

Experimental Investigation on Steel-Concrete Bond in Lightweight and Normal Weight Concrete

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Abstract. The bonding behaviors of Lightweight Aggregate Concrete (LWAC) and normal weight concrete were investigated experimentally. Pullout tests were carried out to measure the bond strengths of three groups of specimens with compressive strength levels of 60, 40 and 20 MPa, respectively.

Test results have shown that the difference of the bond failure pattern between the LWAC and normal weight concrete is significant as the compressive strength of concrete is less than 40 MPa. The corresponding bond strengths of LWAC are lower than those of normal weight concrete. As the compressive strength of concrete is relatively high (> 40 MPa), the bond failure pattern of normal weight concrete is similar to that of LWAC. The bond strengths of LWAC will be higher than those of normal weight concrete because it possesses higher mortar strength. Finally, the use of stirrups leads to about a 20 % increase in the nominal bond strength for both types of concrete at any strength level.

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1. Introduction

The bond strength of reinforced concrete is composed of chemical adhesion between concrete and reinforcing bars, the friction resistance, and mechanical interaction between steel and concrete (Lutz and Gergely 1976). Chemical adhesion mechanism is aroused firstly and prevents slip after loading. Slip was occurred after adhesion is destroyed. Then, the other two kinds of bonding mechanisms, the friction resistance and mechanical interlocking resistance, start to work (Chinn et al. 1955, Eligehausen et al. 1982). At this moment, slip between the reinforcing bars and concrete was occurred, even the splitting of concrete can be observed. In theory, the bond stress should not be over-adhesive or it will lead to permanent deformation or cracks radiating from the reinforcing bars lugs (Kenneth 1991).

The bond failure of steel bars in LWAC is different from that in normal weight concrete. The major difference is that normal weight concrete failure first occurs at the interface of coarse aggregate and mortar. The natural aggregate is not easy to break, so it will cause shear failures in the mortar or fail in interface between mortar and aggregate. However, the strength of lightweight aggregate is quite low. Lightweight aggregate will be broken if it cannot resist the reinforcing bar's rib support (Robins and Austin 1986, Mor 1992, Wilson and Malhotra 1988). Therefore, for ordinary strength concrete, the bond strength of normal

weight concrete is better than that of LWAC. It does not mean that bond strength of normal weight concrete is also better as the concrete strength is higher. Because high-strength LWAC possess high mortar strength (Chen et al. 1999), it can promote the resistance to the bar lugs.

2. Experimental program

Three concrete compressive strength levels, 20, 40 and 60 MPa were chosen for LWAC and normal weight concrete and expanded clay coarse lightweight aggregate was used in LWAC. The mix proportions of LWAC and normal weight concrete are shown in Table 1. The properties of normal and lightweight coarse aggregate are shown in Table 2 and Table 3, respectively. The compressive strength of concrete was measured on 100 × 200 mm cylinders. Six specimens were made for each group for a total of 36 specimens, three specimens were tested for monitor concrete strength at 7 day age, and other specimens were tested with pullout test together. The test methods followed ASTM specifications.

The pullout test uses a 150×150×150 mm standard pullout specimen with No.6 deformed steel bar. The installation of stirrups (No.3 deformed steel bar) is shown in Fig.1. The stirrup spacing (d) is

30, 45 and 60 mm. Three specimens are made for each group for a total of 72 specimens. Also specimens with no stirrups were tested. The pullout test was performed in accordance with ASTM C234 (apparatus is shown in Fig. 2). Specimens were cured in a curing room and then taken out to air dry one day before the tests.

3. Discussion of results

3.1. Concrete compressive strength

The compressive strengths of the 3 groups of concrete made with normal and lightweight coarse aggregate are shown in Table 4. The test results show, at 20 MPa and 40 MPa strength levels, the concrete strengths are close to the target strengths. At 60 MPa strength level, the strength values (approximately 53 MPa) are less than the value of prediction. Comparison of the LWAC strengths and the normal weight concrete strengths shows that the two results are close and acceptable.

3.2. Observation on bond stress-slip curve

The bond stress and slip between steel bar and concrete were recorded by DATA ACQUISITION CONTROLLER 7V14. Measured

slip includes parts of elastic deformation of steel bar. But two LVDTs were fixed on steel bar and closed to the concrete surface only have 5 mm distance, so the elastic deformation was neglected in analysis. Test datum can be drawn the average bond stress-slip diagrams that are shown in Fig. 3.

From the Figure 3 it can be seen that the ultimate slip is a variation from 0.8 mm to 2.5 mm for non-stirrup specimens and there is a variation in the ultimate bond stress from 9.0 MPa to 16.5 MPa. For stirrup specimens, the ultimate slip and the ultimate bond stress both increase conspicuously. The ultimate slip varies from 1.7 mm to 6.8 mm and the ultimate bond stress varies from 12.6 MPa to 20.7 MPa. Whether arranged stirrups in specimens or not, the ultimate slip and the ultimate bond stress both increase with increasing of concrete compressive strength. From the Figure 3, it can also be shown that there is superior modulus of toughness (entire area under the average bond stress-slip diagram) for pull-out specimens with higher concrete strength. As arranged stirrups in pull-out specimens, LWAC specimens enhanced 2~3 times modulus of toughness, and NWC specimens raised 2~4 times.

