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Factors Affecting Bond between Repairing Concrete and Concrete Substrate

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Abstract. ***The correct choice and the method of application of repair materials determine the degree of success in repairing concrete structures for the enhancement of service life. This paper discusses the performance of different repairing materials under different laboratory tests. Laboratory tests, including four-point bending (flexural), splitting tension, and direct shear tests, were conducted on concrete substrate-repairing concrete composite specimens with various bonding materials and various interface texture. The bonding materials used in this study at the interface are; modified Styrene Butadiene Rubber Emulsion (SBE), Acrylic Resin (AR), Epoxy Resin (ER), and cement paste (CP). The flexural composite specimen was 100 ×100 ×500 mm with an interface angle of 30°, 45°, and 90° with the horizontal. The splitting tension composite specimen was cylinder of 150 mm diameter and 300 mm height whilst, the double–L shaped composite specimen was used for direct shear. In order to verify the influence of the strength of repair concrete on the bond strength of old concrete-to-new concrete interface, the substrate concrete was kept unchanged with a compressive strength of 60 MPa. On the other hand, three different concrete mixtures, with compressive strengths 25, 40 and 60 MPa were used for the repair concrete. Three conditions of interface texture were considered in this study; smooth (as-cast), rough, and with dowels (0.5% and 1% of the surface area). The bond strength of Substrate and repair concrete was influenced by the differential stiffness and affected significantly by the roughness, interface angle and the presence of dowels.***

Keywords: **Flexural strength; Tensile strength; Shear strength; Bonding materials; Concrete-to-concrete interface.**

I. INTRODUCTION

Some techniques for repairing and/or strengthening structures involve adding new concrete to an existing concrete substrate. The bond between the old and new concrete usually presents a weak link in the repaired structure. Several studies have focused on the bond mechanism between repair concrete and substrate concrete. In the concrete structural retrofitting applications, which include highway structures where concrete overlays are used for the repair of corrosion-damaged concrete structures, where the deteriorated concrete must be replaced with new concrete, the repair concrete and concrete substrate interface is the most critical component.

In these applications, the properties of the interfacial bond mainly depend on the adhesion between the repair concrete and the concrete substrate at the interface, cohesion in the substrate concrete and in the repair concrete, friction, aggregate interlock, and other time-dependent factors which in turn, depend on other variables [1]. Adhesion to the interface depends on different parameters such as, bonding agent [2], [3], material compaction [4], cleanness and substrate moisture content of repair surface, specimen age, the existence of micro cracking at the substrate, and the shrinkage of the added concrete.

Nevertheless, the surface preparation is commonly pointed out [5]–[7] as one of the most, if not even the most, influencing parameters, and roughness of interface surface. The adhesion at interfaces in concrete structures is important for safety and durability [8], [9].The chances of failure by cracking along the interface are higher because of stress concentration and the rapid change of stress levels along the interface. D. Zhang, T. Ueda, and H. Furuuchi [7] presented the results of laboratory tests to illustrate the contribution of interfacial roughness and substrate concrete on the bond properties. They concluded that the increase of interface roughness leads to an increase of the polymer cement mortar (PCM)-concrete interface area and subsequently to an increase of the fracture energy of the PCM-concrete interface adhesion layer until the failure mode shifts from the adhesion layer to the concrete cohesion layer, a roughness index of approximately 1mm ($0{:}9 \leq Ra \leq 1{:}1$ mm) is proposed as the optimum value of interface roughness.

Repair materials can be divided into three main groups: cement based, modified cement based, and resin based. In developing countries modified cementitious materials are considered a good choice in terms of cost and behaviour in comparison with resin-based materials. Some researchers studied the behaviour of SBR, ER, and cement slurry as bonding materials between old-new concrete either under tensile, [3], [10] or shear stresses [2]. From their study, the results of splitting tensile test, using SBR as a bonding agent possess a good tensile strength compared to cement slurry. Thus, SRB is a better good choice in repairing/resurfacing concrete in tension zone of a flexural member [10]. Whilst, the results obtained from slant shear test showed higher bond strength of ER compared with SBR, produced by different companies [2].

The measured bond strength is highly dependent on the test method used. Several tests are available to measure the bond strength. However, limited information is available on comparison of these various test methods and the resulting bond strength values [11]. The existing tests to determine the bond between concrete substrate and repair material can be divided into three categories according to the stresses which may arise. The first category of tests measures the bond under tension stress; Pull-off test (direct tension), splitting test and flexural test (indirect tension) represent this category. The second category of tests measures the bond

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under shear stresses, and is called direct shear methods such as, double L-shaped, monosurface shear, and Bi-Surface shear. In the third category, the bond strength is measured under the combination of shear and compression stress; e.g., slant shear test.

The slant shear test has become the most accepted test, since it has been adopted by a number of international codes for evaluating the bond of resinous repair materials to concrete substrates; besides the test has been used by many researchers [2], [6] and [11]–[13]. However, there is no agreement among researchers regarding the appropriateness of this test for non-resinous materials [11], [12]. Some researchers used the splitting tensile test either on composite cubes or on composite prism or on composite repair concrete cylinder to evaluate the performance of bonding agents used at the interface surface between new and old concrete [4], [9] and [14]. J.S. Wall, N.G. Shrive, B.R Gamble [15] used the slant shear, splitting tensile, and two different flexural tests for evaluating agents' bond strength between old-new concrete. They concluded that the results of the splitting tensile test had the least scatter of the four tests and are considered more efficient in this regard.

