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EVALUATION OF SHEAR BOND STRENGTH OF A MULTILAYER CONCRETE SYSTEM: EXPERIMENTAL AND ANALYTICAL STUDY

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ABSTRACT

The importance of the bond strength of a multilayer concrete system is increased with the increase of the use of the advanced composite materials of different bases 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 commonly used techniques to prepare the interfacial bonding surface and the relative strength of the concrete system are considered of the dominant factors that govern the structural behaviour of the concrete system. Therefore, it was the motivation of the author to examine the influence of those two factors on the shear bond strength resulted from implementing the slant shear test.

The results of the presented research work show the role of the direction of roughening the surface and the mechanical bonding on the shear bond strength. A simplified and reliable formula was presented to predict the shear bond strength in terms of the surface condition and the relative strength value.

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Key words: Bond Strength, Shear Strength, Multilayer System, Surface Roughness, Adhesive Coat, Steel Connectors, Cohesion, Friction, And Bearing.

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1. INTRODUCTION

The bond strength of a multilayer concrete system plays an important role in the structural behaviour of the concrete members specifically when they are subjected to repair or strengthening [1,2]. Using the advanced composite materials of different bases in the retrofitting of the concrete adds more difficulties to analysis of the multilayer system [3]. The bond strength at the interface was found to be related to several parameters such as the concrete strength, curing time and technique, the surface conditions, the technique of initiating the interfacial bond, the testing methods, the type of the applying load, the load development and history, and the method of evaluation of the nominated bond strength [4,5].

The slant shear test is considered one of the important test methods that is commonly used to predict the shear bond strength of a concrete system [6,7]. In fact several disadvantages were recorded in many research works regarding the using of the slant shear test [8]. These disadvantages were related to the pattern of the induced stresses and the test result is significantly depending on the angle of inclination of the interface [9,10]. It was also reported that the shear bond strength was insensitive to the surface preparation [11]. However, the authors believed that more investigation should be implemented regarding this point. Also, the existence of shear and compressive stresses at the plane of failure can simulate the actual structural behaviour of compression elements in the field.

2. OBJECTIVES

1. Verification of the role of the most commonly used techniques of improving the bond at the interface between old and new concrete layers.
2. Verification of the role of the relative compressive strength of the multilayer concrete on the composite behavior in terms of the shear bond strength.
3. Providing a reliable and simple formula that can express the most probable shear bond strength based on the formula provided in the Euro code 2.

3. EXPERIMENTAL PROGRAM

Table 1 shows the contents of the three concrete mixes that have been used as a repair mix. A preliminary testing program was carried out to specify the compressive and tensile strength of the concrete mixes M1, M2, and M3 and the results were presented in Tables 2 and 3. Mix M1 of w/c=0.6 represents a repair mix of weaker mechanical properties when it is compared with properties of the repaired concrete with w/c=0.5. On the other hand, using the repair mix M3 of w/c=0.4 with super plasticizer represents the case of repair the concrete with a relatively higher strength repair mix. The conducted preliminary testing program was implemented on 36 cube specimens to evaluate the compressive and tensile strength.

Chart 1 illustrates the scheme of the experimental program where (8) different cases of interfacial bonding conditions have been considered to examine the influence of using the physical, the chemical, and the mechanical bond on the shear bond strength of the concrete. The experimental program was implemented using (24) specimens for each mix and (72) specimens for the three repairing mix M1, M2, and M3. Photo1 shows the tested specimens which have been used to examine the physical bond at the interface where the cases of smooth surface SS, parallel roughening PR, normal roughening NR, and grid roughening GR were considered. Photo 2 shows the specimens that have been used to examine the shear bond strength in the case of mechanical bond where mild and high grade steel bars of 10mm diameter were used SC1 and SC2. For the case of chemical bond, water-base material (Adibond-AB) and non-water-base material (Epoxy-EP) were used as a bonding coat at the interface.

Photo 3 shows the form of the tested specimens. The repaired concrete specimens were casted on top of the wooden forms to have the designed shape. After 24 hours from casting, they were cured in water for 28 days. The new concrete layer was poured on top of the old concrete after preparing the interface of the old concrete. The adibond AB was coated on a wet surface while the epoxy EP was coated on a dry surface. Roughening the surface was based on creating grooves of 3mm x 3mm x 120mm width, depth, and length. To avoid damaging the specimen, a distance of 15mm was left from each side of the interface as illustrated in photo 1. The final specimens of the slant shear test were removed from the mould after 24 hours and then they were cured in water for 28 days before testing them in the compression testing machine. Tables 2 and 3 show the compressive and tensile strength test results of the mixes.

4. RESULTS AND ANALYSIS OF THE EXPERIMENTAL STUDY

Computation of the shear bond strength was based on the illustrated mechanism of failure of the slant shear specimens under the compression load. Three different modes of failure were observed. For the cases of smooth surface SS, coating the interface with Adibond AB and, epoxy EP, and the parallel roughening PR, failure at the interface was observed due to the induced shear stress at the plane of failure. The second mode of failure was observed for the case of normal roughening NR and GR where a combination of the shear friction at the interface and the induced shear stress in concrete due to the interlock is the main reason of bonding failure. The mechanical anchoring using steel bars led to induce shear stress at the interface between new and old concretes, shear stress in the steel bars, and shear stress at interface between the steel bar and the concrete. The mode of failure is most probably related to the slip at the aforementioned interfaces.

4.1. Influence of Surface Conditions

Table 4 shows the ultimate compression loads that have been recorded for the slant shear tested specimens. Table 5 and Figures from 1 to 3 present the nominated shear bond strength of the various types of surface bonding conditions. It is clear that the case of the smooth surface exhibited the lowest shear bond strength with respect to the other cases. For purpose of comparison, the shear bond strength of the smooth surface condition SS was taken as a reference. When using the adibond AB and Epoxy EP as a bonding coat, the nominated shear bond strength represent 1.25 and 1.64 of the reference. For the case of roughening the surface, the shear bond strength of using

NR, PR, and GR were 4.20 N/mm^2, 3.58 N/mm^2, and 5.31 N/mm^2 and represent 1.43, 1.22, and 1.81 of the reference. The mechanical bonding of cases SC1 and SC2 exhibited the highest values of shear bond strength when compared to the other cases. The shear bond strength of the mechanical bond SC1 and SC2 were 8.46N/mm^2 and 11.16N/mm^2 and represent 3.59, and 9.64 of the reference. Similar trends were shown when considering the results of the other mixes M2 and M3. The observed modes of failure for all tested specimens were due to bond failure. Table 6 and Figure 4 show the relative shear bond strength when taking the smooth surface condition SS as a reference.

