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Bond Strength of Fusion Bonded Epoxy-Coated Reinforcement in Concrete

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ABSTRACT Fusion-bonded epoxy-coated steel is expected to extend the service life of the reinforced concrete structure in chloride-laden environments. However, the effect of coating on the bond-strength between rebar and concrete is not well understood yet. This research, therefore, studied the effect of epoxy-coating on the bond characteristics of reinforcing bars in concrete. The bond characteristics were assessed through pullout test considering variables viz. concrete strength, embedded length and bar diameter. The load was applied to reinforcing bars embedded in concrete until bond strength between the bar and concrete exceeded. Bond strength of epoxy-coated bars was compared with that of the uncoated bars. It was found that epoxy-coating reduced the bond strength approximately 25% for Ø20mm bar and 12% for Ø16mm and Ø12mm bar. As with uncoated bar, bond strength of coated bars were also increased with concrete strength. However, the bond strength ratio between coated and uncoated bars was found almost independent of concrete strength. Based on the test results, a development length modification factor of 1.33 is proposed for Ø20mm bar and 1.15 for Ø12mm and Ø16mm bar to compensate the bond strength reduction due to the epoxy coating.

KEYWORDS Fusion-Bonded Epoxy-Coat; Steel Corrosion; Embedded Length; Bond Strength; Pullout

1 INTRODUCTION

Reinforced concrete is a composite material in which steel is embedded in concrete in such a manner that the two materials act together in resisting forces. Performance of reinforced concrete is generally evaluated by its strength and durability properties. The most important durability issue with reinforced concrete is its deterioration due to reinforcement corrosion in an adverse environment which greatly reduce the load carrying capacity of the reinforced concrete element. The primary purpose of epoxy-coated bars is to prevent corrosion of steel, which leads to premature deterioration of concrete structures. When steel corrodes, the original volume of the material expands up to 3-6 times. This expansion exerts a radial pressure on the concrete, which causes cracking and spalling (Treece and Jirsa, 1989). Fusion-bonded epoxy-coated reinforcement is increasingly being used as a method of protecting steel reinforcement in concrete from corrosion. An important consideration in the use of epoxy-coated bars is the effect of the coating on the bond between reinforcing bars and concrete (Breen, 2012). A major reason for the reluctance of engineers to adopt epoxy as a protective coating for reinforcing bars in key structures has been the suspicion that coated reinforcing bars might not provide acceptable bond strength in concrete. A number of studies have been carried out to investigate the behavior of coated steel bars. These includes the effect of epoxy coating of steel bars on bond strength (Clifton and Mathey, 1983; Treece and Jirsa, 1989; Cleary and Ramirez, 1991; El-Hawary, 1999; Breen, 2012), analytical calculation of bond strength of epoxy coated bar (El-Hakeem, Abd El-Aziz and El-Reedi, 1997) and the effect of epoxy coating on reinforcement corrosion (Berke and Hicks, 1995; Mišković-stanković et al., 1995).

These studies have indicated epoxy-coating on reinforcement reduces bond capacity in comparison with uncoated (black) bars. Assaad and Issa, (2012) show that as compared to the uncoated bars, the decrease in bond strength was found in the range from 15% to 50% depending on several factors such as coating thickness, bar size and location, deformation patterns, concrete properties and casting conditions. Thus, the determination of bond strength of epoxy-coated reinforcement in concrete is a concern in many parts of the world. This study aims to investigate the bond behavior of fusion-bonded epoxy-coated bar to extend the knowledge gained in the previous studies on the bond strength of coated bars in normal weight concrete.

2 MATERIALS AND METHODOLOGY

2.1 Materials

Concrete- In this study, non-air entrained normal weight concrete with CEM I of strength class 42.5N, stone chips and coarse sand are used. Polycarboxylic ether based retarding superplasticizer was used to achieve the target concrete compressive strengths (cube) of 15MPa, 25MPa and 35MPa at 28 days.

Reinforcing Steel- The reinforcing steel were Ø20mm, Ø16mm and Ø12mm bars for both epoxy-coated and uncoated of Grade 72.5. Figure 1 show the epoxy–coated bar used in this study. Both type of steel inside concrete was subjected to uniaxial tension. The coating thickness of Ø20mm bar was approximately 16 mils (400μm) and that for Ø12 and Ø16mm bars was about 7-12 mils (175-300μm) as per ASTM A934 (2016b) .

Figure 1. Epoxy coated steel used in this study

2.2 Experimental Program

Concrete samples were mixed and the slump was confirmed. Once desired slump was achieved the fresh concrete was poured in cylindrical steel mould to prepare samples for pull out and compressing strength tests. After curing for 28 days the samples were tested for compressive and bond strength. To evaluate the bond strength of fusion-bonded epoxy-coated steel with concrete, pullout test is conducted in the laboratory. The cylindrical specimen dimension was Ø100mm×200mm for Ø12mm and Ø16mm bar and Ø150mm×300mm for the 20mm bar. Embedded lengths of the bars were 75mm and 300mm for Ø12mm bar, 100mm and 200mm for Ø16mm, and 150mm and 250mm for Ø20mm bar. The samples sizes were taken based on previous studies (ASTM A994; Bazant and Sener, 1988; Islam and Naha, 2015). While embedded lengths are taken independently for other bars, this was 250mm for Ø20mm bar in a cylindrical prism of Ø150mm×300mm was taken according to ASTM A775 (2017). All pullout tests were carried out in a 2000 kN capacity Universal Testing Machine (UTM). A typical pullout specimen positioned on the testing machine is shown in Figure 2.

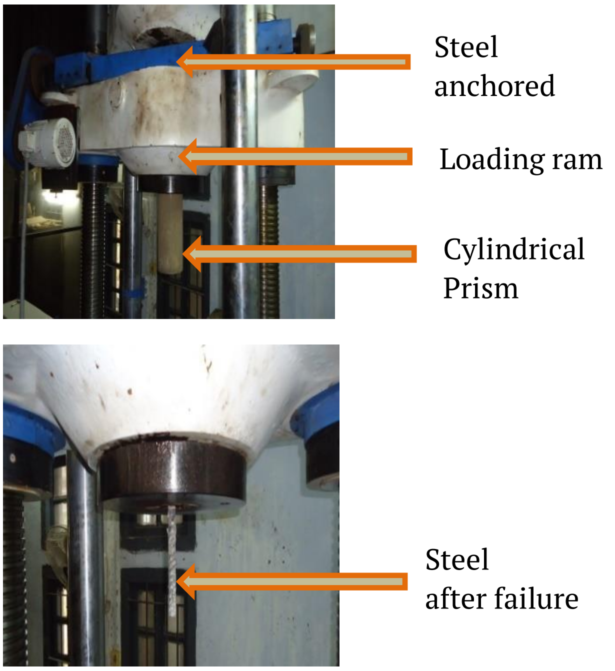

Figure 2. Pullout test with UTM

3 RESULT AND DISCUSSION

3.1 Effect of Compressive Strength

3.1.1 Ø20mm bar - embedded 150mm and 250mm

Test results of Ø20 mm bar embedded 150 mm and 250mm in different strength concretes are shown in Tables 1 and 2. The failure mode of the cylindrical prism is pullout for 150mm embedded length in C15 concrete and splitting for all other cases. For each concrete strength failure mode was similar for both coated and uncoated rebars. It is seen that the average bond strength ratio between coated and uncoated bar is 0.67 at the embedded length of 150mm and 0.75 at the embedded length of 250mm, i.e. strength reduction is about 33% and 25% respectively. As shown in Figures 3 and 4, the bond strength increased linearly with concrete strength.

However, bond strength increased with embedded length (see Figure 5). It is observed that the strength reduction curves are almost parallel to the horizontal axis i.e. strength reduction is independent of the concrete strength, though the failure mode was different for lower grade concrete.

Table 1. Bond strength of 20mm bar (embedded 150 mm) in Φ150×300 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	P	11.85	0.69
	C	P	8.16	
C25	U	S	14.75	0.67
	C	S	9.33	
C35	U	S	16.34	0.68
	C	S	11.24	

U= Uncoated, C= Coated, P= Pullout failure, S= Splitting failure

Table 2. Bond strength of 20mm bar (embedded 250 mm) in Φ150×300 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	S	8.94	0.75
	C	S	6.68	
C25	U	S	10.98	0.75
	C	S	8.28	
C35	U	S	11.77	0.76
	C	S	8.91	

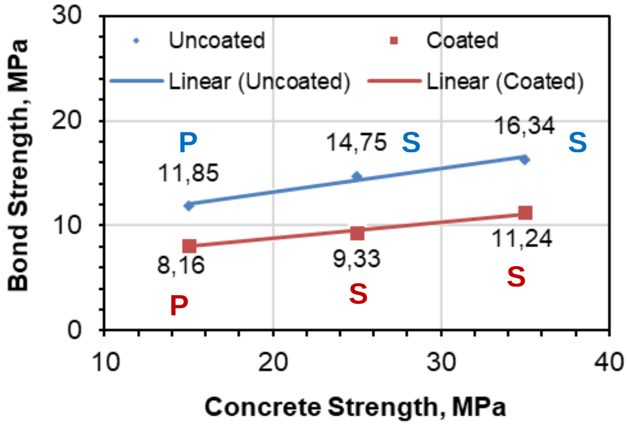

Figure 3. Variation of bond strength with different strength concrete (Ø20mm bar and 150mm embedded length)

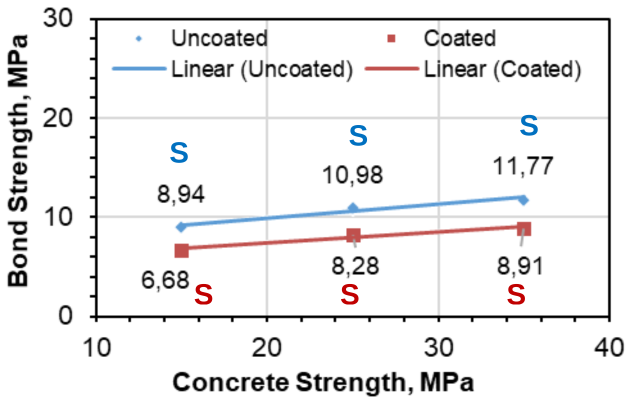

Figure 4. Variation of bond strength with different strength concrete (Ø20mm bar and 250mm embedded length)

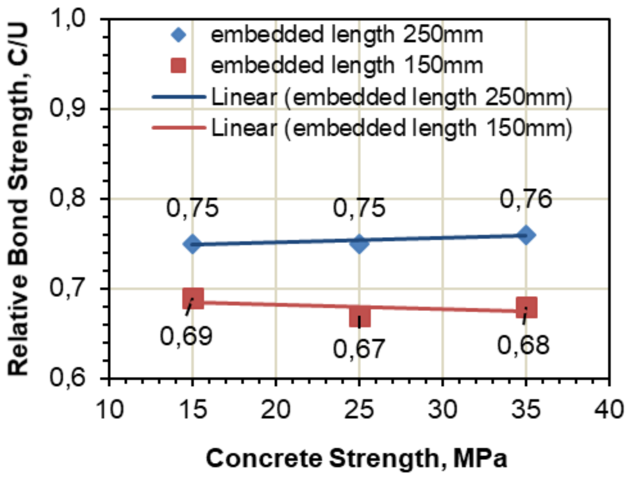

Figure 5. Reduction in bond strength with different embedded length (Ø20mm bar).

3.1.2 Ø16mm bar - embedded 100mm and 200mm

Test results of Ø16mm diameter bar at an embedded length of 100 mm and 200mm in different concrete strength are shown in Tables 3 and 4. The failure mode of the cylindrical prism is pullout inside C15 concrete at the embedded length of 100mm (uncoated bars) and splitting for all other cases. It is seen that the average bond strength ratio between coated and uncoated bar is 0.80 at the embedded length of 100mm and 0.88 at the embedded length of 200mm, i.e. strength reduction is about 20% and 12% respectively.

Table 3. Bond strength of 16mm bar (embedded 100 mm) in Φ100×200 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	P	6.04	0.83
	C	S	5.05	
C25	U	S	13.27	0.79
	C	S	10.42	
C35	U	S	15.91	0.78
	C	S	12.4	

Table 4. Bond strength of 16mm bar (embedded 200 mm) in Φ100×200 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	S	6.4	0.90
	C	S	5.82	
C25	U	S	10.54	0.88
	C	S	9.3	
C35	U	S	11.64	0.88
	C	S	10.32	

Also, it can be concluded that bond strength increases linearly with concrete strength as shown in Figures 6 and 7. However, a minor decrease in bond strength ratio is noted with embedded length (see Figure 8). As with Ø20mm bar, the strength reduction curves are almost parallel to the horizontal axis i.e. strength reduction is independent of concrete strength.

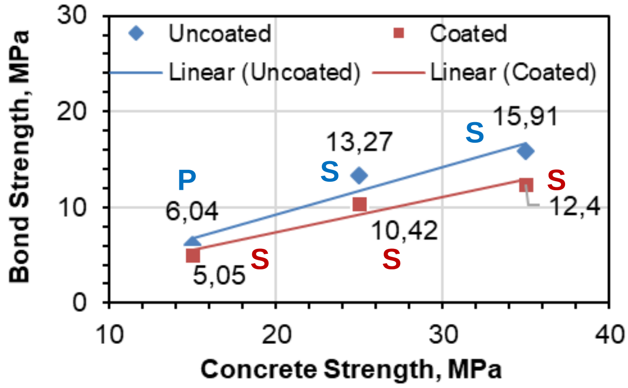

Figure 6. Variation of bond strength with different strength concrete (Ø16mm bar and 100mm embedded length)

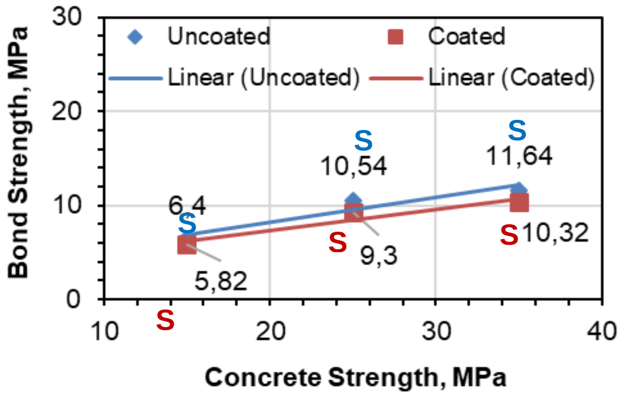

Figure 7. Variation of bond strength with different strength concrete (Ø16mm bar and 200mm embedded length)

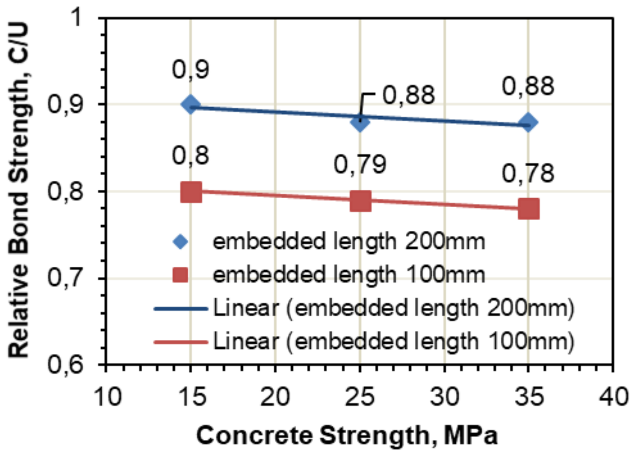

Figure 8. Reduction in bond strength with different embedded length (Ø16mm bar)

3.1.3 Ø12mm bar - embedded 75mm and 150mm

Test results of Ø12mm bars embedded 75 mm and 150 mm in different strength concretes are shown in Tables 5 and 6. Pullout failure of cylindrical specimens is found for 15 MPa concretes while this was splitting for all other cases.

The average bond strength ratio between coated and uncoated bar is found 0.85 for the embedded length of 75mm and that is 0.88 for 150mm embedded length. This indicates strength reduction is about 15% and 12% respectively. As with earlier test results for Ø16 mm and Ø20mm bars, it can be concluded that bond strength increase linearly with concrete strength as shown in Figures 9 and 10.

Table 5. Bond strength of 12mm bar (embedded 75 mm) in Φ100×200 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	P	11.31	0.85
	C	P	9.62	
C25	U	S	19.66	0.84
	C	S	17.68	
C35	U	S	21.29	0.86
	C	S	18.40	

Table 6. Bond strength of 12mm bar (embedded 150 mm) in Φ100×200 concrete cylinder

Concrete Grade	Bar type	Failure mode	Bond Strength, MPa	Bond Strength Ratio C/U
C15	U	P	16.98	0.88
	C	P	14.85	
C25	U	S	21.50	0.89
	C	S	19.45	
C35	U	S	24.75	0.88
	C	S	21.92	

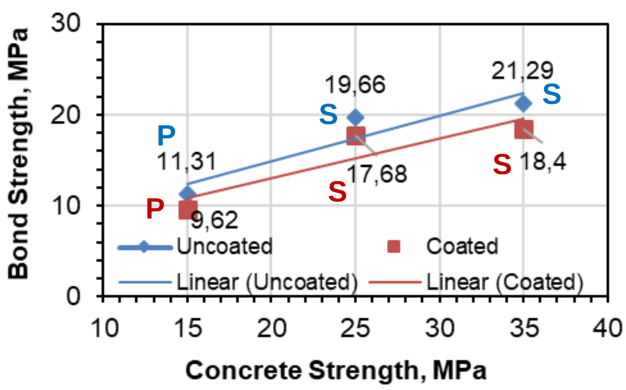

Figure 9. Variation of bond strength with different strength concrete (Ø12mm bar and 75mm embedded length)

However, the strength reduction is decreased with embedded length (Figure 11). The effect of embedment length on bond strength has been addressed in earlier (Kayali and Yeomans, 2000) studies which are in agreement with the results obtained in this study. Kayali and Yeomans (2000) also reported that the bond strength of Ø16mm black and galvanized steel are 19% and 26% greater than that of epoxy coated steel in concrete, respectively. The results are also consistent with the results of this study. It is observed that the strength reduction curves follow the same trend as before and are almost parallel to the horizontal axis which indicates that the strength reduction is independent of the concrete strength.

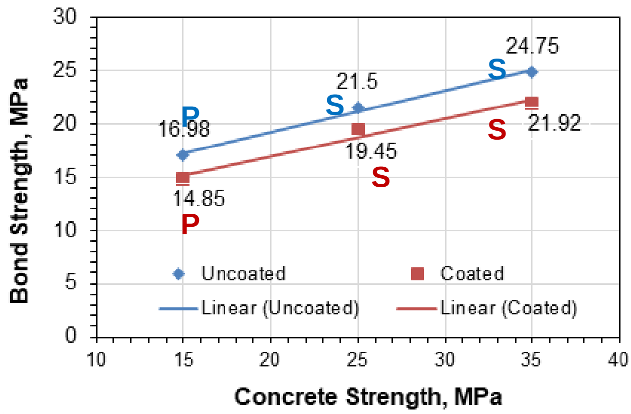

Figure 10. Variation of bond strength with different strength concrete (Ø12mm bar and 150mm embedded length)

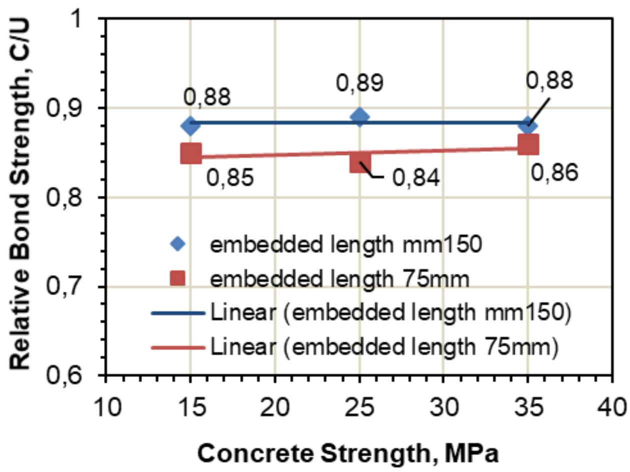

Figure 11. Reduction in bond strength with different embedded length (Ø12mm bar)

3.2 Bond Strength Reduction with Bar Size

The bond strength reductions remain almost the same for Ø12mm and Ø16mm bars, however, a sudden increase of bond strength reduction was found for the 20mm bar. From the analysis, it is seen that strength reduction is about 12% for both Ø12 mm and Ø16 mm bars at the embedded length of 150mm and 200 mm and 25% for 20mm diameter bar at the embedded length of 250mm. The strength reduction with the sizes of the bar is shown in Figure 12. This increase in bond strength reduction for higher diameter bar is mainly attributed to the thickness of the coating on the bar.

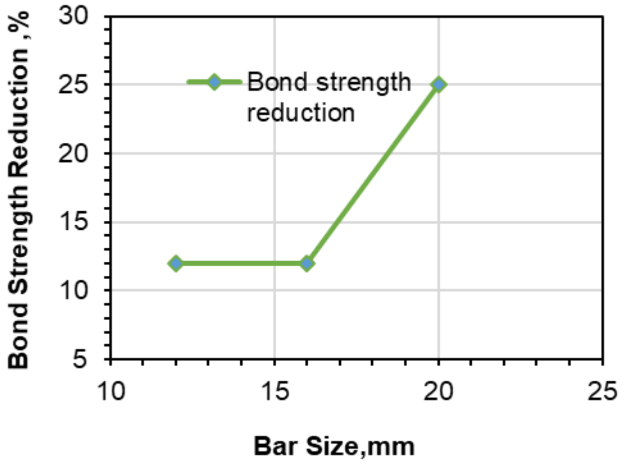

Figure 12. Bond strength reduction with bar size

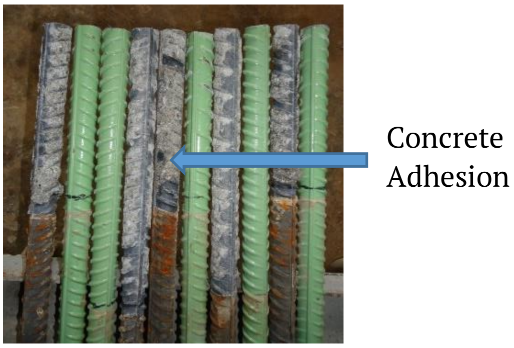

Figure 13. Ø20mm bar surface

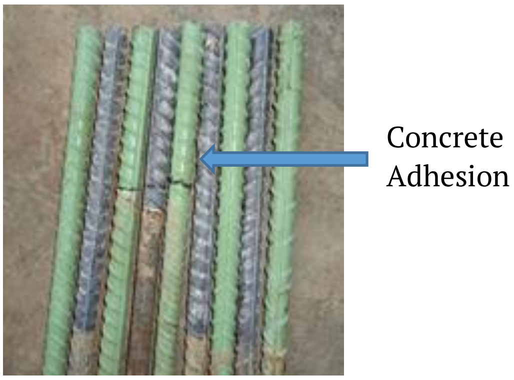

Figure 14. Ø16mm bar surface

It was reported (Miller, Kepler and Darwin, 2003) that the coating thickness has a significant impact on the reduction of bond strength. The coating thickness for 20mm diameter bar is about 16 mils (400μm) and for Ø12 and Ø16mm is about 7 to 12 mils (175 to 300μm).

Figure 15. Ø20mm bar Bond surface in cylinder specimen

One of the significant reason of an increase in bond strength reduction for larger diameter bar is the more adhesion property of uncoated larger diameter bar with concrete than uncoated lower diameter bar, but the adhesion property is almost same for all coated bars, which has observed after the pullout test. So the loss of adhesion is higher for Ø20mm bar than Ø12mm and Ø16mm bars. The relative adhesion property of uncoated bars is shown in Figures 13-16.

Figure 16. Ø16mm bar Bond surface in cylinder specimen

3.3 Loss of Adhesion

The loss of adhesion between epoxy-coated reinforcement and concrete has been documented (Kazakov and Yanakieva, 2009). The concrete in direct contact with epoxy-coated bars had smooth, glassy surface and coated bar appeared clean, with no concrete residual left on the rib dales (see Figures 17). On the other hand, the uncoated bar shown in Figure 17 has mortars attached on its surface indicating better adhesion between concrete and rebars.