A. Momayez, M.R. Ehsani, A.A. Ramezanianpour, H. Rajaie [11] reported results from 164 specimens using different test methods: pull-off, splitting prisms, bi-surface shear (direct shear) and slant shear. They concluded that the bond strength measured is greatly dependent on the test method used and that the bond strength ratios obtained by two different tests can differ by as much as eight times. They also found that the bond strength decreased with the test method in the following order: slant shear, bi-surface shear (pure shear), splitting and pull-off.

R. Saldanha, E. Júlio, D. Dias-Da-Costa, P. Santos [13] designed an innovative test; called Modified Slant Shear Test (M-SST). They used prism specimen of 150 ×150× 600 mm with an interface angle of 30° with the vertical. This modified test depends on the reinforcement they have introduced in both halves of the M-SST specimen. The two halves of composite were reinforced with 6mm stirrups which were held in place using longitudinal reinforcement. Therefore, adhesive failure was enforced to occur as both parts of the slant shear specimen are strengthened, thereby preventing cracking due to Poisson's effect to occur. This method implies that by strengthening the two parts of the composite concrete, the achievement of the adhesive failure (bond failure) could be ensured.

II. RESEARCH SIGNIFICANCE

As a result of the rapid increase in the deterioration of infrastructure worldwide, there is a great deal of interest in bond between existing concrete substrate and repair materials. The bond between concrete parts is affected by several parameters such as the surface preparation, bonding materials, differential concrete strength, and the state of stress which the structure is subjected to in the field. This paper investigates the bond between old and new concrete measured by three different test methods (205 beam specimens were tested in flexural,75 cylinder specimens were tested in splitting and 57 double-L shaped specimens were tested in shear) and three different categories of repair materials; cement based, modified cement based, and resin based. The effect of the interface surface inclination (in flexural test, three different angles of 30°, 45°, and 90° with the horizontal was used), the interface surface preparation (as-cast, rough, and with dowels) as well as the differential stiffness between substrate (with compressive strength, f_{cu} = 60 MPa) and repair concrete (f_{cu} = 25 MPa, 40 MPa, and 60 MPa) are considered in this experimental investigation.

III. MATERIALS AND MIX PROPORTIONS

The constituent materials are CEM I 42.5N Portland cement, natural sand, gravel, tap water as well as silica fume and high-range water-reducing admixture in high strength mix. The cement satisfied the Egyptian Standard Specification ESS 4756-1/2006 [17]. The Silica fume was a very fine by product powder obtained as a fume from the foundry process in the Egyptian company of Iron Foundries. The Silica fume used contains 95% of SiO2. The chemical, physical and mechanical properties of used cement and silica fume are given in Table I.

Table I Chemical Composition and Physical Properties of Portland cement and Silica Fume.

Chemical Composition (%)	Portland Cement	Silica Fume
Loss on ignition	1.36	1.0
SiO2	21.00	95
AL2O3	3.78	0.4
Fe2O3	5.00	0.6
CaO	63.0	0.2
MgO	1.00	0.4
SO3	2.4	0.3
L.O.I	2.11	–
Na2O	0.18	–
K2O	0.13	–
Total	99.99	–
Physical properties		
Specific weight (g/cm3)	3.12	2.2
Specific surface (cm2/g)	3000	150000
Setting time (min)		
- Initial	135	–
- Final	240	–
Mechanical properties		
Compressive strength (MPa)		
- 2 days	19.6	–
-7days	–	–
-28 days	50.1	

In this research program, the fine aggregate was natural siliceous sand with 4.75 mm maximum particle size. The specific gravity and volumetric weight of sand were 2.60 and 1550 kg/m^3, respectively. The coarse aggregate was gravel of two sizes (10 mm and 20 mm), with specific gravity 2.66, and volumetric weight of 1650 kg/m^3. The grading of the used sand and gravel aggregates was satisfied by the ESS 1109/2008 [17] and is shown in Figs. 1 and 2.

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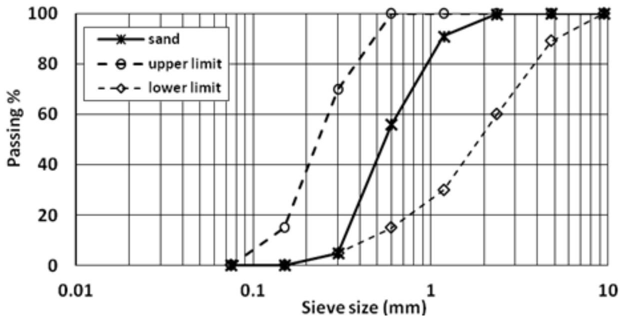

Fig. 1 Sieve analysis of sand.

The high-range water-reducing admixture used was the sulphated naphthalene formaldehyde condensate type. The repair materials used in this study are, modified Styrene Butadiene Rubber Emulsion (SBR), Acrylic Resin (AR), Epoxy Resin (ER), and cement paste (CP) with cement ratio to water of 2:1. The details of binder materials and its technical Specifications are shown in Table II. The proportions and the mechanical properties of the concrete mixes are given in Table III.

