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Enhancement of bonding efficiency between overlay and substrate concrete using Styrene-Butadiene Rubber Latex and different surface roughness methods

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Abstract

The present study aims to accurately assess the binding efficiency between the substrate and the overlay using Styrene-Butadiene Rubber Latex (SBR) and ordinary Portland cement as a bonding mortar. Four different roughening techniques for the substrate surface were compared: surface roughening with a steel wire brush;, surface roughening by scarifying double parallel grooves in one direction; surface roughening by scarifying double parallel grooves in two directions; and surface roughening by scarifying double parallel grooves in one direction, drilling the substrate, and fixing screws in the double grooves. A total of 24 repaired prism specimens were tested for flexural strength with 45° and 90° angles between overlay and substrate. The cylinder specimens were also tested for splitting tensile strength and for slant shear strength at a 30° angle between overlay and substrate. The repaired specimens were cured at 23±2°C for 28 days before the flexural, splitting, and slant shear strength tests were performed. The experimental tests indicated that the best bonding strength was obtained in flexural strength tests when the surfaces were roughened by scarifying, carefully drilling the substrate, and fixing screws in the double grooves at a 45° angle between overlay and substrate.

Keywords: Cement-SBR mortar, Substrate surface roughness, Repaired concrete, Flexural strength, Splitting strength, Slant shear strength

1. Introduction

Despite the many defects of concrete materials (ie: low tensile strength, high permeability and porosity, weak resistance to freezing and thawing, and weak cracking resistance) reinforced and non-reinforced concrete is widely used in various buildings, bridges, retaining walls and many other structures. Concrete deteriorates significantly when exposed to severe weather conditions under loading, which causes breakage and cracking to occur over time. This leads to a decrease in the structure's mechanical strength [1]. Also, moisture and dehydration cycles lead to rapid damage and deterioration in the structure of the concrete materials [2]. The damage and deterioration of the concrete structure begins on the surface and then continues to the internal structure of the member, requiring the removal of deteriorated concrete and replacement with a new repair material. To ensure the integrated structural bonding between fresh and hardened concrete, a binder is required. The bonding strength depends on the presence of a rough or clean surface [3].

Styrene-Butadiene Rubber Latex (SBR) is a polymeric material which is widely used to improve the mechanical properties of new and old concrete [4]. SBR is a type of high polymeric dispersion emulsion. It is assembled from butadiene, styrene and water, which creates a good bonding strength with concrete materials and enhances the adhesion strength of fresh to hardened concrete [5, 6]. SBR products are relatively expensive compared to cement materials. Therefore, the choice of mixing ratios and methods of use with cement is important [7]. Surface roughness plays an essential and very important role in obtaining a good bond between fresh and hardened concrete [8, 9]. To increase the surface roughness and raise the efficiency of bonding between the fresh and hardened concrete, there are preparation techniques such as shot blasting, sand blasting, and steel wire brushing, partially chipping, scarifying in one or two directions and drilling to obtain a partially chipped surface [10].

Preparing the existing concrete surface is one of the factors that play a fundamental role in obtaining good bonding strength before the process of overlaying fresh concrete. The damaged concrete should be removed to avoid damaging the binder layer. During the process of crushing and removing the deteriorated concrete layer, micro-cracks will be created under the prepared surface, making it weak [11]. Micro-cracks have a very negative impact on the bonding strength of the overlay concrete. Also, micro-cracks may develop due to increased stress in the overlay area [12]. Increasing the surface roughness is important to provide complete friction and interlock between overlay and substrate concrete, but care must be taken not to cause micro-cracks [13]. Also, compacting the binder layer is considered an important factor in obtaining good bonding strength before overlaying fresh with hardened concrete [14].

The objectives of the current experimental study were to determine the following: (i) the effect of cement paste mixed with a bonding agent (SBR) on the bond strength between the overlay and substrate concrete, taking into account the different methods of increasing the surface roughness, and (ii) the efficiency of the

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Table 1 Chemical and physical characteristics of the used cement

Characteristics	**Value**
CaO	64.11%
SiO_2	22.01%
Al_2O_3	5.88%
Fe_2O_3	2.84%
MgO	2.23%
SO_3	2.01%
L.O.I	0.95%
Free lime	0.87%
Physical and mechanical characteristics	
Initial setting time	110 minutes
Final setting time	245 minutes
Blain	3452 m^2/kg
Autoclave	0.061%
Specific gravity	3.09
3 Days compressive strength	28MPa
7 Days compressive strength	35MPa

mechanical performance of the bonding strength of the repaired specimens through flexural strength, splitting strength, and slant shear stress tests.

