BOND STRENGTH OF LIGHT-WEIGHT CONCRETE PULL-OUT SPECIMENS CONTAIN STEEL FIBERS

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Abstract: Bond between reinforcing steel bar and concrete has a critical influence on the structural behavior of reinforced concrete members. The nature of the concrete makes the bond characteristics inherently variable. The variability of the bond affects some of the more practical parameters such as the embedded length, bar diameter and cover thickness, which, in turn, considerably influence the length of the reinforcing elements used in the fabrication of the composite. In this investigation, the bond strength of normal weight, lightweight and fibrous lightweight concretes are investigated by use pull-out test results. The embedded lengths, bar diameter and cover thickness are taken as variables. The experimental work indicated that steel fibers specimens exhibited increase in bond strength about (75.45%), (126.36%) and (174.54%) when using (0.5%), (1%) and (1.5%) of total volume steel fibers respectively. Also, the specimens that are poured with (16mm) bar diameter have bond strength lower than that of small bar diameter for two types of concrete. In all concrete specimens, the specimens with large embedded length and concrete cover tend to fail by bond strength higher than that of small embedded length and concrete cover.

Keywords: bond strength, lightweight concrete, normal weight concrete, steel fiber and pull-out.

1. Introduction

The utilization of steel in reinforcing concrete is a typical mechanism for increasing the tensional resistance capacity of concrete sections. However, such rise in capacity depends largely on to what extent steel and concrete could behave as one unit in
supporting the applied loadings. That is, both the reinforcement (steel rods, fiber, or wire mesh) and the enveloping concrete should experience similar deformation; otherwise, the applied stresses could cause local failure such as segregation or discontinuity. Furthermore, in order to ensure significant increase in the structural capacity, the magnitude of specific reinforcement characteristics especially yield strength, ultimate strength and modulus of elasticity need to be much larger than those of the concrete [1]. Generally, the bond between concrete and steel reinforcement is due to a spectrum of factors. Following are the primary three of them; first, the pressure applied on the reinforcement by the concrete as a result of drying shrinkage[2]; second, the adhesion effect of each other; and third, the slippage resistance resulting from the friction interlock between concrete and tension rod due to the micro-movement of the later [3].

The material is now being used in an ever increasing number of applications, ranging from one step house casting to low density void fills. Lightweight concrete has a surprisingly long history and was first patented in 1923, mainly for use as an insulation material. Significant improvements over the past 20 years in production equipment and better quality surfactants (foaming agents) has enabled the use of foamed concrete on a larger scale. Not everyone knows that density and compressive strength can be controlled [4]. In the lightweight this is done by introducing air through the proprietary foam process which enables one to control density and strength precisely. Normal weight concrete has a density of 2,400 kg/m³ while densities of lightweight concrete range from 1,800, 1,700, 1,600 down to 300 kg/m³. Compressive strengths range from up to 40 MPa down to almost zero for the really low densities. Generally it has more than excellent thermal and sound insulating properties, a good fire rating, is non-combustible and features cost savings through construction speed and ease of handling [5].

Steel fibers reinforced concrete is important as it plays a part in developing of modern concrete technology, hence it represents a new construction concrete. Lately, efforts have been exerted in recent literatures to explore the ability of using (SFRC), chemical and mineral admixtures in producing high strength steel fiber reinforced concrete. Anyway, very limited studies were publishing in spite of the powerful demand and an effective importance of high strength steel fiber reinforced concrete in many special applications [6].

2. Experimental Program

This investigation was included three categories; the first category of six specimens studies the bond of normal concrete with different steel bars diameters (10mm and 16mm), different embedded lengths (200mm and 300mm) and concrete cover(92 mm and 117 mm) , the second category of six specimens studies the bond of LWC by adopting the same above bar diameters, embedded lengths and concrete cover, and the third category of three specimens is studding the effect of steel fiber on the bond strength of LWC specimens with bar diameter 10mm, embedded length 200mm and concrete cover92 mm. The pull-out load was applied as shown in Plate (1).
Table 1. Specimens Description

| Specimen No. | Height (mm) | Width (mm) | Thickness (mm) | Embedded Length (mm) | Bar Diameter (mm) | Concrete Cover (mm) | Steel Fibers Ratio (%) |
|--------------|-------------|------------|----------------|----------------------|-------------------|---------------------|-----------------------|
| N1           | 400         | 400        | 200            | 200                  | 10                | 92                  |                       |
| N2           | 400         | 400        | 200            | 300                  | 16                | 92                  |                       |
| N3           | 400         | 400        | 200            | 200                  | 16                | 92                  |                       |
| N4           | 400         | 400        | 200            | 300                  | 10                | 92                  |                       |
| N5           | 400         | 400        | 250            | 200                  | 10                | 117                 |                       |
| N6           | 400         | 400        | 250            | 200                  | 10                | 117                 |                       |
| L1           | 400         | 400        | 200            | 200                  | 10                | 92                  |                       |
| L2           | 400         | 400        | 200            | 300                  | 16                | 92                  |                       |
| L3           | 400         | 400        | 200            | 200                  | 16                | 92                  |                       |
| L4           | 400         | 400        | 200            | 300                  | 10                | 92                  |                       |
| L5           | 400         | 400        | 250            | 200                  | 10                | 117                 |                       |
| L6           | 400         | 400        | 250            | 200                  | 10                | 117                 |                       |
| LS1          | 400         | 400        | 200            | 200                  | 10                | 92                  | 0.5                   |
| LS2          | 400         | 400        | 200            | 200                  | 10                | 92                  | 1                     |
| LS3          | 400         | 400        | 200            | 200                  | 10                | 92                  | 1.5                   |

Plate 1. Test Set up.

