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ABSTRACT

The important of bond strength of a multilayer concrete system is increased with the increase of the use of the advanced composite materials in the field of repair or strengthening. Experimental and analytical models based on different testing methods are developed in attempt to evaluate the actual bond strength of the system. The most common techniques used to prepare the interfacial bonding surface can be classified into physical, chemical, and mechanical techniques.

Analytical and experimental study was conducted to find out the dominant factors that control the tensile bond strength at the interface. The variables were the surface roughness, the chemical coating, and the steel connectors. The experimental study was conducted on 48 specimens which were prepared for the splitting test. The analytical modeling was carried out using ANSYS12.0.1, where 8 different cases of surface conditions were considered. Interface of smooth surface (SS) was used as a reference while the physical bond was expressed in terms of horizontal roughening (HR), vertical roughening (VR) and grid roughening (GR). The mechanical bonding was induced by using mild steel bar (SC1) and high grade steel bar (SC2).

The results of the presented research work show the role of the relative rigidity of the mixes on the tensile bond strength. Simplified and reliable formulas were presented to relate the experimental and theoretical tensile bond strength based on the interface condition. The results also show that using the grid roughening (GR) gave the highest value of the tensile bond strength. The case of using the epoxy (EP) gave competitive tensile bond strength values.

Good agreement between the experimental and theoretical results and similar trends were observed for the cases (SS), (HR), (VR), (GR) and (AB). Slight differences were found for the cases (EP), (SC1) and (SC2).

KEYWORDS

Relative rigidity (RR), tensile bond strength, multilayer system, surface roughness, adhesive coat, steel connectors, slippage, shear resistance.

1. INTRODUCTION

Bonding condition at the interface of old and new concrete layers plays an important role in the actual composite behavior of the repaired or strengthened concrete system. Also, specifying the interface condition if it is fully bonded, partially bonded, or not bonded has an adverse effect in the design of the multilayer system and consequently the designed load carrying capacity [1]. The design approach based on the interface condition and the construction practices to achieve the design criteria is considered an important factor that governs the structural efficiency of the repaired concrete system [2, 3].

Interfacial bond can be classified into physical bond, chemical bond, and mechanical bond. Combination of different types of bond may be initiated. However, probability of failure should be considered with great care in this case as the failure of the multilayer system is relatively complicated when compared with the case of a single-bond phase [4, 5]. It was also found that bond strength at the interface is related to the relative strength of the repair system, curing time of the new concrete, test methods to evaluate bond strength, the type and history of the applied load, and precautions that have been taken during the implementation to initiate the bond at the interface [6].

It has been proposed a wide range of test methods for evaluating bond characteristics and performance necessary to reform the overall material. These tests include tensile bond tests, slant shear tests, twist off shear test, and flexure tests. Most of the attention focused on tensile tests, including the pipe grip uni-axial tension test, a friction-grip tensile test, a dog- bone test, and pull off tests [7, 8]. A core pull-off test of the proposed European standards for repair materials is also included [9, 10, 11]. Undoubtedly, tensile bond tests are gaining popularity because of its simplicity and ability to meet most of the requirements mentioned above.

Tensile bond strength can be assessed using either the direct tension test or the indirect tension test by using the splitting test or the flexural test [12, 13, 14].

2. OBJECTIVES

1. Verifying the role of the relative rigidity of the concrete system which composes the old and new mixes.
2. Verifying the influence of the type of the bond initiated ate the interface between the old and new concrete.
3. Conducting analytical study using ANSYS program to investigate the influence of the relative rigidity of the concrete system and the condition of the interface.
4. Relating the results of the analytical modelling to the experimental results.

3. RESEARCH PLAN

The reference mix of the old concrete was nominated as M2 while three concrete mixes were used as a repairing mix and they were denoted as M1, M2, and M3. Details of the concrete mixes were given in Table 1. Twenty four concrete cubes were used to implement the compression and splitting tests. The compressive and tensile strength of the used mixes after 7 and 28 days of curing were recorded in Table 2. The relative rigidity of the concrete mixes was denoted by M1/M2, M2/M2, and M3/M2. Eight cases of substrate preparation were considered as given in Figures 1 and 2. Three types of bond were used: physical, chemical, and mechanical bond. The case of smooth surface (SS) was used as reference. Forty eight bond test specimens were used to assess the tensile bond strength. The analytical modelling using ANSYS-12.0.1 was conducted using 8 different models based on the substrate condition. These models were denoted by SS, HR, VR, GR, AB, EP, SC1 and SC2 as explained in Figures 1 and 2.

4. ANALYTICAL MODELING

4.1 ANSYS-12.0.1 Computer Code

The ANSYS12.0.1 source code is classified as a general finite element analysis program that can be applied in the analysis of reinforced concrete structures. This program contains a wide library of different elements for representing concrete, steel bars and any used meshes. Also, this program is able to find the load displacement curves at different stages of loading, the crack shape, deformation shape, the stresses and strains for different elements at different stages of loading.

4.2 Modeling of Concrete Specimens

3-D finite elements analysis was conducted for the concrete specimens. ANSYS-12.0.1 has several three-dimensional elements in its library; namely Solid45, Solid64, Solid65, and Solid95. In this study, SOLID65 for the concrete as it is suitable for presentation of compression stress-strain curve for concrete other properties. The reinforcing steel bars were modelled using LINK8 3-D element. The numerical solution scheme adopted for non-linear analysis was an incremental load procedure.

4.3 (3-D) Concrete Solid; Solid65

Solid65 is used in general for the three-dimensional modelling of concrete solids with or without reinforcing bars. The element is capable of depicting cracking in tension and crushing in compression. In concrete applications, the capability of the element may be used to model the concrete while the rebar capability is available for modelling reinforcement behavior. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal X, Y, and Z directions and up to three different rebar specifications may be defined as shown in Figure 3-a. The most important aspect of this element is the treatment of nonlinear material properties. The concrete is liable to crack in three orthogonal directions. A thoughtful suitable mesh to divide the concrete test specimen was used.

4.4 (3-D) Link Spar Elements, Link8

Steel reinforcement was modelled by a 3-D link spar element, link8, which needs two nodes and has three degrees of freedom for each node as translations in x, y and z directions. The element is capable of plastic deformation as shown in Figure 3-b.

4.5 Concrete Behavior

Development of a model for the behaviour of concrete is a challenging task. Concrete is a brittle material and has a different behaviour in compression than in tension. The tensile strength of concrete is typically 8-15% of the compression strength.

4.6 Failure Criteria for Concrete

The element adopted for concrete is capable of predicting the failure of the concrete material. Both cracking and crushing modes are accounted for the concrete specimens. The two input strength parameters i.e., ultimate uni-axial tensile and compressive strengths are required to define the failure surface for the concrete. Consequently, a criterion for failure of the concrete due to a multi-axial stress state is defined it's manual.

In concrete elements, cracking occurs when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of concrete element is set to zero in the direction parallel to principal tensile stress direction. Crushing occurs when all the principal stresses are compressive and lie outside the failure surface; subsequently, the elastic modulus is set to zero in all directions and the element is effectively disregarded.

Input strength parameters, fc, ft, fcb, f1 and f2 are needed to define the failure surface. The ultimate uni-axial compressive strength fc, was taken based on test results of cube concrete samples for each specimen, and ft was taken as recommended by the ACI Specifications as 0.1 fc. The parameters fcb, f1 and f2 were considered as 1.2 fc, 1.45 fc, and 1.725 fc, respectively.

Additional concrete material data, such as the shear transfer coefficient is also required. Typical shear transfer coefficient ranges from 0.0 to 1.0, with zero-value representing a very smooth crack (complete loss of shear transfer) and 1.0 representing a very rough crack (no loss of shear transfer). This feature may be applied for both the open and closed crack approaches. Shear transfer coefficients were taken as 0.6 for open crack and 0.8 for closed crack. A value of 0.6 for stress relaxation after cracking was considered in the analysis. These values revealed better behaviour for the test concrete specimens according to the correlative study conducted.

4.7 Results and Analysis of Analytical Modeling

The results given in Tables from 3 to 10 and Figures from 7 to 14 show that increasing the relative rigidity of the concrete mix from M1/M2 to M3/M2 led to increase the induced normal stresses X1, X2, and X3. The middle third of the specimens was subjected to tensile stresses when the stresses X1 and X3 were considered. For the case of normal stress X2 the whole section was subjected to tensile stresses. Considering the normal stress X1, it can be shown that minimum values of 0.0398 N /mm^2, 0.0502 N /mm^2, and 0.0580 N /mm^2 were observed for the case of smooth surface (SS) while maximum values of 1.200 N /mm^2, 1.270 N /mm^2, and 1.360 N /mm^2 were shown for the case grid roughening (GR). Similar results were given for the case of normal stress X3.

Tables from 3 to 10 and Figures from 7 to 14 show that the normal stresses X2 induced at the horizontal section passing the centre of the specimen were tensile stresses where the maximum values were at the edges while the minimum values were at the centre. The minimum values were 0.002 N / N /mm^2 for the case of grid roughening (GR) while the maximum values were 0.751 N /mm^2 and observed for the case of mechanical bonding (SC2). The case of mechanical bonding (SC1) and chemical bonding (EP) gave maximum tensile stresses X2 of values 0.6297 N /mm^2 and 0.7020 N /mm^2 respectively which represented 83.8% and 93.5% of the case (SC2).

Tables from 4 to 6 and Figures from 8 to 10 showed the influence of roughening the surface using three different techniques to crate physical bond at the interface which were (HR), (VR), and (GR). The results indicated the significant effect of using the grid roughening (GR) with respect to the other two techniques. The maximum tensile stresses X1 induced for the case of (GR) were 1.200 N /mm^2, 1.27 N /mm^2, and 1.360 N /mm^2 while they were 0.400 N /mm^2, 0.530 N /mm^2, and

0.636 N /mm^2 for the case of (HR) and they were 0.4904 N /mm^2, 0.650 N /mm^2, and 0.857 N /mm^2 for the case of (VR).

Tables from 7 to 10 and Figures from 11 to 14 showed that using the epoxy coat (EP) to induce the bond at the interface led to better results when compared with the case using the Adibond (AB) which reflected the potential of the not water based coating on improving the bond characteristic at the interface. The maximum tensile stress X1 induced for the case of the using (EP) represented 2.4 times of that induced for the case of (AB).