The mechanisms of load transfer at the interface between old and new concretes are mainly related to the cohesion, the friction, and the steel connectors. It is believed that cohesion failure is occurred at the early age as it depends mainly on the tensile strength of the concrete and the tensile bond strength at the interface. On the other hand, failure due to friction is mainly depending on the shear bond strength i.e. the surface conditions and the shear strength of the concrete. Roughening the surface also induces bearing blocks which significantly increases the resistance of the multilayer system to fail. Using steel connectors enhances dramatically the behaviour of the multilayer system i.e. the composite behaviour and consequently, the load carrying capacity of the concrete.

4.2. Influence of Relative Rigidity of the Mix (RS)

Table 7 and Figure 5 show the effect of the relative rigidity of the mixes (Mi/M2) on the shear bond strength. The shear bond strength was significantly increased when the relative rigidity RS $\geq$ 1 if it is compared with the case of RS < 1. In case of smooth surface SS, the shear bond strength values of M2/M2, and M3/M2 were 4.39 N/ mm^2 and 5.22 N/ mm^2 while it was 2.93 N/ mm^2 for the case of M1/M2. For the case of the smooth surface SS, the relative shear bond strength of M1/M2, M2/M2, and M3/M2 was 0.87, 1.00, and 1.19. In case of physical bond, the shear bond strength of the normal roughening NR was 8.61 N/ mm^2 and 10.73 N/ mm^2 for the case of M2/M2 and M3/M2.The relative shear bond strength of M1/M2, M2/M2, and M3/M2 was 0.50, 1.00 and 1.25. For the case of parallel roughening PR, the relative shear bond strength of the relative stiffness M1/M2, M2/M2, and M3/M2 was 0.52, 1.00, and 1.42. For the case of grid roughening GR, the relative shear bond strength was 0.67, 1.00, and 1.41 for the case of M1/M2, M2/M2 and M3/M2. The relative shear bond strength of using mechanical bonding with mild steel bars was 0.97, 1.00, and 1.20 while it was 0.97, 1.00, and 1.17 for the case of relative stiffness M1/M2, M2/M2, and M3/M2.

The results in Table 7 show the negative impact of using relatively weak concrete to repair stronger concrete. As shown in Table 7, the composite concrete of relative stiffness M1/M2 exhibited relative strength values ranged from 0.49 up to 0.97. On the other hand, when the relative stiffness RS≥1, the relative shear bond strength ranged from 1.07 up to 1.42. The second observation was related to the significant impact of using the steel connectors to bond relatively weak concrete stronger one. Using the steel connectors increases the relative shear bond strength from about 0.49 up to 0.97 depending on the surface conditions under consideration. The third observation shows that using the mechanical bond in terms of steel bars was slightly affected by the relative stiffness of the concrete Mi/M2 while the physical and chemical bond was significantly affected by the RS value. Figure 8 concluded the influence of the compressive strength of the repairing mix M1, M2, and M3 on the shear bond strength according to the interface condition.

5. ANALYTICAL STUDY

The analytical model was based on the mathematical models developed by the Euro code 2, 2004 [2] as given below:

$V_u = C*f_{ctd} + \mu*\sigma_n + \rho*f_y (\mu \sin\alpha + \cos\alpha)$ Equation 1

The coefficients of cohesion and friction were proposed as follows:

$C = 1.062 Rvm^{0.145} / \gamma_{coh}$ Equation 2

$\mu = 1.366 Rvm^{0.041} / \gamma_{fr}$ Equation 3

Where:

V_u: Shear friction, N/mm^2

C: Coefficient of cohesion

f_{ctd}: Tensile strength of the weakest concrete , N/mm^2

μ: Coefficient of friction,

σ_n: Normal stress acting on the interface , N/mm^2

ρ: Reinforcement ratio (As/Ac)

f_y :Yield strength of the reinforcement, N/mm^2

α: Coefficient for dowel action or the angle between the shear reinforcement and shear plane

R_{vm}: Mean valley depth, mm

γ_{coh}: Partial safety factor for the coefficient of cohesion

γ_{fr}: Partial safety factor for the coefficient of friction,

The results in Table 8 and Figures from 6 to 9 show that the analytical model gave higher shear bond strength values when compared with the values that have been given from the experimental study. The experimental shear bond strength of the AB case was 3.66N/mm^2, 7.19N/mm^2, and 7.69N/mm^2 while they were 8.84N/mm^2, 14.86N/mm^2, and 15.72N/mm^2 for the case of the analytical model. The shear bond strength from the experimental study represents 0.41, 0.48, and 0.49 of the shear bond strength from the analytical study. However and as indicated in Table 9, the relative shear bond strength (q_r) ranged from 0.33 to 0.67 regardless of the mix type and the surface condition. Figure 10 proposed the experimental shear bond strength to be given from the equation:

$q_{exp} = 0.251(q_{ana})^{1.23}$

Taking into consideration that $R^2 = 0.85$.

Table 10 and Figure 11 show the relation between the relative compressive strength fc_i/fc_2 and the relative shear bond strength q_{exp}/q_{ana} for the different surface conditions. With the exception of using the adibond AB where the R^2 value was 0.81, the R^2 value ranged from 0.94 to 1.00. The simplified forms of such equations can be easily used to assess the experimental shear bond strength of the studied surface conditions which are commonly used in practice.

Table 1 : Repair 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 also used as the repaired concrete mix**					

Table 2 : Compressive strength (N/mm^2)

Mix Type	Curing Time (days)	Compressive Strength (N/mm^2)			
		Number of Specimens			Average
		1	2	3	
M1	7	12.59	12.98	13.10	12.89
	28	15.93	16.19	17.21	16.44
M2	7	21.24	21.87	22.67	21.93
	28	27.22	28.12	28.43	27.92
M3	7	30.89	31.11	31.78	31.26
	28	37.82	38.40	38.82	38.35

Table 3 : Tension strength (N/mm^2)

Mix Type	Curing time (days)	Tensile Strength (N/mm^2)			
		Number of Specimen			Average
		1	2	3	
M1	7	3.11	2.54	1.98	2.54
	28	3.11	2.83	2.54	2.83
M2	7	3.11	1.98	2.54	2.54
	28	3.39	2.26	2.68	2.78
M3	7	3.11	2.83	2.83	2.92
	28	4.24	3.68	3.11	3.68

Table 4 : Compression load from the slant shear test (KN)

Surface Condition	Comp. Strength (N/mm^2)	Repair mix type		
		M1	M2	M3
		16.44	27.93	38.36
Smooth Surface	SS	138.17	207.01	246.37
Adibond	AB	172.70	339.44	363.26
Epoxy	EP	227.22	281.71	390.24
Parallel Roughening	PR	169.20	335.71	478.30
Normal Roughening	NR	198.25	406.27	506.62
Grid Roughening	GR	250.59	477.73	673.18
Mild Steel Connector	SC1	266.11	306.30	366.65
High Grade Connector	SC2	351.20	362.05	423.80

Table 5 : Nominated shear bond strength test results (N/mm^2)

