Influence of Surface Roughness on Adhesion Between the Existing and New Plain Concretes

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ABSTRACT

The bonding that exists between the old concrete and the new concrete depends largely on the quality of substrate surface preparation. The accurate representation of substrate surface roughness can help determine very precisely the correct bonding behavior. In this work, the experimental program aimed to investigate the bond strength between two plain concretes, the first one is a concrete substrate as existing concrete, the second one is a new concrete overlay. Four types of original concrete substrate surface preparation were used: as-cast (without surface preparation) as a reference, wire-brushed, grooves and drilled holes. Adhesion strength is quantified at 30 days based on the results of the slant shear test and splitting cylinder tensile test, as well as shrinkage test which was made after 56 days of casting the new overlay concrete. The results generally indicate that the surface roughness of the concrete substrate is very much required to obtain superior mechanical bond of the composites; whereby the concrete with grooves and drilled holes substrate providing the most superior mechanical bond.

Keywords: Bond strength; New concrete overlay; Original concrete substrate; Slant shear test; Splitting tensile test; Surface roughness; Shrinkage.

1 Introduction

Developed infrastructure is a vital factor of economic growth and the prosperity of human life in many countries around the world. Many structures which make up the entire infrastructure and especially those made of reinforced concrete, such as buildings, bridges and pavements, etc. be suffered from severe deterioration. In the structural elements, these problems lead to cracks and breakdown in the concrete elements due to aggressive environmental impact such as exposing to different types of salts, freeze-thaw cycles and increase in unexpected live loads, etc. [1].

Nowadays, the most important and main challenges facing civil engineers are saving and rehabilitation of degraded constructions, as well as, developing and enhancing the durability and efficiency of these constructions. Furthermore, rehabilitation and repairing methods of the concrete are beneficial to the owner as compared to rebuilding [2]. The idea of rehabilitating and strengthening of the concrete structures is to apply a new concrete layer over an existing concrete to increase the resistance of the structural component and thereby

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increase the durability over time [3]. The linkage between the existing and new concrete layers is often weak [3,4]. Bonding quality of these layers is the main successful objective of the restructuring process being repaired. Furthermore, the successful development and performance of the structure directly depend on the roughness of the surfaces [5,6].

It has been recently observed that a numerous number of concrete structures existing in some regions around the world which had been repaired are still facing the risks of collapse and failure. It has been observed that the main reasons for this failure are the chemical bonding and interaction between the two layers materials. In addition, the physical and mechanical bonding depends on the porosity and roughness of the surfaces, as well as the shear and tensile strengths between two surfaces [7]. The problem of study lies in the inefficiency of bonding between the existing and new concrete layers at the maintenance of concrete structures, as a result of the surrounding environmental conditions, such as the difference in temperature as well as excessive loads. For this reason, many researchers interested in the repair of concrete structures have conducted several experiments to bond the existing and new concrete layers. The results were varied due to the difference in the use of bonding material, the method of bonding the existing concrete, the smoothness of the surface to be repaired, environmental effects and differences of expansion and shrinkage between both concretes. Therefore, the study will seek to increase the bond between the existing and new concrete when changing the roughness of existing concrete. Thus, reducing the use of chemical additives which are used to improve adhesion between existing and new concrete, especially since the use of such materials are considered a high cost. In addition, identifying the best mechanical methods that improve adhesion, will reduce the cost of repair, strengthening the structural elements and extending the age of the concrete members.

2 Materials and Methods

2.1 Materials

Ordinary Portland cement (OPC) that complies with the requirements of BS EN 197-1:2011 was used. The physical properties and chemical compositions of OPC is provided in Table 1.

Table 1. *Chemical compositions and physical properties OPC.*

Chemical composition (mass %)		Physical properties	
Items	Value	Items	Value
Silicon dioxide (SiO_2)	20.14	Specific gravity	3.15
Aluminum oxide (Al_2O_3)	5.91	Specific surface area(m^2/g)	2977
Ferric Oxide (Fe_2O_3)	2.99	Strength activity index at 3 days (MPa)	26
Calcium oxide (CaO)	62.9	Strength activity index at 28 days MPa	44
Magnesium Oxide (MgO)	1.59		
Sodium oxide (Na_2O)	0.18		
Potassium oxide (K_2O)	0.88		
Sulfur oxide (SO_3)	2.11		
Phosphorus oxide (P_2O_2)	0.9		
LOI	0.4		

Coarse aggregate of different maximum size viz; 19 mm, 14 mm was obtained from the quarries of Al-Alus in Al-Kums area. The coarse aggregate has a specific gravity of 2.72, water absorption of 0.41 % and bulk density of 1530 kg/m^3. Natural sand with maximum size of 1.2 mm, used as a fine aggregate was collected from Zlitan area. The fine sand has a fineness modulus of 2.7, specific gravity of 2.66 and water absorption of 0. 85 %.

