Effect of Surface Texture on Bond Strength of GFRP Rebar in Concrete

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ABSTRACT

GFRP (Glass Fiber Reinforced Polymer) rebars are frequently used as reinforcement for reinforced concrete. This concrete being a composite material resists the flexural & shear loads, if adequate bond exists between GFRP rebars and concrete & through which transfer of stresses take place between them. The bond strength of such concrete is a function of several factors. Out of these factors, surface texture of GFRP rebars is one of the most important parameters. Experimental study was carried out with data acquisition system and linear displacement transducers to determine the effect of surface texture (sand coatings on GFRP rebars) on adhesion & frictional component of the bond strength. Overall and post peak bond behavior was studied through pullout tests using strain controlled universal testing machine. The results of experimental work showed that by sand coating on GFRP rebars, bond strength increased for both large and small diameter rebars. Furthermore for smaller diameter rebars, the effect of sand coating was more pronounced as compared to medium & larger diameter rebars. The sand coating improved the friction between GFRP rebars and the surrounded concrete. Moreover, after failure of chemical adhesion due to slip, friction between broken sand particles and rough surface of GFRP rebars provided further resistance to slip which consequently improved the bond strength.

Key Words: **GFRP, Bond, Bonded Length, Fracture Process Zone, Strain Energy, Radial and Circumferential Stresses.**

1. INTRODUCTION

Reinforced concrete is a composite material and it can perform its designated functions only if there exists adequate bond between the reinforcement and concrete [1-4]. This reinforcement can be of steel, GFRP rebars, carbon fiber rebars etc. GFRP rebars are now widely used to reinforce the concrete due to a number of advantages like reduced self weight, high tensile strength and elimination of corrosion problems [5]. At the same time there are some draw backs like brittle behaviour in tension at failure [5-6]. Since there are no well defined ribs on GFRP rebars like in deformed steel bars, therefore the bond between GFRP rebars and concrete is one of the most critical areas that needs to be

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addressed to ensure proper composite action of GFRP reinforced concrete. Bond strength of GFRP rebars results from chemical adhesion, friction and the friction between broken concrete particles and rebars rough surface. As the bearing resistance of deformed steel bars is not present in GFRP rebars, therefore, the probability of pull out failure is more incase of GFRP rebars. In this experimental study, in order to improve the bond strength, a technique of sand coating was used. The sand particles are glued to GFRP rebars using resin just after their manufacturing. In this way another parameter of bond strength is added. The mechanism of improvement in bond strength depends upon a number of factors like tensile strength of the resin, friction between concrete and sand particles.

The transition zone between sand particles and concrete depends upon the quality of the concrete and sand used for surface coating.

The shearing stress present at the surface of GFRP rebar is a function of number of parameters e.g. cover to the rebar, bonded length, surface characteristics of GFRP rebar etc. Out of these, cover to the reinforcement and bonded length are important and research is going on these parameters. [7-10]. Incase of sand coated rebars, these parameters still effect the bond performance. However, in order to study the effect of sand coating on the bond strength of GFRP rebars, cover to the reinforcement and bonded length were kept same. Experimental evaluation was done using pull out tests. In this experimentation two sets of samples were casted. In one set GFRP rebars used were not coated with sand and in the other set GFRP rebars were coated with sand particles. The cover to the rebars was kept same. Similarly bonded length used was also kept same. In this way all parameters of the experimentation were kept same except the surface texture. The testing was done with strain controlled Universal Testing Machine. The data acquisition system of the machine recorded the data at every 50 milli second. The results were plotted and conclusions were drawn. The results of experimentation showed that by surface coating of GFRP rebars, bond strength improved for all bar diameters. However, the extent of increase was different in different bar diameters. This may be due to other parameters like cover etc. This improvement in bond strength by using the sand coating can off set the draw back of non availability of bearing resistance as it is present incase of deformed steel bars.

2. FRACTURE MECHANICS APPROACH

The bond behaviour is nonlinear for normal strength concrete [7,11-12,15]. Strain softening and stress redistribution in concrete adjoining the GFRP rebars cause non linearity after formation of cracks. This behaviour of concrete can be explained on the basis of non linear fracture mechanics. The FPz (Fracture Process zone) in front of primary cracks and longitudinal splitting cracks would be large as shown in Fig. 1. Hence sufficient energy is consumed in crack initiation and propagation [2,4-5].

