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# 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. Pull-out 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 showed that the difference in the bond failure pattern between LWAC and normal weight concrete was significant as the concrete compressive strength became lower than 40 MPa. The corresponding bond strengths of LWAC were lower than that for normal weight concrete. As the compressive strength of concrete became relatively high (> 40 MPa), a bond failure pattern in normal weight concrete occurred that was similar to that in LWAC. The bond strength of LWAC is higher than that for normal weight concrete because it possesses higher mortar strength. Stirrup use leads to an increase of approximately 20% in nominal bond strength for both types of concrete at any strength level.

**Key words:** lightweight concrete; bond strength; concrete strength; mortar strength.

## 1. Introduction

The bond strength of reinforced concrete is produced by chemical adhesion between the concrete and reinforcing bars, the friction resistance and mechanical interaction between steel and concrete (Lutz and Gergely 1976). The chemical adhesion mechanism is aroused first and prevents slip after a load is applied. Slip occurs after adhesion is destroyed. The other two kinds of bonding mechanisms, friction resistance and mechanical interlocking resistance, then begin to work (Chinn *et al.* 1955, Eligehausen *et al.* 1982). Slip can occur between the reinforcing bars and concrete. Concrete splitting can also 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 occurs first 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 the interface between the mortar and aggregate. However, the strength of lightweight aggregate is quite low. Lightweight aggregate will be broken if it cannot resist the

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reinforcing bar's wedging action (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. This does not mean that the bond strength of normal weight concrete becomes better as the concrete strength becomes higher. Because high-strength LWAC possess high mortar strength (Chen *et al.* 1999), it can promote resistance to bar lug stress.

In this study, a series of experiments using standard pull-out specimens at various concrete strengths were conducted. From the bond stress-slip curve and failure pattern results, the difference in bond mechanism between LWAC and normal weight concrete could be investigated.

## 2. Experimental program

Three concrete compressive strength levels, 20, 40, and 60 MPa were chosen for LWAC and normal weight concrete and the expanded clay coarse lightweight aggregate used in the LWAC. The LWAC and normal weight concrete mix proportions are shown in Table 1. The normal and lightweight coarse aggregate properties are shown in Tables 2 and 3, respectively. The compressive strength of the concrete was measured using 100Ψ × 200 mm cylinders. Six specimens were made for each group for a total of 36 specimens. Three specimens were tested to monitor the concrete strength at an age of seven days. Other specimens were tested when the pull-out specimens were tested. The test methods followed ASTM specifications.

Table 1 Mix proportions of concrete (1 $m^3$)

| LWAC | W/C | Cement (Kg) | Water (Kg) | Natural sand (Kg) | LWA (Kg) | | | S.P. (Kg) | Absorption (30 min) (Kg) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 13~19 (mm) | 9~13 (mm) | 5~9 (mm) | | |
| 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 (30 min) (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

| Item | 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 | Particle Density ($kg/m^3$) | Absorption (30 minutes, %) | Absorption (24 hours, %) |
|---|---|---|---|
| 13 $^{mm}$ ~ 19 $^{mm}$ | 1461 | 8.77 | 13.47 |
| 9 $^{mm}$ ~ 13 $^{mm}$ | 1304 | 3.13 | 7.76 |
| 5 $^{mm}$ ~ 9 $^{mm}$ | 1430 | 5.12 | 8.92 |