Surface Condition	Comp. Strength (N/mm^2)	Repair mix type		
		M1	M2	M3
		16.44	27.93	38.36
Smooth Surface	SS	2.93	4.39	5.22
Adibond	AB	3.66	7.19	7.69
Epoxy	EP	4.81	5.97	8.27
Parallel Roughening	PR	3.58	7.11	10.13
Normal Roughening	NR	4.20	8.61	10.73
Grid Roughening	GR	5.31	10.12	14.26
Mild Steel Connector	SC1	8.46	11.68	13.98
High Grade Connector	SC2	11.16	13.80	16.16

Table 6 : Relative shear bond strength with respect to SS condition

Surface Condition	Comp. Strength (N/mm^2)	Repair mix type		
		M1	M2	M3
		16.44	27.93	38.36
Smooth Surface	SS	1.00	1.00	1.00
Adibond	AB	1.25	1.64	1.47
Epoxy	EP	1.64	1.36	1.58
Parallel Roughening	PR	1.22	1.62	1.94
Normal Roughening	NR	1.43	1.96	2.06
Grid Roughening	GR	1.81	2.31	2.73
Mild Steel Connector	SC1	2.89	2.66	2.68
High Grade Connector	SC2	3.81	3.15	3.10

Table 7 : Relative shear bond strength with respect to the relative strength (RS)				
Surface Condition	**Comp. Strength (N/mm^2)**	**Repair mix type**		
		M1/M2	**M2/M2**	**M3/M3**
		0.59	**1.00**	**1.37**
Smooth Surface	SS	0.87	1.00	1.19
Adibond	AB	0.51	1.00	1.07
Epoxy	EP	0.49	1.00	1.39
Parallel Roughening	PR	0.52	1.00	1.42
Normal Roughening	NR	0.50	1.00	1.25
Grid Roughening	GR	0.67	1.00	1.41
Mild Steel Connector	SC1	0.97	1.00	1.20
High Grade Connector	SC2	0.97	1.00	1.17

Table 8 : Experimental and analytical shear bond strength (N/mm2)				
	Mix type	**M1**	**M2**	**M3**
Surface Condition	**fc (N/mm2)**	**16.44**	**27.93**	**38.36**
	Combination	**M1/M2**	**M2/M2**	**M3/M2**
SS	Exp	2.93	4.39	5.22
	Ana	7.6	10.08	11.5
AB	Exp	3.66	7.19	7.69
	Ana	8.84	14.86	15.72
EP	Exp	4.81	5.97	8.27
	Ana	10.82	12.78	16.70
PR	Exp	3.58	7.11	10.13
	Ana	10.98	17.89	23.8
NR	Exp	4.20	8.61	10.73
	Ana	12.19	20.81	24.98
GR	Exp	5.31	10.12	14.26
	Ana	14.37	23.78	31.88
SC1	Exp	8.46	11.68	13.98
	Ana	14	18.08	20.97
SC2	Exp	11.16	13.80	16.16
	Ana	17.96	21.91	24.27

Table 9 : Relative shear bond strength between (Experimental / Analytical) shear bond strength (q_r)

f_{cr}	0.59	1.00	1.37
SS	0.41	0.43	0.44
AB	0.41	0.48	0.49
EP	0.44	0.47	0.49
PR	0.33	0.40	0.43
NR	0.34	0.41	0.43
GR	0.37	0.43	0.45
SC1	0.60	0.65	0.67
SC2	0.62	0.63	0.67