2.2 Mix Proportion

Each of the composite specimens consists of the same material, i.e existing (concrete substrate) and new concrete overlay were designed as normal concrete. The design method used for normal concrete mixtures is based on absolute volume method, and the target strength of the normal concrete used was approximately 30 MPa. Samples representing the existing and new concrete were prepared using the mix proportions shown in Table 2.

Table 2. *Mix proportions for plain concrete.*

Items	Cement	Water	Fine aggregate	Coarse aggregate
Quantity (kg/m^3)	396	185	425	1344

2.3 Preparation and Processing of Samples

In order to gain proper bond strength the surface must be prepared prior to performing the overlay. In this study, each test specimen consisted of two equal layers of thickness; normal strength concrete (plain concrete substrate) will be used as original substrate material which represents the existing concrete, the other layer is also composed of the same type of concrete (the difference in casting time) which represents the new concrete (plain strength concrete overlay). Original concrete substrate specimens are placed in lubricated half piece of specimen mold. After casting, the fresh specimens were left at room temperature in their molds for 24 hours. After one day, the specimens were demoulded, cleaned from suspended parts of concrete or oil or any particles and dust, and cured for 28 days in a water curing tank. At 28 days of casting and curing in the water, specimens were taken out from the water tank for surface preparation. Four types of concrete substrate surface preparation were used: as-cast (without surface preparation) (CS) as a reference, wire-brushed (WS), grooves (GS), and drilled holes (DS), as shown in Figure 1. After surface preparation, all the concrete substrate specimens were left to dry for 1 month. Thus, the total period applied to the concrete substrate specimens before casting the new concrete as a repair material was 58 days. Before casting the new concrete overlay, the concrete substrate specimens were saturated in the water for one day, followed by 25 minutes of drying. The concrete substrate specimens were then placed into their moulds; in the case of the slant shear and shrinkage samples, the slanting side was facing upward to be overlaid with the new concrete overlay. For the tensile splitting samples, the substrate halves with different surface roughness were placed vertically at one side of the cylindrical moulds, and the moulds were then filled with new concrete (Figure 2). The composite specimens were left at room temperature in their molds for 24 hours. After 24 hours, the specimens were demoulded, and cured in water (for slant shear and tensile splitting samples) for 30 days. The specimens for the shrinkage test were left at room temperature until the testing days.

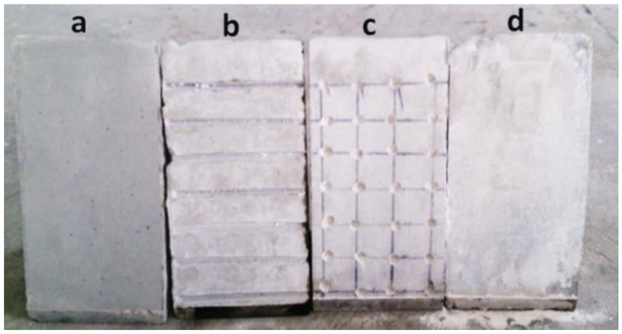

Figure 1: *Different surface roughness of concrete substrate specimens. (a) as-cast (b) grooves (c) drilled holes (d) wire-brushed.*