In the case of using mechanical bonding, the maximum tensile stress X1 for the case of (SC2) represented 1.16 times that induced for the case of (SC1). Similar results are obtained when the normal stresses X3 are considered.

5. RESULTS AND ANALYSIS OF EXPERIMENTAL WORK

5.1 Compressive and tensile strength test results

Tables 1and 2 show the concrete mixes, and the compressive and tensile strengths of the concrete cubes which were tested after 7 and 28 days. The concrete mix M2 was taken as reference. The relative rigidity was expressed in terms of the relative tensile strength after 28 days. The results show that the compressive and tensile strengths were increased with the increase of the curing time and the decrease of the w/c ratio. The concrete mixes M1, M2, and M3 were used to prepare the new concrete layer on top of the old concrete which was prepared from the concrete mix M2.

5.2 Tensile Bond Strength Test Results

Tables 11 and 12 and Figures from 15 to 17 show the results of the tensile bond strength from the splitting test. The results indicated that increasing the relative rigidity of the mixes led to increase the tensile bond strength. This observation was found for all cases of preparing the interface. The minimum values of tensile bond strength were found for the case of the smooth surface (SS) where the tensile bond strength ranged from 0.130 N /mm^2 for the case of M1/M2 up to 0.180 N /mm^2 for the case of M3/M2. The percentage of increase of the tensile strength due to changing the relative rigidity from M1/M2 to M3/M2 was 38.5%. The case of improving the bond at the interface using the grid roughening (GR) gave the highest tensile bond strength values where the tensile bond strength ranged from 1.270 N /mm^2 to 1.770 N /mm^2 depending on the relative rigidity of the mix. The tensile bond strength of the case of the epoxy coat (EP) ranged from 1.231 N /mm^2 to 1.590 N /mm^2 and represented 97.0%, 91.0%, and 90.0% of the case of using the grid roughening (GR).

5.3 Relating the Experimental and Theoretical Tensile Bond Strengths

The comparison between the experimental and theoretical tensile bond strength for the different cases of surface preparation and mixes was shown in Tables 13 and 14. In most cases, the theoretical tensile bond strength was equal to or lower than that obtained from the experimental study with the exception to the case of (VR) of relative rigidity M3/M2 where the relative tensile bond strength of this case, (σ thoe./ σ exp.) ranged from 0.875 to 1.032. Good agreement was found for the cases (SS), (HR), (VR), (GR) and (AB) where the relative tensile bond strength of these cases ranged from 0.300 to 1.032 while it ranged from 0.711 to 0.971 for the cases (EP), (SC1) and (SC2). In most cases the relative tensile bond strength was increased with the increase of the relative rigidity of the mix from M1/M2 to M3/M2.

Figures 18 and 19 were used to get the formulas that relate the experimental and theoretical tensile bond strengths for the different cases of interface condition:

$$f_{exp(SS)} = 2.64 f_{theo(SS)} + 0.03 \quad \text{Eq.[1]}$$

$$f_{exp(HR)} = 0.61 f_{theo(HR)} + 0.26 \quad \text{Eq.[2]}$$

$$f_{exp(VR)} = 0.82\, f_{theo(VR)} + 0.15 \quad \text{Eq.[3]}$$

$$f_{exp(GR)} = 3.05\, f_{theo(GR)} - 2.34 \quad \text{Eq.[4]}$$

$$f_{exp(AB)} = 3.2952 f_{theo(AB)} - 0.02 \quad \text{Eq.[5]}$$

$$f_{exp(EP)} = 4.84\, f_{theo(EP)} + 0.45 \quad \text{Eq.[6]}$$

$$f_{exp(SC1)} = 2.21 f_{theo(SC1)} + 0.41 \quad \text{Eq.[7]}$$

$$f_{exp\,(SC2)} = 3.98 f_{theo(SC2)} + 0.01 \quad \text{Eq.[8]}$$

5.4 Mechanisms of Failure

It is of particular interest to investigate the mechanisms of failure at the interface. It is clear from the results that the failure is depending on the stress type, value, and distribution. The tensile bond strength depends on the relative rigidity of the concrete system and, the area, and type of stress induced to resist failure.

In case of smooth surface (SS), the whole plane of failure was exposed to tensile stresses. Roughening the interface increased the area of the plain of failure and induced shear resistance due to interlocking. The highest tensile bond strength was found for the case of the grid roughening (GR). The reduction in the tensile bond strength for the cases of (HR) and (VR) could be attributed to the direction of loading with respect to the direction of roughening. Using deformed steel bars led to higher tensile bond strength when compared with the plain steel bars. This is due to the interlocking and the larger surface area of the deformed steel bars. Using the epoxy (EP) may need further investigation to justify the significant increase in the tensile bond strength.

6. CONCLUSIONS AND RECOMMENDATIONS

The conducted experimental and analytical work concluded the following:

1- The tensile bond strength depends on the relative rigidity of the concrete layers (M_i /M_2) and the best results are found when the relative rigidity (RR)>1.

2- The results show that the physical bond using grid roughening (GR) provides the highest tensile bond strength. Also using the epoxy (EP) shows the best results with respect to the techniques of initiating chemical bond and it is found to be competitive to the case of the grid roughening (GR.)

3- Using ANSYS12.0 source code leads to underestimate the tensile bond strength with the exception of the case of physical bond (VR) with (M3/M2).

4- The results of the conducted research work provide simplified formulas to evaluate the tensile bond strength in terms of the most commonly used surface bonding conditions.

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Table 1: Concrete Mixes

Repair Mix	w/c	Cement (kg)	Water (kg)	Sand (kg)	Dolomite (kg)	Admixture
M1	0.6	350	210	644.00	1196.00	Non
M2	0.5	350	175	656.25	1218.75	Non
M3	0.4	350	140	668.50	1241.50	With Super plasticizer
	Mix M2 was taken as reference					

Table 2 : Compressive and Tensile Strength

Mix Type	Curing Time (days)	Average Compressive Strength (N/mm^2)	Average Tensile Strength (N/mm^2)
M1	**7**	**12.89**	**2.54**
	28	**16.44**	**2.83**
M2	**7**	**21.93**	**2.54**
	28	**27.92**	**2.78**
M3	**7**	**31.26**	**2.92**
	28	**38.35**	**3.68**

Table 3: Analytical Results of Stresses in X Direction for Specimens of Smooth Surface (SS)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	**M2**	**M3**	**M1**	**M2**	**M3**	**M1**	**M2**	**M3**
0	-0.3624	-0.4302	-0.4811	**0.0697**	**0.0864**	**0.1007**	-0.4750	-0.5851	-0.6634
25	-0.0898	-0.1320	-0.1648	0.0573	0.0712	0.0818	-0.1296	-0.2637	-0.3599
50	0.0291	0.0258	0.0228	0.0446	0.0559	0.0642	0.0697	0.0629	0.0591
75	**0.0398**	**0.0502**	**0.0580**	0.0397	0.0502	0.0580	**0.0697**	**0.0864**	**0.1007**
100	0.0210	0.0264	0.0307	0.0402	0.0502	0.0576	0.0438	0.0541	0.0635
125	-0.0181	-0.0214	-0.0241	0.0479	0.0580	0.0654	0.0028	0.0071	0.0111
150	-0.0557	-0.0826	-0.1058	0.0697	0.0864	0.1007	-0.0602	-0.0928	-0.1197

Table 4: Analytical Results of Stresses in X Direction for Specimens of Horizontal Roughening Surface (HR)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-0.6900	-1.2000	-1.1520	**0.3200**	0.3900	0.2640	-0.3800	-0.2600	0.0800
25	0.0300	-0.0070	-0.1680	0.0700	0.2900	0.2300	**0.0600**	-0.0500	0.1300
50	0.3500	**0.5300**	**0.6360**	0.0290	0.2200	0.2200	0.0100	**0.3900**	**0.2250**
75	**0.4000**	0.2200	0.0300	0.0300	0.2200	0.2236	0.0090	0.2100	0.1300
100	-0.5000	-0.5820	-0.5330	0.0800	0.2900	0.2310	0.0500	-0.0700	0.1400
125	-0.5000	-0.6200	-0.8000	0.1900	0.3900	0.2640	0.0400	-0.0580	-0.0500
150	-0.6000	-0.6300	-0.8500	0.2000	**0.4000**	**0.2800**	-0.2600	-0.0582	-1.3900

Table 5: Analytical Results of Stresses in X Direction for Specimens of Vertical Roughening Surface (VR)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	**0.4904**	**0.6500**	**0.8570**	0.4000	0.2980	0.0790	-0.1500	0.3000	**1.3230**
25	0.3500	0.4000	0.5500	0.1700	0.1400	0.0300	-0.0040	1.2500	-0.0270
50	0.1800	0.2515	0.3500	0.0800	0.0600	0.0360	**1.5000**	0.2900	0.0080
75	0.0640	0.2069	0.3700	0.3400	0.2400	0.1250	0.2570	0.0400	0.0030
100	0.1250	0.1890	0.4200	0.3110	0.2400	0.1180	-0.0170	1.8300	-0.4900
125	0.1120	0.1250	0.2500	0.4500	0.3700	0.2020	-0.0080	2.0700	-0.6000
150	-0.1000	-0.1200	-0.2100	**0.7000**	**0.6000**	**0.4150**	0.0000	**2.5000**	0.0000

