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Enhancement of the bond strength of epoxy coated steel by the addition of fly ash

W. Yeih [a,*], J.J. Chang [a], C.L. Tsai [b]

[a] Department of Harbor and River Engineering, National Taiwan Ocean University, 2 Pei-Ning Road, Keelung 202, Taiwan, ROC

[b] Department of Construction Engineering, National Yunlin University of Science and Technology, Touliu, Yunlin Hsien 640, Taiwan, ROC

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Abstract

In this paper, the bond strength of epoxy coated steel enhanced by the addition of fly ash added is examined. The experimental data shows that when the weight ratio of fly-ash/epoxy is 0.5 the largest improvement in bond strength is achieved. Other combinations using different weight ratios will result in bond improvement compared to a plain epoxy coating, but only specimens with a 0.5 fly-ash/epoxy weight ratio develop a bond strength at the level of that of uncoated rebar. Furthermore, it was found that the shear stiffness per length and the critical debonding shear force per length follow the same trend as bond strength.

Keywords: Bond strength; Fly ash; Epoxy coating

1. Introduction

Corrosion leads to serious damage when a reinforced concrete (RC) structure is exposed to a severe environment. Reducing the possible damage from corrosion is a very important issue to engineers. Several corrosion prevention methods have been studied and used in engineering practice, for example, corrosion inhibitors [1], cathodic protection [2] and coated rebar [3]. Among these methods, coated rebar is currently the most popular choice. For example, a report on the increasing use of coated rebar in North America can be found in the report by Manning [4].

Although coated rebar has been widely used for corrosion prevention, it has some inherent drawbacks that cause some researchers to have doubts about its use. One of the major problems for epoxy coated rebar is bond degradation between the bar and the concrete. Bond between rebar and concrete is a major factor in RC design and this property relates to the force transmission between the concrete and rebar. Some design parameters, for example the development length, strongly relate to the bond strength. As reported in many research articles [5–7] the bond strength of coated rebar will have a 15–50% reduction compared to bare steel rebar, and accordingly there is a suggested modified parameter in the ACI building code [8] and ASSHTO regulations [9]. However, modifying a design parameter such as the development length sometimes requires using additional rebar. From an economic point of view, this is not necessarily efficient.

Unlike other researchers who attempted to determine how much bond strength reduction the epoxy coating will induce, we have considered another direction to recover the bond strength loss by improving the performance of the coating materials themselves [10]. Previous studies [10,11] have shown that adding sand into the epoxy can increase the bond strength, the extent of this depending on the weight percentage and the nominal size of the sand used [11]. Furthermore, we have shown that when the size of the sand is the same the shape of the sand particles dominates the efficiency of bond strength improvement [12]. Sands with more irregular shape contribute much more interlocking effect and consequently result in a greater improvement in bond strength.

In this study, the sand was replaced by fly ash. Fly ash particles generally have a size of about 20 μm, with a hollow spherical shape. From our previous experience using sand [11,12], it was not expected that a significant

* Corresponding author. Fax: +886-2-24632932.
E-mail address: wcyeih@mail.ntou.edu.tw (W. Yeih).

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bond strength improvement would be obtained by adding fly ash into the epoxy coating. This is because the fly ash particles do not have as strong a mechanical friction property as sand nor a size large enough to produce a wedge effect to increase the interlock force. However, it was hoped that the pozzolanic characteristics of the fly ash would increase the mechanical behavior. A single rebar pullout test [13–15] was performed to evaluate the bond characteristics such as the bond strength, the shear stiffness per unit embedded length and the critical debonding force per unit embedded length.

2. Experimental

2.1. Materials

A unified concrete mix of w/c ratio equal to 0.62 was used, the details of which are listed in Table 1. The average 28-days compressive strength of the concrete was 23 MPa. Number rebar 4 made by Taiwan Steel Company was used with a Young's Modulus (E_f) of 203 GPa and a typical yield strength of 409 MPa. The geometrical properties of the rebar are shown in Table 2. The fly ash was Class F and its physical and chemical properties are tabulated in Table 3. The epoxy used was Ameron Amerlock 400®.

Table 1
Mix design for concrete (w/c = 0.62)

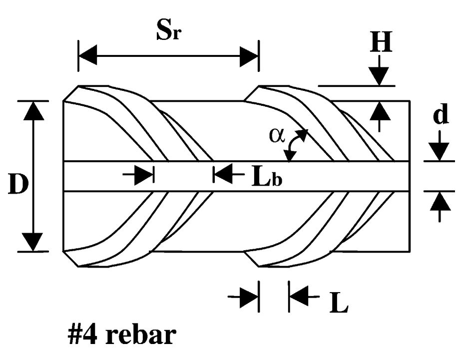
Material	Mix proportions (kg/m^3)
Water	193
ASTM type I cement	311
Sand	889
Coarse aggregate	971

2.2. Variables design and parameters measured

In this study, the main issue to be examined was the bond strength improvement achieved by adding fly ash into the coating composite. For simplicity, it was preferred to maintain the concrete and epoxy material with properties unchanged. Therefore, as stated in Section 2.1, only one concrete mix design was chosen. To keep the epoxy coating material unchanged, a single epoxy formulation was used and the coating thickness was controlled such that direct bond strength comparisons could be made. For this reason, a coating thickness of 250 ± 30 μm was chosen. By keeping other factors unchanged, different amounts of fly ash were added into the epoxy coating material by weight ratios of fly-ash/epoxy varying from 0 (plain epoxy coating) to 0.1, 0.3, 0.5, 0.7 and 1. Above a weight ratio combination of 1, the composite (epoxy and fly ash) became hard to mix uniformly.

During the specimen pullout tests, the pullout load values and slip displacement values of the rebar were

Table 2
Configuration of #4 rebar



Typical cross-sectional area (cm^2)	1.19
D (mm)	12.30
d (mm)	3.99
L_r (mm)	1.36
L_b (mm)	2.24
H (mm)	0.74
α (deg)	66
S_r (mm)	8.23

Table 3
Chemical and physical properties of fly ash

The main chemical composition of fly ash (weight percentage)	$SiO_2 + Al_2O_3 + Fe_2O_3$	86.94%
	CaO	0.45%
	MgO	0.40%
	K_2O	1.07%
	Na_2O	0.27%
Physical properties	Specific weight	2.06
	Water content	0.53%
	Ignition loss	7.50%

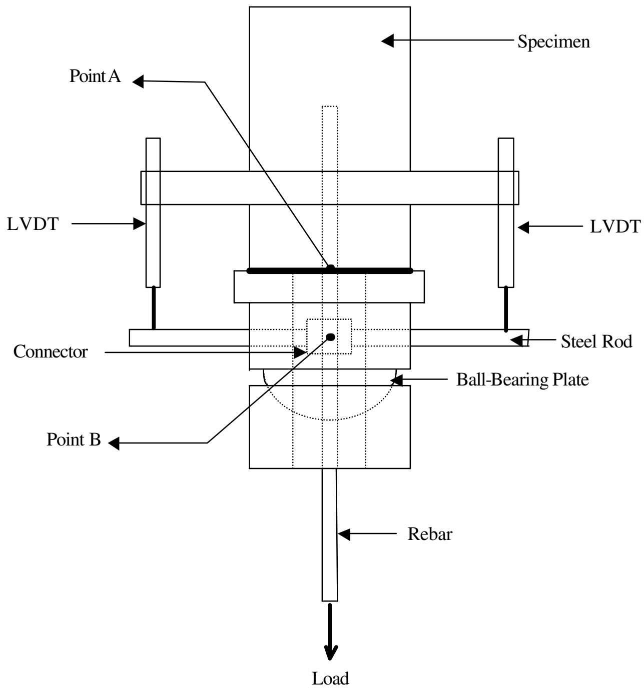


Fig. 1. Displacement measurements for rebar near the concrete surface.

recorded. As shown in Fig. 1, the average displacement value from two LVDTs represents the slip displacements at the point of connection to the rebar. This location may vary from one experiment to another. To have the same displacements, a modified formula such as [16] can be used:

$$U_{\mathrm{cal}} = U_{\mathrm{measured}} - \frac{PL_{\mathrm{off}}}{E_{\mathrm{f}}A_{\mathrm{f}}} \tag{1}$$

where U_{cal} is the calculated displacement of point A on the rebar, which just near the concrete surface as shown in Fig. 1; U_{measured} is the measured displacement at the point of the clipping point B in Fig. 1; P is the pullout load; L_{off} is the offset length, the distance between points A and B; E_{f} is the Young's Modulus of the rebar and A_{f} is the nominal cross-sectional area of the rebar.

A typical pullout force versus displacement curve is given in Fig. 2. There exist three stages in the pullout test. In the first stage, the load and displacement maintains a linear proportional relationship and no debonding occurs in this stage. The slope of P/U is then called the shear stiffness, K_{s}. The shear stiffness increases as the embedded length of the rebar increases, and thus the value K_{s} is not a constant. In [13], a parameter called the shear stiffness per length is defined as

$$K = \frac{K_{\mathrm{s}}}{L_{\mathrm{emb}}} \tag{2}$$

where K is the shear stiffness per unit embedded rebar length and L_{emb} is the embedded length of the rebar. It is

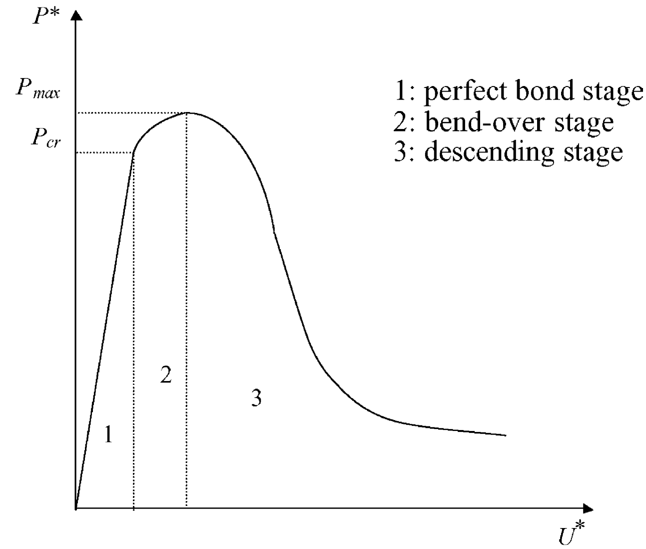


Fig. 2. A typical pullout load diagram versus displacement curve.

shown in [13] that this parameter is constant while the rebar geometry is unchanged. After a critical load, P_{cr}, the curve turns over such that the stiffness is lost. This critical load also depends on the embedded length. For the same reason, the definition in [13] is used to define the critical shear debonding load per unit embedded length q_y as

$$q_y = \frac{P_{\mathrm{cr}}}{L_{\mathrm{emb}}} \tag{3}$$

The second stage is called the bend-over stage due to its curve shape. The load then increases to the maximum, P_{max}, with significant slip occurring. From the maximum pullout load, the bond strength can be defined by dividing P_{max} by the nominal embedded area of the rebar. After the maximum pullout load, the curve descends as shown in Fig. 2. This stage is called the descending stage.

The above-mentioned three parameters were used in this study to evaluate the bond characteristics.

2.3. Preparation of pullout specimens and experiments conducted

The rebar was cleaned using #200 sandpaper to remove surface rust before coating. Different composite coating materials were prepared by mixing varying amounts of fly ash into the epoxy as previously noted. The coating was applied to the surface of each rebar using a paint brush. The coated rebar was then cured at 200 °C for 1 h to achieve the best coating properties according to manufacturer's suggestions. To ensure coating thickness control, for each specific group of designated variables 20 rebar were painted and the coating thickness of each was measured at 30 points. Eight rebar with the required thickness range for the experimental requirements were selected as pullout specimens.

Previous experience indicated that if the embedded length was too long, unwanted splitting failure of the concrete might occur. To guarantee a sliding failure along the interface, the embedded length was only 4 cm, determined from preliminary tests. The exact embedded length of each specimen was measured individually. The specimens were cast in steel molds and demolded after 24 h and cured in lime-saturated water for 28 days. To ensure the position of the rebar, a stabilizing device was used to locate the rebar. After the curing process, the specimens were then loaded into a testing machine. The machine loaded the rebar at a rate of 1.27 mm/min. The pullout displacement and force were measured using LVDTs and a load cell, and recorded using a data acquisition system. In order to calculate the desired displacement, as mentioned in Section 2.2, the offset length L_{off} was recorded for each specimen. For each group, once an unwanted splitting failure occurred in a specimen, it was discarded from that group. Among all eight specimens, six had the desired pullout failure. Six specimens from successful trials in one group were used to obtain the average bond characteristics for a specific group. Furthermore, a statistical analysis was carried out to obtain the standard deviations in various bond characteristics.

3. Results and discussion

3.1. The bond strength

The average bond strength for uncoated rebar was reported as 7.43 MPa with a standard deviation of 0.17 MPa. The average bond strength for plain epoxy coated rebar was about 6.52 MPa with a standard deviation of 0.19 MPa. It can be seen that there is a 12% decrease in the average bond strength when epoxy-coated rebar was used. The bond strengths for various fly ash–epoxy coating materials are shown in Fig. 3. In this figure, the dotted line is the average bond strength for bare steel rebar and the solid line is the average bond strength for plain epoxy coated rebar. The symbols represent the average value for various groups with numerical values nearly. The values in the bracket are standard deviations. From this figure, it can be seen that for the 0.5 weight ratio of fly-ash/epoxy group, the average bond strength for coated rebar is at or above the level of the bare steel rebar. Although the average bond strength value for the 0.5 weight ratio of fly-ash/epoxy group is a little higher than that for the bare steel rebar, it can only be said that a recovery in bond strength to the level of the bare steel rebar using 0.5 fly-ash/epoxy combination had been achieved. For other weight ratios, the average bond strengths all show some improvement with a maximum effect at about the 0.5 fly-ash/epoxy weight ratio. Considering the standard deviations, it could be inferred that the use of fly-ash/epoxy weight ratios in the range 0.3–0.7 can improve the bond strength.

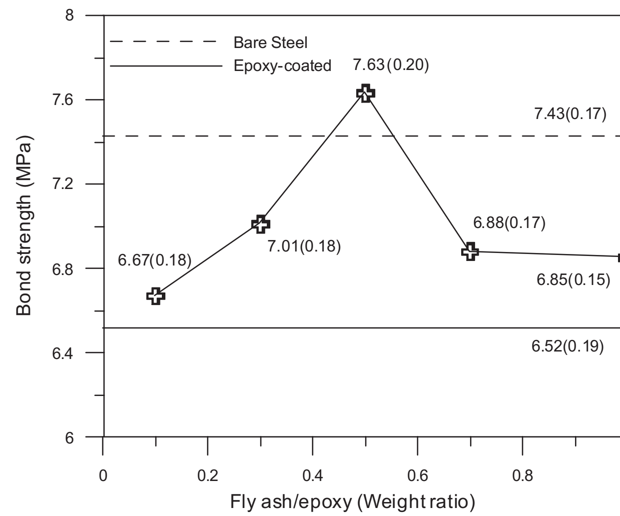


Fig. 3. Bond strength comparison for various coatings.

The trend seen in Fig. 3 can be explained as follows. To improve the coating property, additions of a better-behaved particle can be made to the coating to form a composite. From the point of composite materials, once such a particle is added the property should be improved as the volume fraction of the particle increases, provided that the composite is sound. From this point of view, one can claim that if the presence of foreign particles increases the mechanical behavior, such a composite should be better. Nevertheless, one condition is very important, that is the composite should be sound. This means that the binding force between the epoxy and the foreign particles should be perfect. However, as the volume fraction of foreign particles increases, the amount of epoxy available may not be enough to cover each particle such that the composite becomes unsound and the mechanical strength decreases as a result. According to this, when the amount of particles exceeds a critical value, the bond strength starts to decrease as the amount of particles increases. These results thus indicate that a weight ratio of fly-ash/epoxy of 0.5 is the optimal mix proportion for bond strength improvement.

As explained earlier, fly ash is a small size particle (usually around 20 μm) and has a hollow spherical shape. It may be expected that these characteristics may reduce the friction effect and produce little contribution to the interlock force. However, once the fly ash reacts with the CH (calcium hydroxide) to form CSH gel, it contributes to the mechanical behavior considerably. Such a reaction is known as the pozzolan reaction [17]. In order to demonstrate that the pozzolan reaction is what allows fly ash to improve the bond strength, another group of samples, a sandwich type fly ash–epoxy coating, was prepared. For these samples, epoxy was first brushed onto the rebar, and then fly ash was added into the fresh epoxy. Finally another layer of epoxy was brushed on top to prevent any fly ash contact with the concrete. The weight ratio of fly-ash/epoxy for this group was selected at 0.3 and the coating thickness was also kept within the range required. By comparing this group with the previous 0.3 weight ratio group, the uniformly mixed fly ash–epoxy composite, it can be seen in Fig. 4 that this sandwich type group produced a worse average bond strength value than the plain epoxy coated rebar with a 13.7% decrease in the average bond strength compared to bare steel rebar. This means that when the fly ash does not have a chance to react with CH, adding fly ash into the coating material has no effect at all. From this, it can be concluded that the reason why adding fly ash can improve the coating property mainly comes from the chemical (pozzolan) reaction, not a mechanical contribution.

3.2. *The shear stiffness per unit length and critical debonding shear force per unit length*

The variation in shear stiffness per unit length, K, showed a similar trend as the bond strength, as illustrated in Fig. 5. For the range of samples used, a weight ratio of fly-ash/epoxy of 0.5 was optimal, which was similar to that of bond strength. The critical debonding shear force per unit length, q_y, showed a similar trend (Fig. 6). The critical debonding shear force per unit length, q_y, represents the binding soundness for the concrete to rebar. When a plain epoxy coating is applied, the value of q_y drops which means that the binding characteristics decrease. However, when fly ash is added appropriately to the coating, additional chemical binding force contributed from the pozzolan reaction increases the binding capacity for the coating. The shear stiffness per unit length, K, represents the rigidity of this composite to an applied load. It thus appears that appropriately adding fly ash can improve the stiffness of the coating.

To verify that the improvement of adding fly ash in the epoxy derives from the pozzolan reaction of fly ash, the shear stiffness per unit length (K) as well as the critical debonding shear force per unit length (q_y) for the sandwich type fly ash–epoxy coating and uniformly mixed specimens are compared as shown in Figs. 7 and 8, respectively. It can be found that the shear stiffness

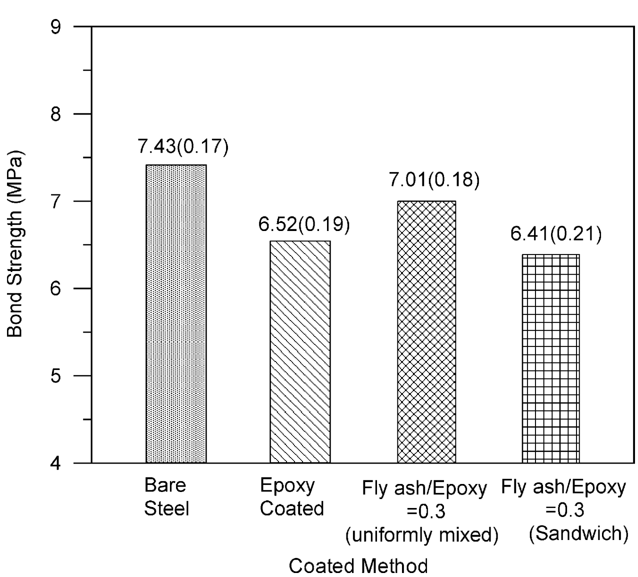


Fig. 4. Bond strength comparison for uniformly mixed coating composite and sandwich type coating composite.

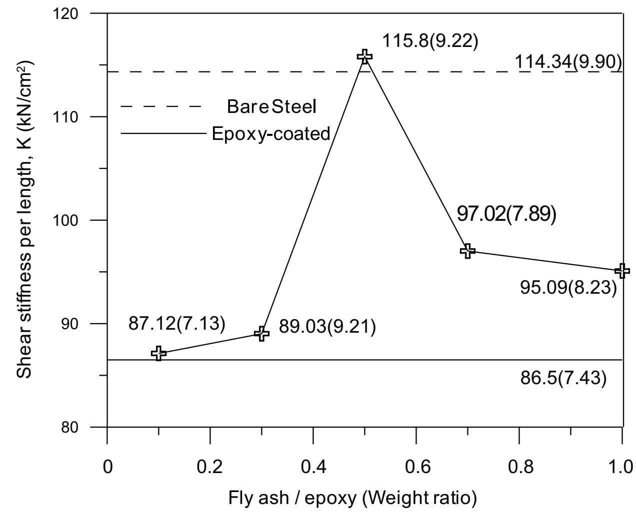


Fig. 5. The shear stiffness per unit length, K, versus various weight ratios.

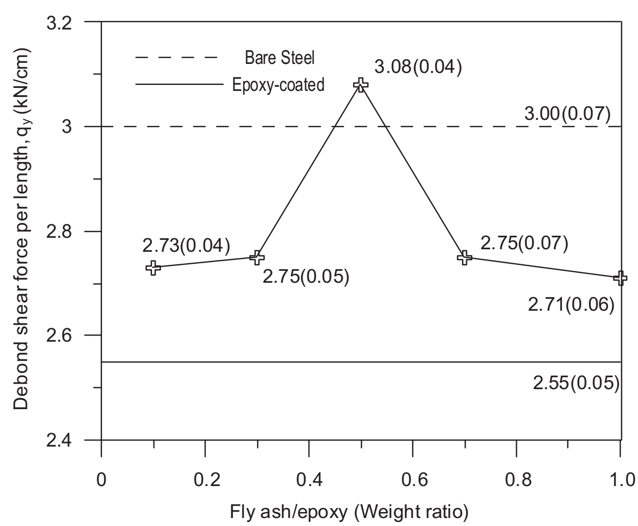


Fig. 6. The critical debonding shear force per unit length, q_y versus various weight ratios.

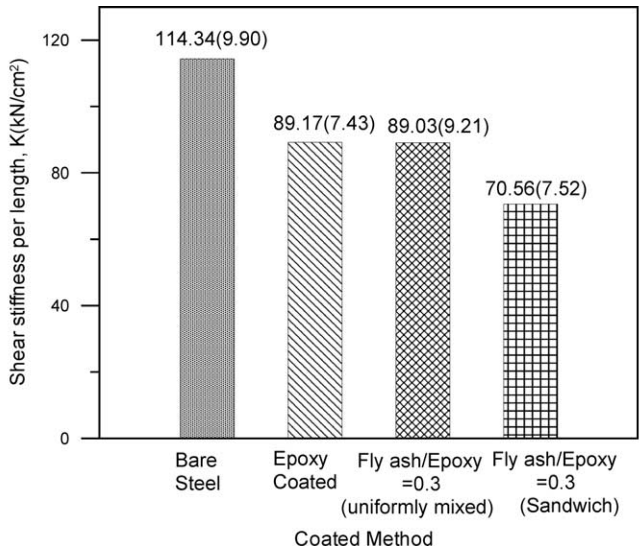


Fig. 7. A comparison of K for uniformly mixed coating composite and sandwich type coating composite.

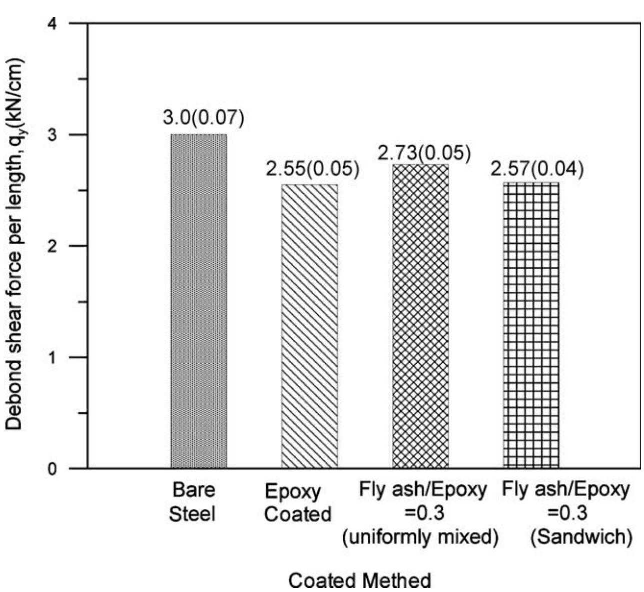


Fig. 8. A comparison of q_y for uniformly mixed coating composite and sandwich type coating composite.

per unit length of the uniformly mixed fly ash–epoxy coating group is close to that of plain epoxy coated rebar. However, the sandwich type fly ash–epoxy coating group shows the lowest overall value. For the critical debonding shear force per unit length, the value of sandwich type coating is close to that of plain epoxy coating but the uniformly mixed type coating has a higher value. Remember that q_y represents the chemical binding force for the coating, and so it can be concluded that adding fly ash into the epoxy enhances the chemical binding characteristic of the coating. These results also indicate that the pozzolan reaction of fly ash is the major mechanism to enhance the bond quality.

4. Conclusion remarks

In this study, fly ash was added into an epoxy coating to improve the bond characteristics. It was found that the bond strength, the shear stiffness per length and the critical debonding shear force per length all had the same trend. At ratios of fly-ash/epoxy below 0.5, increasing the amount of fly ash produced a higher value for each bond parameter. However, above 0.5 weight ratio, this trend was reversed. From the experimental results, a weight ratio of 0.5 can improve the bond strength to a level at or above that of bare steel rebar. These results thus indicate that 0.5 weight ratio is a critical parameter for fly ash addition to the epoxy coating. Further, it was verified that the bond improvement of fly ash derives mainly from its pozzolan reactions with CH in concrete.

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