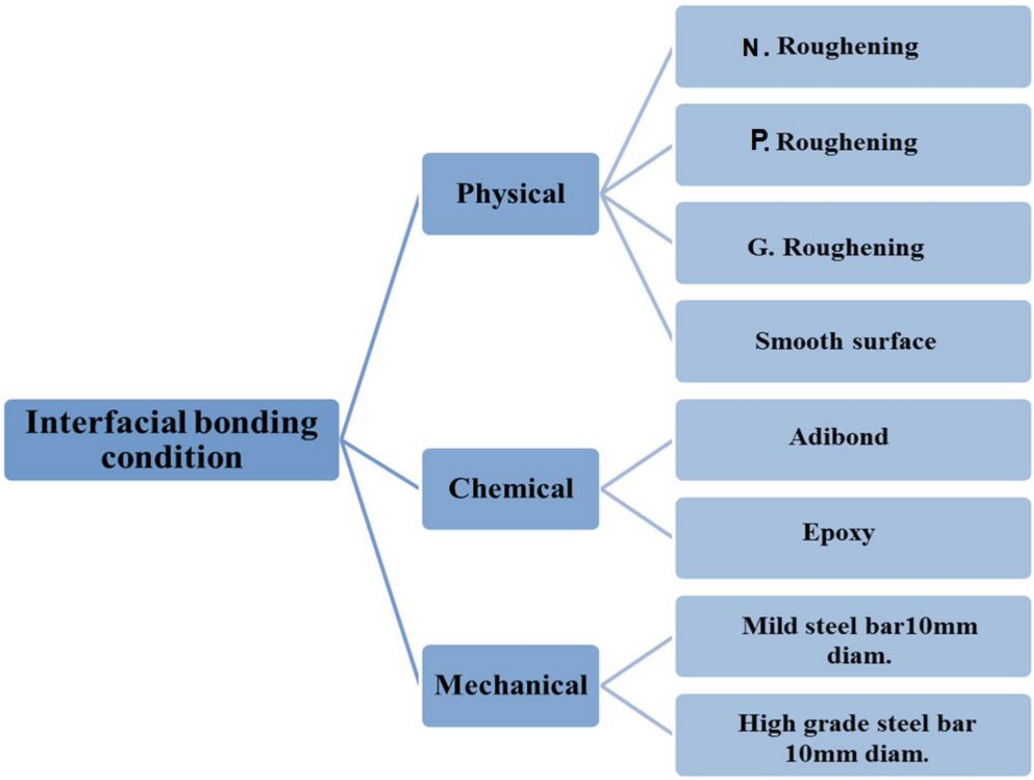


Chart [1]: Cases of creating bond at the interface

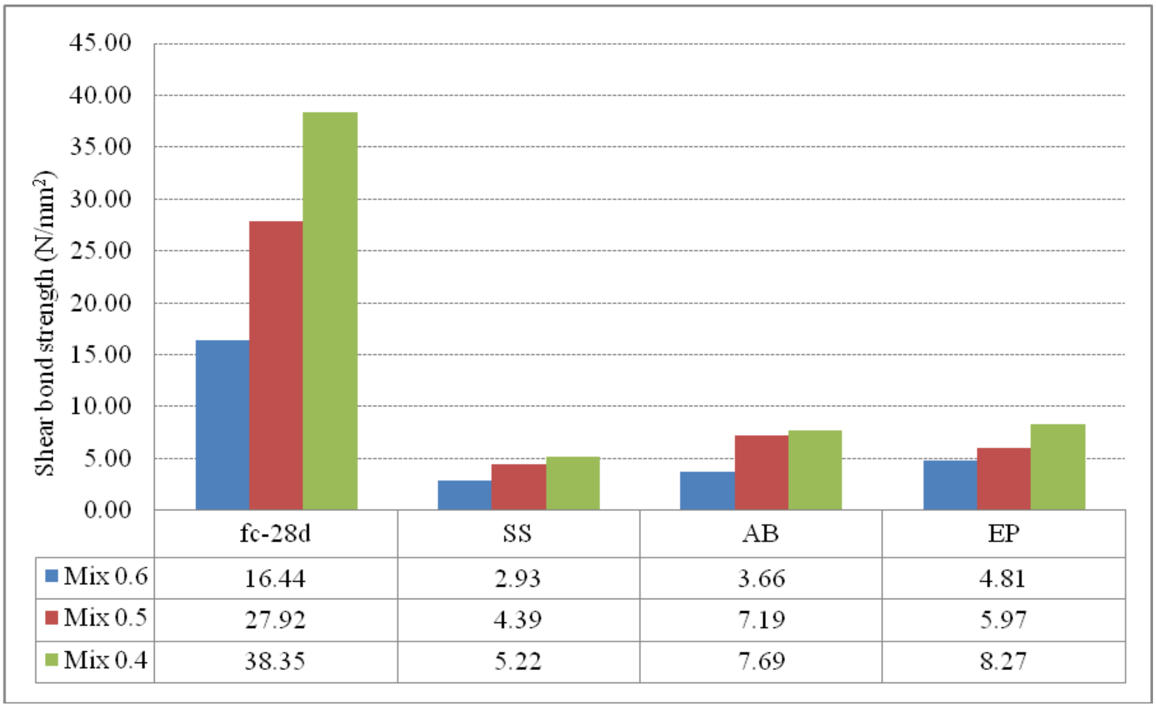


Figure 1: Effect of type of repair mix on shear bond strength - Case of chemical bond

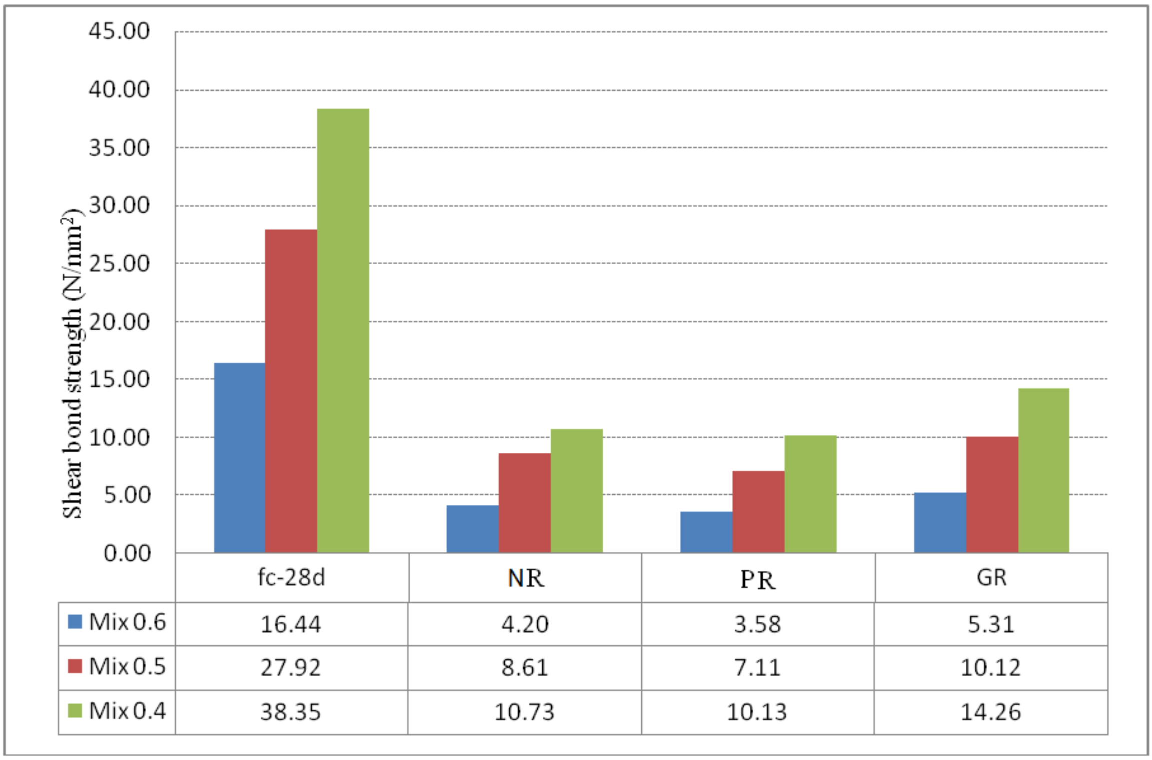
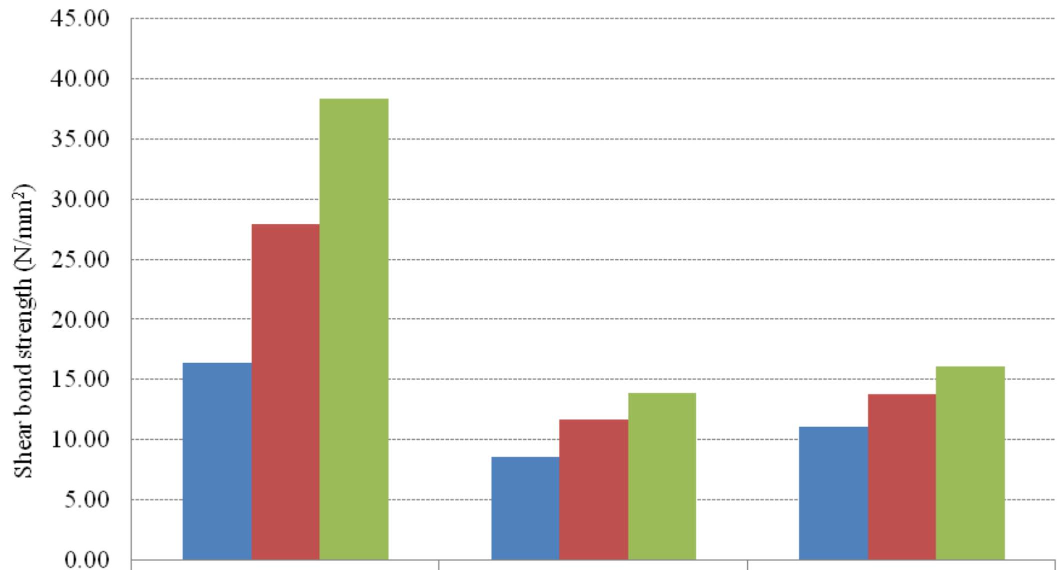
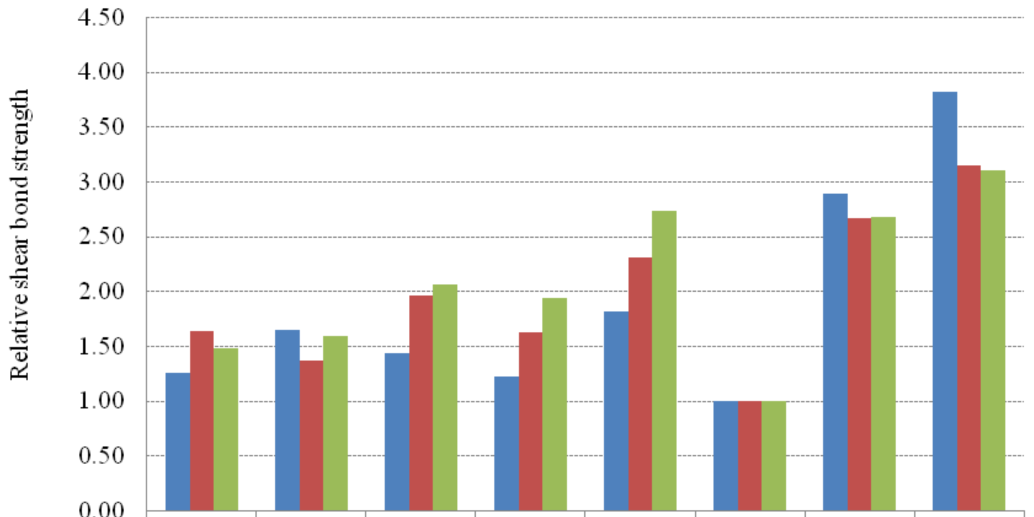