Table 6: Analytical Results of Stresses in X Direction for Specimens of Grid Roughening Surface (GR)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-0.2162	-0.3190	-0.4240	0.0700	0.1220	0.0700	**0.4800**	0.2800	**0.4800**
25	0.5702	0.7800	0.8500	0.0200	0.0260	0.0300	0.4500	0.2000	-0.1070
50	0.9900	1.1240	1.2500	0.0020	0.0270	0.0830	0.0700	0.1220	0.0700
75	**1.2000**	**1.2700**	**1.3600**	0.0880	0.1200	0.0870	0.1000	0.0600	0.0400
100	1.1600	1.2500	1.3200	0.1200	0.1250	**0.2000**	-0.7900	**0.3900**	-0.9000
125	0.6200	0.7800	0.9500	0.1400	0.1590	0.1240	-0.0970	-0.8000	-0.8900
150	-1.0620	-1.1520	-1.2420	**0.2000**	**0.1800**	0.1900	0.0000	0.0000	0.0000

Table 7: Analytical Results of Stresses in X Direction for Specimens Coated With Adibond (AB)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-1.0068	-1.1734	-1.2955	**0.1937**	**0.2359**	**0.2713**	-1.3196	-1.5958	-1.7862
25	-0.2497	-0.3601	-0.4438	0.1594	0.1943	0.2204	-0.3600	-0.7193	-0.9692
50	0.0808	0.0705	0.0614	0.1240	0.1525	0.1729	0.1938	0.1718	0.1593
75	**0.1105**	**0.1370**	**0.1562**	0.1105	0.1370	0.1562	**0.1937**	**0.2359**	**0.2713**
100	0.0585	0.0721	0.0827	0.1118	0.1370	0.1552	0.1217	0.1476	0.1710
125	-0.0503	-0.0586	-0.0649	0.1332	0.1583	0.1761	0.0080	0.0195	0.0300
150	-0.1547	-0.2254	-0.2849	0.1937	0.2359	0.2713	-0.1675	-0.2531	-0.3223

Table 8: Analytical Results of Stresses in X Direction for Specimens Coated With Epoxy (EP)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-1.9956	-2.7270	-3.5931	**0.3864**	**0.6669**	**0.7020**	-3.8775	-5.7623	-7.5849
25	-0.4514	-0.8203	-1.1287	0.3540	0.6612	0.7006	-0.9737	-2.8541	-3.0624
50	0.1688	**0.3979**	0.1645	0.2561	0.4667	0.4939	0.3203	**0.8475**	0.5176
75	**0.2060**	0.3103	**0.3744**	0.2060	0.3103	0.3744	**0.3864**	0.6669	**0.7020**
100	0.1088	0.1400	0.2083	0.2330	0.3983	0.4710	0.2416	0.3599	0.4681
125	-0.1067	-0.1681	-0.1997	0.2905	0.5634	0.5550	0.0124	0.0272	0.0725
150	-0.3087	-0.5231	-0.8030	0.3864	0.6669	0.7020	-0.3343	-0.5912	-0.9125

Table 9: Analytical Results of Stresses in X Direction for Specimens Anchored with Mild Steel Bar of 10 mm diam. (SC1)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-2.3577	-2.8470	-3.4530	**0.4300**	**0.5193**	**0.6297**	-3.8852	-4.6920	-5.6900
25	**0.1643**	**0.1984**	**0.2406**	0.2901	0.3503	0.4240	-1.2626	0.1005	0.1210
50	0.1077	0.1301	0.1577	0.2205	0.2660	0.3220	-0.0636	0.3413	0.4140
75	0.0073	0.0080	0.1228	0.0073	0.0088	0.1228	**0.3364**	**0.5192**	**0.6290**
100	0.0705	0.0851	0.1032	0.2204	0.2660	0.3220	0.1756	0.2827	0.3420
125	-0.1364	-0.1640	-0.1900	0.2901	0.3503	0.4240	-0.0304	-0.0469	-0.0569
150	-0.3861	-0.4660	-0.5650	0.4300	0.5190	0.6297	-0.4579	-0.5529	-0.6706

Table 10: Analytical Results of Stresses in X Direction for Specimens Anchored with High Grade Steel Bar of 10 mm diam. (SC2)

Points	X1 (N/mm^2)			X2 (N/mm^2)			X3 (N/mm^2)		
	M1	M2	M3	M1	M2	M3	M1	M2	M3
0	-2.6700	-4.0085	-4.0085	**0.4870**	**0.7310**	**0.7310**	-4.4010	-6.6050	-6.6050
25	**0.1860**	**0.2790**	**0.2790**	0.3280	0.4932	0.4932	0.0942	-2.1460	-2.1460
50	0.1220	0.1831	0.1831	0.2490	0.3748	0.3748	0.3202	-0.1081	-0.1081
75	0.0080	0.0120	0.1020	0.0080	0.0124	0.0124	**0.4871**	**0.5719**	**0.5719**
100	0.0798	0.1198	0.1198	0.2490	0.3740	0.3740	0.2652	0.2980	0.2980
125	-0.1544	-0.2318	-0.2318	0.3280	0.4932	0.4932	-0.0441	-0.0516	-0.0516
150	-0.4370	-0.6560	-0.6560	0.4870	0.7310	0.7310	-0.5180	-0.7784	-0.7784

Table 11: Ultimate Load of Indirect Tension Test (KN)

Mix	Relative tensile strength (f_{ti}/f_{t2})	Surface condition							
	f_{t2}/f_{ti}	SS	AB	EP	HR	VR	GR	SC1	SC2
M1/M2	1.07	4.50	12.50	50.00	17.50	18.45	45.00	23.35	26.45
M2/M2	1.00	5.50	15.00	75.00	20.00	26.25	57.50	28.20	39.70
M3/M2	0.93	6.50	17.50	90.00	22.50	29.10	62.50	34.20	39.65

Table 12 : Nominated Tensile Bond Strength of Different Interfacial Bonding Conditions (N/mm^2)

Mix	Relative Tensile Strength (f_{ti}/f_{t2})	Surface Condition							
	f_{t2}/f_{ti}	SS	AB	EP	HR	VR	GR	SC1	SC2
M1/M2	1.07	0.13	0.35	1.231	0.50	0.52	1.27	0.66	0.75
M2/M2	1.00	0.16	0.42	1.482	0.57	0.74	1.63	0.80	1.12
M3/M2	0.93	0.18	0.50	1.590	0.64	0.82	1.77	0.97	1.12

Table 13: Comparison between Theoretical and Experimental Stresses in X Direction for SS, HR, VR and GR Conditions.

Specimen	SS			HR			VR			GR		
	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp
M1/M2	0.130	0.039	0.300	0.500	0.400	0.808	0.520	0.490	0.939	1.270	1.200	0.942
M2/M2	0.160	0.0502	0.310	0.570	0.530	0.936	0.740	0.650	0.875	1.630	1.270	0.781
M3/M2	0.180	0.058	0.320	0.640	0.630	0.989	0.820	0.850	1.032	1.770	1.360	0.769

Table 14: Comparison between Theoretical and Experimental Stresses in X Direction for AB, EP, SC1 and SC2 Conditions.

Specimen	AB			EP			SC1			SC2		
	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp	Exp.	Theo.	Theo./Exp
M1/M2	0.35	0.2100	0.5936	1.231	1.2060	0.9797	0.66	0.4700	0.7113	0.75	0.6500	0.8684
M2/M2	0.42	0.3100	0.7303	1.482	1.3100	0.8839	0.80	0.6800	0.8521	1.12	0.9700	0.8634
M3/M2	0.50	0.4156	0.8392	1.590	1.4744	0.9273	0.97	0.7220	0.7460	1.12	1.0900	0.9714