3. Materials and Properties

The following materials are used in manufacturing tested specimens:

3.1. Cement

The physical and chemical tests of cement were performed according to American Specifications ASTM-C150[7].

3.2. Fine Aggregate

The sand specifications are smooth, rounded and have the fineness modulus of (2.69). The requirement of mixing is achieved by using only the passing sand from the sieve (4.75mm).
3.3. Normal weight Coarse Aggregate

Crushed gravel of maximum size (14 mm) was used. The grading of gravel emphasized to the BS882:1992 [8] Specification.

3.4. Lightweight Coarse Aggregate

Porcelanite aggregate was used as lightweight coarse aggregate. The maximum size of lightweight aggregate is 12mm with specific gravity (1.51). The grading and physical properties of Porcelanite aggregate conformed to the ASTM (C330) [9] standards. Table (2) illustrates the sieve analysis results of lightweight aggregate.

| Property               | Results | Limitation |
|------------------------|---------|------------|
| Specific gravity**     | 1.51    | -          |
| Absorption %           | 31      | -          |
| Dry loose unit weight (kg/m³) | 717    | 880        |
| Aggregate crushing value (%) | 15     | -          |

*Physical analysis was made in the national center for construction laboratories and research
** The specific gravity for the normal coarse aggregate 2.50.

3.5. Steel Fibers

Hooked end steel fibers are used with different volume fractions of (V_f = 0.5%, 1% and 1.5%) of concrete volume. The steel fibers dimensions are around 50mm length and 0.5 mm diameter with aspect ratio of 100, see Figure (1). The properties of steel fiber are presented in Table (3).

| Property               | Specifications |
|------------------------|----------------|
| Relative density       | 7860 kg /m³    |
| Yield strength         | 1130 MPa       |
| Modulus of elasticity  | 200x103MPa     |
| Strain at portion limit| 5650 x10-6    |
| Poisson's ratio        | 0.28           |
| Average length         | 50 mm          |
| Nominal diameter       | 0.5 mm         |
| Aspect ratio           | 100            |

*Supplied by manufacturer

4. Mechanical Properties of Concrete

Table (4) shows the mechanical properties of concrete that used in this investigation.
Table 4. Compressive Strength of Concrete

| Concrete Types | Spec. No. | $f_{c'}$ (28day) (MPa) | Average $f_{c'}$ (28 days) (MPa) | $f_t$ (MPa) | Average $f_t$ (MPa) | $f_r$ (MPa) | Average $f_r$ (MPa) | $E_c$ (GPa) | Average $E_c$ (GPa) |
|----------------|-----------|------------------------|-------------------------------|------------|-------------------|------------|-------------------|------------|-------------------|
| NWC*           | 1         | 25.5                   | 3.45                          | 3.95       | 29.1              |            |                   |            |                   |
|                | 2         | 23.8                   | 24.8                          | 3.75       | 3.89              | 3.81       | 28.6              | 28.8       |
|                | 3         | 25.1                   | 2.81                          | 2.96       | 3.1               | 3.11       | 22.2              | 21.7       |
| LWC**          | 1         | 21.0                   | 2.92                          | 3.17       | 22.1              |            |                   |            |                   |
|                | 2         | 20.2                   | 20.8                          | 3.15       | 3.06              |            |                   |            |                   |
|                | 3         | 21.2                   |                                |            |                   |            |                   |            |                   |

* Normal weight concrete
** Lightweight concrete

4.1. Concrete Compressive Strength ($f_{c'}$)

Standard (150 x 300)mm concrete cylinders are tested according to (ASTM C39)[10] to perform the concrete compressive strength test at age of 28 days. The concrete mixes are divided into two groups, the compressive strength of two mixes used in this study are illustrated in Table (4).

4.2. Splitting Tensile Strength ($f_t$)

Standard (150 mm x 300 mm) concrete cylinder are cast and tested according to (ASTM C496)[11] to determine the splitting tensile strength of concrete, see Table (4).

4.3. Flexural Strength ($f_r$)

According to (ASTM C78) [12], standard (100*100*500) mm prisms are used to perform the flexural strength test (modulus of rupture test), see Table (4).

4.4. Static Modulus of Elasticity ($E_c$)

According to (ASTM C469) [13], it has been used the chord-modulus method to calculate the modulus of elasticity by drawing a diagram between the stress and strain of loaded axially cylinder, see Table (4).

5. Specifications of Steel Bars

According to ASTM A615 [14], testing of steel bars was carried out, see Table (5).

Table 5. Properties of Steel Bars

| Nominal Diameter (mm) | Bar Type | $f_y$ (MPa) | $f_u$ (MPa) | $E_s$ (GPa) | Elongation % |
|-----------------------|----------|-------------|-------------|-------------|--------------|
| 10                    | Deformed | 412         | 591         | 200         | 10.8         |
| 16                    | Deformed | 404         | 566         | 200         | 10.3         |
6. Mix Design

Two concrete mixes were designed; normal weight concrete with average compressive strength ($f'_c=24.8$ MPa) and lightweight concrete with compressive strength ($f'_c=20.8$MPa). The design of these mixes is conducted according to ACI committee 211.1-91[15]. Many trail mixes were made to ensure the required strength. The mix proportions of normal strength concrete and lightweight concrete are shown in Table (6).

| $f'_c$ (MPa) | Cement (kg/m$^3$) | Sand (kg/m$^3$) | Natural coarse aggregate (kg/m$^3$) | Light weight (kg/m$^3$) | weight | w/c |
|--------------|-------------------|----------------|------------------------------------|----------------------|--------|-----|
| 24.8         | 450               | 560            | 1200                               | --                   | 0.46   |
| 20.8         | 450               | 650            | --                                 | 460                  | 0.4    |

7. Results and Discussion

7.1. