles of temperature changes epoxy and polyester resin mortars showed losses of 21 and 37% in their respective shear bond strengths. This higher loss of adhesion recorded for polyester resin mortar can be attributed to high shrinkage (see Section 3.3) and higher thermal coefficient of expansion of polyester resin mortar which is usually 4–10 times as large as that of epoxy resin mortar and substrate concrete. Noting the bond strength of polyester resin mortar at zero cycle of temperature change, it can be said that the bond failure with a properly prepared substrate could be due to internal stresses developed when there is a difference in thermal properties or dimensional behaviour. These failures are not due to insufficient bond strengths. It is also interesting to note the role of the epoxy bonding agent used with ordinary s/c mortar, the shear bond strength of which, shows an 8% gain after exposure to 200 thermal cycles. This can be attributed to two factors: the relatively low elastic modulus of these materials, because these bonding agents have no fillers or aggregates, and continued curing (post curing) of resins at high temperature.

Examination of the very limited published results relating to the effect of thermal cycles on the repair/concrete bond strength indicates that, whilst the composite prisms made by employing one of the resinous systems (epoxy primer) failed at loads corresponding to average slant shear bond strengths which were 5–27% higher than the strength of the control concrete, for the case of composite prisms repaired with the other two resinous systems failure occurred at loads corresponding to average slant shear bond strengths which were 0–26.5% lower than the strength of the control concrete. It can be said that the resins tested showed 6% lower strength for the repair in slant shear bond than the control concrete [31]. It is worth mentioning that, although the failure load quoted for the epoxy primer belongs to the crushing of the concrete in the slant shear prisms, the values mentioned for the resinous mortars appear to belong to the diagonal failure along the repair joint rather than failure by the crushing of concrete. It may be said that the bond between the epoxy primer and the two halves of the slant shear prisms had been higher than the strength of the monolithic prism tested and, therefore, it is most likely that the mentioned value for increase in the bond strength of the primer due to the 60 cycles of temperature changes is underestimated.

In terms of evaluating the performance of repair materials for the bond between parent concrete and repair under cyclic heating and cooling, Schupack' [28] states that a single high thermal shock sometimes can degrade the composite, as can any of the various cyclic changes over a period of time. According to schuback's findings, one does not have to make any calculations to see that the change in volume or shape of an epoxy due to changes in temperature, wetting and drying, freezing and thawing, or loads is likely to be very different from that of the concrete to which it is attached. These differences can cause high stress at the bond line that may lead to failure. This may explain some unexpected fluctuations in bond gain or loss reported in Table 6 for the repair materials tested.

The reduction in the shear bond strengths of repair materials after being subjected to thermal cycles are attributed to the differential strains at the concrete-repair interface. These differential strains, arising from thermal incompatibility between concrete and repair material due to significantly different coefficients of thermal expansions, tend to disrupt and weaken the bond strength between repair material and concrete with increasing numbers of thermal cycles.

4. CONCLUSIONS

From the results of the experimental program, the following conclusions can be made:

1. Although among the different surface preparations applied to substrate concrete the cast face of the concrete proved to be the strongest, the saw cut surface (second strongest surface obtained), due to its inclusion of both bared aggregates and hardened cement paste, was chosen as the most suitable surface for assessing the shear bond strength along a repair/concrete interface.
2. It has been demonstrated that slant shear, cylindrical shear, and friction-transfer test methods provide viable approaches to estimation of bond strengths of different repair systems under different circumstances.
3. While the results obtained from pull-off and friction-transfer methods showed a very good correlation with each other, the slant shear results, due to the involvement of compressive stresses along the repair/concrete interface, showed a different trend.
4. Despite the sensitivity of the cylindrical shear test to the shrinkage property of the repair material, it can be used successfully for dynamic assessment of repair/concrete adhesion because the applied stress is a percentage of the ultimate bond strength. In this method, Poisson's ratio of the repair material appeared to have no effect on the repair/concrete bond strength, but shrinkage of the repair material affected the ultimate bond strength significantly.
5. The bond strengths of the repair mortars vary widely depending on their nature and the exposure environment. Shear bond strengths of six resinous and cementitious mortars, measured by different test methods, ranged from about 1.5 to about $9\,\mathrm{N/mm^2}$ for epoxy resin mortar and styrene butadiene rubber modified cementitious mortar, respectively.
6. From the results of cyclic load tests, it can be said that, depending on the nature of the repair system (resinous, ordinary s/c mortar, and polymer modified cementitious mortars), the maximum safe service stress that is suggested ranges from 20 to 40% of the original shear bond strength and the critical stress level differs

for different repair materials. In this regard, whilst 40% of the original bond strength can be used for the polyester resin mortar, the stress level for the polymer modified cementitious mortars should not exceed 20% of their original bond strengths.

7. After exposure to 300 freeze-thaw cycles, the percentage bond losses were seen to be 77, 63, 33, and 25 recorded for polyester resin, SBR. cementitious, epoxy resin, and s/c + epoxy bonding agent, respectively. It should be noted that ordinary s/c mortar + cement bonding grout showed a 30% gain in its shear bond strength at the end of 300 freeze-thaw cycles.
8. At the end of 200 thermal cycles, the shear bond losses for different repair systems were seen to be 89, 37, 21, 3, and 3 percent for s/c mortar + cement bonding grout, polyester resin, epoxy resin, SBR added cementitious, and fiber reinforced acrylic mortar, respectively. It was also seen that after 200 cycles of thermal exposure, s/c mortar + epoxy bonding agent showed about an 8% gain in its shear bond strength.

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