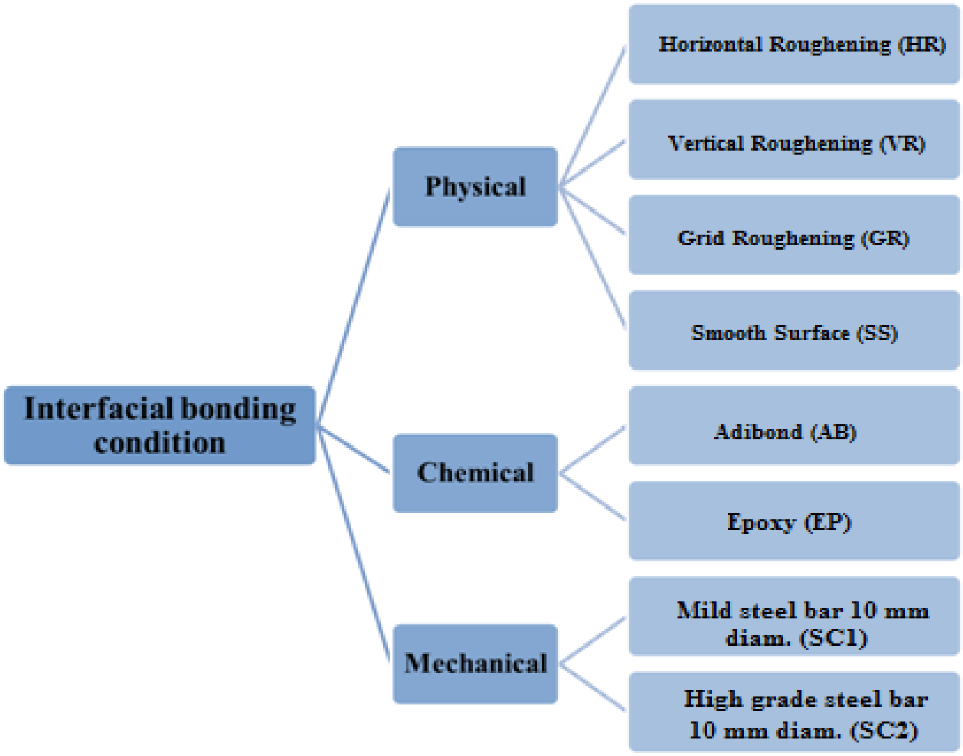


Figure 1: Interfacial bonding condition

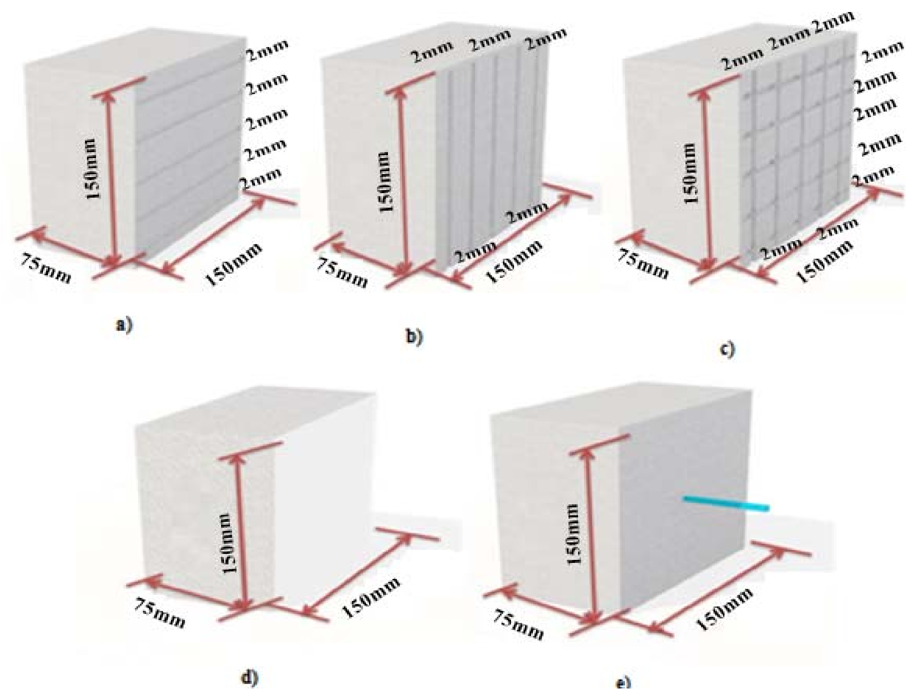
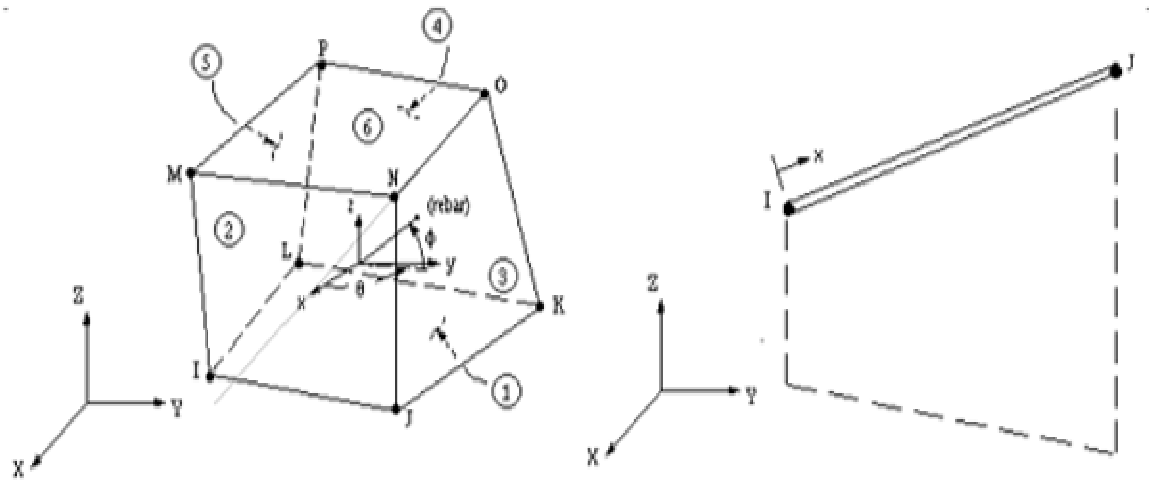
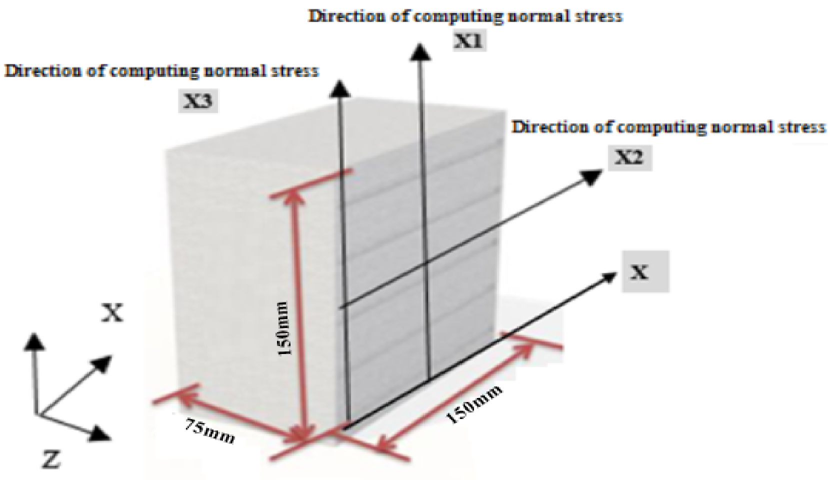


Figure 2: Details of surface condition of old concrete; a) (HR); b) (VR); c) (GR); d) (SS&AB&EP); e) (SC1& SC2).



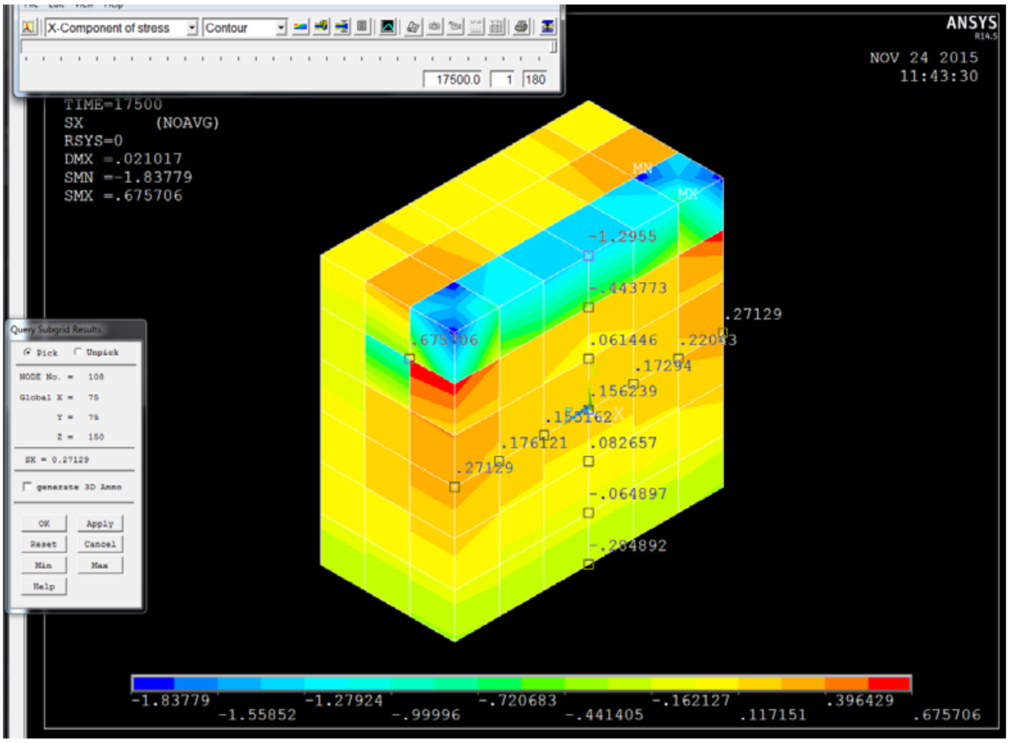
a) Solid 65 b) Link 8

Figure 3: Geometry and Node Locations for Element Types

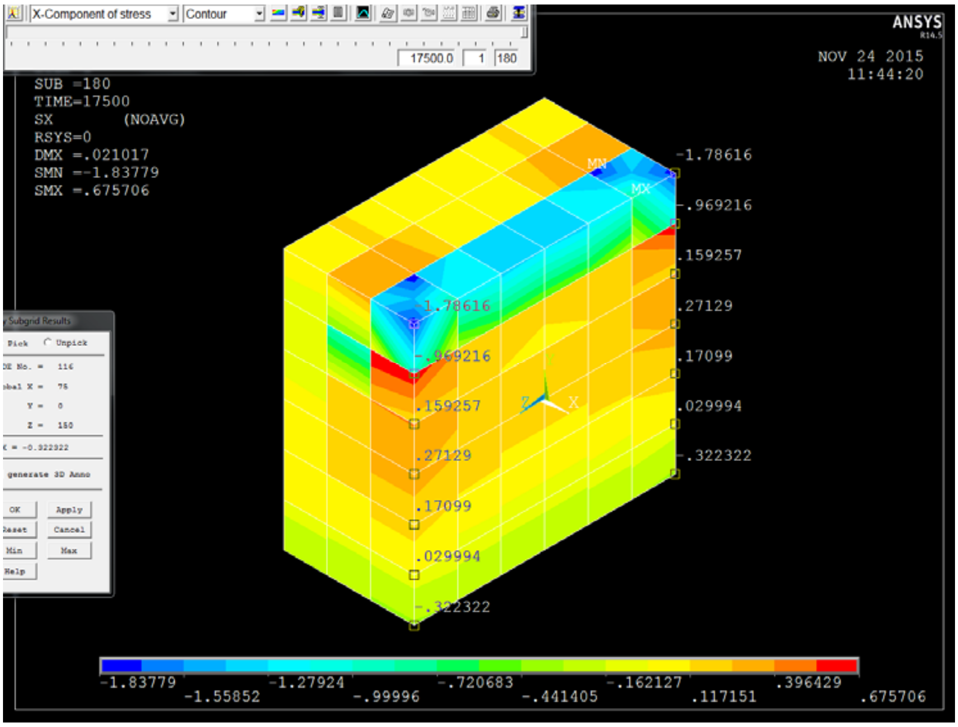


- X1: Normal stress induced along the vertical axis passing the centroid of the specimen.
- X2: Normal stress induced along the horizontal axis passing the centroid of the specimen.
- X3: Normal stress induced along the vertical axis passing the edge of the specimen.