The concrete surface in (refer to Figure 18) direct contact with the uncoated bar was dull and rough, and uncoated bars that were removed from the concrete had concrete particles attached to the shaft, deposited on rib dales (see Figure 19).

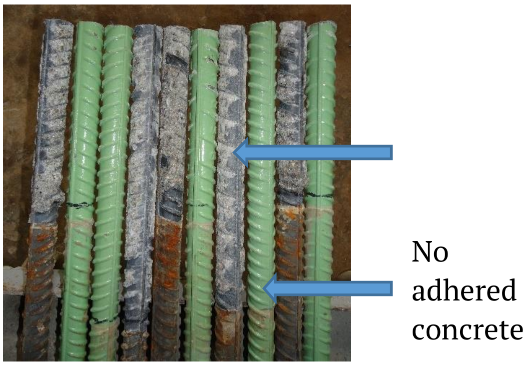

Figure 17. Steel Surface after pullout failure

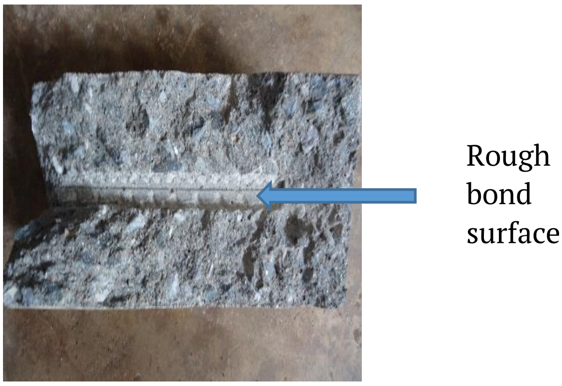

Figure 18. Concrete bond surface (uncoated)

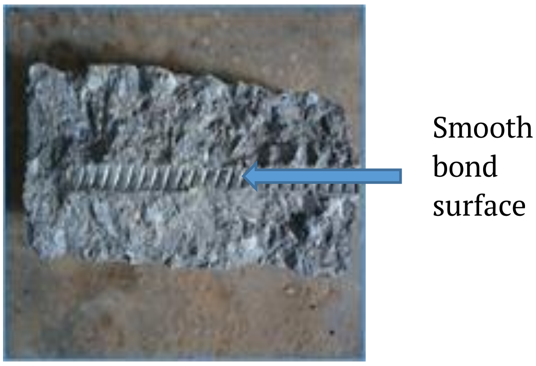

Figure 19. Concrete bond surface (coated)

4 CONCLUSION

Considering the type of deformation pattern, the type and the thickness of coating material the following conclusion can be drawn based on the results and analysis on the pullout test on coated and uncoated bars in concrete:

a) Bond strength reduction for 20mm diameter bar is approximately 33% and 25% at an embedded length of 150mm and 250mm; whereas for 16mm diameter bar the strength reduction is about 20% and 12% at embedded length of 100mm and 200mm; and for 12mm diameter bar the strength reduction is about 14% and 12% at embedded length of 75mm and 150mm respectively. It is concluded that the bond strength increases with embedded length.

b) Based on the larger embedded length, average strength reduction is 25% for Ø20mm bar and 12% for Ø16mm and Ø12mm bar i.e bond strength reduction varies with the bar size.

c) For all bar sizes considered in this study, the bond strength ratio between coated and uncoated bars slightly in different grade concretes i.e bond strength reduction due to coating is independent of concrete strength. However, for both coated and uncoated bars, the overall bond strength increased with the concrete strength.

d) Pullout failure occurs in low strength concrete and splitting failure occurs in high concrete strength.

The loss in bond strength due to the introduction of the epoxy coating was found to be within tolerable limit. By applying some design modification, it is possible to use the epoxy coated bar for durable reinforced concrete production. The development length could be increased to mitigate the loss of bond strength. Alternately, the manufacturer can use a relatively large rib bearing area by changing the bar deformation pattern, as the strength reduction decreases with the increase of rib bearing area (Choi *et al.*, 1991). To widespread the use of fusion bonded epoxy-coated bar the above factors should be considered during design.

5 DESIGN IMPLICATIONS

Based on the test results, to apply the epoxy-coated bars, a development length modification factor of 1.33 for Ø20mm bar and 1.15 for Ø16mm and Ø12mm are proposed from this study.

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