From observed the development of the average bond stress-slip curve, as concrete compressive strength is low level (near 20 MPa level), the development of the average bond stress-slip curve approximates parabolic curve that is similar to the stress-strain curve of concrete. As the concrete strength attains to 60 MPa level, the development of the average bond stress-slip curve is similar to steel stress-strain curve that has a yield point. As concrete strength is low, the concrete deformation is larger than steel deformation when pull-out specimens have failed. So, the measured slip

main controlled by the concrete deformation. This is a chief reason that the average bond stress-slip curve is similar to the stress-strain curve of concrete. High concrete strength leads to enhancement of concrete allowable stress. The steel stress is increase with increasing of concrete allowable stress. Before bond failure, steel has yielded already and gradually elongate owing to yielding. Therefore, as concrete strength is high, the average bond stress-slip curve is similar to steel stress-strain curve.

It can also seen that all the yield points occur at bond stress arrive at 13 MPa no matter concrete compressive strength and whether arranged stirrups in specimens. If the ultimate bond stress cannot reach to 13 MPa, the specimen will not have the state of yield. The main reason is that the bond yield strength only correlates with steel quality. And all specimens used the same 6# steel bars in this study. Regardless of concrete compressive strength, the requirement of yield load is same for pull-out specimens.

3.3. Bond failure pattern

Generally, bond failure can be divided into two modes—side-split failure and shear pullout failure. Side-split failure occurs when the wedging action of the steel lugs on a deformed bar causes cracks in the surrounding concrete. If the lugs crush the concrete by bearing, a shear pullout failure without splitting the concrete is called shear pullout

failure.

The test result shows that the failure modes of non-stirrup specimens of LWAC and normal weight concrete are the side-split failure type. The difference of bond failure patterns between the LWAC and normal weight concrete, whether high or low strength concrete, is that LWAC cracks through the aggregate, so that the bond failure surface of the concrete is smoother, see Figure 4(b) and Figure 4(d). However, in low-strength normal weight concrete (< 40 MPa), most of natural aggregate are not broken and a rough bond failure surface appears along the interface of aggregate and mortar (Figure 4(a)). On the contrary, if the strength of normal weight concrete is high (> 40 MPa), the natural aggregate displays a failure pattern like lightweight aggregate, and the condition of the failed surface is similar to LWAC (see Figure 4(c)). The difference of bond failure patterns between LWAC and normal weight concrete is similar to the difference of compression failure patterns.

Stirrup specimens of LWAC and normal weight concrete appear shear pullout failure (Figure 5). As the concrete strength is relatively low (< 40 MPa), a rough bond failure surface appears in normal weight

concrete and the bond failure surface of LWAC is smoother. As the concrete strength is high (> 40 MPa), the bond failure pattern of normal weight concrete is similar to that of LWAC, aggregate will break first and then the reinforcing bar would be pulled out.

3.4. Bond strength

Literature (Mathey et al. 1961) suggests that when the bar slides 0.01in (0.254 mm) at loading end, bond stress reaches critical bond strength levels. Critical bond strength is mainly related to chemical adhesion force. When bond stress reaches critical bond strength, the interface between the reinforcing bar and concrete do not reach failure (the adhesion mechanism failed but have not crack happen) and can still resist external forces until the ultimate bond stress, called nominal bond strength.

Critical bond strength and nominal bond strength can be measured on the average bond stress-slip curve (is shown in Fig. 3) of the pullout test. The results are shown in Fig. 6 to Fig. 11. Each statistic in the figures is the average of three test results. Fig. 6 shows that there is no obvious difference of critical bond strength (at the same concrete

strength level) in various stirrups spacing (d), whether the normal weight concrete or the LWAC. The reason is that critical bond strength is governed by adhesive force. Even when the stirrup is installed, it does not increase the adhesion between the reinforcing bar and concrete. As a result, no matter how wide the stirrup spacing, it does not influence critical bond strength much. However, Fig. 7 shows that after being installed, the stirrups in the normal weight concrete and LWAC, nominal bond strength are 20 % higher than the one without stirrups. The outcome indicates that the stirrups will generate the bonding effect of the concrete, so the concrete can resist higher stress and promote nominal bond strength. Besides, the stirrups in the concrete also absorb the stress of the concrete to resist crack extension.

The results of Figs. 8 and 9 shows that the critical bond strength and nominal bond strength of LWAC are lower than those of normal weight concrete as the concrete compressive strengths are less than 40 MPa. The critical bond strength and nominal bond strength of LWAC are similar to those of normal weight concrete as the concrete compressive strengths are approximately 40 MPa. The bond strengths of LWAC are higher than those of normal weight concrete as concrete are

in high strength level (> 40 MPa). The result indicates that the bond strength of high-strength LWAC is not inferior to that of similar level strength normal weight concrete. Moreover, it is superior to normal weight concrete.

Fig. 8 also shows that the critical bond strengths increase with an increase of concrete strength. In the case of LWAC, the increase tendency of the critical bond strength behaves relatively stronger. As aggregate possesses little adhesion, this increase tendency is considered mostly contributed by the increase of mortar adhesion (strength). Since the rib support resistance of mortar is highly related to the mortar strength, it is then believed that the increase of the rib support resistance of mortar will behave in a similar tendency.