Figure 4: Location of computed normal streeses X1, X2, and X3 of the tested specimens

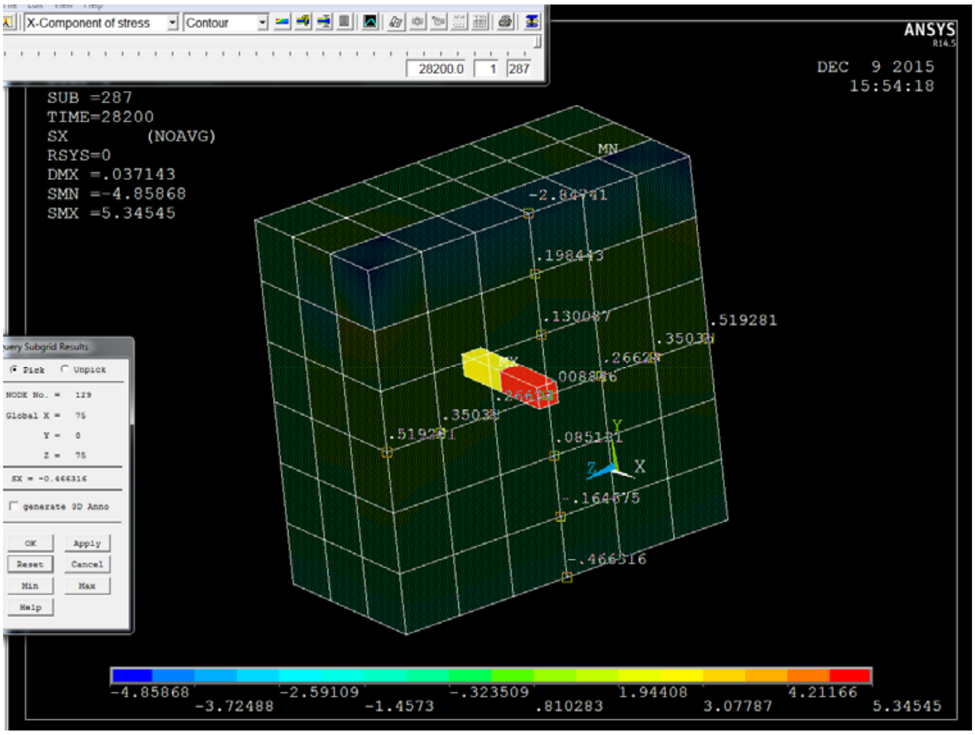


a)

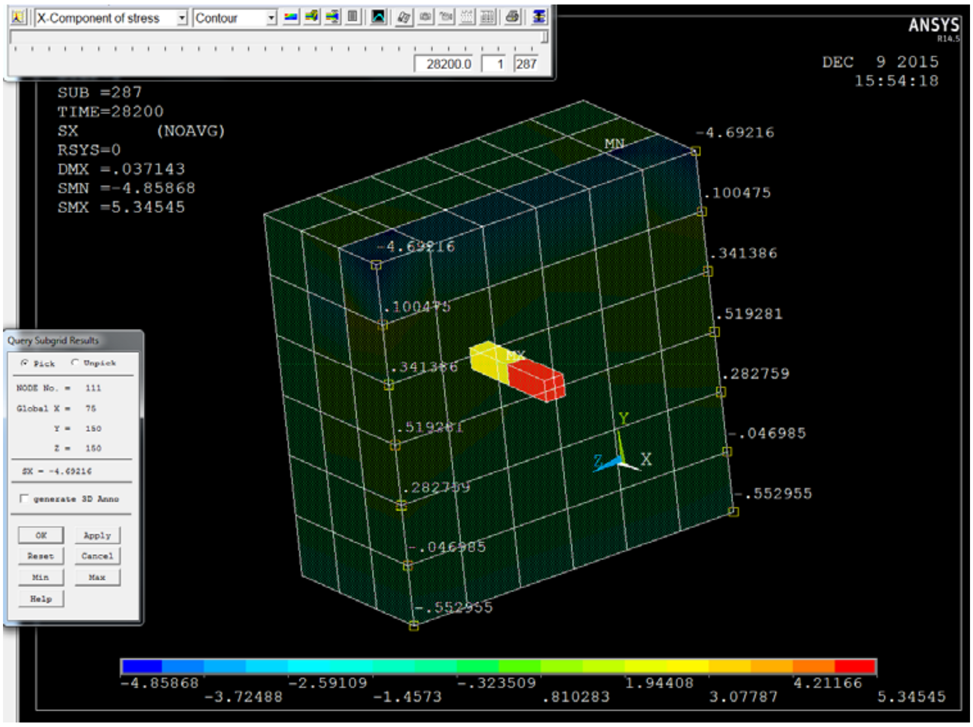


b)

Figure 5: Normal stress: a) X1 and X2; b) X2 for the case of specimens coated with Adibond coat **AB**

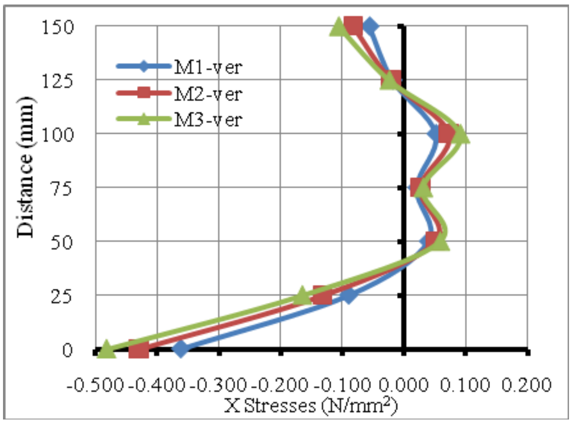


a)

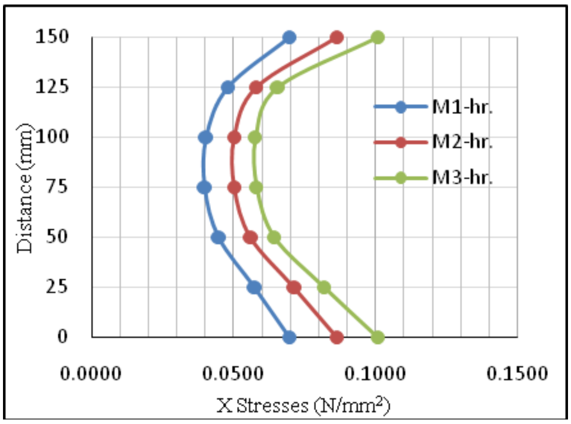


b)

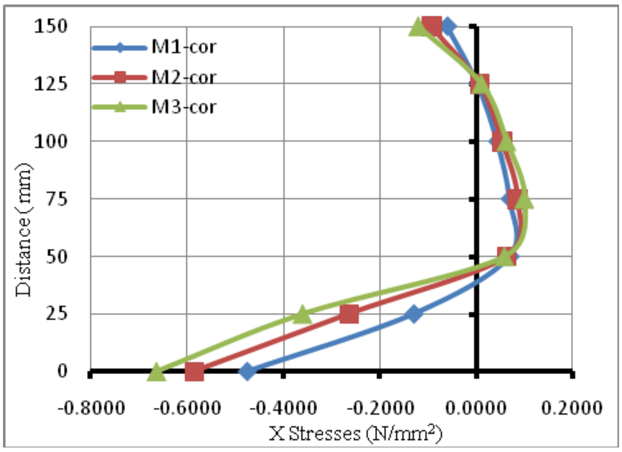
Figure 6: Normal stress: a) X1; X2 b) X3 for the case of specimens anchored with mild steel bar **SC1**



a) X1

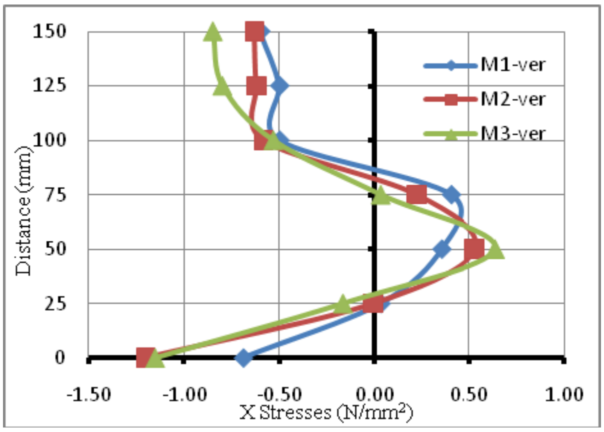


b) X2

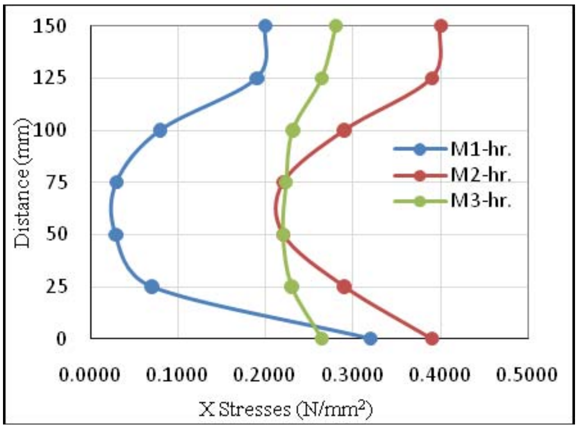


c) X3

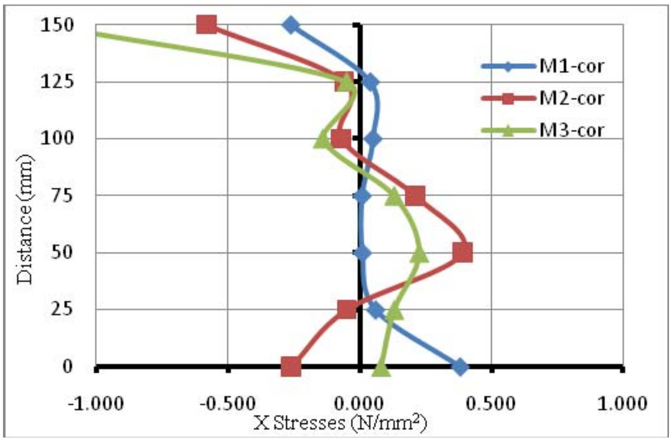
Figure 7: Normal stresses induced in specimens of Smooth Surface (SS); a) X1; b) X2; c) X3.