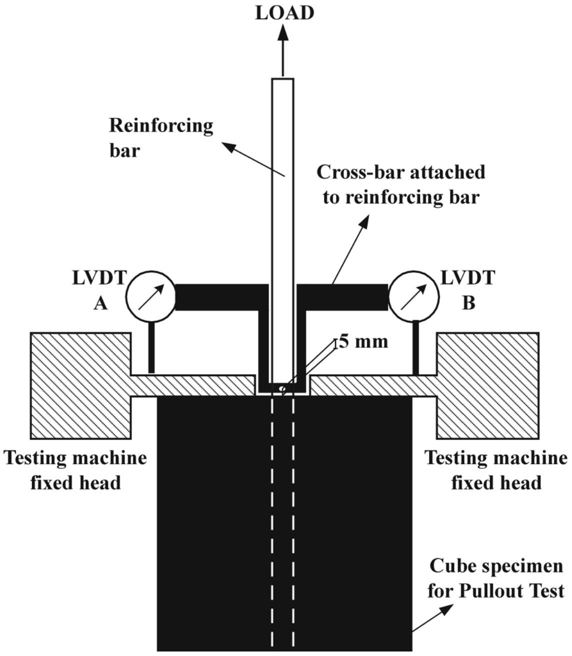


Fig. 1 Apparatus used for Pull-out test

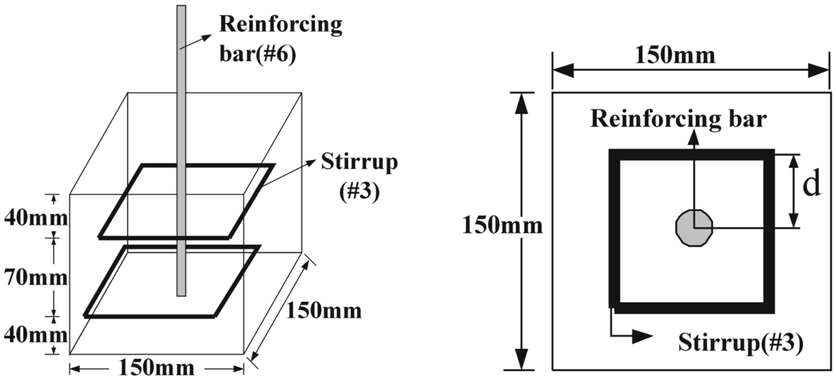


Fig. 2 Test specimen

The pull-out tests were performed in accordance with ASTM C234 on a 150 × 150 × 150 mm standard pull-out specimen with a No. 6 steel bar (the apparatus is shown in Fig. 1). The stirrup

Table 4 Properties of steel bars

| Numbers | Nominal diameter (mm) | Yielding strength (MPa) | Ultimate strength (MPa) |
|---|---|---|---|
| NO.3 | 9.5 | 281 | 476 |
| NO.6 | 19 | 420 | 680 |

installation (No. 3 deformed steel bar) is shown in Fig. 2. The properties of the steel bar are shown in Table 4. The stirrup spacing was fixed at 70 mm. The distances (d) of the stirrup legs from the bar were 30, 45, and 60 mm. The bar was bonded along the entire 150 mm cube side length. Specimens with no stirrups were also tested ($d = \infty$). Three specimens were made for each group, for a total of 72 specimens. Specimens were cured in a curing room and 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 5. 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 predicted value. Comparison of the LWAC strengths and normal weight concrete strength shows that the two results are close and acceptable.

### 3.2 Bond stress-slip curve

The bond stress and slip between steel bar and concrete were recorded using a 7V14 DATA ACQUISITION CONTROLLER. Measured slip included the elastic deformation of the steel bar. Because the LVDTs were fixed onto the steel bar and only a 5 mm distance from the concrete surface (shown in Fig. 1), the elastic deformation was small enough to be neglected.

Table 5 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 | (21.7) | 19.5 | (20.0) | 39.9 | (39.6) | 37.8 | (39.4) | 43.3 | (44.3) | 45.3 | (44.7) |
| | 23.1 | | 19.1 | | 39.8 | | 41.3 | | 45.4 | | 43.5 | |
| | 22.5 | | 21.5 | | 38.9 | | 39.2 | | 44.3 | | 45.4 | |
| 28 | 26.9 | (27.4) | 24.6 | (23.1) | 43.2 | (43.5) | 44 | (43.7) | 51.9 | (51.9) | 52.4 | (53.8) |
| | 27.5 | | 23.7 | | 44.6 | | 44.6 | | 52 | | 54 | |
| | 27.8 | | 22.4 | | 42.9 | | 42.9 | | - | | 54.9 | |

※(21.7): The value is an average value.