2. Materials and methods

2.1 Concrete

A concrete mix with a compressive strength of 35 MPa was used to cast concrete specimens to be cut and repaired later. The components of the concrete mix were 360 kg/m^3 of ordinary Portland cement, 690 kg/m^3 of clean river sand with 2.92 fineness modulus, 1165 kg/m^3 of clean crushed river gravel with 6.42 fineness modulus and 12.5mm maximum aggregate size. All mixed with 162 liters of clean tap water.

2.2 Cement

Ordinary Portland cement conforming to the ASTM C150 [15] specifications from the Delta Cement Factory in Iraq, was used and mixed with the bonding agent (SBR). The chemical and physical properties of cement used in this research are shown in Table 1. Cement tests were conducted according to the standard specifications ASTM C191 [16], ASTM C204 [17], ASTM C151 [18] and ASTM C109 [19].

2.3 Styrene-Butadiene Rubber Latex (SBR)

High polymeric dispersion emulsion, available in the local markets, has been used as a bonding agent with cement paste. The characteristics of the SBR used are shown in Table 2.

Table 2 Characteristics of the used SBR-Latex

Color	White
Appearance	Emulsion
Solid content	45%
Specific gravity	1.081
Butadiene content	37% by weight
Styrene content	63% by weight
Sodium alkyl sulfate	0%
Sodium phosphate	0%
pH value	9.5

2.4 Specimens geometry

The prismatic specimens shown in Figure 1 (a) and (b) with dimensions (10*10*40 cm) with overlay angles of 90° and 45°, respectively, were adopted for the flexural strength test of the repaired specimens. For splitting strength test, cylindrical specimens, as shown in Figure 1 (c) with dimensions (10*20 cm), were adopted. Figure 1 (d) represents the geometry of the approved specimens for slant shear test with an overlay vertical angle of 30° and dimensions of (10*10*30 cm) to be vertically tested under compression.

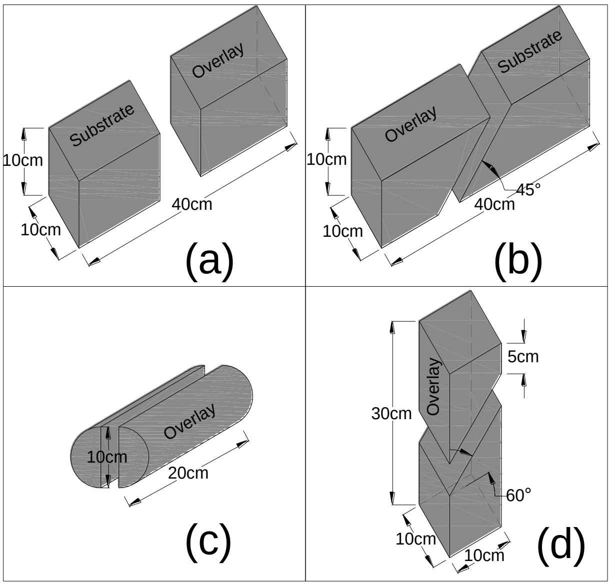

Figure 1 (a) and (b) flexural test specimens, (c) splitting test specimens and (d) slant shear test.

2.5 Preparation of substrate surface

The previously cast substrate concrete specimens with a compressive strength of 35 MPa (prisms and cylinders), were cured for 28 days in water at 23±2°C. They were then cut according to the geometry adopted in Figure 2 (a), (b), (c) and (d). Afterwards, the surface roughness of the substrate concrete specimens were performed as detailed below:

- Surface roughening with a steel wire brush for 15 minutes / m^2 as shown in Figure 2 (a). The steel wire brush was replaced four times during this study.
- Surface roughening by scarifying double parallel grooves in one direction, as shown in Figure 2 (b). The average groove depths were 1.5 cm.
- Surface roughening by scarifying double parallel grooves in two directions, as shown in Figure 2 (c). The average groove depths were 0.75 cm.