a) X1

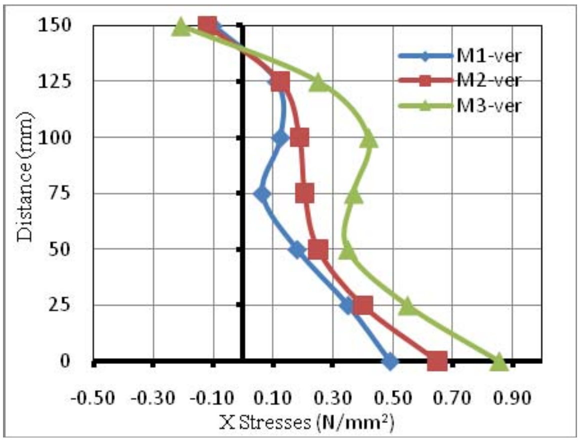


b) X2

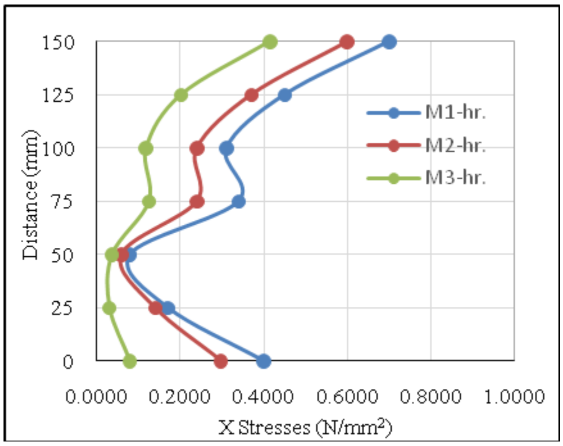


c) X3

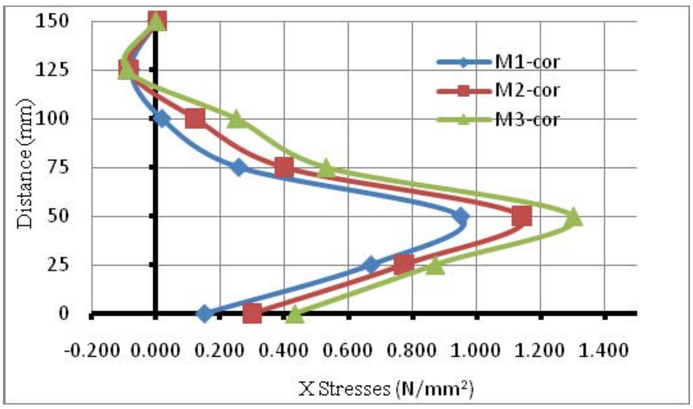
Figure 8: Normal stresses induced in specimens of Horizontal Roughening (HR); a) X1; b) X2; c) X3.



a) X1

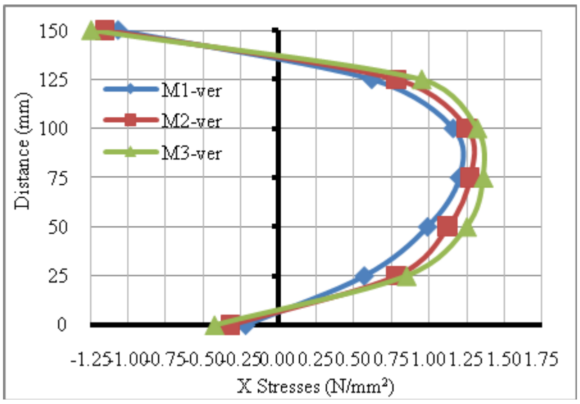


b) X2

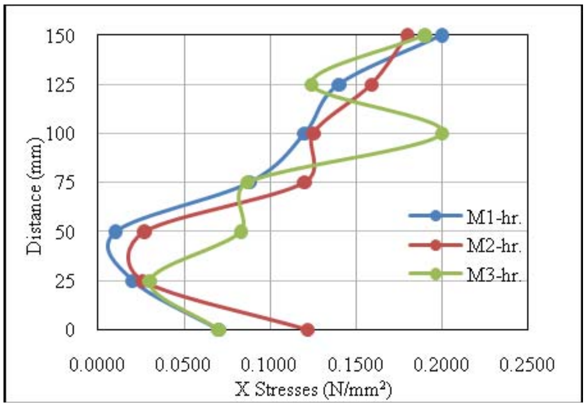


c) X3

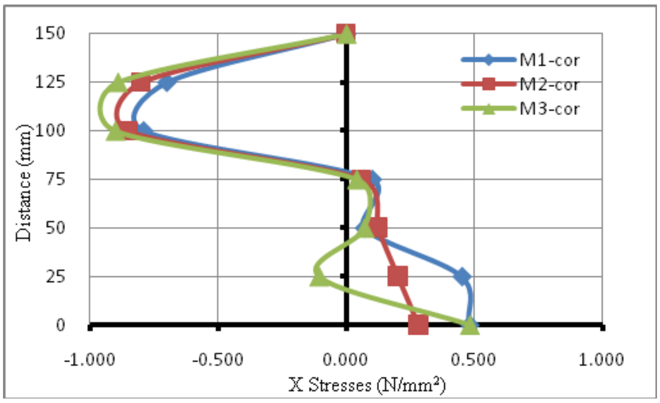
Figure 9: Normal stresses induced in specimens of Vertical Roughening (VR); a) X1; b) X2; c) X3.



a) X1

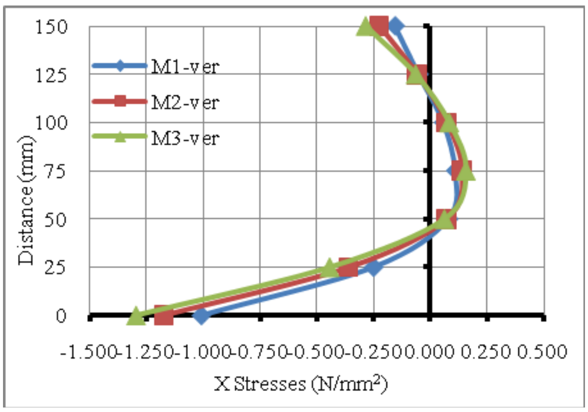


b) X2

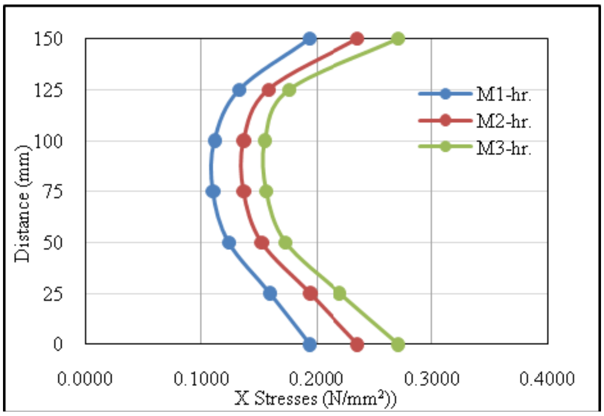


c) X3

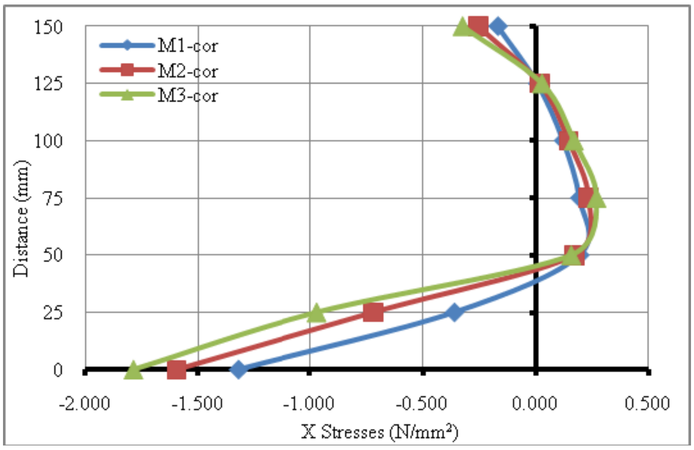
Figure 10: Normal stresses induced in specimens of Grid Roughening (GR); a) X1; b) X2; c) X3.