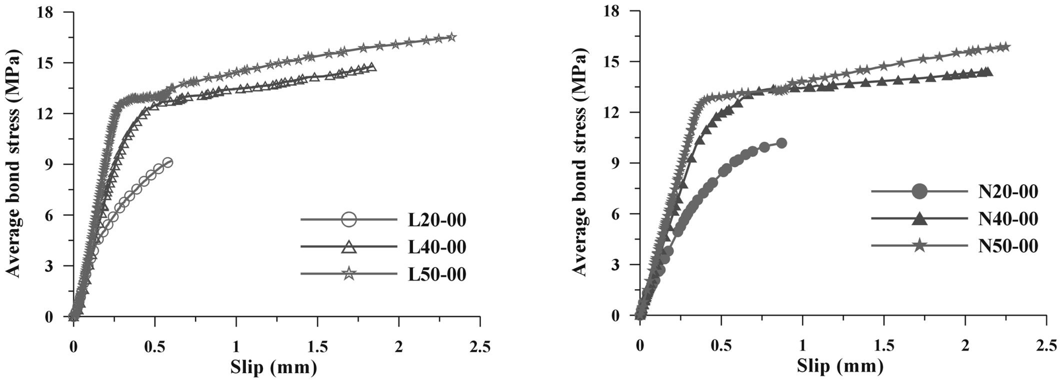
Table 6 Test results of pull-out specimens

| Item | Distance of stirrup d(mm) | Critical bond strength (0.01” slip)(MPa) | Ultimate bond strength (MPa) | Ultimate slip (mm) | Fail mode |
|---|---|---|---|---|---|
| L20 | 30 | 6.1 | 12.6 | 1.46 | P |
| | 45 | 6.3 | 12.1 | 1.37 | P |
| | 60 | 6.1 | 11.8 | 1.20 | S |
| | ∞ | 5.9 | 9.0 | 0.60 | S |
| L40 | 30 | 7.8 | 18.3 | 5.22 | P |
| | 45 | 7.5 | 18.0 | 4.77 | P |
| | 60 | 8.1 | 17.6 | 3.29 | S |
| | ∞ | 7.4 | 14.8 | 1.85 | S |
| L60 | 30 | 11.4 | 20.7 | 5.14 | P |
| | 45 | 10.7 | 20.2 | 6.85 | P |
| | 60 | 10.5 | 19.9 | 5.98 | S |
| | ∞ | 10.4 | 16.5 | 2.32 | S |
| N20 | 30 | 7.0 | 12.9 | 1.62 | P |
| | 45 | 7.3 | 12.8 | 1.45 | P |
| | 60 | 7.3 | 12.6 | 1.30 | S |
| | ∞ | 6.6 | 10.1 | 0.87 | S |
| N40 | 30 | 8.3 | 17.7 | 4.17 | P |
| | 45 | 7.9 | 17.3 | 5.16 | P |
| | 60 | 8.1 | 17.6 | 4.56 | S |
| | ∞ | 7.6 | 14.4 | 2.14 | S |
| N60 | 30 | 10.4 | 19.7 | 6.53 | P |
| | 45 | 9.9 | 19.4 | 6.33 | P |
| | 60 | 10.6 | 19.6 | 6.10 | S |
| | ∞ | 9.8 | 15.9 | 2.24 | S |

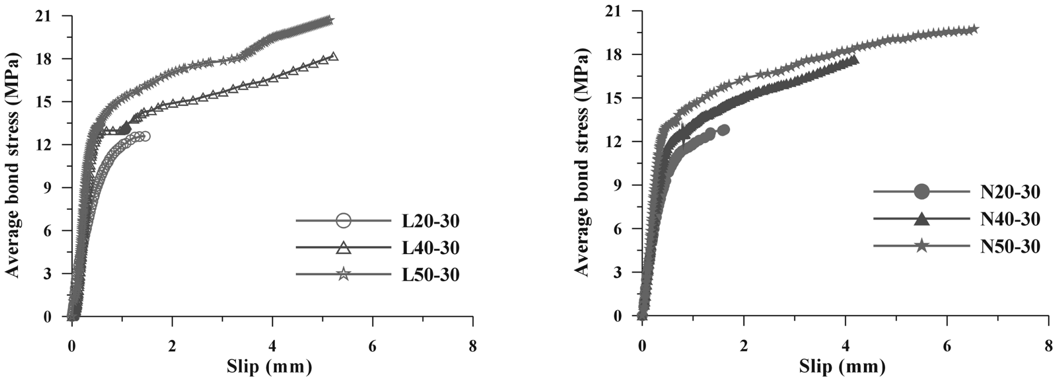
∞ *: Non-stirrup P: shear Pull-out failure S: side-Split failure