The normalized bond strength results are shown in Fig. 10, as the concrete compressive strengths are less than 40 MPa, the bond strength provided by normal weight concrete per unit compressive strength is higher than LWAC, but when in medium or high strength (≥ 40 MPa) concrete, the result is the opposite. As observed from failure patterns, all lightweight aggregate in LWAC have aggregate shear failure whether the LWAC are in high or low strength level. This signifies that the rib

support resistance of lightweight aggregate is weak and that the rib support resistance of mortar primarily provides the bond strength of LWAC. In the general strength (< 40 MPa) case, most normal weight aggregate at bond failure surface are not broken and the aggregate can provide higher rib support than lightweight aggregate. Therefore, it promotes whole bond strength. When in high-strength concrete, the failure pattern of normal weight concrete is similar to that of LWAC. Both have the results of aggregate failure and the rib support provided by the aggregate is relatively low. The main control factor of bond failure in both concrete is mortar. For high-strength concrete, the higher mortar strength of LWAC resulted in the larger bond strength of LWAC.

3.5. Bonding behavior of concrete

As mentioned in the previous study (Chen et al. 1999), with the same extent of concrete strengths, the mortar strength of LWAC is higher than that of normal weight concrete. Thus, the mortar of LWAC provides higher rib support resistance and further lead to larger bond strength. As the concrete strength increases, this effect becomes more

significant. Fig. 9 depicts qualitatively the variations of rib support resistance with respect to the strengths of aggregate and mortar for normal and lightweight concretes. Conceptually, the total rib support resistance of concrete is contributed by those from the mortar and aggregate. As the rib support resistance of aggregate remains roughly unchanged, the variation of rib support resistance of concrete is dominated by that of the mortar resistance. Since the increase tendency (associated with the increase of concrete strength) of mortar resistance for LWAC is more significant than that of normal weight concrete, as already discussed in the previous section, the total rib support resistance of LWAC can exceed that of normal concrete as the concrete strength is relatively high. For high strength concrete, consequently, the bond strength of LWAC can become larger than that of normal weight concrete.

4. Conclusions

Using two different types of coarse aggregates in various strength concrete mixtures, the test results show that the aggregate types and concrete compressive strength influenced the bonding behaviors of

concrete. The conclusions can be summarized as follows:

- (1). The nominal bond strength of normal weight concrete and LWAC could increase approximately 20 % by adding stirrups and the influence of stirrups to critical bond strength is less.
- (2). While concrete strength is less than 40 MPa, the bond failure surface of LWAC through lightweight aggregate. The bond failure surface of normal weight concrete along the surface of aggregate, and most aggregate are not broken. The corresponding bond strengths of LWAC are relatively lower than those of the normal weight concrete.
- (3). As the compressive strength of concretes is relatively high (> 40 MPa), the bond failure pattern of LWAC is similar to that of normal weight concrete. The bond strengths of LWAC will be higher than those of normal weight concrete because it possesses higher mortar strength.
- (4). In high-strength concrete, the rib support resistance of aggregate is relatively weak; the rib support resistance of mortar primarily provides the bond strength of reinforced concrete. This effect is significant in LWAC.

References

- Chinn, J., Feruson, P.M., and Thompson, J.N., "Lapped Splices in R.C. Beam, "ACI Journal, V.52, No.2, Oct. 1955, PP.201-214.
- Eligehausen, R., Popov, E.P., and Bertero, V.V., "Local Bond Stress-Slip Relationships of Deformed Bars under Generalized Excitations," V.4, Proceedings of the Seventh European Conference on

Earthquake Engineering, Athens, Sept. 1982, PP.69-80.

H.S. Wilson and M. Malhotra, "Development of high strength lightweight Concrete for Structural application," International Journal of Cement Composites and lightweight Concrete, May 1988, PP.79-90.

H.J. Chen, T. Yen, T.P. Lia, Y.L. Huang, "Determination of the dividing strength and its relation to the concrete strength in lightweight aggregate concrete, "Cement and Concrete Composites, V.21, 1999, PP.29-37.

Kenneth Leet, "Reinforced concrete design," Second Edition, McGraw-Hill, Inc., 1991, PP.231-242.

Lutz, L. A. and P. Gergely, "Mechanics of Bond and Slip of Deformed Bars in Concrete, "ACI Journal, Proceeding, V.64, No.11, PP.711-721, Nov. 1976.

Mor, A., "Steel-Concrete Bond in High-Strength Lightweight Concrete," ACI Materials Journal, Jan.-Feb. 1992, PP.76-82.

Robins, P. J., and Austin, S. A., "Bond of Lightweight Aggregate Concrete Incorporating Condensed Silica Fume," Fly Ash, Silica Fume, slag and Natural Pozzolans, ACI, Detroit, PP.941-958, 1986.

Mathey, R. G., and Watstein, D., "Investigation of Bond in Beam and Pullout Specimens with High-Yield –Strength Deformed Bars," ACI Journal, Vol.57, No.9, pp.1071-1090, March 1961

Table 1 Mix proportions of concrete (1m³)

LWAC	W/C	Cement (Kg)	Water (Kg)	Natural sand (Kg)	LWA (Kg)			S.P. (Kg)	Absorption (30min) (Kg)
					3/4"~1/2"	1/2"~3/8"	3/8"~#4		
L20	0.65	297	194	734	179	213	175	0	29
L40	0.40	480	194	664	166	197	162	0	29
L60	0.26	580	151	760	0	207	277	19	19
Normal Concrete	W/C	Cement (Kg)	Water (Kg)	Natural sand (Kg)	Coarse aggregate (Kg)			S.P. (Kg)	Absorption (30min) (Kg)
N20	0.70	280	197	781	1056			0	—
N40	0.48	410	196	672	1056			0	—
N60	0.42	450	189	659	1056			4.5	—