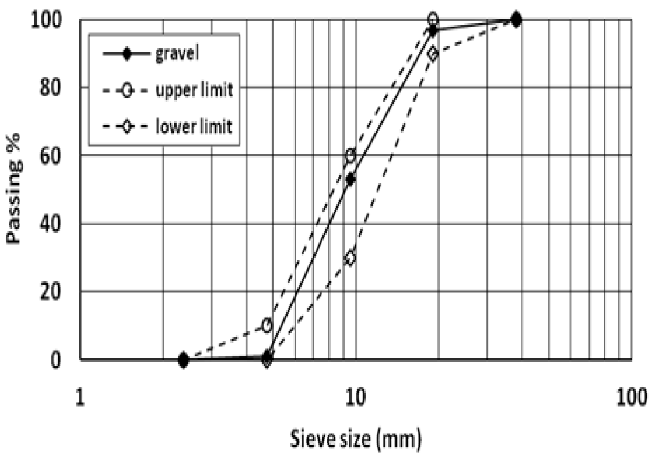

Fig. 2 Sieve analysis of gravel

Table II Bonding materials and its technical Specifications

Designation	Bonding materials used and the Technical Specifications	
	Binder description	Technical Specifications
SBR	Modified Styrene Butadiene Rubber Emulsion	One-component Colour: white liquid Specific gravity: 1.01 at 20°C ASTM-C-882 Compressive strength: 60 MPa
AR	Acrylic Resin Dispersion	One-component Colour: white liquid Specific gravity: 1.04 ASTM-C-882
ER	Epoxy Resin	Two-component Colour: Transparent Specific gravity: 1.44 at 25°C Max overlay time: 60 min at 25°C Bond strength: 11.4 MPa ASTM-C-882
CP	Cement paste	Obtained by mixing ordinary Portland cement and water with ratio 2:1.

Table III Concrete Mix Proportion and its Properties

Mix designation	Mix proportion (Kg/m^3)						
	Cement content	Sand content	Gravel content		Water content	Silica fume (SF)	Superplasticizer (SP. %)
			Max. Size 10mm	Max. Size 20mm			
M25	275	820	–	1230	138.5	–	–
M40	500	606	376	750	200	–	–
M60	500	604	374	748	132	100	15 (2.5%)

Mix designation	Mix properties			
	Comp. Strength f_{cu} (MPa)	Flexural Strength f_r (MPa)	Split. Tens. Strength f_{sp} (MPa)	Shear Strength q (MPa)
M25	25.0	4.5	2.41	2.68
M40	40.3	5.5	3.04	2.88
M60	60.2	9.5	4.60	3.91

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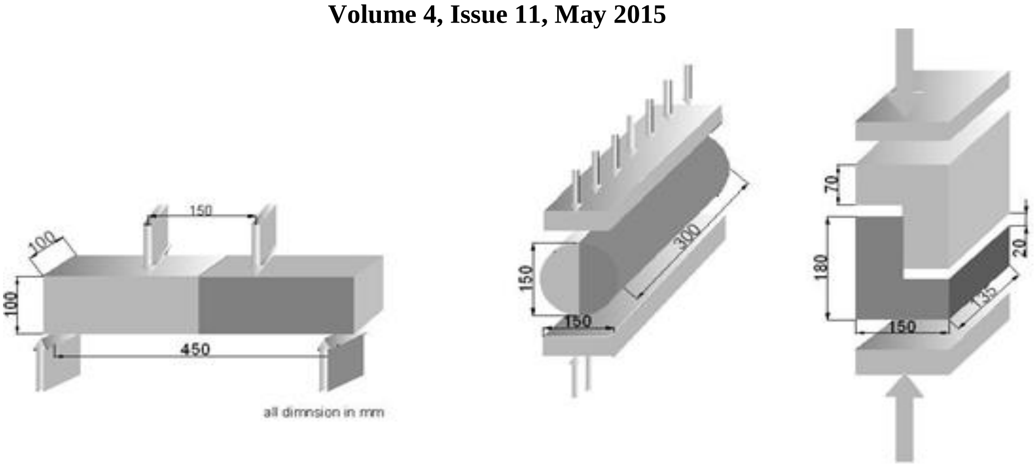

a) Flexural test b) Splitting test c) Shear test

Fig. 3 Dimensions of tested specimens (in millimetres) and test methods.

A) B) C)

Fig.4 Fabrication of different samples for flexural, splitting tensile and double-l sheer tests.

A) B) C)

Fig. 5 Roughness surface preparation and surface with dowels for some of the specimens halves.

IV. TEST PROGRAM AND SPECIMENS PREPARATION

A. TEST PROGRAM

In this paper the substrate concrete was high strength concrete with target strength of 60 MPa; however, the repair concretes were selected from different strengths of 25 MPa, 40 MPa, and 60 MPa, in order to study the effect of variation of concrete strength on old-new concrete bond strength. The three groups marked as C1, C2, and C3 for old concrete/new concrete are made of 60MPa/25MPa, 60MPa/40MPa, and 60MPa/60MPa, respectively. The bonding surface was prepared in different ways, smooth (as-cast), rough, and presence of 0.5%, 1% reinforcement dowels.