The results of pull-out tests were presented in Table 6. The Table shows that the ultimate slip values are from 0.60 mm to 2.32 mm for non-stirrup specimens and the ultimate bond stress values are from 9.0 MPa to 16.5 MPa. For stirrup specimens, the ultimate slip and the ultimate bond stress both increased significantly. The ultimate slip varied from 1.00 mm to 6.83 mm and the ultimate bond stress varied from 12.1 MPa to 20.7 MPa. The bond behaviors of LWAC and normal weight concrete, as revealed by the test results, are discussed below.

From the average bond stress-slip curve (shown in Fig. 3), a yielding point can be found when the concrete compressive strength is high (at 60 MPa level) that is different to that of lower strength concrete. As the concrete strength is low, the stress in the steel is small and is still under elastic limit when pull-out specimens fail. The steel deformation is relatively smaller and the measured slip is governed by the concrete deformation. Thus, the average bond stress-slip curve does not show a yielding point. High concrete strength leads to concrete bond strength enhancement. The steel stress



(a) Bond specimens without stirrup



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

Fig. 3 Average bond stress-slip curves

increases with increasing concrete strength. Before bond failure, the steel at the load end will yield first and gradually elongate. Therefore, as the concrete strength is high, the average bond stress-slip curve has a yielding point.

All the yielding points occur at 13 MPa (average bond stress) regardless of whether the specimen's concrete compressive strength is high or low or arranged in stirrups or not. If the ultimate bond stress cannot reach 13 MPa, the specimen will not reach the yielding state. The bond yielding strength only correlates with the steel yielding strength. All specimens used the same NO. 6 steel bars with 420 MPa yielding strength. As the average bond stress reaches 13 MPa, the stress in the bar (402 MPa) is near yielding strength (420 MPa) and yielding occurs. Regardless of the concrete compressive strength, the yielding load requirement was the same for all pull-out specimens.

### *3.3 Bond failure pattern*

Generally, bond failure can be divided into two modes – side-split failure and shear pull-out 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 the bearing, shear pull-out failure without concrete splitting results.

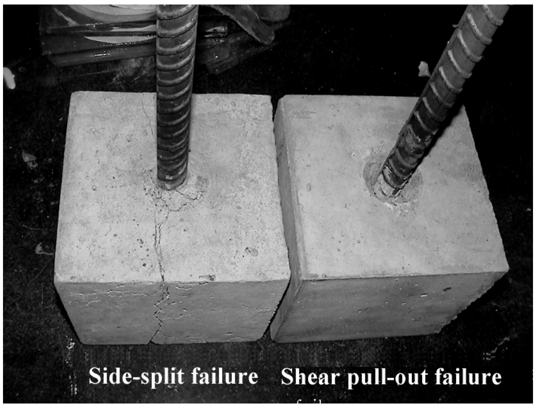
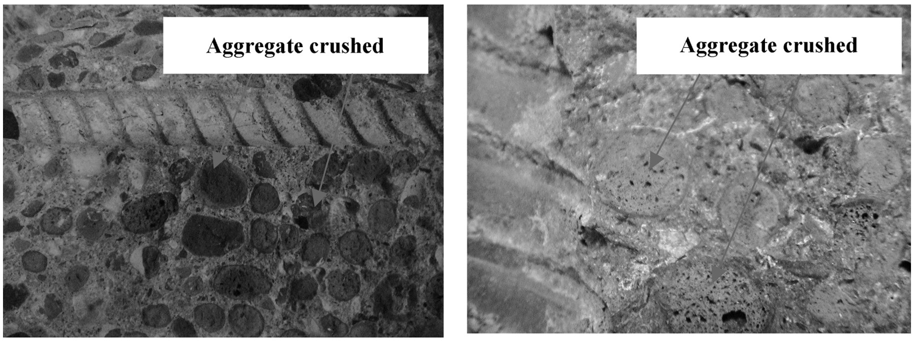