L40 : Lightweight aggregate concrete at a 40 MPa strength level

N60 : Normal weight concrete at a 60 MPa strength level

S.P. : Superplasticity

Table 2 Properties of natural aggregate

	Specific gravity (S.S.D.)	Absorption (%)	Bulk gravity (kg/m ³)	Fineness modulus
Coarse aggregate	2.62	1.19	1544.51	-
Natural sand	2.64	0.60	-	2.67

Table 3 Properties of lightweight aggregate

Grading	(kg/m ³)	Absorption (30 minutes, %)	Absorption (24 hours, %)
3/4"~1/2"	1461	8.77	13.47
1/2"~3/8"	1304	3.13	7.76
3/8"~#4	1430	5.12	8.92

Table 4 Concrete compressive strength

Curing days	20 MPa level		40 MPa level		60 MPa level	
	LWAC (MPa)	NWC (MPa)	LWAC (MPa)	NWC (MPa)	LWAC (MPa)	NWC (MPa)
7	19.6	19.5	39.9	37.8	43.3	45.3
	23.1 (21.7)	19.1 (20.0)	39.8 (39.6)	41.3 (39.4)	45.4 (44.3)	43.5 (44.7)
	22.5	21.5	38.9	39.2	44.3	45.4
28	26.9	24.6	43.2	44	51.9	52.4
	27.5 (27.4)	23.7 (23.1)	44.6 (43.5)	44.6 (43.7)	52 (51.9)	54 (53.8)
	27.8	22.4	42.9	42.9	-	54.9

(21.7) : the value is an average value.