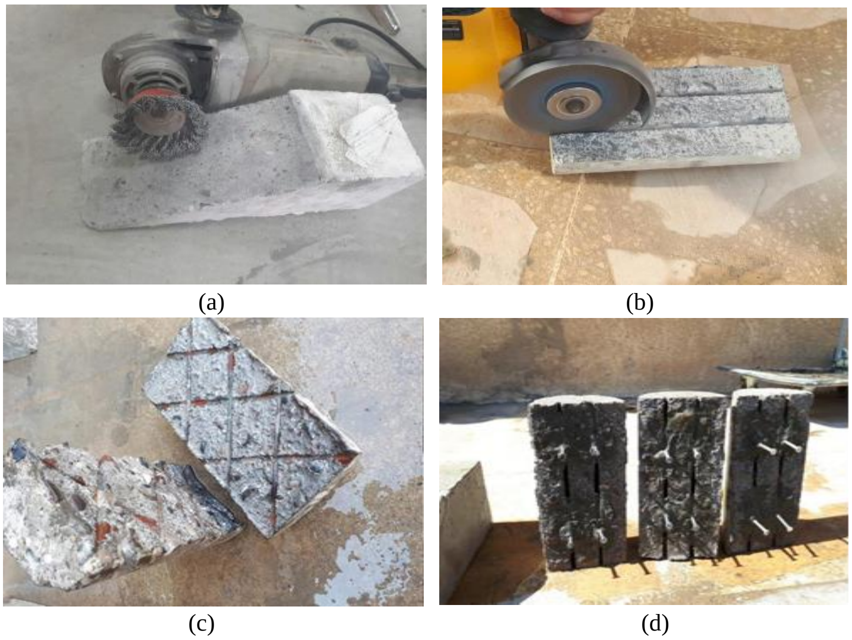

Figure 2 Surface roughness of the substrate concrete specimens

Surface roughening by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves as shown in Figure 2 (d). The average groove depths were 1.5 cm. A two-component epoxy of liquid plastic (EcoPoxy) was used to fix the screws in the substrate grooves with a 2:1 mix ratio.

2.6. Applying the Cement-SBR paste and casting the overlay concrete

Laboratory conditions and procedures were followed according to the standard specifications ASTM C882 [20] and ASTM C1059 [21] while mixing cement-SBR mortar. Portland cement was mixed with SBR in the ratio of (1:0.5) by weight, respectively. The cement-SBR paste was applied to the previously prepared rough surface as mentioned in Figure 2 (a), (b), (c) and (d). A concrete mix with a compressive strength of 35 MPa (the same compressive strength of the substrate) was prepared. All the specimens were cured in 23±2°C water for 7 days. The specimens were extracted from water and prepared according to the required engineering shapes shown in Figure 1. The various surface roughening methods were performed, as mentioned previously. Within 10 minutes after applying the SBR, the cement-SBR mortar was applied with a thickness of 15 mm. The thickness of the layer was unified by hand and then stacked with a square section metal rod. The thickness of the cement-SBR mortar layer was preserved at 15 mm by adding an amount necessary to compensate for the decrease in the thickness of the layer due to stacking. The overlay layer was then cast with a compressive strength equal to the compressive strength of the substrate. The specimens were covered with a polyethylene sheet for 24 hours. After demolding, the specimens were cured in 23±2°C water for 28 days. The mechanical bonding performance between the overlay layer and the substrate was tested by the flexural strength, splitting strength, and the slant shear test. All control specimens were cured in 23±2°C water for 28 days.

3. Results and discussion

3.1 Flexural strength

The flexural strength test was performed according to ASTM C78 [22] Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading). This loading method was chosen to avoid placing a concentrated load directly on the area between the overlay and the substrate. Figure 3 illustrates the combined effect of applying cement-SBR mortar and substrate surface roughness methods on the flexural strength of concrete prism specimens. Each data point represents an average of three repaired prisms with a standard deviation of 3.004 for all repaired prisms (45° and 90°). A significant enhancement, about 99% in flexural strength, was observed in specimens where the substrate surface was prepared at an angle of 90° and whose surface was roughened by scarifying and drilling the substrate and fixing screws in the double grooves compared with the control specimens. As for the specimens where the surface of the substrates were prepared at an angle of 45°and whose surface was roughened by scarifying and drilling the substrates and fixing screws in the double grooves, a very significant enhancement of about 2.6 times the flexural strength was observed compared with the control specimens. The reason for the increase in flexural strength may be due to the high interlocking between the cement-SBR mortar and the scarifying surface. In addition to that, the screws resist shear stress at an angle of 45°. Conversely, specimens whose surfaces have been initialized at 45° and whose surfaces were scarified by making double parallel grooves in two directions, had an enhancement of about 24% compared to the control specimens. In general, the repaired concrete specimens whose surfaces were roughened either by scarifying double parallel grooves in one direction or by steel wire brush method (at an angle of overlay 45° or 90°), showed a decrease in their flexural strength compared to the control specimens. The flexural strength is expressed as:

$$fr = \frac{3P.l}{2bd^2} \quad (1)$$

where fr = flexural strength (in MPa), P = failure load (in N), l is the effective length between supports (in mm), b = specimen width (in mm) and d = specimen depth (in mm).