Flexural and splitting testes were used to measure the effectiveness of repair materials in tension bond, whilst shear bond was measured using double –L shaped specimens. Fig.3 shows the dimensions of the tested specimens and loading used in the tests.

The flexure specimens were 100 × 100 × 500 mm prisms which were loaded with two equal concentrated loads at the middle third. In these specimens the effect of bond surface inclination at mid-span of 30°, 45°, and 90° with horizontal axis was studied. The splitting tensile test was carried out on cylindrical specimens of 150 mm diameter × 300 mm high, which is composed of two parts in the direction of the axis, one-half base concrete and one half of repair concrete. The test compression load was applied along the bond surface in the longitudinal direction of the cylinder. In the shear test, a shear force was applied on the bond surface as shown in Fig. 3 (shear plan of 90 × 135 mm). For each test, two specimens were used and the mean value was considered. This study was carried out on 205 beam specimens tested in flexure, 75 cylinder specimens tested in splitting and 57 double-L shaped specimens tested in shear.

B. SPECIMENS PREPARATION

The same concrete mix was used for the concrete in the substrate portion of all specimens. Thick Styrofoam plates were used to define the geometry of the substrate concrete from new concrete and sand was placed beyond the plate. For the bond surface with dowels, headless 50mm length dowels were distributed on the Styrofoam plates and 25mm of its length facing the casting direction. Mixing of concrete components was carried out in the laboratory by using a horizontal mixer and the concrete was placed in lubricated steel (prisms and cylinders) or wooden (double-L shape) forms. After the half portion of the moulds had been filled of concrete and compacted, the surfaces of concrete were levelled and they were kept in laboratory conditions, Fig 4. After 24 hours the specimens were removed from the forms and after cleaning they were cured in water for 28 days. The specimens halves (Fig. 5) were lifted from water, then the repairing surface of some of specimens was roughened using steel wire brush and with the help of drill to remove the slurry cement from surfaces to obtain ~2-3 mm depth roughness.

The specimens were kept to dry for one week prior to applying the bonding material, the bond surface was cleaned from any extra dust or loose particles and grease. The bonding materials of SBR, AR, ER, and CP were prepared for application. SBR, water, cement, and fine sand were prepared with ratios 1:1:1:1 and mixed well before applying on the bond surface, while AR was mixed with water with ratio 1:1 and for the binder materials of CP the cement was mixed with water with ratio of 2:1, respectively. The epoxy resin (ER) was prepared by adding the hardener to the resin in ratio 1:2 and mixed until obtaining uniform color.

A stiff brush was then used to distribute the binder materials on the bonding surface. Thereafter, the specimens were left for about 30 minute before placing in the lubricated moulds once again and then the repairing concretes were cast and compacted with tamping and vibrator. The specimens were covered with wet burlap and plastic sheets and left for 24 hours in the laboratory. The composite specimens were demoulded and cured in water for additional 28 days until testing. In parallel, three continuous specimens of each mix were cast for the purpose of comparison.

V. TEST RESULTS AND DISCUSSION

In this research, all the specimens either composite or continuous-bond were tested after 28 days age of new concrete. Each group of specimens is identified with two parts. The first refer to the interface surface texture – S (as-cast), R (rough), DL (0.5% dowels), and DH (1% dowels) - and the second part refers to the concrete strength of the new/old concrete – C1 (25MPa/60MPa), C2 (40MPa/60MPa), and C3 (60MPa/60MPa). Other details such as the interface surface inclination or the repair materials are illustrated in the figures.

A. MODE OF FAILURE

The mode of failure is characterized by the location of the failure in the specimens: either along the interface surface (bond failure) or in concrete in any side of the bond surface (non-bond failure). Bond failure (adhesive failure) occurred in all of composite specimens with identical high strength of concrete substrate and repair concrete (C3), Fig. 6a. On the other hand, non-bond failure (cohesive failure) mainly occurred in most of composite specimens with low strength of repair concrete (C1), Fig. 6b, since failure depends on the compressive strength of the weakest concrete. However, for moderate strength repair concrete (C2) a few specimens failed partially in the repair concrete and the bond surface materials, Fig. 6c.

It was also noted that the specimens of cohesive failures increased with the interface surface roughness and with dowels particularly when the differential stiffness of the composite is present. The previous observation coincides with P. Santos, E. Júlio [6].

A) B) C)

Fig. 6 Specimens after failure; A: Bond Failure, B: Mix Failure, C: Non-Bond Failure.

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B. FLEXURAL TEST

Flexural test with adopting three different angles with the horizontal at the concrete substrate and repair concrete interface, (30°, 45° and 90°), was used to assess the effect of interface inclination angle on bond strength. However, to allow comparison of the results with different angles and different modes of failure, an equivalent flexural strength was calculated considering the vertical cross sectional area in this test. The average value of flexural strength of continuous-bond specimens; i.e., specimens that were monolithically cast in a single stage, is present in Table III.