Figure 2: Effect of type of repair mix on shear bond strength - Case of physical bond



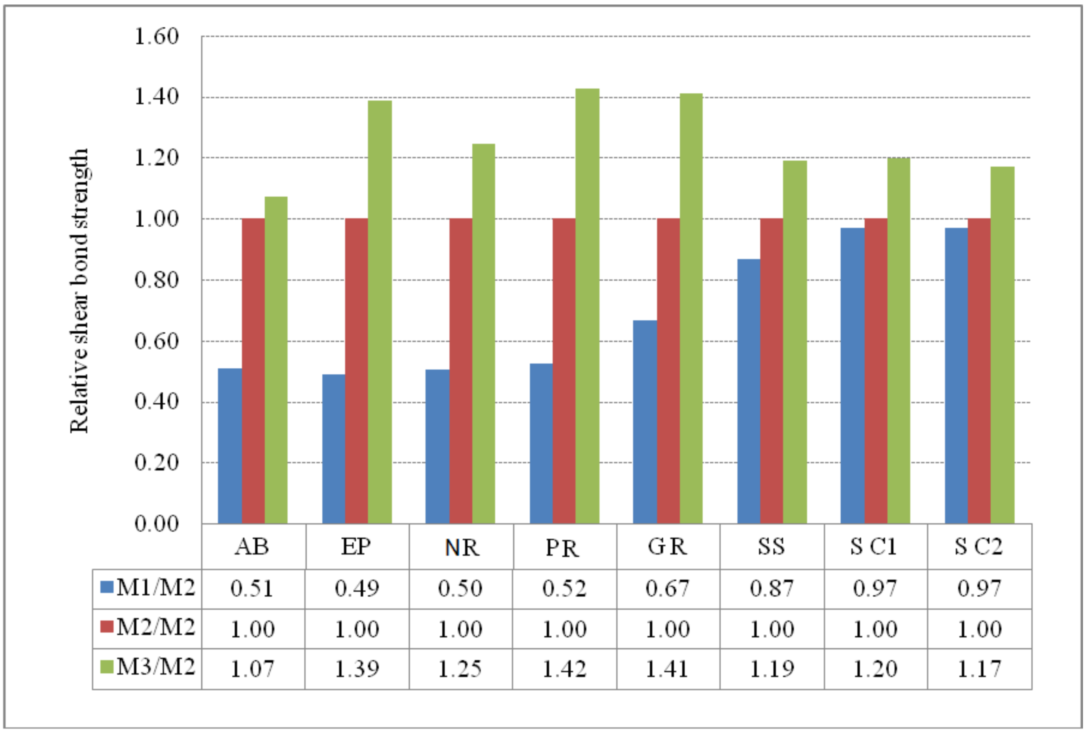
	fc-28d	SC1	SC2
Mix 0.6	16.44	8.64	11.16
Mix 0.5	27.92	11.68	13.80
Mix 0.4	38.35	13.98	16.16

Figure 3: Effect of repair mix on shear bond strength- Case of mechanical bond



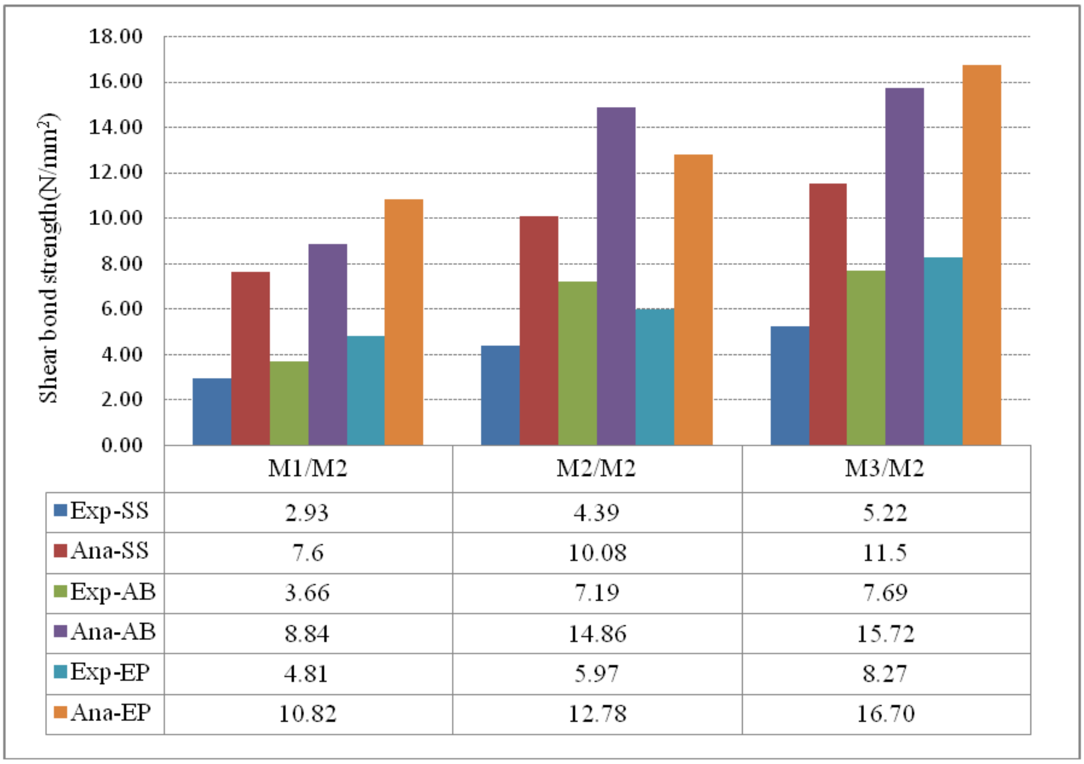
	AB	EP	NR	PR	GR	SS	S C1	S C2
M1/M2	1.25	1.64	1.43	1.22	1.81	1.00	2.89	3.81
M2/M2	1.64	1.36	1.96	1.62	2.31	1.00	2.66	3.15
M3/M2	1.47	1.58	2.06	1.94	2.73	1.00	2.68	3.10