3.2 Splitting tensile strength

The splitting tensile strength test for the repaired concrete specimens was carried out according to the standard specifications ASTM 496 [23]. Each specimen for the splitting tensile test is a composite cylinder of 100 mm diameter *200 mm high as shown in Figure 1 (c). This test at this stage aimed to

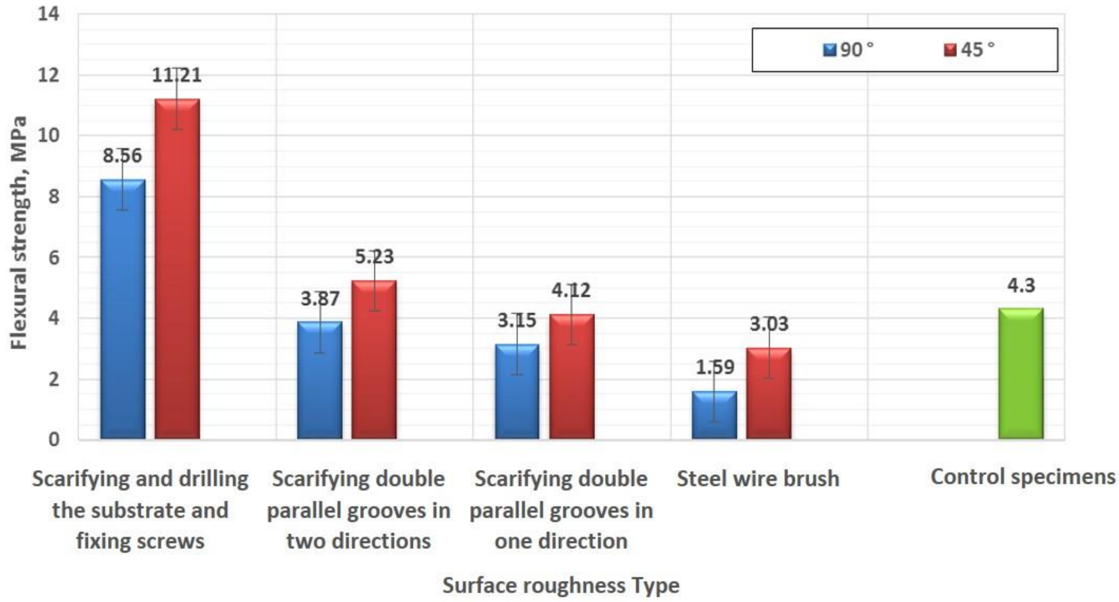

Figure 3 Effect of surface roughening type on flexural strength of repaired prisms.

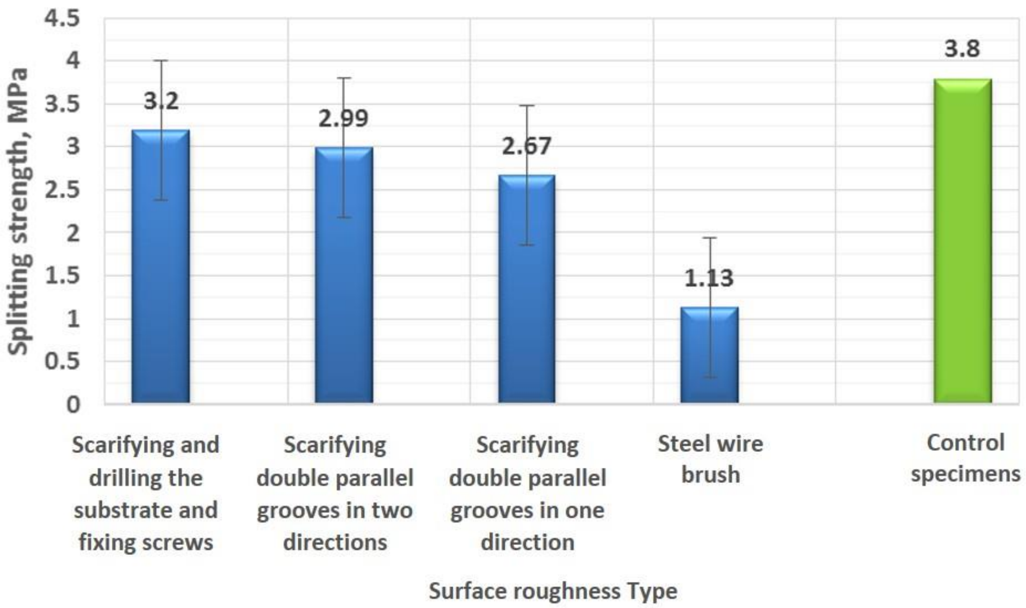

Figure 4 Effect of surface roughness type on spitting strength of repaired cylinders