Where σ_{ys} is yield strength of concrete, r_p is radius of

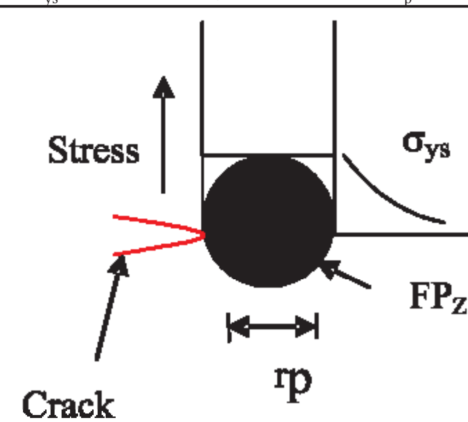


FIG. 1. FRACTURE PROCESS ZONE IN NORMAL STRENGTH CONCRETE [7,15]

fracture process zone, and K_1 is stress intensity factor.

3. EXPERIMENTATION

Concrete of compressive strength about 40 MPa was used in the experimentation. The results of compressive strength tests are shown in Table 1 and Fig. 2. Plain and sand coated GFRP rebars having diameters 9.5, 13, 19 and 22mm having yield strength of 415 MPa were used in pull-out tests as shown in Fig. 3. The concrete cylinders 150mmØ diameter and 300mm height were used in pullout tests. In order to achieve the desired bonded lengths, PVC pipes were used. These smooth surface pipes broke the bond between GFRP rebars and concrete.

Cylinders after concrete pouring for pullout tests, as shown in Fig. 4, were covered with polyethylene sheet and tied with thread to prevent the loss of moisture through evaporation. After 24 hours, demoulding was done and all the specimens were placed in water tank for curing purpose. It was made sure that projecting bars should not be submerged. The samples for compressive strength were tested at 3,7,14 and 28 days. Pullout tests were performed at the age of 28 days.

4. TESTING

Pullout samples were tested in a pullout assembly specially designed for this purpose and having hinge on one side as shown in Fig. 5. This hinge eliminates any eccentricity developed during the fixing of rebar in the testing machine. Load was applied through 1000kN strain controlled UTM (Universal Testing Machine).

TABLE 1. PROPERTIES OF NORMAL STRENGTH CONCRETE

Cylinder Size	Maturity Period (Days)	Ultimate Load (KN)	Average Load (KN)	Compressive Strength (MPa)
Cylinder (150Øx300mm)	3 Days	265	270	14.8
	3 Days	275		
	7 Days	471	491	26.9
	7 Days	511		
	14 Days	667	668	36.5
	14 Days	669		
	28 Days	755	755	41.4
	28 Days	755		