Figure 4: Influence of surface conditions on the relative shear bond strength



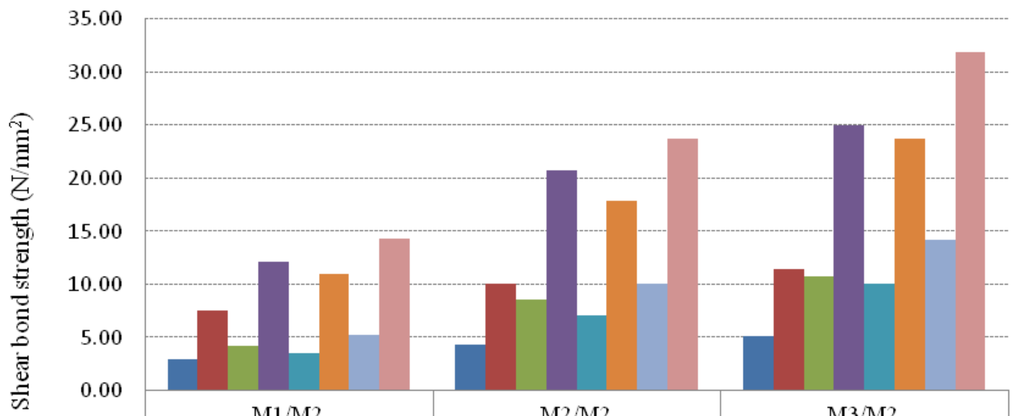
	AB	EP	NR	PR	GR	SS	S C1	S C2
M1/M2	0.51	0.49	0.50	0.52	0.67	0.87	0.97	0.97
M2/M2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
M3/M2	1.07	1.39	1.25	1.42	1.41	1.19	1.20	1.17

Figure 5: Influence of stiffness of the mix on the relative shear bond strength



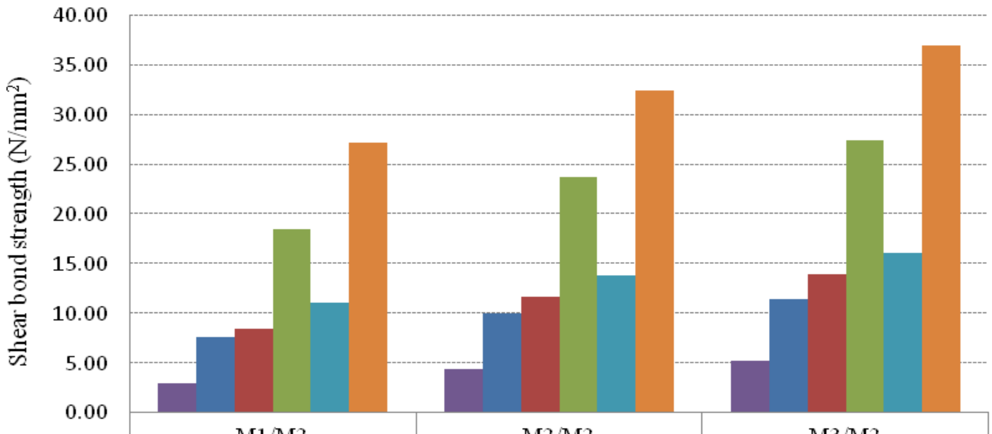
	M1/M2	M2/M2	M3/M2
Exp-SS	2.93	4.39	5.22
Ana-SS	7.6	10.08	11.5
Exp-AB	3.66	7.19	7.69
Ana-AB	8.84	14.86	15.72
Exp-EP	4.81	5.97	8.27
Ana-EP	10.82	12.78	16.70

Figure 6: Experimental and analytical shear bond strength (N/mm^2)



	M1/M2	M2/M2	M3/M2
Exp-SS	2.93	4.39	5.22
Ana-SS	7.6	10.08	11.5
Exp-NR	4.20	8.61	10.73
Ana-NR	12.19	20.81	24.98
Exp-PR	3.58	7.11	10.13
Ana-PR	10.98	17.89	23.8
Exp-GR	5.31	10.12	14.26
Ana-GR	14.37	23.78	31.88

Figure 7: Experimental and analytical shear bond strength (N/mm^2)



	M1/M2	M2/M2	M3/M2
Exp-SS	2.93	4.39	5.22
Ana-SS	7.6	10.08	11.5
Exp-SC1	8.46	11.68	13.98
Ana-SC1	18.455	23.72	27.47
Exp-SC2	11.16	13.80	16.16
Ana-SC2	27.26	32.45	37.07

Figure 8: Experimental and analytical shear bond strength (N/mm^2)