a) X1

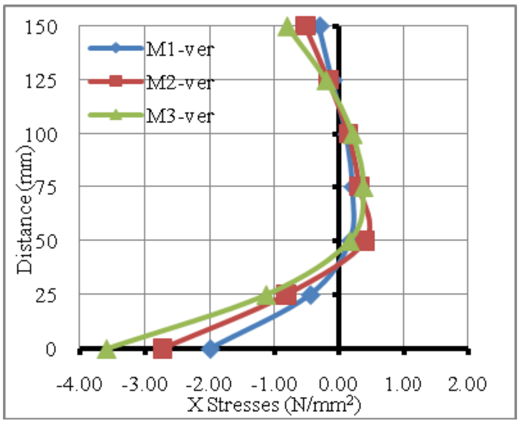


b) X2

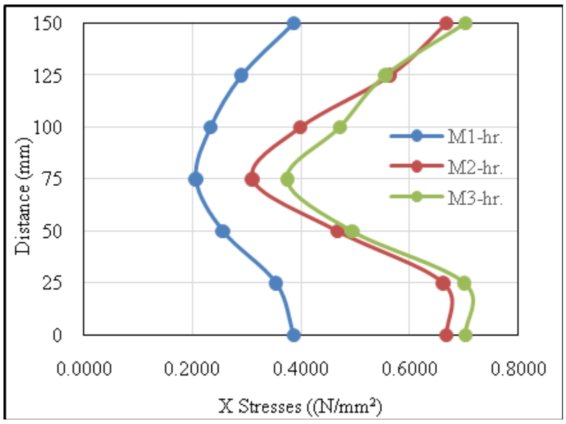


c) X3

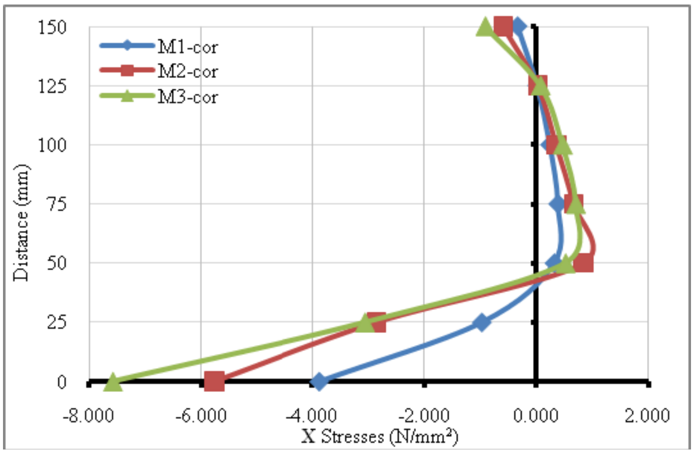
Figure 11: Normal stresses induced in specimens coated with Adibond coat (AB); a) X1; b) X2; c) X3.



a) X1

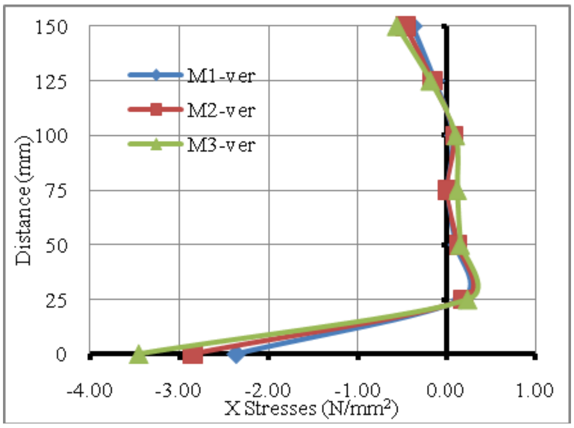


b) X2

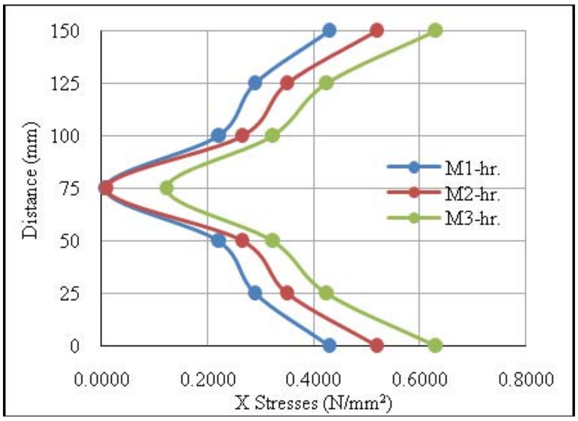


c) X3

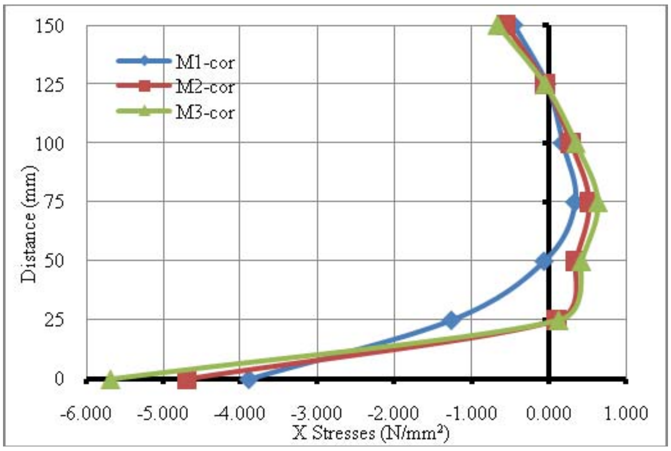
Figure 12: Normal stresses induced in specimens coated with Epoxy coat (EP); a) X1; b) X2; c) X3.



a) X1

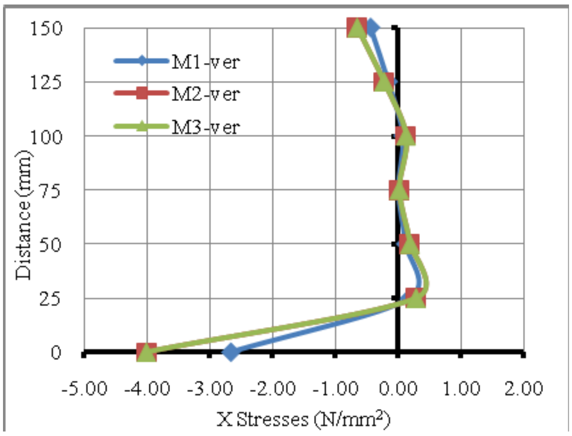


b) X2

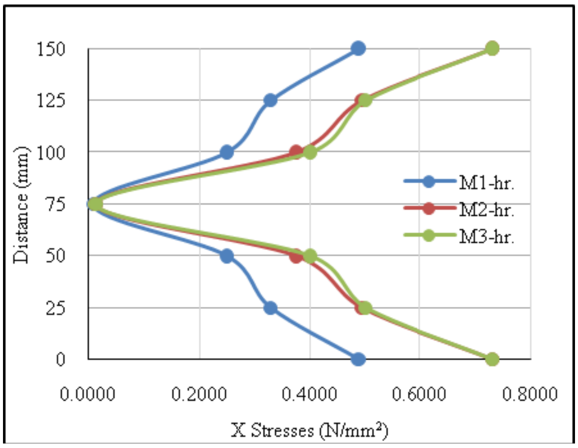


c) X3

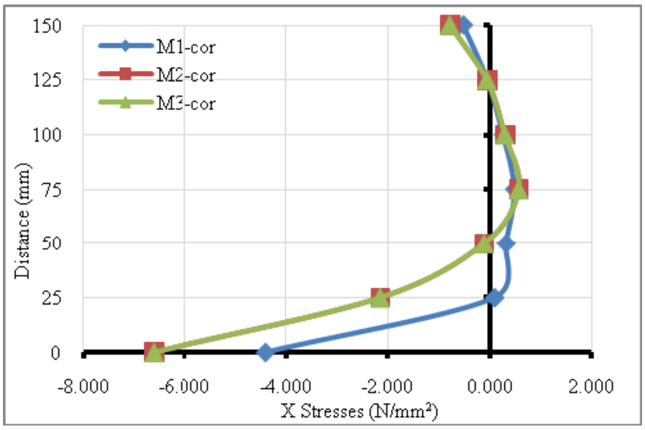
Figure 13: Normal stresses induced in specimens anchored with mild steel bar (SC1); a) X1; b) X2; c) X3.



a) X1



b) X2



c) X3

Figure 14: Normal stresses induced in specimens anchored with high steel bar (SC2); a) X1; b) X2; c) X3.

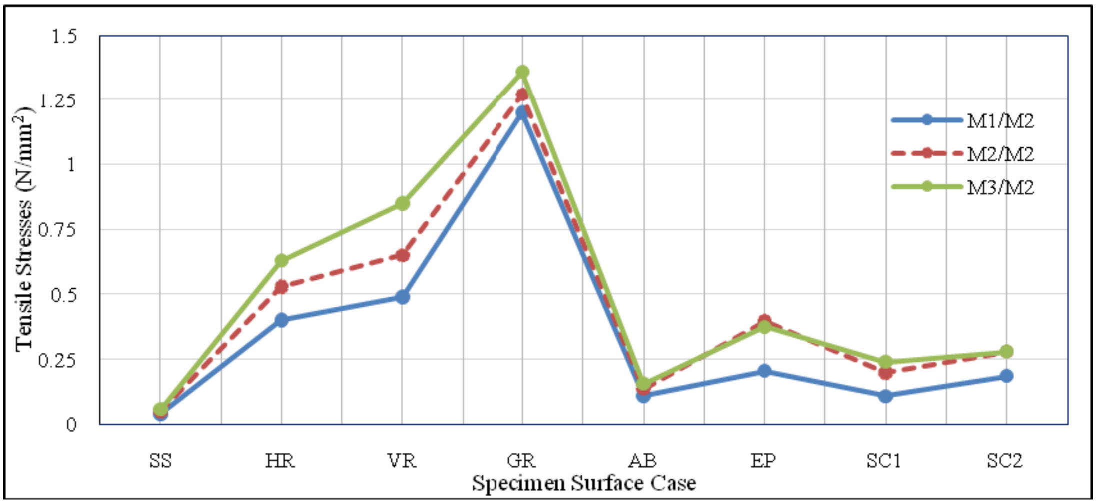


Figure 15: Theoretical tensile bond strength of different concrete mixes.