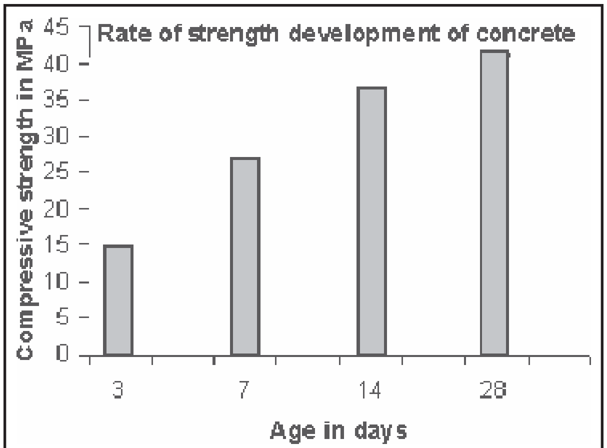


FIG. 2. COMPRESSIVE STRENGTHS OF CONCRETE

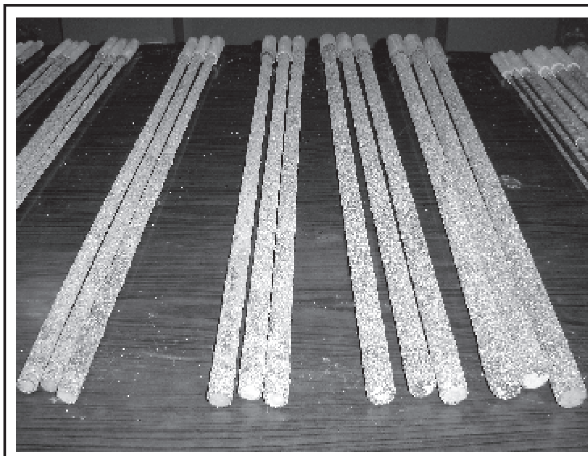


FIG. 3. GFRP REBARS FOR PULL OUT TESTS

Data acquisition system was used to measure the slip between GFRP rebar and the concrete. Pull out rebar was gripped from one side of the machine and hinged bar of the assembly was on the other side. Pullout samples were failed by the formation of splitting cracks approximately at an angle of 120^o as shown in Figs. 6-7. Concrete key

CASTING
FIG.5. LINE DIAGRAM OF PULLOUT ASSEMBLY

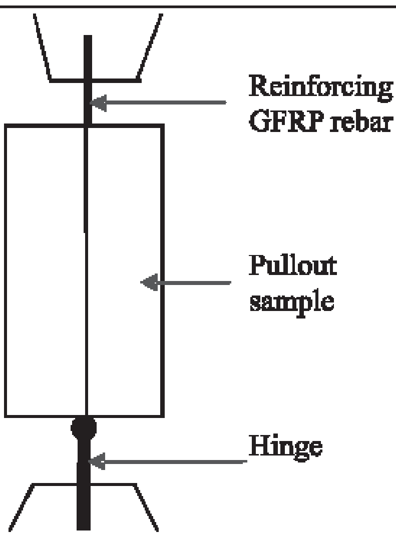


FIG. 6. FORMATION OF LONGITUDINAL SPLITTING

CRACKS DURING PULLOUT TEST
FIG. 7. FORMATION OF LONGITUDINAL SPLITTING CRACK

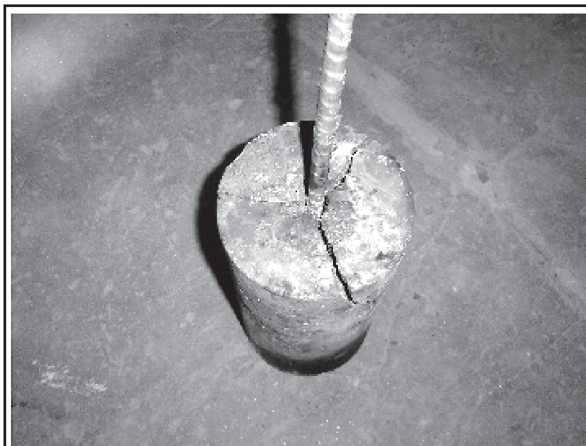


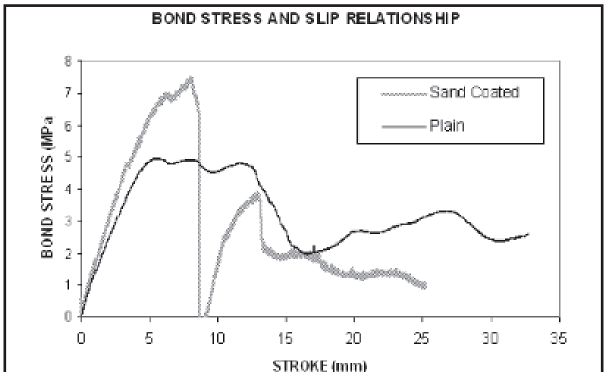
FIG. 4. SAMPLES IMMEDIATELY AFTER CONCRETE

FIG 8. CONCRETE KEY OF GFRP REBARS AFTER PULLOUT TESTS

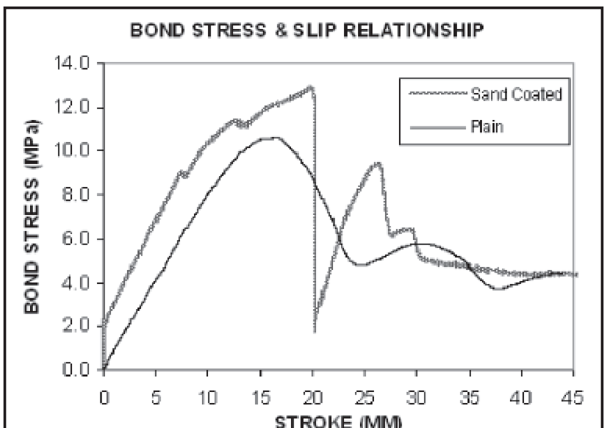
was formed between plain/low rib height GFRP rebar and the concrete as shown in Fig. 8.