evaluate the bonding strength between the overlay and the substrate through applying cement-SBR mortar as well as methods of surface roughness. A splitting strength test of repaired specimens was performed at 28 days after pouring the overlay concrete (56 days after pouring the substrate concrete). Figure 4 represents the experimental results of the splitting tensile strength of repaired specimens. Each data point represents an average of six repaired cylinders with a standard deviation of 0.8117. A significant decrease was observed in the splitting strength of repaired specimens. The repaired cylinder specimens that were prepared by applying the cement-SBR mortar and had its surface roughened by scarifying and drilling the substrate and fixing screws in the double grooves were the most resistant to the splitting test. There was a decrease of less than 16% in its splitting strength compared to the control specimens. It was observed that roughening with a steel wire brush was not useful enough to increase the bonding strength between the overlay and the substrate. The failure almost always occurred in the overlay transition zone between overlay and substrate. Such behavior is consistent with other authors [24, 25] in that the overlay transition area was the weakest link in the overlay-substrate composite system [26]. The splitting tensile strength is expressed as:

$$f_{sp} = \frac{2P}{\pi A_{sp}} \tag{2}$$

where f_{sp} = splitting strength (in MPa), P = failure load (in N), A_{sp} = the area of the bonding plane in (mm^2) taken as 200,000mm^2.

3.3. Slant shear strength

The slant shear strength test for the repaired concrete specimens was performed according to the standard specifications ASTM-C882 [27] and ASTM C882 [20]. Slant shear strength test specimens consisting of composite prisms (100 * 100 * 300 mm) were prepared as shown in Figure 1 (d). The concentrated load was applied to slant shear specimens. Slant shear strength can be calculated as:

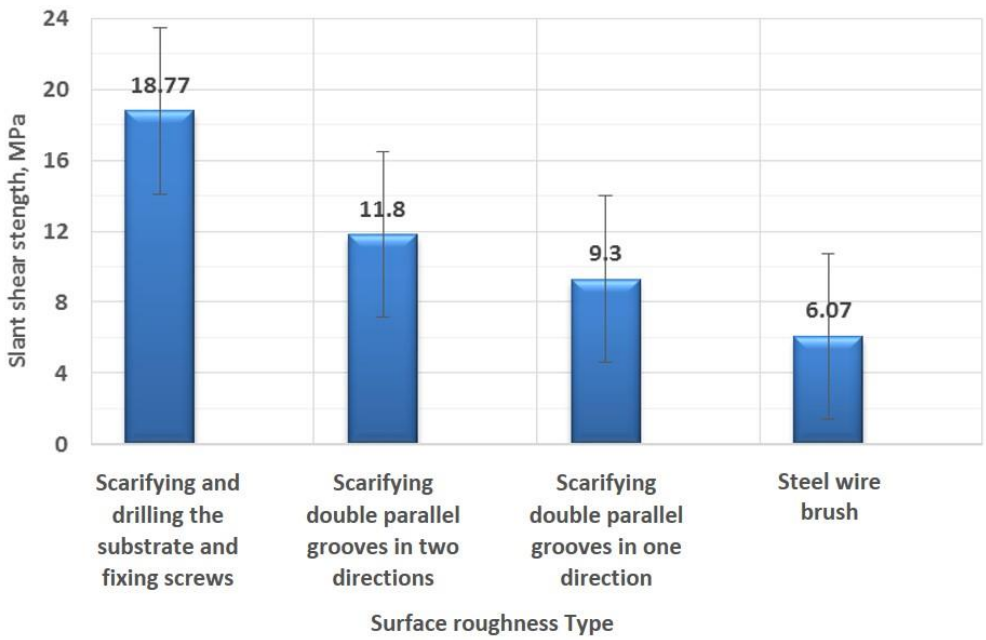

Figure 5 Effect of surface roughness type on slant shear strength of repaired specimens

Table 3 The minimum accepted values of flexural strength, splitting tensile strength and slant shear strength ACI 546-06 [28].