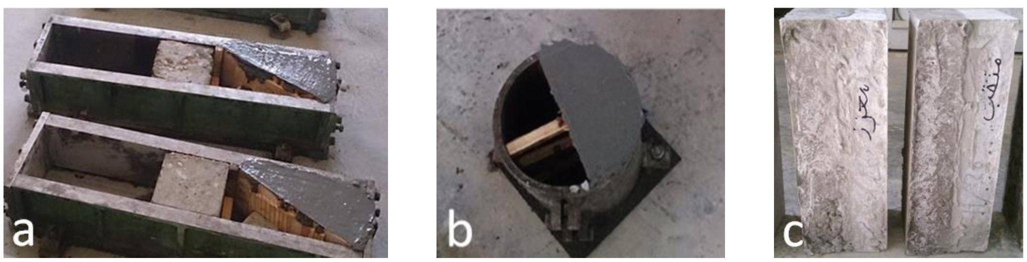

Figure 2: *Specimens preparation. (a) Slant shear test specimen (b) Splitting tensile test specimen (c) shrinkage test specimen.*

2.4 Testing of Specimens

The study of the surface quality is quantified by slant shear test, splitting cylinder tensile test and shrinkage test.

Slant shear test has been selected for being sensitive to roughness. The adopted geometry for the slant shear specimens was a 15 cm x15 cm x 30 cm prism with the interface line of 30° to the vertical (Figure 3). The specimens were tested under compression using the standard procedure for the testing of cubes of compressive strength according to ASTM C 882 standard [8].

The nominal shear strength between the concrete over layer can be calculated as follows.

$$\text{Slant shear strength (MPa)} = \frac{F}{A} \tag{1}$$

Where:

F is the maximum force recorded (in N), and A is the area of the slant surface (in mm^2). The slant surface area can be taken as a nominal value of 150 x 150/sin 30°.

The splitting tensile test was conducted to determine the bond strength between two layers of concrete, according to ASTM C496 [9]. In the present study, new concrete overlay was cast and bonded with the concrete substrate specimens to form a cylindrical composite cylinder (300 mm height x 150 mm diameter) as shown in Figure 4. The splitting tensile strength was calculated using the following equation:

$$\text{Splitting tensile strength (MPa)} = \frac{2F}{\pi A} \quad (2)$$

Where:

F is the maximum force recorded (in N), and A is the area of the bond plane (in mm²). The bonded area can be taken as a nominal value of 300 *150 = 45,000 mm².

As for shrinkage test, three composite specimens with dimensions of 12 cm×12 cm×35 cm were prepared. After casting the new concrete overlay as shown in paragraph no 2.3, approximately 24 hours after shrinkage test composite specimens cured at room temperature in their molds, they were demolded as ASTM C596 [9]. After composite specimens removed from the mold, using a super glue, stainless steel discs were adhered onto all four surfaces of each composite specimen centred about the length and width, where the measurement direction was perpendicular to the specimen composite specimen axis as shown in Figure 5.

Figure 3: *Slant shear test set-up.*

Figure 4: *Splitting tensile test set-up.*

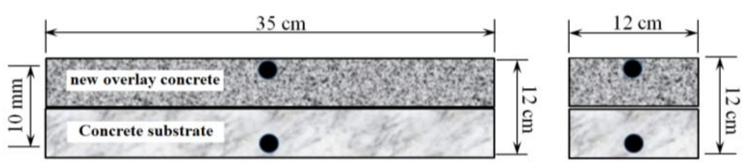

Figure 5: *The shape and dimensions of the shrinkage test sample.*

The initial shrinkage reading was taking after 6 days of curing in the air. All specimens were exposed to drying conditions up to 56 days. Initial shrinkage reading was taking using stain gauge and length comparator complying with ASTM C596 (the gauge length is 100 mm). The drying shrinkage measurements were taken at the periods of exposure of 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 56 days, and the results of average for each of two opposite surfaces reading of three specimens were taken.

3 Results and Discussions

3.1 Slant Shear Test Properties

Over the year, slant shear test is the most common type of tests to determine the bonding strength under combined state of compression and shear stresses. This test has become the most acceptable method and has been officially adopted in many international standards.

The experimental slant shear strength test results were shown in Table 3. As demonstrated in Table 3, the average slant shear bond strength was the highest in the grooved surface (12.26 MPa) and then wire brush and drill holes surfaces which were 7.79 MPa, 7.15 MPa respectively. Compared with the control specimen which represented by CS, the slant bond strength increases in the order of as cast surface (CS), drilled holes (DS), wire-brushed (WS) and finally grooved (GS) as shown in Figure 6. The relative percentage increases in bond strength were found to be around 81.9 % for DS, 95.9 % for WS and 210.4 % for GS.

Table 3. *Slant shear strength and failure modes for different types of surface treatment.*

Surface preparation	Sample No.	Max. force F (kN)	Comp. stress (MPa)	Shear Stress τ (MPa)	τ Average (MPa)	S.D.	C.V.	Failure mode
As-cast	CS1	155.6	6.92	3.46	3.99	2.9	0.75	A
	CS2	59.7	2.65	1.33				
	CS3	323.3	14.4	7.18				
Wire brush	WS1	461.3	20.5	10.3	7.79	2.17	0.28	A
	WS2	275.3	12.2	6.12				
	WS3	312.6	13.9	6.95				
Drill holes	DS1	156.9	6.97	6.97	7.15	2.17	0.28	A
	DS2	199.6	8.87	8.87				
	DS3	126.3	5.61	5.61				
Grooves	GS1	482.7	21.5	10.7	12.26	2.02	0.17	B
	GS2	656.8	29.2	14.6				
	GS3	516.5	23	11.5				

τ = Slant shear bond strength; S.D. = standard deviation C.V.= Coefficient of variation.
A = Interface failure; B = Interface failure with partially substrate failure.

Thus, the different roughness surfaces improve the slant bond strength by between 81.9 and 210.4 %, with the grooved surface presenting the highest value of increase; i.e. the most efficient. Hence, this confirms that the surfaces with different roughness provide significant improvement in slant bond strength of the composites in comparison to the control. The minimum acceptable slant bond strength which set out in the ACI Concrete Repair Guide in the range of 6.9–12 MPa [10]. Thus, the results obtained show that the surfaces treated in this study are actually required in order to fulfill the minimum prescribed slant bond strength of the composite. In conducting the slant shear test on the studied specimens, the failure modes can be classified into two types, type (A) is the interface failure; type (B) is the interface failure with partially substrate failure. The observations refer that the control specimen, drilled holes and wire-brushed exhibit type A failure; i.e. a total interfacial failure or complete de-bonding of the composite, while the grooved surface reveals a type (B) failure mode which is interface failure with partially new concrete overlay failure. Hence, low slant bond strength shown in the specimens with different roughness mentioned is compatible with failure mode of these specimens. However, the highest slant bond strength shown by the grooved surface is compatible with the observed failure mode; i.e. Interface failure with partially substrate failure.

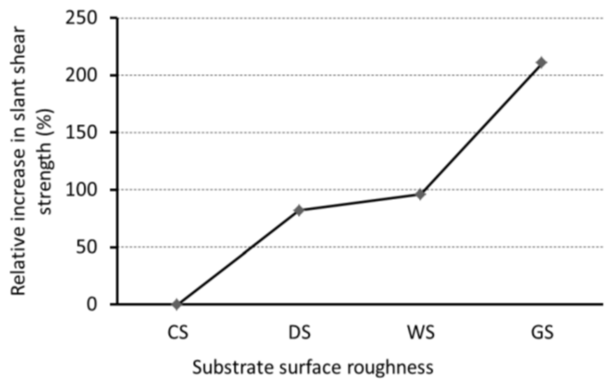

Figure 6. *Relative increase in slant shear bond strength for the different types of surface treatment.*

3.2 Splitting Tensile Test Properties

The splitting tensile test supplies measure of the indirect tensile capacity of the composite interface. The splitting tensile test results are shown in Table 4, whereas the percentage increase in the splitting tensile strength of the different types of surface treatment relative to that of the reference composite is shown in Figure 7. The results show that different types of surface treatment were able to significantly increase the splitting tensile strength of the composites when compared to the control composite (SC). Compared with the control composite, with the use of rough interface surface, the splitting tensile strength significantly increased for example, with about 1.44 %, 4.02 % and 7.62 % for WC, DC and GS, respectively. Hence, the grooved surface was the most efficient types of surface treatment, as it gave the highest increase in the splitting tensile strength among the composites in comparison with the reference composite, which indeed agree with the trend for slant bond strength results given and explained previously. Two types of failure modes of the splitting tensile test can be spotted, namely A = pure interface failure; B = interface failure with partially substrate failure. Obviously, the results reveal the relationship between the types of surface treatment and splitting bond tensile strength and the failure mode in the splitting tensile test. The observation show that the control composite (as-cast) and wire-brushed surfaces exhibit type (A) failure; i.e. a pure interface failure, while both the grooved and drilled holes surfaces reveal a type (B) failure mode which is interface failure with partially new concrete overlay failure. Based on the ACI concrete repair guide [10], which shows the classification of

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minimum acceptable bond tensile strength, whereby all of the results obtained in this study were excellent, since the splitting bond tensile strength was higher than 2.1 MPa.