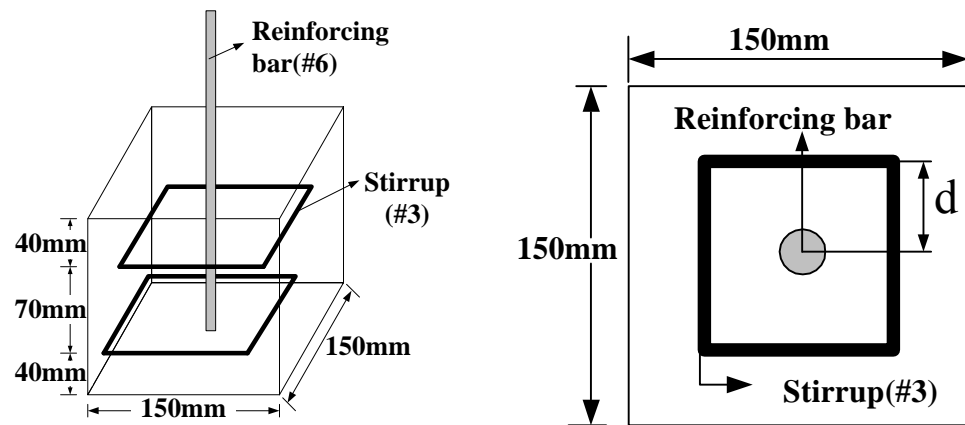


Figure 1 Test specimen

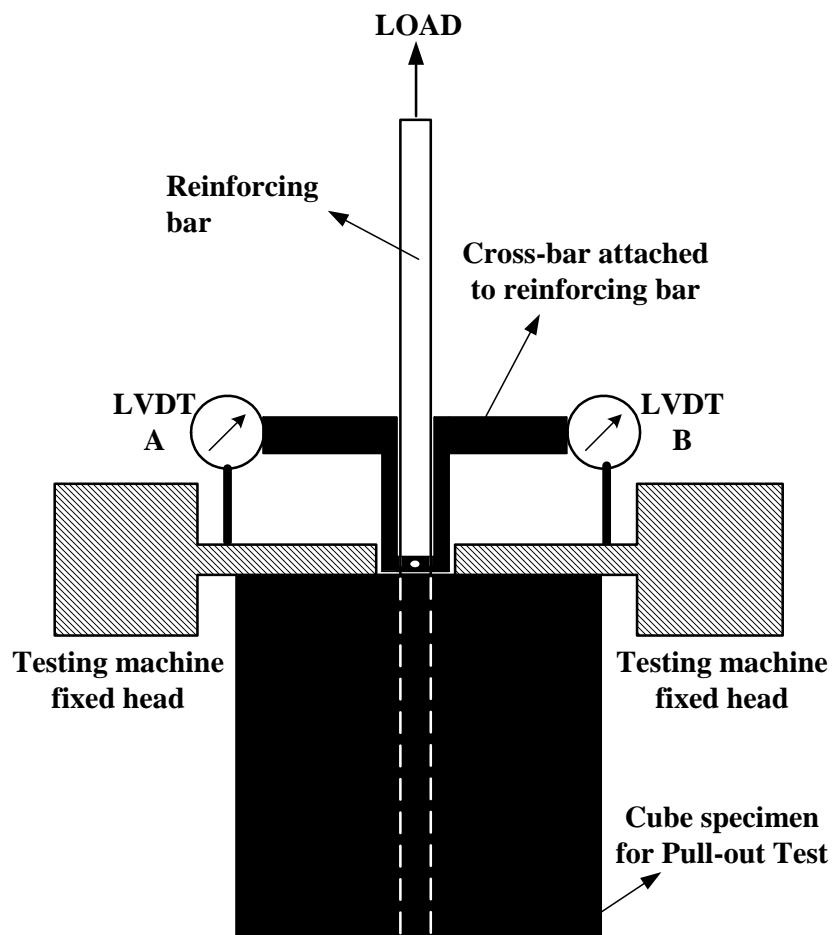
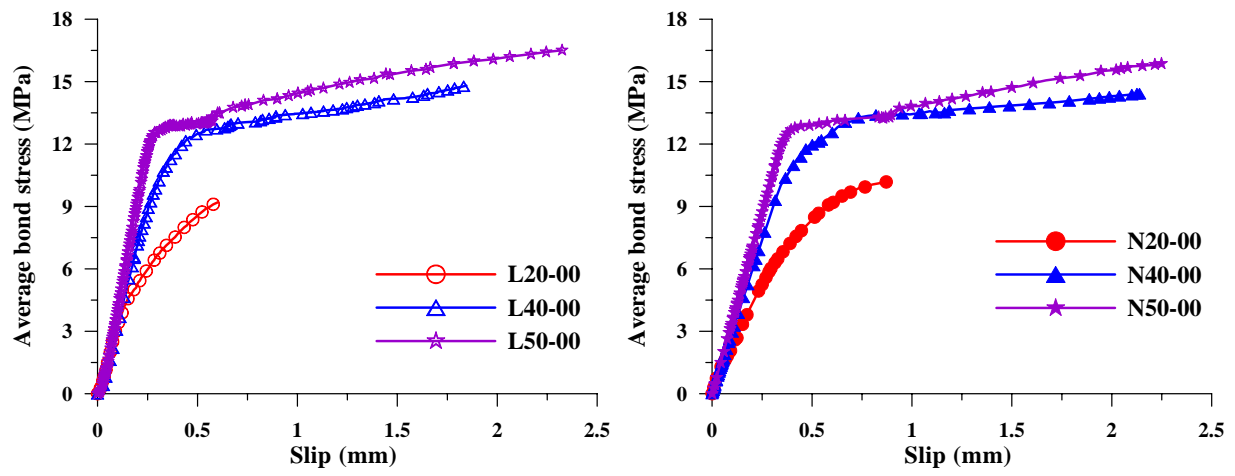
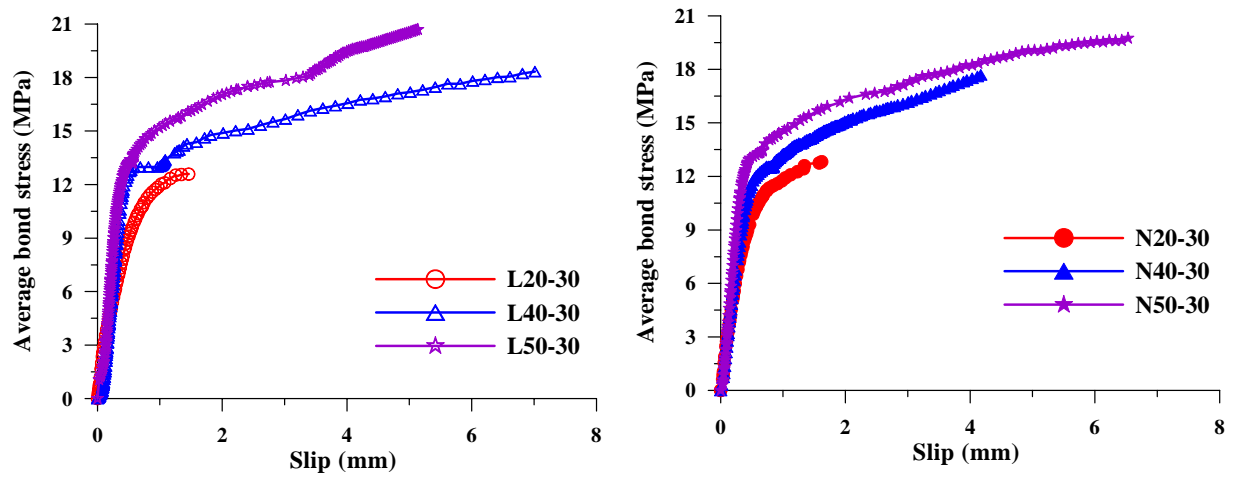


Figure 2 Apparatus used for Pullout test



(a) Bond specimens without stirrup

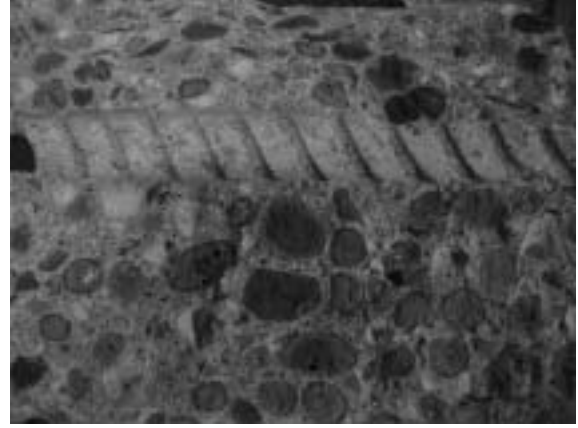


(b) Bond specimens with stirrup (d=30)