Fig. 4 Comparisons of the failed specimens



**(a) Low-strength LWAC** **(b) High-strength LWAC**

**(c) Low-strength normal weight concrete** **(d) High-strength normal weight concrete**

Fig. 5 Pictures of the failed surface

The test result shows that the LWAC non-stirrup specimens and normal weight concrete failure modes were of the side-split failure type (shown in Fig. 4). The difference in bond failure patterns between the LWAC and normal weight concrete, whether high or low strength concrete, was that LWAC cracked through the aggregate. The bond failure surface of the concrete was smoother (shown in Fig. 5(a) and Fig. 5(b)). In low-strength normal weight concrete (< 40 MPa), however, most of the natural aggregate was not broken and a rough bond failure surface appeared along the aggregate/ mortar interface (Fig. 5(c)). Conversely, if the strength of normal weight concrete was high (> 40 MPa), the natural aggregate would display a failure pattern similar to that of a lightweight aggregate, and the failed surface condition would be similar to that of LWAC (Fig. 5(d)). The difference in bond failure patterns between LWAC and normal weight concrete is similar to the difference in compression failure patterns.

LWAC stirrup specimens and normal weight concrete display shear pull-out failure (Fig. 4). When the concrete strength is relatively low (< 40 MPa), a rough bond failure surface appears on normal weight concrete. The bond failure surface of LWAC is smoother. As the concrete strength becomes higher (> 40 MPa), the normal weight concrete bond failure pattern becomes similar to that of LWAC; the aggregate breaks first and, then, the reinforcing bar is pulled out.

### *3.4 Bond strength*

The literature (Mathey *et al.* 1961) suggests that when the bar slides 0.01 in (0.254 mm) at the load end, the bond stress reaches critical bond strength levels. When the bond stress reaches critical