Table 4. *Splitting tensile strength and failure modes for different types of surface treatment.*

Surface preparation	Sample No.	Max. force F (kN)	Ten. strength T (MPa)	T Average (MPa)	S.D.	C.V.	Failure mode
As-cast	CS1	447	9.5	9.71	0.28	0.029	A
	CS2	473	10.03				
	CS3	452.7	9.6				
Wire brush	WS1	451	9.57	9.85	0.3	0.03	A
	WS2	480	10.18				
	WS3	462	9.8				
Drill holes	DS1	488.8	10.37	10.1	0.21	0.021	B
	DS2	475.6	10.1				
	DS3	469.5	9.96				
Grooves	GS1	477	10.2	10.45	0.35	0.034	B
	GS2	481	10.4				
	GS3	510	10.8				

T = Splitting tensile strength; S.D. = standard deviation C.V.= Coefficient of variation.
A = Pure interface failure; B = Interface failure with partially substrate failure.

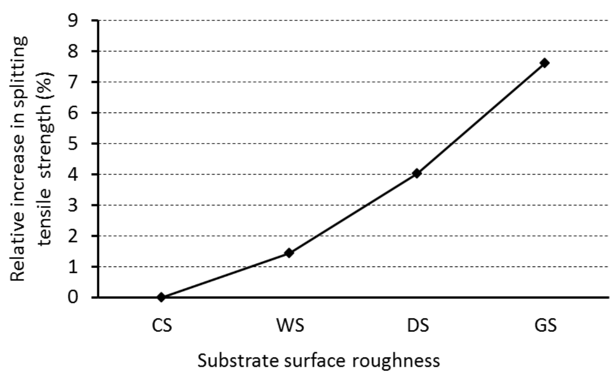

Figure 7. *Relative increase in splitting tensile strength for the different types of surface treatment.*

3.3 Shrinkage (Volume Changes)

When shrinkage is restrained, permanent tensile stresses develop in the new concrete that result in the formation of tensile cracks in the new concrete material itself, or in splitting at the interface of the new concrete overlay and the concrete substrate. Since most of the repair materials, including new concrete are applied to an older concrete substrate that has negligible shrinkage, new concrete overlay with very low shrinkage potential should be chosen to minimize the compatibility problems between concrete overlay and substrate concrete. Shrinkage values for the different types of surface treatment whether the direction of the measurement is perpendicular to the long axis or short axis of specimen, are shown in Figure 8 and Figure 9. In both cases and at all measurement durations (i.e. at 3, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 and 56 days), it can be observed that the composite specimens with grooved and drilled holes surfaces showed low shrinkage compared with the control and wire-brushed surfaces composites. The significant reduction in shrinkage values for composite specimens with grooved and drilled holes surfaces could be attributed to the strong overlap between old concrete substrate and new concrete overlay (penetration of the concrete material into the grooves and holes) leading to prevents the new concrete overlay from the movement. Shrinkage values for the different types of surface treatment at 56 days are demonstrated in Figure 10. Compared with the control composite, with the use of rough interface surface, shrinkage values significantly decreased for example, with about 48 % and 24 % and for DC and GS, respectively, and when calculating the shrinkage values with the direction of the long axis, about 53 %, and 43 % and 32 % for DC, GS and WS, respectively with the direction of the short axis of composite specimen. However, according to Emmons et al. [11], shrinkage values of repair materials in excess of 0.05%, and 0.1% at 30 days are considered to represent moderate and high levels of drying shrinkage, respectively, that can potentially result in premature failures, whereby all of the shrinkage values obtained in this study were less than the mentioned values.