Figure 3 Average bond stress-slip curves



(a)Low-strength normal weigh concrete



(b)Low-strength lightweight aggregate concrete



(c)High-strength normal weigh concrete



(d)High-strength lightweight aggregate concrete

Figure 4 Maps of the failed surface



Figure 5 Comparisons of the failed specimens

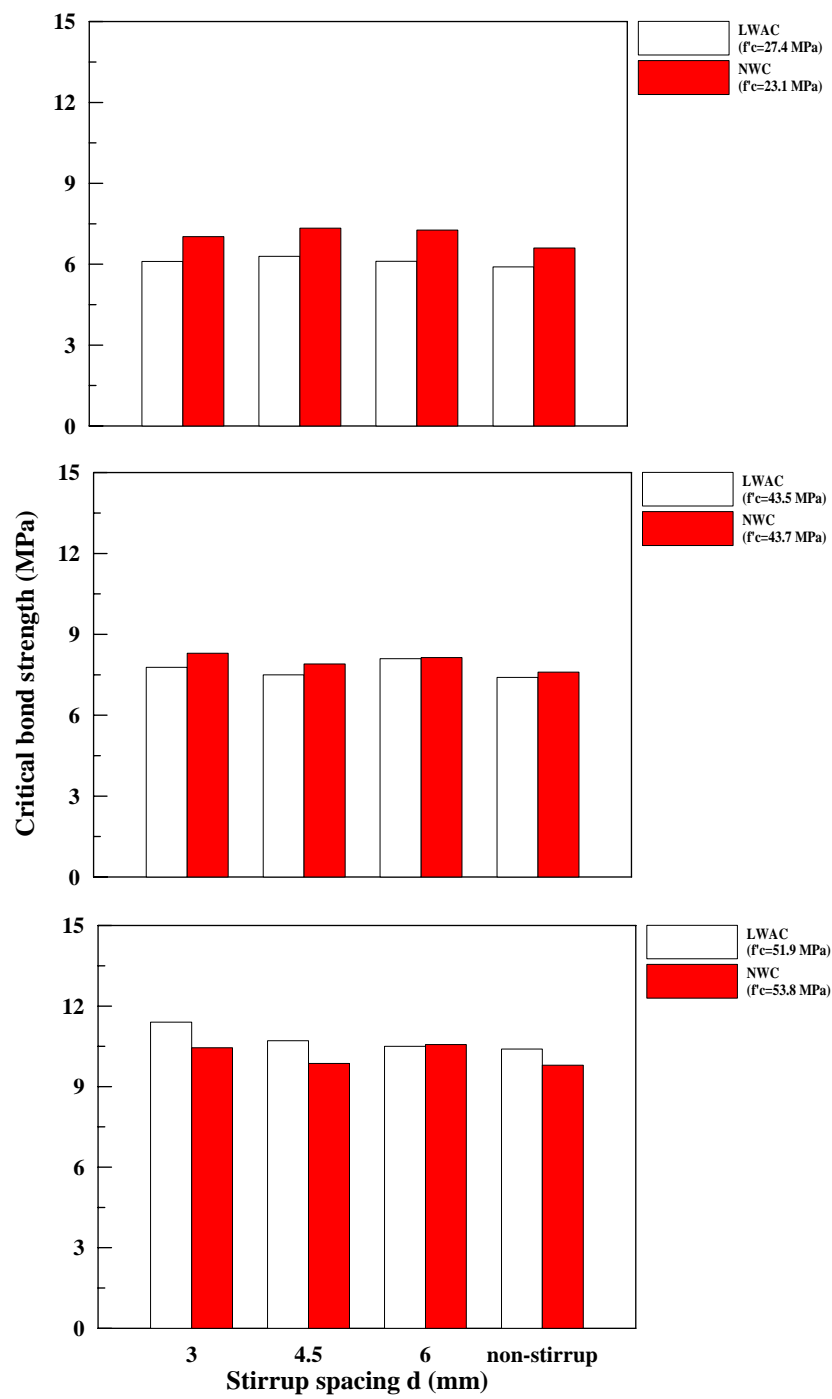