Figures 7–11 show the average value of the bond strength at each angle of interface surface of composite specimen for different binder materials and with repair concrete of different strengths

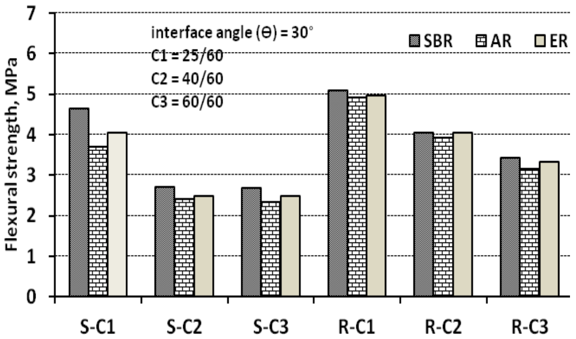

Fig. 7 Flexural strength results of different binder materials (as-cast, rough specimens, Θ=30°).

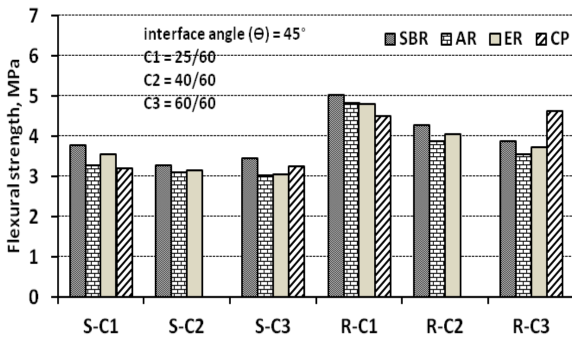

Fig. 8 Flexural strength results of different binder materials (as-cast, rough specimens, Θ=45°).

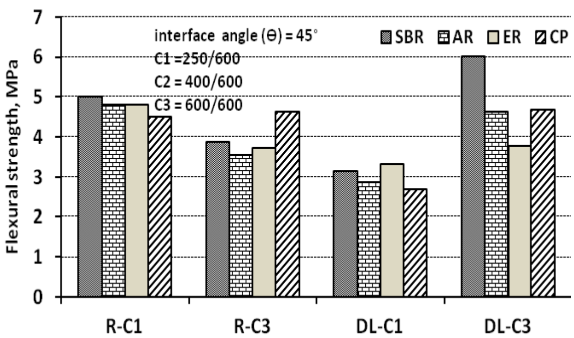

Fig. 9 Flexural strength results of different binder materials (rough, with dowels specimens, Θ= 45°).

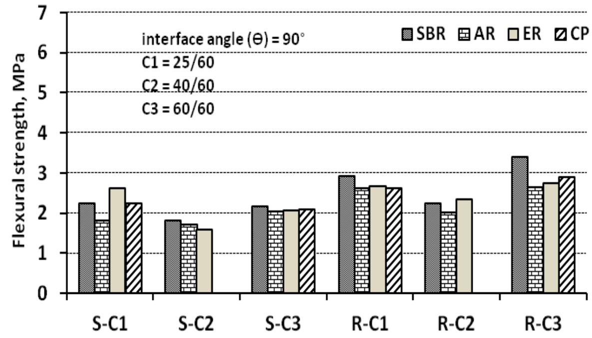

Fig. 10 Flexural strength results of different binder materials (as-cast, rough specimens, Θ= 90°).

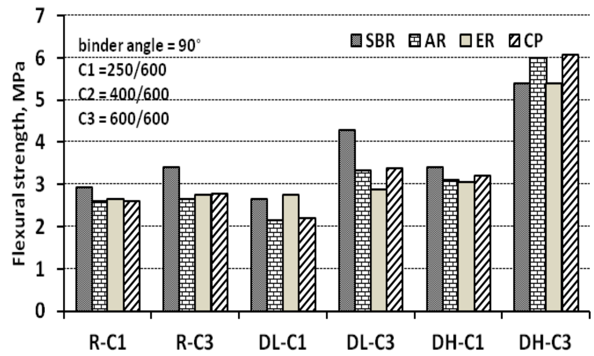

Fig. 11Flexural strength results of different binder materials (rough, with dowels specimens, Θ= 90°).

In general, the binder of Styrene Butadiene Rubber type (SBR) showed relatively the highest values followed by Epoxy Resin binder (ER) then the Acrylic Resin (AR) binder showed less values in as-cast (with smooth surface) specimens. The difference between the bond strength of specimens with AR and ER binder relatively vanished when the difference in concrete stiffness/strength of substrate and the repair concrete was reduced and with rough interface surface. For cement paste binder material (CP), the bond strength produced was reasonable and ensured higher bond strength especially when the strength of repaired concrete and the concrete substrate were identical and with roughened interface surface (S-C3 and R-C3), compared to the AR and ER specimens. The bond strength of the interface increased with the surface roughness, as expected. Nevertheless, an increase in the bond strength with the increase of the difference of the concrete strength/stiffness between the substrate concrete and the added new concrete was observed (more obvious with interface angle 30°, 45° in FIG. 7, 8), in contrary to what was expected, and agrees with Santos et al. observation [6].

The variation of bond strength due to the effect of the surface roughness or presence of dowels (with 0.5% and 1% of the surface area) compared to the corresponding composite specimens of smooth (as-caste) interface surface is shown in Table IV. From Table IV, Figs 7–10 it can be observed that the flexural strength increases, for different interface angles, with the surface roughness. This increase in flexural strength did not show a

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specific behaviour concerning the effect of differential stiffness of new and old concrete in this test. For specimens with dowels the flexure strength increased specially with C3 group, while with C1 group and angle of 45° the flexural strength was reduced. Additional increase occurred by increasing the dowels ratio (from 0.5% to 1.0% of surface area) compared with specimens of smooth interface surface and with no dowels. Specimens with similar stiffness, C3, showed extreme values in the flexural strength produced from the presence of 1% of dowels, was about 165% in average.

The effect of interfacial surface angle of inclination on the flexural strength could be noted, where with the 45° angle the flexural strength was highest followed by that with the 30° angle and then 90°, which reflect the importance of the interfacial surface angle in increasing the flexural bond strength.

C. SPLITTING TENSILE TEST

The splitting tensile strength was calculated by the following equation:

$$\sigma = {}^{2P}/_{\pi A} \quad (1)$$

Where σ = splitting strength, MPa; P = failure load, N; A = surface bond area, mm^2.

For monolithic specimens (without interface plane) the average value is shown in Table III.

The bond strength values obtained from the specimens with SBR as bonding agent were higher compared to the values obtained from specimens that used other materials as a bonding agent (AR, ER, and CP); in particular, the specimens with similar compressive strength of the parent and repair concrete in the case of smooth, rough interface surface (S-C3 and R-C3) and with dowels, Fig. 12.

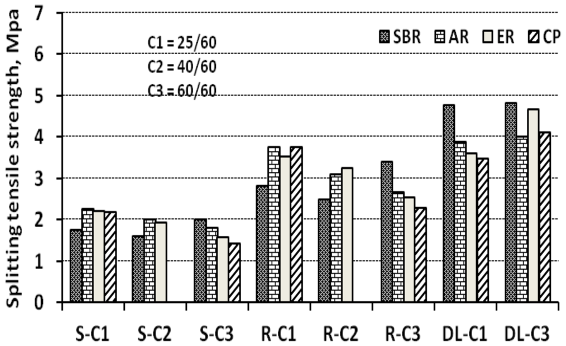

Fig. 12 Splitting tensile strength results of different binder materials (as-cast, rough, with dowels specimens).

However, for S-C1 and R-C1 (smooth and rough interface surface) the ER, AR, and CP were relatively close in the splitting tensile strength and higher than SBR bonding material by around 26.7%, 30% in average for smooth and rough surface, respectively.

With the use of rough interface surface, the splitting tensile strength significantly increased for example, with about 61.71%, 65.93%, 60.91%, and 71.23% for SBR, AR, ER, and CP of group R-C1 compared with group S-C1 with smooth interface surfaces, respectively. Additional increase took place when using dowels especially with SBR binder by about 68.2% compared to the rough surface, whilst, slight increase of 3.73%, and 1.7%, took place with AR, and ER binders, respectively. On the other hand, the utilization of dowels in similar composite specimen's strength (DL-C3) provided 41.7%, 25.92%, 83.14%, and 79.13% (57.5% in average) additional enhancement in splitting tensile strength with SBR, AR, ER, CP, respectively, compared to the rough specimens in group R-C3, Fig. 12.

D. SHEAR TEST

The bond strength in this test was calculated by dividing the maximum load at failure by the surface bond area; that is equal to 90mm × 135mm. The average shear strength (q) of monolithic specimens is recorded in Table III.

Fig. 13 shows the shear strength of different binder materials and of different surfaces texture. Two main observations that can be noted from these results: the first is the shear strength of ER as a bonding agent possessed the highest shear strength compared to the other bonding agents of SBR, AR, and cement slurry (CP), except in group R-C3 where SBR showed the highest value followed by ER and AR. The second observation is that the cement past, CP, exhibited the lowest shear strength in all groups.

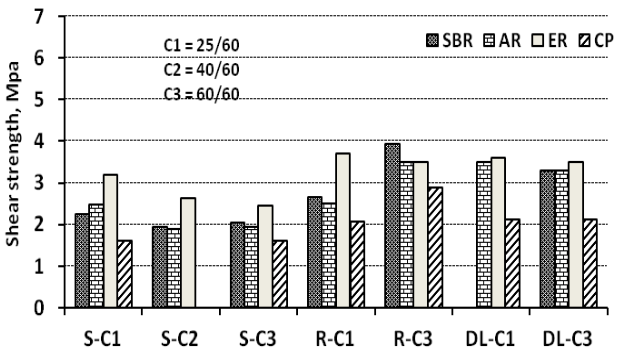

Fig. 13 Shear strength results of different binder materials (as-cast, rough, with dowels specimens).

E. COMPARISON OF TESTS

Figs. 14–17 show a comparison between the measured bond strength by different methods for as-cast and rough interface surface specimens. The monolithic specimens' results of repair concrete (low strength of the composite specimen) are shown in the figures for the purpose of comparison with specimens' bond strength of the corresponding test. Generally, the double-L shear test gave mostly the highest strength of all repair materials with as-cast and rough interface surface specially the composite specimens with similar compressive strength (S-C3, and R-C3) except for the CP binder material with as-cast surface, which gave lower value. The flexural strength gave lower values than the shear strength followed by the splitting tensile strength except in the case of composite specimens with differential stiffness and with AR bind-

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er, the splitting tensile was higher by about 25.6% in S-C1 group.