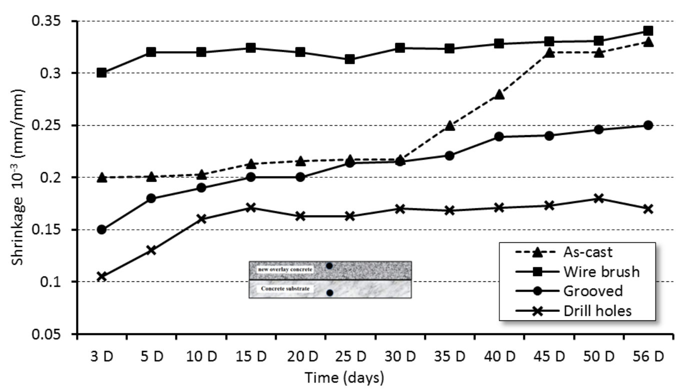

Figure 8.*Shrinkage values for the different types of surface treatment; The direction of the measurement is perpendicular to the long axis.*

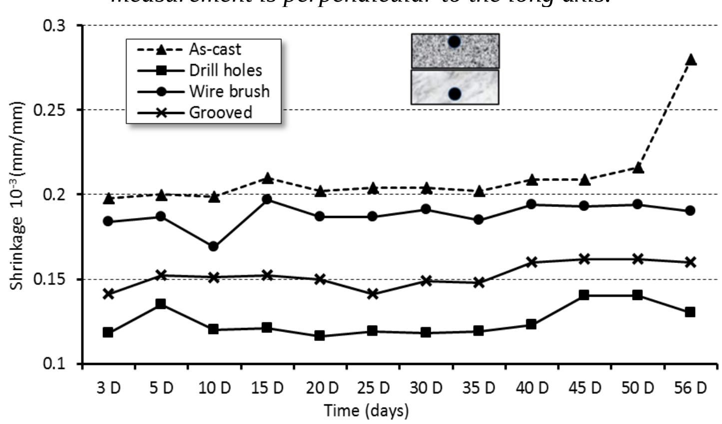

Figure 9.*Shrinkage values for the different types of surface treatment; The direction of the measurement is perpendicular to the* short axis.

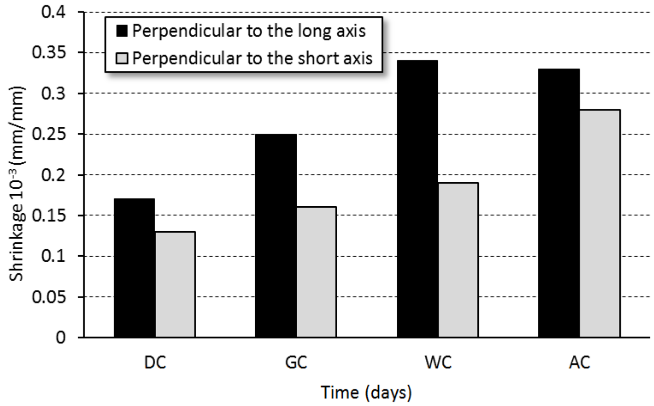

Figure 10. *Shrinkage values for the different types of surface treatment* at 56 days.

4 Conclusions

Based on the results and observations, the following conclusions can be drawn:

- The surface roughness suggested in this study; i.e. wire-brushed, grooves and drilled holes significantly affect adhesion with new concrete overlay, since all concrete substrate surface preparation methods revealed higher bond strengths compared with that of the as-cast (control specimen).
- Grooved and drilled holes surfaces were the preparation method of the substrate surface that presented the highest values of bond strength in shear and in tension, from all the considered techniques.
- Based on ACI Concrete Repair Guide, the results obtained show that the surfaces treated in this study are indeed required in order to achieve the minimum prescribed slant bond strength of the composite.
- All the results obtained from the split tensile strength test shows that new plain concrete overlays have excellent bond quality, since the splitting bond tensile strength was higher than 2.1 MPa.
- The observations of failure mode in the slant shear test show that the control specimen, drilled holes and wire-brushed exhibit a total interfacial failure, while the grooved surface reveal interface failure with partially new concrete failure. In addition, the failure mode in the split cylinder tensile strength test show that the control composite (as-cast) and wire-brushed surfaces exhibit a pure interface failure, while both the grooved and drilled holes surfaces reveal interface failure with partially new concrete overlay failure.
- The composite specimens with grooved and drilled holes surfaces showed low shrinkage compared with the control and wire-brushed surface composites. However, all the shrinkage values obtained in this study were less than the permissible limit according to Emmons et al. (0.1% at 30 days).

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