Figure 6 Relationship between critical bond strength and stirrup spacing

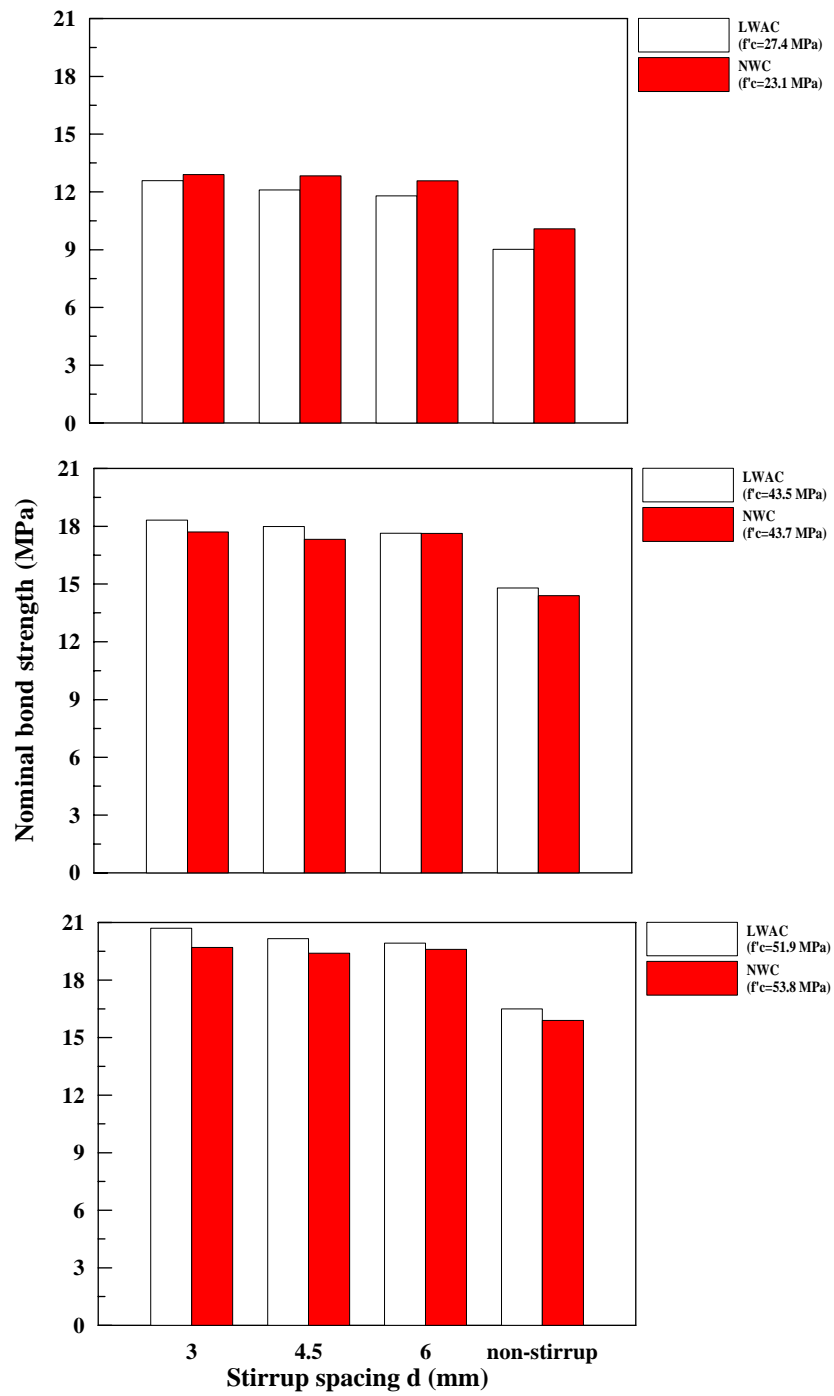


Figure 7 Relationship between nominal bond strength and stirrup spacing

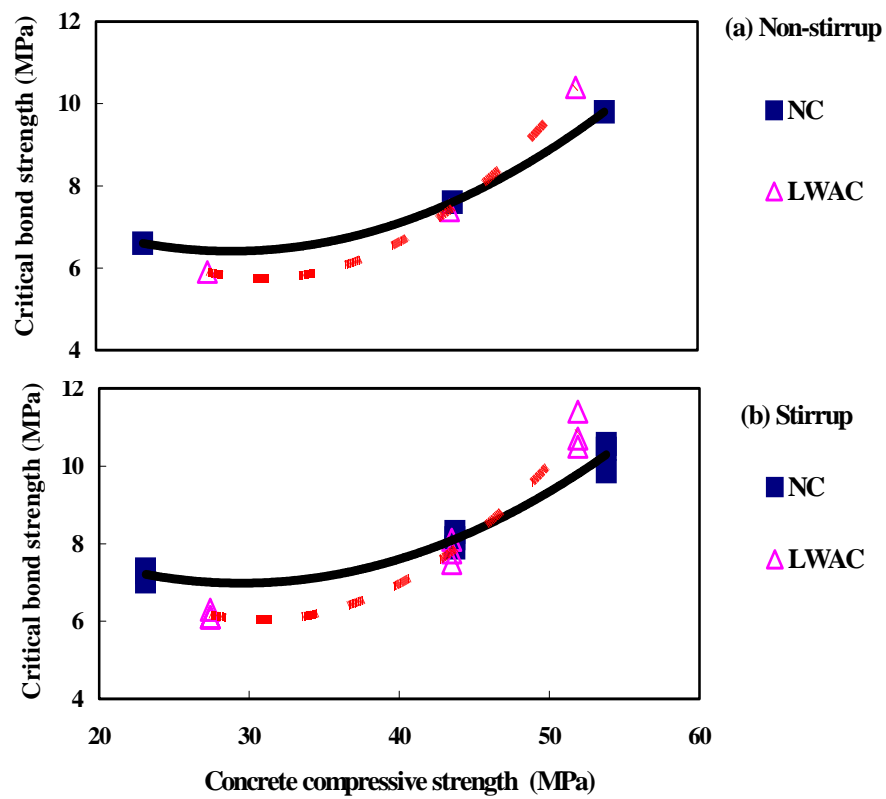


Figure 8 Relationship between critical bond strength and compressive strength

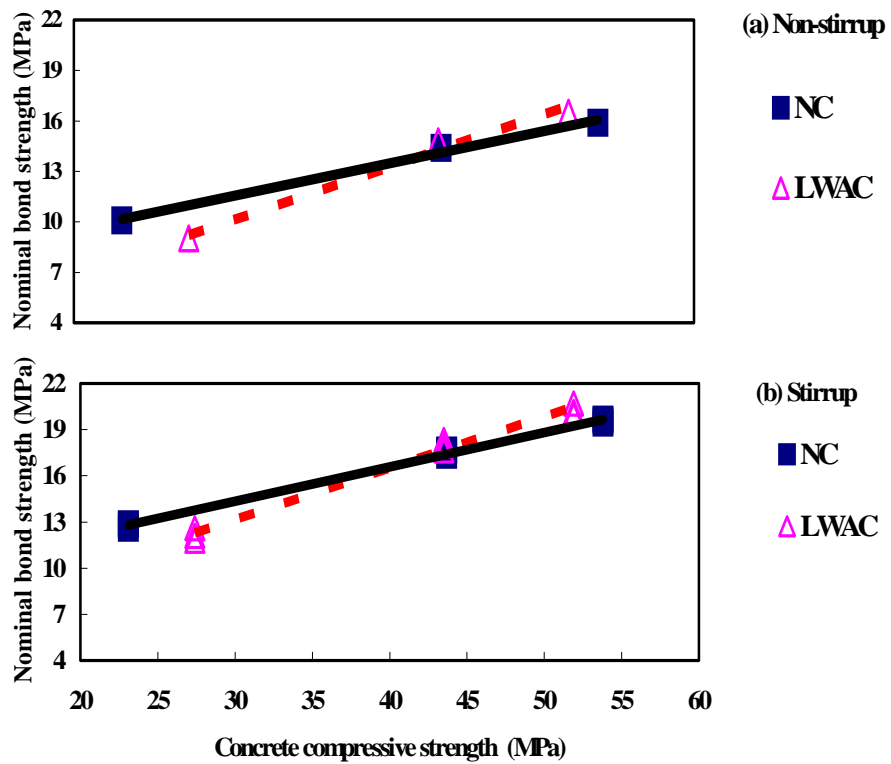