The results of composite concrete in group C3 of similar concrete compressive strength were more comparable both for as-cast and rough interface surface specimens, S-C3 and R-C3. This may be attributed to the mode of failure of all specimens in bond. The increase in flexural strength was 8%, 12.8%, 29.3%, and 48%, for SRP, AR, ER, and CP, respectively, compared with the splitting strength of the corresponding composite concrete in group S-C3; whilst, the increase, was 0.0, 0.0, 7.8%, and 21.3% in group R-C3, respectively. On the other hand, the maximum increase in the shear strength was 18.4% in ER binder concrete in S-C3 group, while it was about 15.9%, 31.6%, 28.7%, and 3.2% in SBR, AR, ER, and CP binder concrete in group R-C3, respectively, compared to the corresponding flexural strength. The figures also show that regardless of the test method used, the monolithic specimens had the highest bond strength. It is noted, however, that some of the repair materials may result in bond strengths that are higher than that of the continuous specimens, see Fig. 18. The splitting tensile strength and/or shear strength in composite concrete with AR or ER or CP binder materials of group R-C1 exhibited higher bond strength than the corresponding continuous specimens.

The effect of the roughened surface and the presence of dowels on the bond strength were more pronounced in both the splitting and shear tests especially with identical concrete, the improvement was higher compared to the flexure test (Table IV).

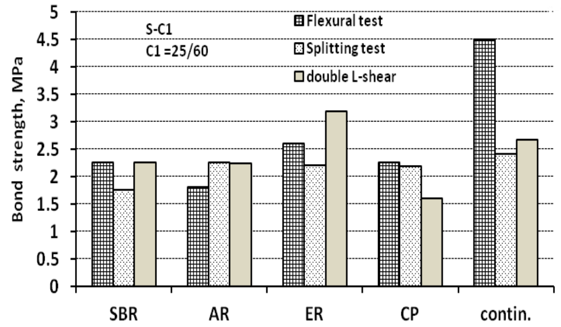

Fig. 14 Effect of different tests on bond strength (as-cast specimens, C1 group).

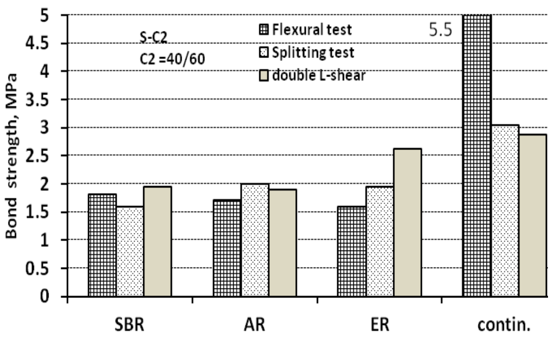

Fig. 15 Effect of different tests on bond strength (as-cast specimens, C2 group).

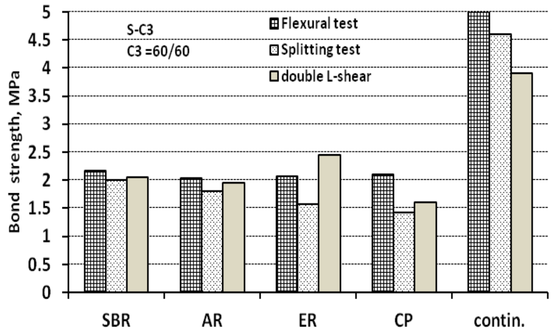

Fig. 16 Effect of different tests on bond strength (as-cast specimens, C3 group).

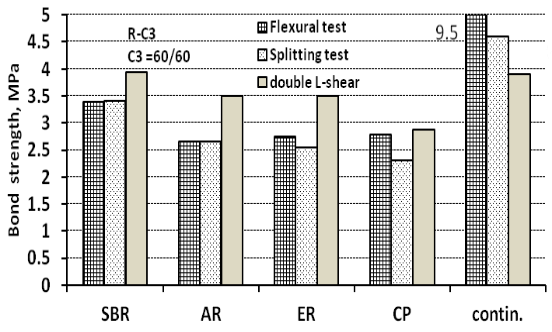

Fig. 17 Effect of different tests on bond strength (rough specimens, C3 group).

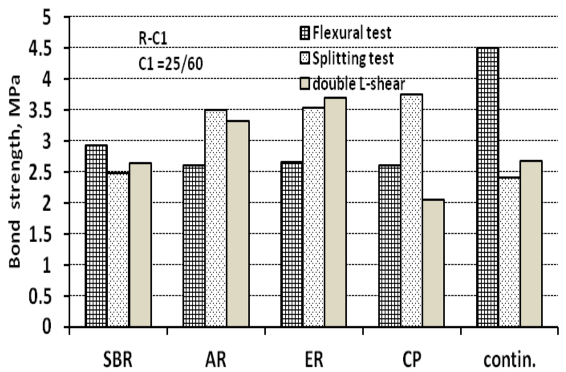

Fig. 18 Effect of different tests on bond strength (rough specimens, C1 group).

The two tests seemed to be appropriate in evaluating the bond strength of old-new concrete with different binders materials in tension and in shear, respectively. They differentiate well between the binder materials and the different factors that affect the bond strength, particularly when the strength of the concrete substrate and the repair concrete are identical (high strength concrete). This may be attributed to the large bonded surface area and the nature of the two tests compared to the flexure test with interface angle 90°.