5. TEST RESULTS AND DISCUSSION

The results of the experimentation are shown in Figs. 9-16. It is clear from these results that bond strength of sand coated rebars is greater than that of plain GFRP rebars. Two values of bonded lengths were selected for each set of the experiments. In the first set 5db bonded length and in the second set 7db bonded length was used. As it is shown in Figs. 14-17 that bond strength increased from 17-58% incase of 9.5, 13, 19 and 22mm GFRP rebars for 5db bonded length. Similarly incase of 7db bonded lengths, bond strength increased from 35-53% for 9.5, 13 19 and 22mm GFRP rebars. These values have shown in Tables 2-3.



19mm DIA BAR WITH 7db BONDED LENGTH
FIG. 12. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF
22mm DIA BAR WITH 7db BONDED LENGTH



OF 13mm DIA BAR WITH 7db BONDED LENGTH
FIG. 11. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF

The mathematical models for sand coated and plain GFRP rebars are shown in Tables 4-5.

Incase of plain rebar, as the load is applied on pullout

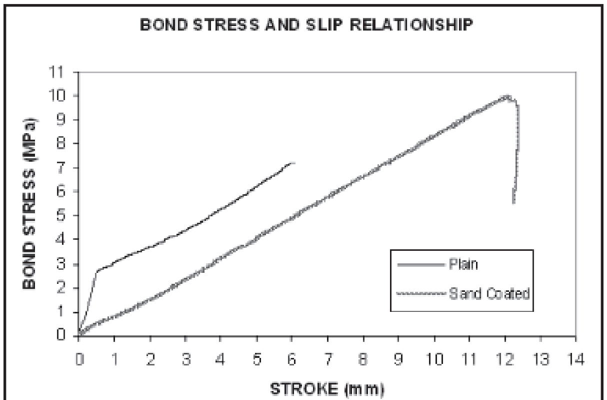
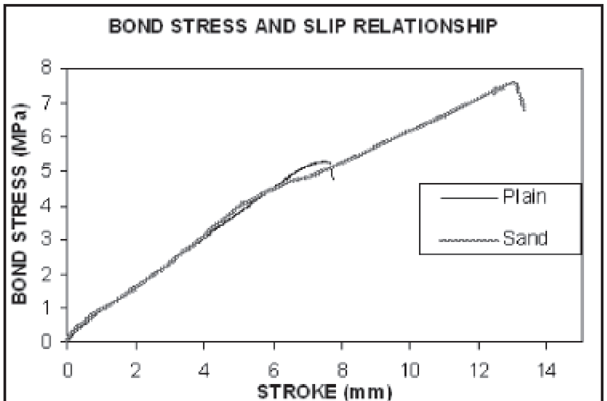


FIG. 9. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF 9.5mm DIA BAR WITH 7db (DIAMETER OF REBAR) BONDED



LENGTH
FIG. 10. EFFECT OF SAND COATING ON BOND BEHAVIOUR

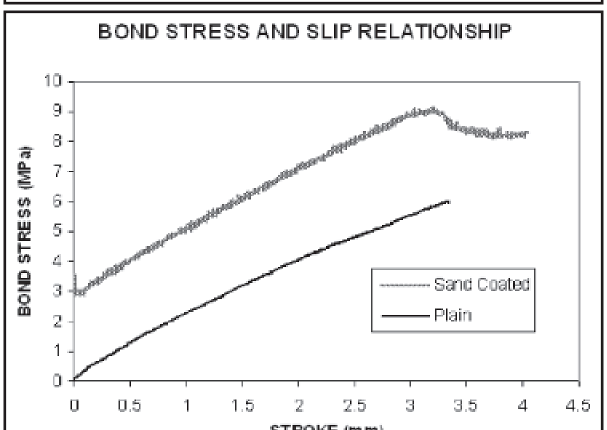


FIG. 13. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF 9.5mm DIA BAR WITH 5db BONDED LENGTH

sample, first chemical adhesion and friction is broken, then the friction between broken concrete particles and plain GFRP rebar provide the bond strength. As the load is further increased, samples fail by pullout. Incase of sand coated rebar, as the load is increased the bond between sand particles and surrounding

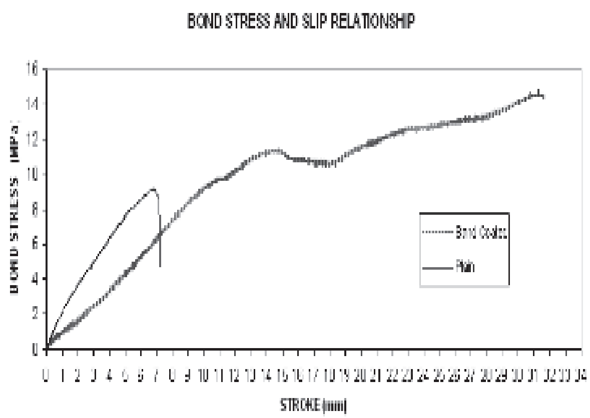
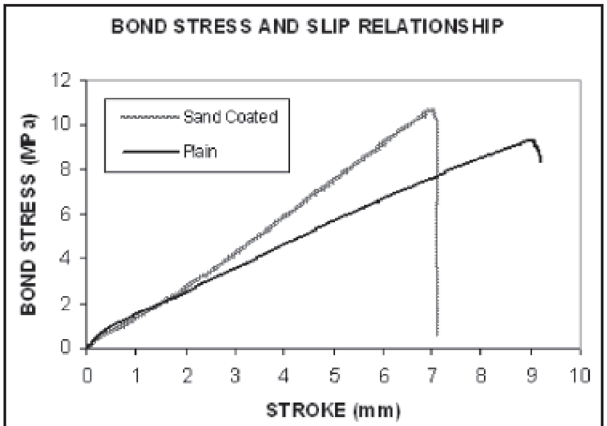


FIG. 14. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF 13mm DIA BAR WITH 5db BONDED LENGTH



22mm DIA BAR WITH 5db BONDED LENGTH
FIG.17 DISTRIBUTION OF STRESSES IN CONCRETE KEY

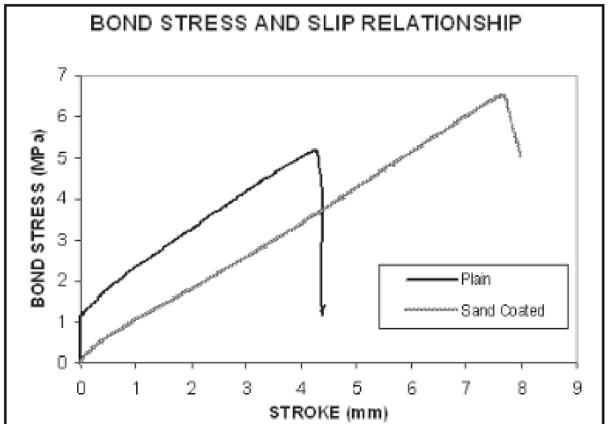


FIG. 15. EFFECT OF SAND COATING ON BOND BEHAVIOUR OF 19mm DIA BAR WITH 5db BONDED LENGTH

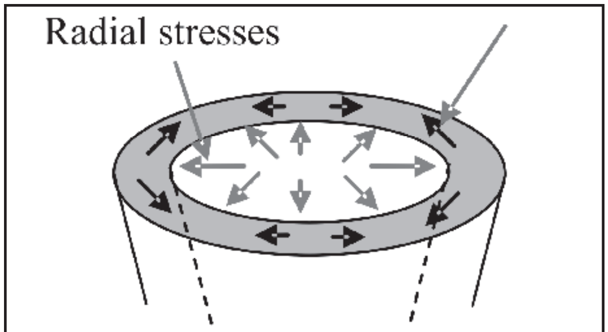


FIG. 16. EFFECT OF SAND COATING ON BOND BEHAVIOR OF

TABLE 2. COMPARISON OF BOND BEHAVIOR FOR PLAIN AND SAND COATED GFRP REBARS

Bar Dia (mm)	Bond Stress (Lb=5db) (MPa)		Percentage Increase in Bond Stress
	Plain	Sand Coated	
9.5	6.1	9.0	48
13	9.2	14.5	58
19	9.0	10.5	17
22	5.25	6.5	24

TABLE 3. COMPARISON OF BOND BEHAVIOR FOR PLAIN AND SAND COATED GFRP REBARS

Bar Dia (mm)	Bond Stress (Lb=7db) (MPa)		Percentage Increase in Bond Stress
	Plain	Sand Coated	
9.5	4.9	7.5	53
13	10.0	13.5	35
19	7.3	10.0	37
22	5.5	7.5	37

Same failure pattern was obtained in sand coated GFRP rebars as shown in Fig. 7. The type of bonding of sand particles with GFRP rebar determines its effectiveness in enhancing the bond performance.

In case of splitting failure, when a reinforcing bar is pulled out of concrete then two types of stresses are produced in the concrete. Radial stresses and circumferential tensile stresses as shown in Fig. 17 [14]. The same types of stresses setup in the sand coated pullout samples. The interlocking between sand particles and adjoining concrete provides the resistance to the slippage.

It is evident from all the equations of tables 4 and 5 that all the mechanisms of bond strength development are a concrete is broken. Further bond strength is provided by friction between broken sand particles and surrounding concrete.

In general terms, the sand coating increases the frictional component of bond strength to the extent that the absence of ribs can be overcome with the help of sand coating surface treatment. The sand particles are glued to GFRP rebar with the same epoxy which joins glass fibers with each other in GFRP rebar manufacturing. In plain/low rib height rebar, the surface is plain however in sand coated rebar irregular shape of sand particles develops significant friction with surrounding concrete. The mechanics of low ribs in plain rebars cause splitting type of bond failure [15].

TABLE 4. MATHEMATICAL MODEL FOR $5d_b$ BONDED LENGTH PLAIN AND SAND COATED GFRP REBARS.

No.	Bonded Length: $5d_b$		Equation
	Bar Dia. (mm)	Surface Texture	
1.	9.5	Sand Coated	$u=-0.427\delta^2 + 3.237\delta$ -(1)
2.	9.5	Plain	$u=-0.165\delta^2 + 2.294\delta$ -(2)
3.	13	Sand Coated	$u=-0.016\delta^2 + 0.929\delta$ -(3)
4.	13	Plain	$u=-0.087\delta^2 + 1.903\delta$ -(4)
5.	19	Sand Coated	$u=0.022\delta^2 + 1.376\delta$ -(5)
6.	19	Plain	$u=-0.018\delta^2 + 1.177\delta$ -(6)
7.	22	Sand Coated	$u=0.007\delta^2 + 0.776\delta$ -(7)
8.	22	Plain	$u=-0.220\delta^2 + 1.739\delta$ -(8)
u is Bond strength, and δ is Slip between concrete and GFRP rebars			

TABLE 5. MATHEMATICAL MODEL FOR $7d_b$ BONDED LENGTH PLAIN AND SAND COATED GFRP REBARS.

No.	Bonded Length: $7d_b$		Equation
	Bar Dia. (mm)	Surface Texture	
1.	9.5	Sand Coated	$u=-0.103\delta^2 + 1.739\delta$ -(9)
2.	9.5	Plain	$u=-0.118\delta^2 + 1.543\delta$ -(10)
3.	13	Sand Coated	$u=-0.030\delta^2 + 1.129\delta$ -(11)
4.	13	Plain	$u=-0.048\delta^2 + 1.463\delta$ -(12)
5.	19	Sand Coated	$u=0.002\delta^2 + 0.814\delta$ -(13)
6	19	Plain	$u=0.047\delta^2 + 0.505\delta$ -(14)
7.	22	Sand Coated	$u=-0.018\delta^2 + 0.801\delta$ -(15)
8.	22	Plain	$u=-0.011\delta^2 + 0.789\delta$ -(16)
u is Bond strength, and δ is Slip between concrete and GFRP rebars			

function of slip between rebar and the concrete.

6. CONCLUSIONS

(i) Bond performance of GFRP rebars can be improved by using the sand coating treatment. There can be 17-58% increase in bond strength by sand coating the GFRP rebars.

(ii) Improvement in bond strength is less for 19 and 22mm dia rebars for 5db bonded length. This may be due to the fact that tangential stresses are so significant that it immediately dislodge the sand coating from the surface and cause slip leading to failure.

(iii) Increase in bonded length from 5-7db did not have significant impact on bond strength for both sand coated and plain rebars except for 19 and 22mm diameter rebars, where increase in bonded length improved the bond strength.