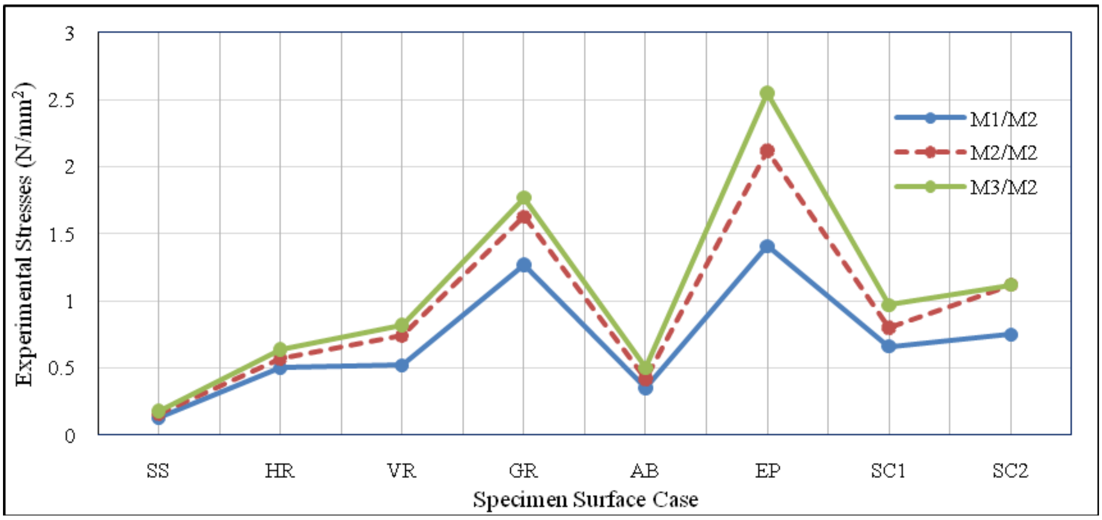


Figure 16: Experimental tensile bond strength of different concrete mixes

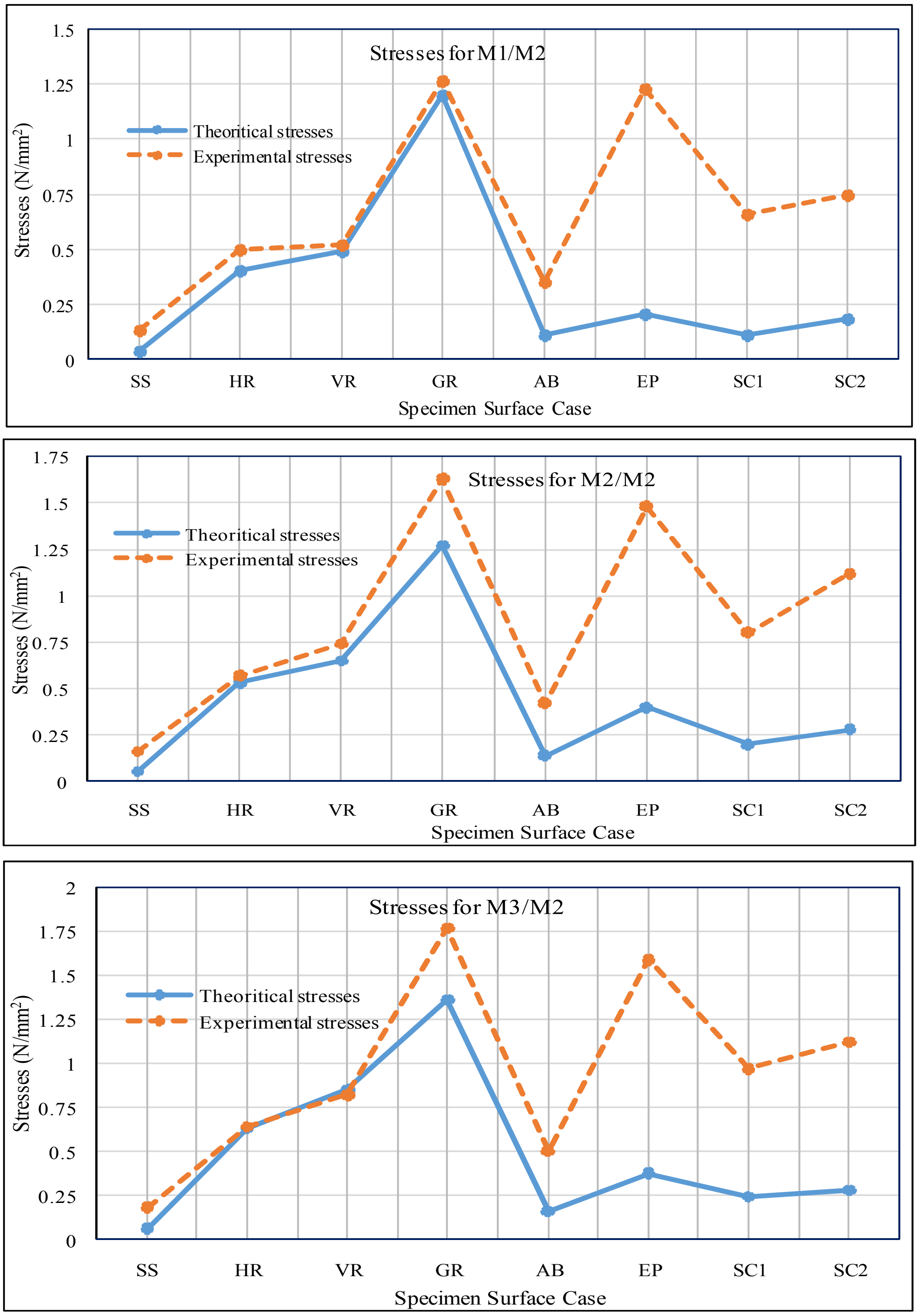


Figure 17: Comparison between experimental and theoretical tensile bond strength of different concrete mixes; a) M1/M2; b) M2/M2; c) M3/M2.

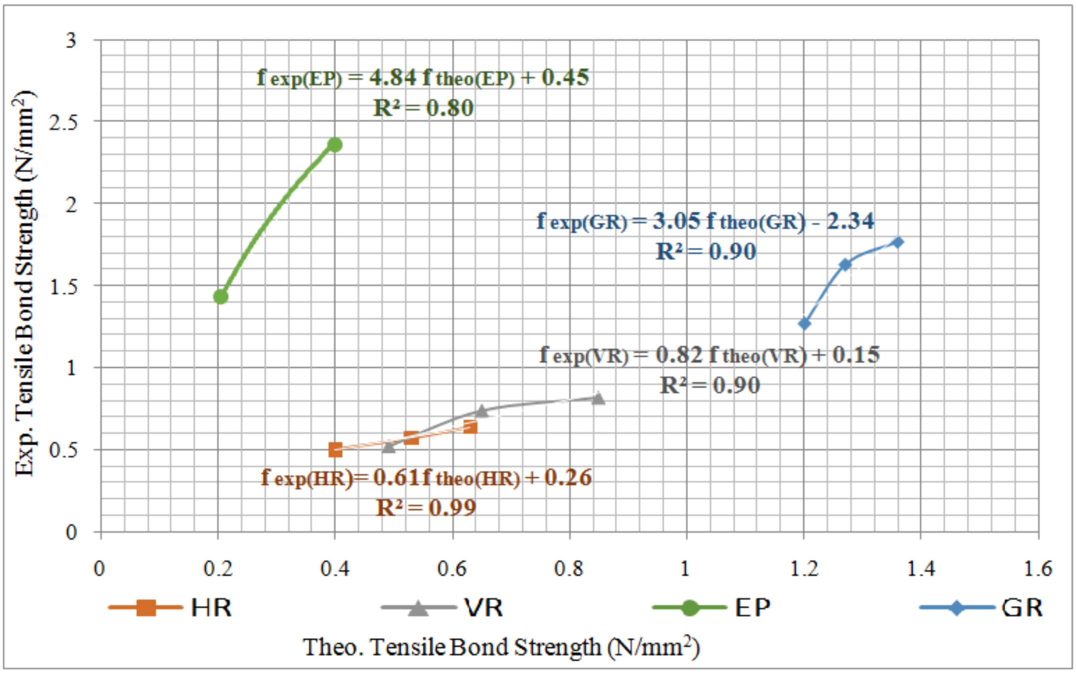


Figure 18: Experimental and theoretical tensile bond strength for the cases HR, VR, GR, and EP.

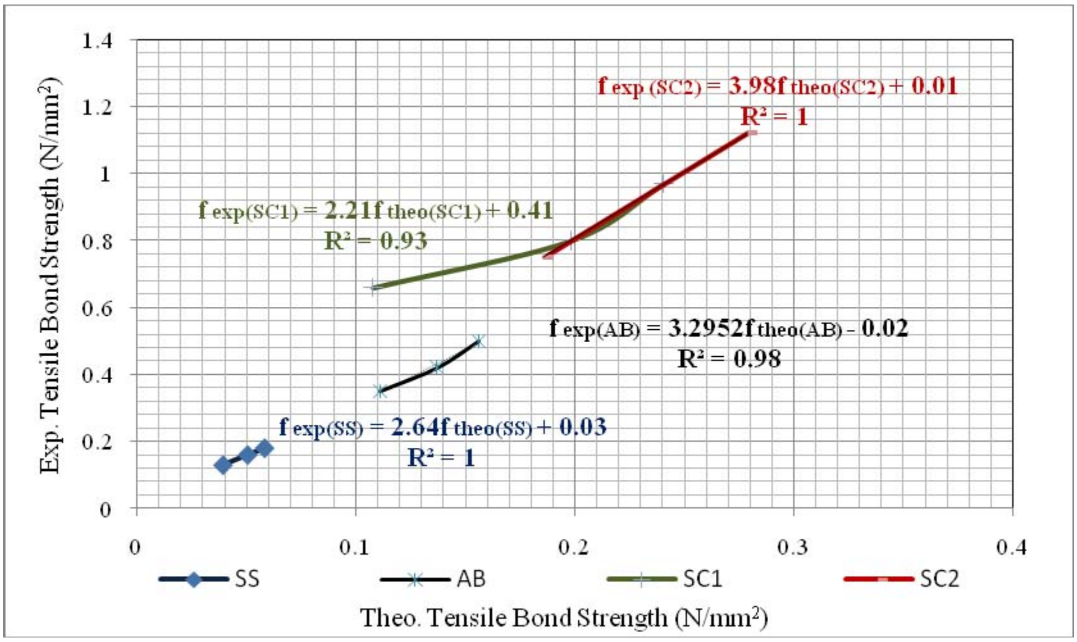


Figure 19: Experimental and theoretical tensile bond strength for the cases SS, AB, SC1 and SC2.