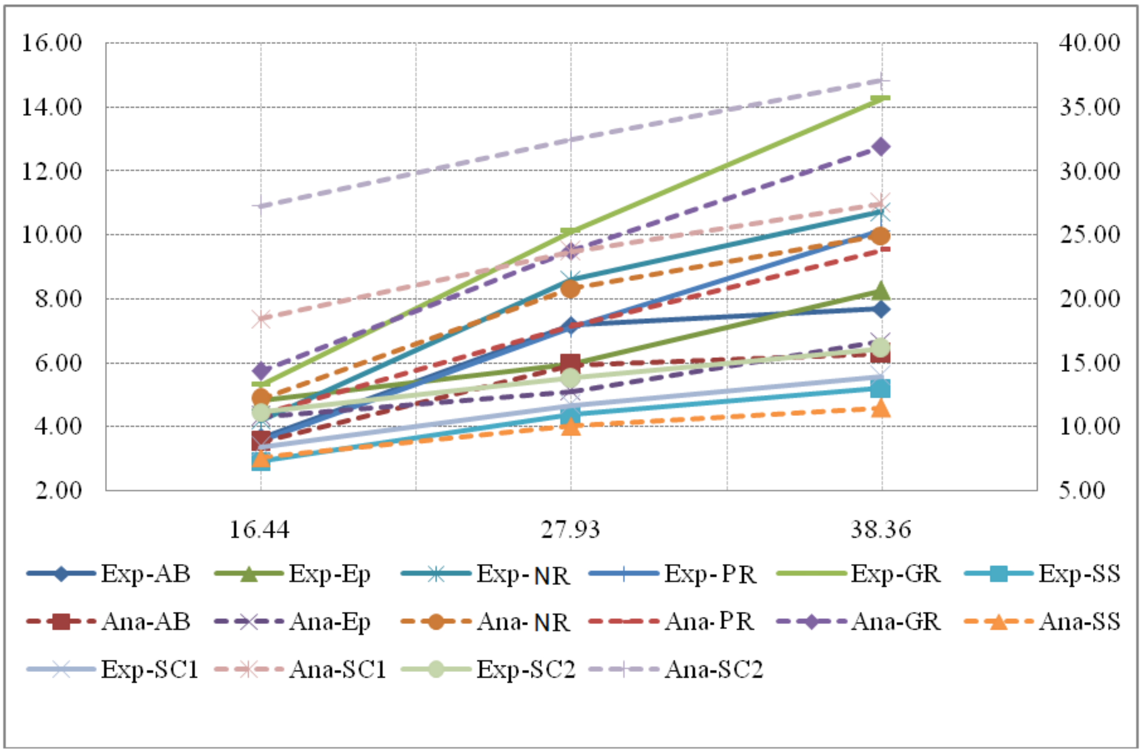


Figure 9: Experimental and analytical shear bond strength (N/mm^2)