Description	Test method	Bond Strength (MPa)			Recommended Value MPa
		At 1 Day	At 7 Days	At 28 Days	
Flexural strength	ASTM C78	----	----	8.3	> 8.3
Splitting strength	ASTM C496	----	2.8	12	> 2.8
Slant shear strength	ASTMC882	2.8 to 6.9	6.9 to 12	14 to 21	------

$$\tau_n = f_n . Cos\alpha \quad (3)$$

$$f_n = \frac{P}{A_n} \quad (4)$$

Where τ_n = slant shear strength (in MPa), α = inclined vertically angle of the slant surface, taken as 30°, f_n = normal compressive strength (in MPa), P = failure load (in N), A_n = area of the slant bonding plane in (mm^2), taken as 20,000 mm^2

Figure 5 shows the effect of substrate surface roughness on slant shear strength. Each data point represents an average of six repaired samples with a standard deviation of 4.670. It was noted that the roughness of the surface scarified by double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves was more effective than the other methods that were studied in this research. This surface roughness method shows an almost 1.6 times higher slant shear strength than the slant shear strength of specimens scarified by double parallel grooves in two directions. In addition, it was almost 2 times higher than the strength of specimens with surface roughness created by scarifying with double parallel grooves in one direction and 3.1 times higher than the strength of specimens with surface roughness created by a steel wire brush. Such behavior is consistent with the experimental work of Abo Sabah, et al. [27].

4. Validity of the experimental results

The Standard Concrete Repair Guide ACI 546-06 [28] specifies the minimum acceptable values of flexural strength, splitting tensile strength, and slant shear strength between the concrete substrate and the repair material, as shown in Table 3. Depending on the criteria specified in the standard guide, the repair material and the appropriate method of repair can be chosen [29]. When comparing the experimental results of the flexural strength obtained in this study as shown in Figure 3, with the minimum flexural strength limits specified in the standard guide in Table 3, it was observed that repairing the specimens with surface roughness created by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves at an angle of 45° and 90°, and applying the cement-SBR mortar, excellent results of flexural strength were achieved. As for the splitting tensile strength tests shown in Figure 4, it yielded satisfactory results, but they were not as expected. The results obtained from slant shear strength tests shown in Figure 5 were quite satisfactory. The fixing screws appear to have played a key role in resisting slant shear forces in addition to the cement-SBR mortar.

These results can also be inferred by the final report submitted by Sprinkel, et al. [30] on the evaluation of the quality of the bonding strength in terms of tensile bond strength. The quality of the evaluation is shown in Table 4.

Table 4 Assessment bond quality in terms of tensile bond strength [30].

Bond quality	Bond Strength (MPa)
Excellent	>2.1
Very good	1.7–2.1
Good	1.4–1.7
Fair	0.7–1.4
Poor	0–0.7

5. Conclusions

The efficiency of bonding strength performance in repairing concrete specimens using a cement-SBR mortar and various methods of substrate surface roughness has been studied. Experimental tests included flexural strength, splitting strength, and slant shear strength. From the experimental results, some conclusions can be presented as follows:

1. The surface roughness of the substrate concrete plays a key role in increasing the bond strength between the overlay and the substrate in that, the higher the substrate roughness the greater the bonding strength.
2. Substrate surface roughness created by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves, was the most effective method among all of the substrate surface roughness methods employed.
3. The flexural strength of the repaired specimens was significantly improved using the substrate surface roughness created by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves. The flexural strength increased approximately 2.6 times compared to the control specimens.
4. The angle between the overlay and substrate had a direct impact on the development of the flexural strength. Flexural strength increased from 8.56 to 11.21 MPa once the angle was changed from 90° to 45°, respectively.
5. The results of the splitting strength tests indicated that the bonding strength of the specimens treated with a surface roughness created by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves was higher than those treated with the all other methods. Failures occurred in the transition zone between the overlay and the substrate by separation of cement-SBR mortar from the substrate.
6. The results of slant shear strength tests showed that the bonding strength of the specimens treated with a surface roughness created by scarifying double parallel grooves in one direction, drilling the substrate and fixing screws in the double grooves was higher than those treated with the all other methods.
7. The results of the experimental tests of flexural strength, splitting strength, and slant shear strength of repaired concrete specimens indicated a reasonable validity compared to the minimum acceptable values of ACI 546-06 at age of 28 days.

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