(iv) Incase of sand coated rebars bond strength developed mainly due to interlocking friction between sand particles and surrounding concrete. After the slip, friction between broken concrete particles and surrounding concrete, further increase of the bond strength.

(v) Taking into account the mechanism of bond strength development, the absence of ribs in GFRP plain rebars can be offset by using the sand coating treatment.

(vi) The sand coating changed the mode of failure from pullout to splitting. Hence absence of ribs in GFRP plain is offset by sand coating surface treatment because both provide the same failure mechanism.

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REFERENCES

[1] Abrishami, H.H., and Mitchell, D., "Analysis of Bond Stress Distributions in Pullout Specimens", Journal of Structural Engineering ASCE, Volume 122, No. 3, Paper No. 10368, pp 255-261, 1996.

[2] Ahmed, K., Siddiqi, Z.A., and Ashraf, M., "Effect of Cover and Development Length of Twisted Steel on Bond Stress and Slip Relationship for High Strength Concrete", Pakistan Journal of Engineering and Applied Sciences, Volume 2, pp. 79-88, 2009.

[3] Ahmed, K., Siddiqi, Z.A., and Yousaf, M., "Slippage of Steel in High and Normal Strength Concrete", Pakistan Journal of Engineering and Applied Sciences, Volume 1, pp. 31-40, 2007.

[4] Tastani, S.P., Pantazopoulou, S.J., "Experimental Evaluation of the Direct Tension Pullout Bond Test", Bond in Concrete from Research to Standards, Budapest, Hungary, 2002.

[5] Tastani, S.P., and Pantazopoulou, S.J., "Bond of GFRP Bars in Concrete: Experimental Study and Analytical Interpretation", Journal of Structural Engineering ASCE, Volume 10, No. 5, Paper No. 17521, pp. 381-391, 2006.

[6] Tighiouart, B., and Benmokrane, D., "Investigation of Bond in Concrete Member with Fiber Reinforced Polymer (FRP) Bars", Construction and Building Materials, Volume 12, pp. 453-462, 1998.

[7] Tue, N.V., and Krumbach, R., "Description of Bond Between a New Developed Reinforcing Steel and High Strength Concrete", LACER, No. 2, pp. 171-189, 1997.

[8] Mo, Y.L., and Chan, J., "Bond and Slip of Plain Rebars in Concrete", Journal of Materials in Civil Engineering, Volume l8, No. 4, pp. 208-211, 1996.

[9] Weisse, D., and Holschemacher, K., "Some Aspects About the Bond of Reinforcement in UHSC", LACER, No. 8, pp. 251-261, 2003.

[10] Wang, X., and liu, X., "A Strain Softening Model for Steel-Concrete Bond", Cement and Concrete Research, Volume 33, pp. 1669-1673, 2003.

[11] Sener, S., and Bazant, Z.P., "Size Effect on Failure of Bond Splices of Steel Bars in Concrete Beams", Journal of Structural Engineering ASCE, Volume 125, No. 6, Paper No. 17521, pp. 653-660, 1999.

[12] Ma, J., Schneider, H., and Donnecke, C., "Preliminary Study on Fracture Behavior of Ultra High Strength Concrete", LACER No. 7, pp. 281-290, 2002.

[13] ACI 408R-03, "Bond and Development of Straight Reinforcing Bars in Tension", Reported by ACI Committee 408, pp. 4-7, 2003.

[14] Ahmed, K., Siddiqi, Z.A., and Ghaffar, A., "Comparison of Bond Behaviour of Hot Rolled and Cold Twisted Steel Reinforcement in High Strength Concrete", Mehran University Research Journal of Engineering and Technology, [ISSN 0254-7821] Volume 27, pp. 365-377, Jamshoro, Pakistan, 2008.

[15] Ahmed, K., Siddiqi, Z.A., Ghaffar, A., and Saleem, M., "Bond Behavior of Twisted Steel in High Strength Concrete", Proceedings of International Conference on Cement Based Materials ACBM-ACI [ISBN No:978-969-546-016-0], Volume 2, pp. 1011-1022, Lahore, Pakistan, 11-14 September 2007.

[16] ACI 446.1 R-91, "Fracture Mechanics of Concrete: Concepts, Models and Determination of Material Properties", Reported