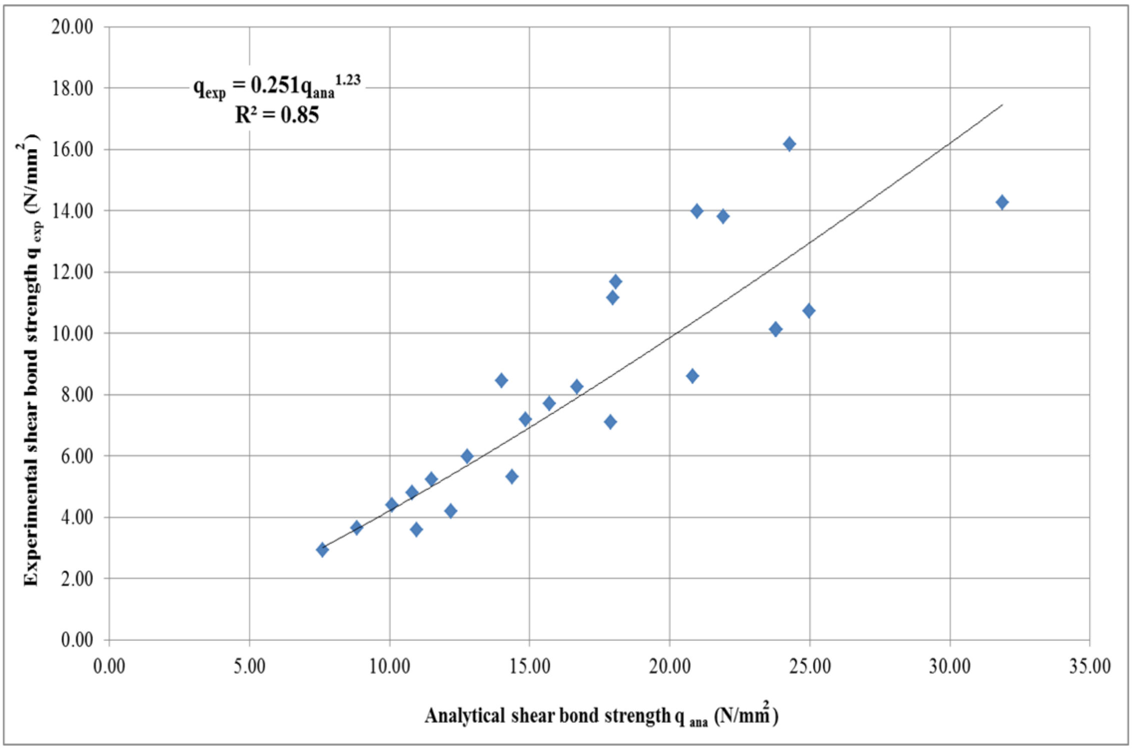


Figure 10: Relation between experimental and analytical shear bond strength

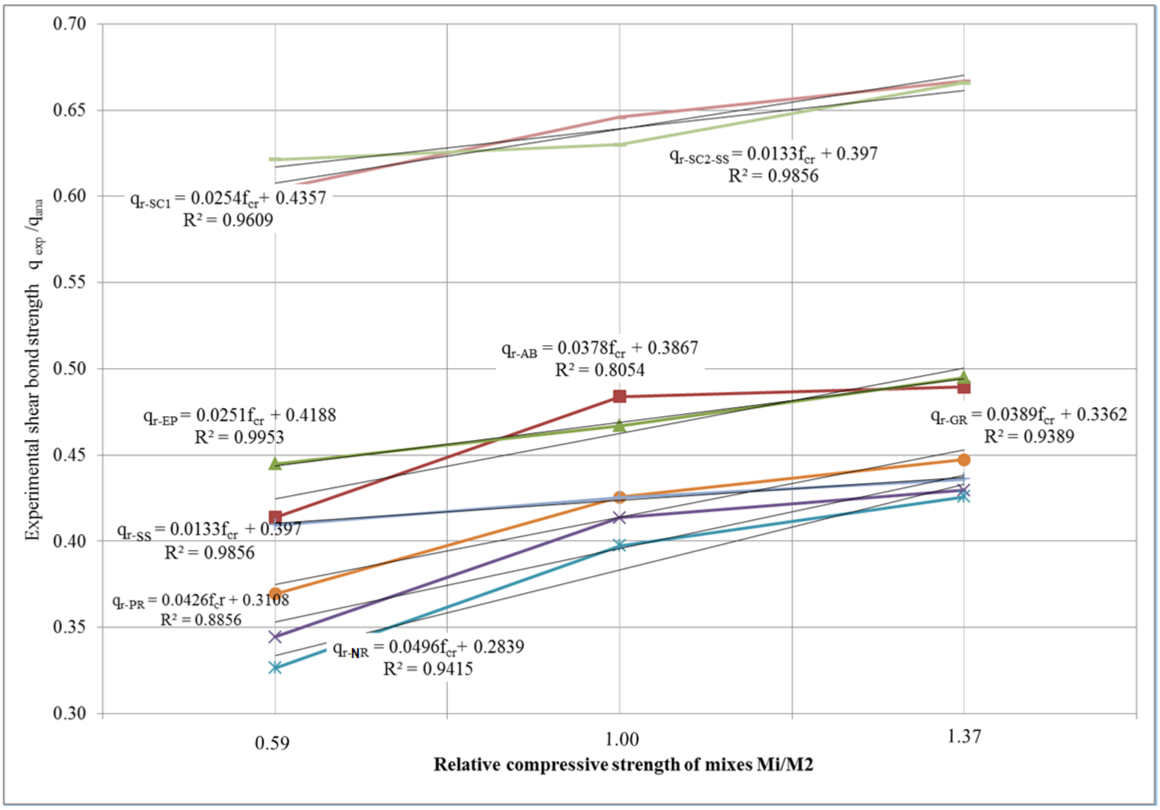
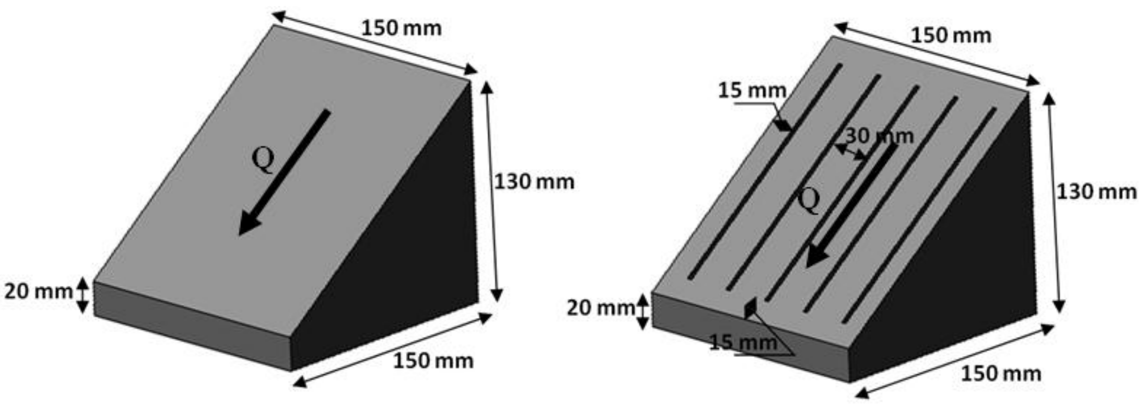
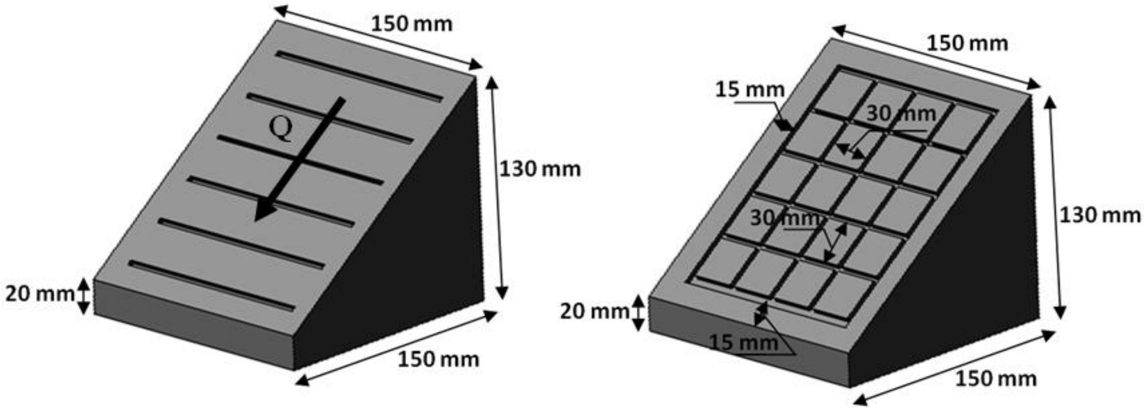


Figure 11: Relation between relative shear bond and compressive strength of mixes Mi/M2



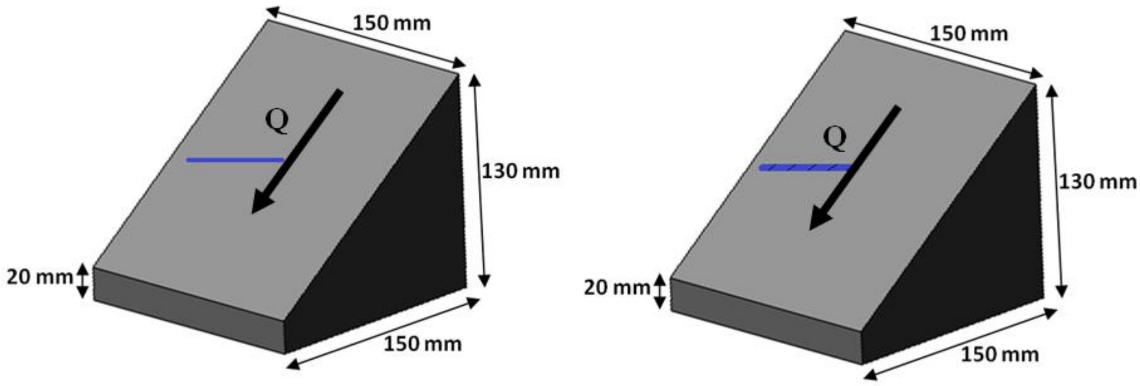
Smooth surface Rough surface with parallel grooves

Photo 1: Details of roughening the surface relative to the direction of the shear force



Rough surface with normal grooves Rough surface with grid grooves

Cont. Photo 1: Details of roughening the surface relative to the direction of the shear force



Mild Steel Deformed Steel

Photo 2: Details of steel connectors

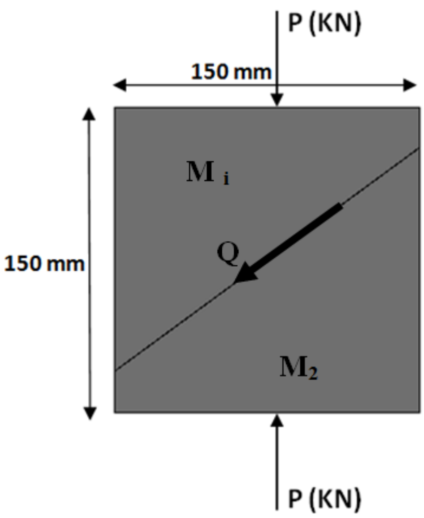


Photo 3: Complete specimen for slant shear test

6. CONCLUSIONS AND RECOMMENDATIONS

The conducted research which included experimental and analytical work concluded the following:

1. The shear bond strength depends on the relative strength of the mix Mi/M2 and the composite behavior is significantly improved when the relative strength RS≥1.
2. The mechanical anchoring (the mechanical bonding using steel bars) significantly improves the shear bond strength with respect to the physical and chemical bonding conditions. Also, it is clear that the shear bond strength by roughening the surface using either NR or GR is improved with respect to the case of PR.
3. Using the Euro Code 2 leads to overestimate the shear bond strength and the results of this research suggest using the given model in Figure 9 to evaluate the in-situ shear bond strength.
4. The results of the conducted research work provide a simplified formula to evaluate the shear bond strength in terms of the relative compressive strength of concrete and the relative shear bond strength for the different bonding surface conditions.
5. The steel connectors should directly be included in the analytical models.

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