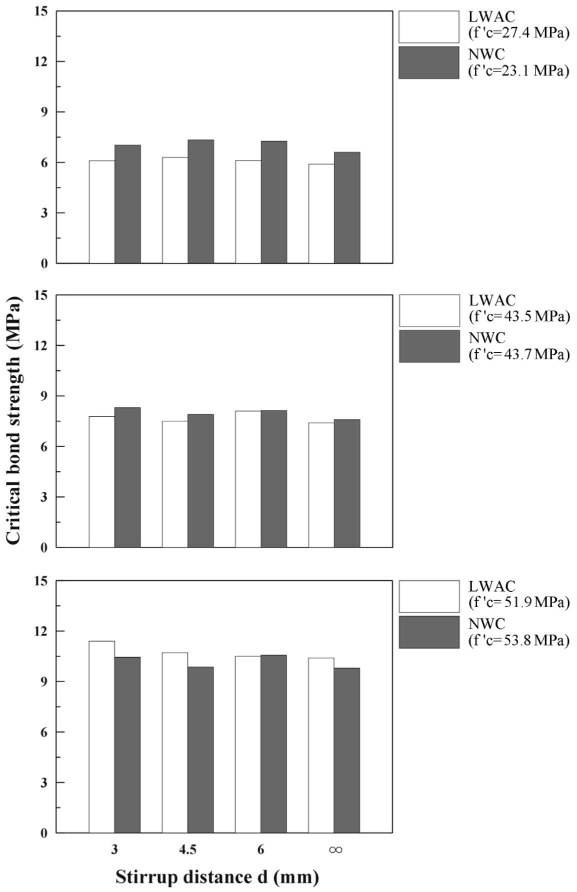


Fig. 6 Relationship between critical bond strength and stirrup distance

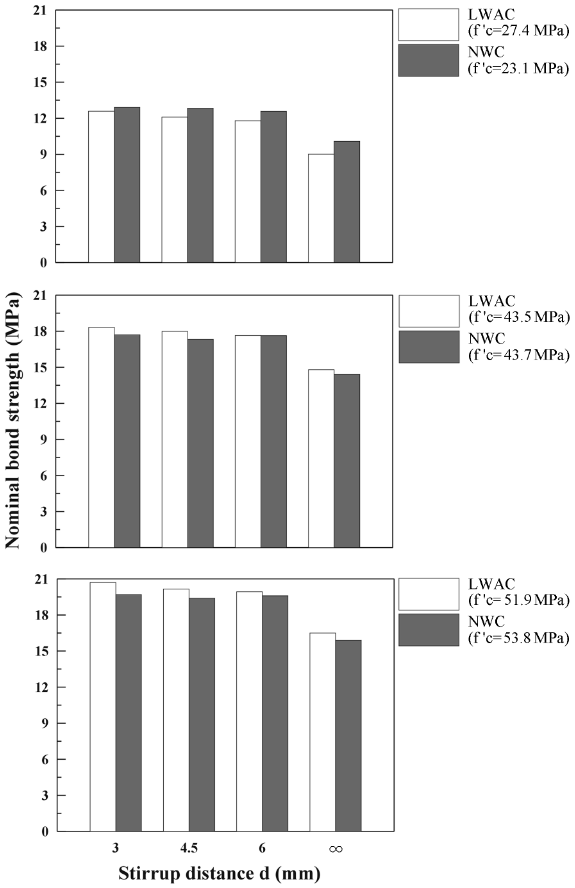


Fig. 7 Relationship between nominal bond strength and stirrup distance

bond strength, the interface between the reinforcing bar and concrete does not reach failure (the adhesion mechanism fails but no cracks occur) and the bond can still resist external forces until the ultimate bond stress, called nominal bond strength, occurs.

The critical bond and nominal bond strengths can be measured on the average bond stress-slip curve (as shown in Fig. 3) of the pull-out test. The results are shown in Figs. 6 to 9. Each statistic in the figures is the average of three test results. Fig. 6 shows that there is no obvious difference in critical bond strength (at the same concrete strength level) at various stirrup distances (d), whether the specimen is normal weight concrete or LWAC. This is because the 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. Therefore, regardless of how wide the stirrup distance, it does not influence the critical bond strength. However, Fig. 7 shows that after being installed, the nominal bond strength is 20% higher than that for specimens without stirrups. This outcome indicates that the stirrups generate a bonding effect on the concrete, allowing the concrete to resist higher stress and promote nominal bond strength. The stirrups in the concrete also absorb concrete stress to resist crack extension.

The stirrups cause the failure mode to shift from side-split to shear pull-out. Shear pull-out failure gives the highest possible bond strength. From Fig. 7, the stirrup distance (d) has no appreciable influence on the bond strength. This is because the stirrup spacing is fixed at 70 mm. Although the stirrup distances are different, the effect is limited.