From Fig. 17 the results of the splitting tensile strength test with rough specimens and identical concrete (R-C3) showed that SBR, AR, ER, and CP as a bonding agent restored 76%, 58%, 55%, and 50% of the capacity of monolithic specimen in tensile strength, respectively. Whilst in shear strength test gave 100%, 90%, 90%, and 74% of the capacity of monolithic specimen, respectively.

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Table IV Variation of Bond Strength of Rough and Dowels Interface Specimens to Corresponding As-Cast Interface Surface Specimens

Specimen designation / Binder material	Rough Interface surface (R)			0.5% Dowel (DL)		1.0% Dowel (DH)	
	C1=25/60 (R-C1)	C2=40/60 (R-C2)	C3=60/60 (R-C3)	C1=25/60 (DL-C1)	C3=60/60 (DL-C3)	C1=25/60 (DH-C1)	C3=60/60 (DH-C3)
Flexure test with 30° interface angle							
SBR	+11.0	+49.30	+27.90	–	–	–	–
AR	+33.0	+63.67	+34.59	–	–	–	–
ER	+22.37	+63.45	+34.46	–	–	–	–
Flexure test with 45° interface angle							
SBR	+32.75	+30.13	+12.44	-16.67	+75.19	–	–
AR	+46.56	+24.60	+17.91	- 14.10	+53.71	–	–
ER	+34.98	+28.57	+22.09	- 6.36	+11.36	–	–
CP	+40.0	–	+43.09	- 18.52	+44.44	–	–
Flexure test with 90° interface angle							
SBR	+30.22	+25.0	+57.41	+17.78	+97.92	+52.0	+157.41
AR	+45.0	+18.42	+31.03	+20.0	+64.00	+72.5	+196.0
ER	+1.92	+48.57	+32.61	+5.10	+39.13	+17.24	+160.9
CP	+16.0	–	+38.01	- 2.04	36.36	+42.0	+145.46
Splitting test							
SBR	+61.71	+55.0	+70.0	+172.0	+140.5	–	–
AR	65.93	+55.5	+77.22	+72.12	+122.2	–	–
ER	+60.91	+68.4	+62.42	+63.64	+197.5	–	–
CP	+71.23	–	+62.0	+58.45	+190.14	–	–
Shear test							
SBR	+17.77	–	+92.2	–	+60.49	–	–
AR	+48.70	–	+79.49	+41.7	+68.72	–	–
ER	+15.99	–	+42.86	+12.85	+42.86	–	–
CP	+28.75	–	+80.0	+53.75	+71.88	–	–

However, in flexure strength the maximum capacity restored was 36% of the capacity of monolithic specimen by using SBR binder material. This observation implies the important effect of roughness in increasing the bond strength and restoring a high value of strength.

VI. CONCLUSIONS

Based on the experimental results, the following conclusions can be drawn:

1- SBR showed relatively the highest bond strength in tension followed by ER, AR, respectively. CP bonding material showed reasonable results especially in the case of identical strength concrete for the two halves of the composite and with roughened surface. That makes it more suitable and economical in the case of structure subjected to tensile stresses. On the other hand, in the case of shear stress, the epoxy resin (ER) produced the highest results in all cases whilst, cement paste (CP) gave the lowest values in shear.

2-The differential stiffness has significant effect on the resulting bond strength as well as the mode of failure which changed from adhesive to cohesive failure with the increase of the differential stiffness between new and substrate concrete. All specimens with both halves of the same compressive strength (60/60 MPa) presented adhesive failures, whereas all the others (25/60 MPa and 40/60 MPa) exhibited cohesive failures and combined failure, showing the importance of differential stiffness on the failure mechanism. With the increase of differential stiffness, the bond strength produced at as-cast and rough interface surfaces, increased, which was more pronounced in the flexural test with interface surface angle of 30° and 45° with the horizontal axis.

3- The bond strength of old concrete–to–new concrete interface increased significantly with the surface roughness or with the use of dowels. Additionally, it's greatly affected due to the differential in the concrete stiffness and the dowels percentage. In general, with the decrease of differential stiffness the improvement in bond strength produced is relatively increased for roughened and with the use of dowels specimens compared to as-cast interface surface specimens (splitting test and shear test, Table IV).

4- The inclination of interfacial surface angle affect significantly the bond strength produced, where with the angle of 45° the bond strength in flexural was the highest followed by the angle 30° and then 90° which reflects the importance of the interfacial surface angle in increasing the flexural bond strength.

5- For bond strength evaluation of different binder materials the two halves of the composite should be chosen with identical high strength concrete (with as-cast surface). This choice implies that by strengthening the two parts of the composite concrete, the achievement of the adhesive failure (bond failure) could be ensured (e.g. S-C3 group).

6- In this study the measured bond strength decreases with the test method in the following order: shear, flexure, and splitting, in the case of similar strength concrete (C3 group) except with CP binder which gave lower values in shear strength with smooth surface. The maximum increase of shear strength was about 18.4% and 56% compared to flexure and splitting strength, respectively.

7- Bond strength is greatly dependent on the test method used. It is essential that the bond tests be selected such that they represent the state of stress the structure is subjected to in the field. The splitting tensile and double-shear tests seem to be appropriate in evaluating the bond strength of old-new concrete with different binder materials in tension and in shear, respectively, where, they differentiate well between the binder materials and the different factors that affect the bond strength in this study.

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