Figure 9 Relationship between nominal bond strength and compressive strength

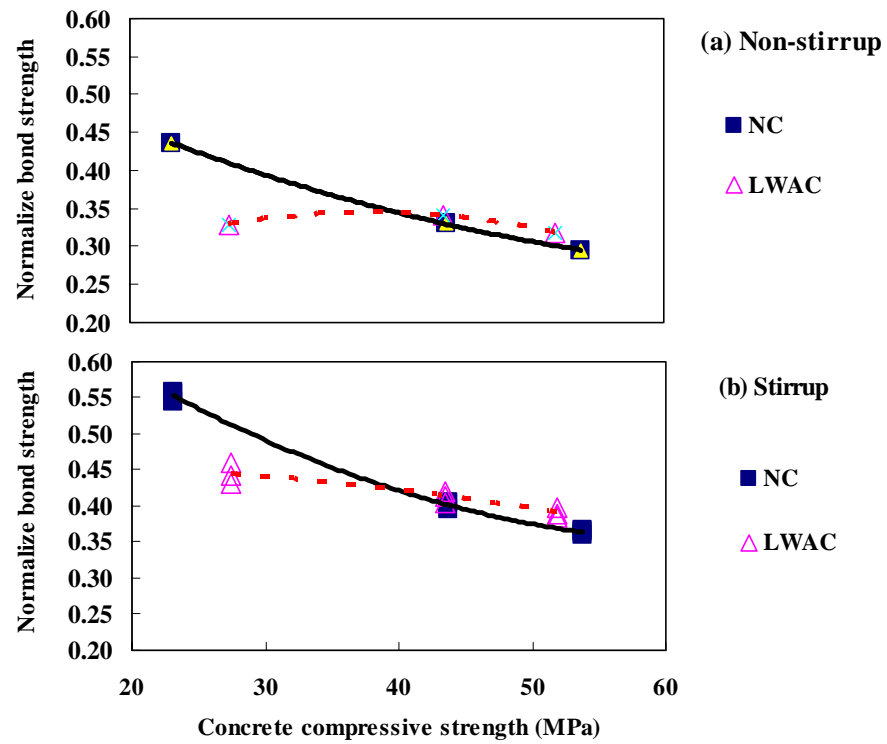


Figure 10 Normalized bond strength in relation to compressive strength

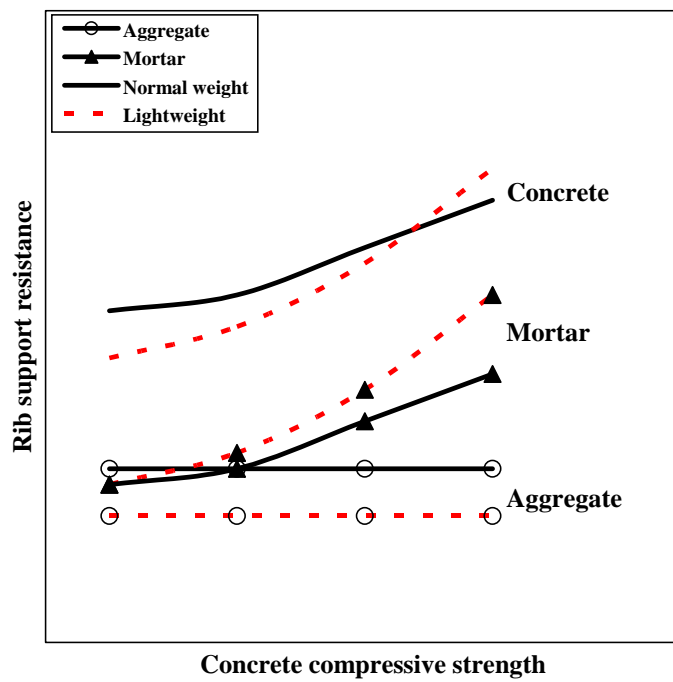


Figure 11 Development of rib support resistance

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