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

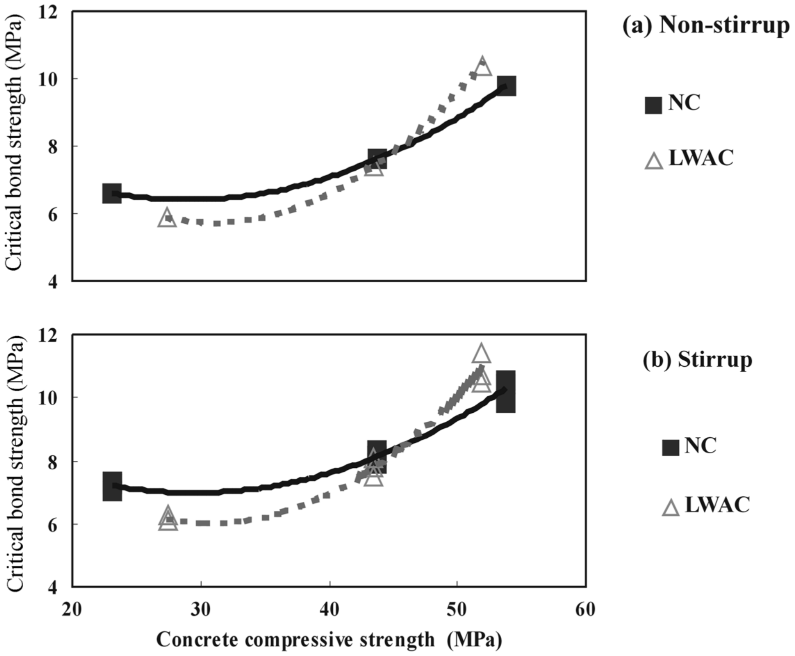


Fig. 8 Relationship between critical bond strength and compressive strength

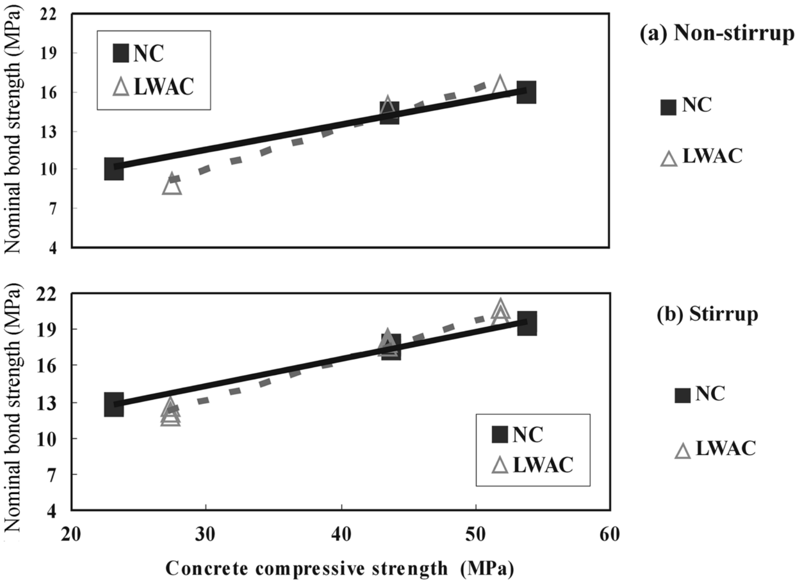


Fig. 9 Relationship between nominal bond strength and compressive strength

strengths are higher than those for normal weight concrete as concrete approaches high strength levels (> 40 MPa).

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

The normalized bond strength results are shown in Fig. 10. As the concrete compressive strengths become less than 40 MPa, the bond strength provided by normal weight concrete per unit of compressive strength become higher than that for LWAC. However, when the concrete is medium or high strength (≥ 40 MPa), the result is the opposite. As observed from the failure patterns, all LWAC lightweight aggregate exhibited shear failure whether the LWAC was high or low strength. This signifies that the wedging action resistance of lightweight aggregate is weak and that the wedging action resistance of the mortar primarily provided the LWAC bond strength. In the general strength (< 40 MPa) cases, most normal weight aggregate at the bond failure surface is not broken and the aggregate can provide higher wedging action than can the lightweight aggregate. Therefore, the aggregate promotes bond strength. In high-strength concrete cases, both concretes have aggregate failure and the wedging action provided by the aggregate is relatively low. The main bond failure control factor in both concretes is the mortar.

As mentioned in the previous study (Chen *et al.* 1999), with the same concrete strength, the LWAC mortar strength is higher than that for normal weight concrete. Thus, LWAC mortar provides higher wedging action resistance and leads to greater bond strength. Fig. 11 qualitatively depicts the variations in wedging action resistance with respect to the aggregate and mortar strengths for normal and lightweight concretes. Conceptually, the total concrete wedging action resistance is

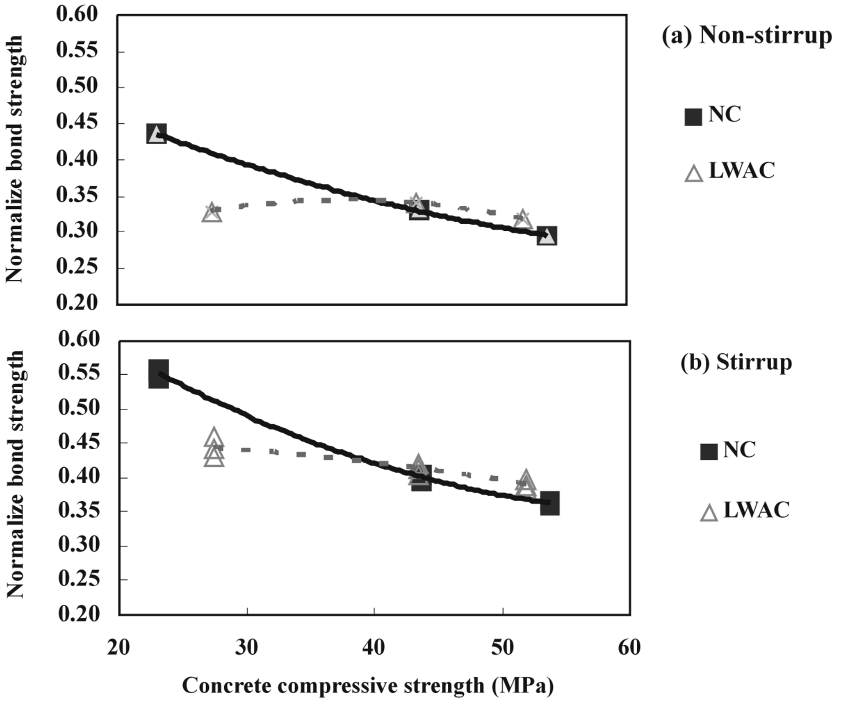


Fig. 10 Normalized bond strength in relation to compressive strength

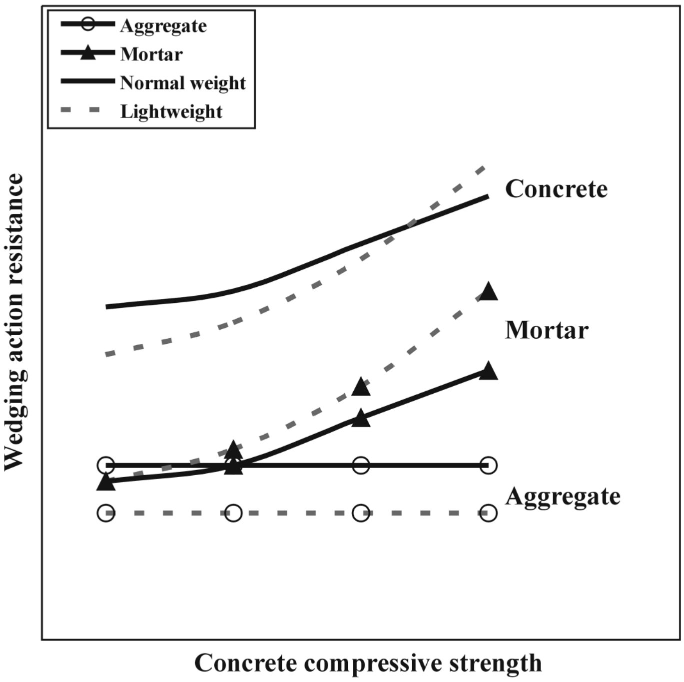


Fig. 11 Development of wedging action resistance

contributed to by the mortar and aggregate. As the aggregate wedging action resistance remains roughly unchanged, the variation in concrete wedging action resistance is governed by that of the mortar resistance. Because the mortar's tendency to increase resistance (associated with the increase of concrete strength) in LWAC is more significant than that for normal weight concrete, the total wedging action resistance of LWAC can exceed that of normal concrete as the concrete strength becomes relatively high. For high strength concrete, the bond strength of LWAC can become larger than that for normal weight concrete.

## 4. Conclusions

Using two different types of coarse aggregates in various strength concrete mixtures, the test results showed that the aggregate types and concrete compressive strength influenced the bonding behaviors of the concrete. The conclusions are summarized as follows:

(1) The nominal bond strength of normal weight concrete and LWAC could be increased by approximately 20% by adding stirrups. Stirrups cause the failure mode to shift from side-split to shear pull-out. The stirrups have less influence on the critical bond strength.

(2) When the concrete strength is less than 40 MPa, the bond failure surface of LWAC occurs through lightweight aggregate. The bond failure surface of normal weight concrete occurs along the surface of the aggregate. Most of the aggregate in this situation is not broken. The corresponding bond strength of LWAC is relatively lower than that for normal weight concrete.

(3) As the compressive strength of the concrete becomes relatively high (> 40 MPa), the LWAC bond failure pattern becomes similar to that of normal weight concrete. The LWAC bond strength is higher than that for normal weight concrete because it possesses higher mortar strength.

(4) In high-strength concrete, the wedging action resistance of the aggregate is relatively weak. The wedging action resistance of the mortar provides the primary bond strength in reinforced concrete. This effect is significant in LWAC.

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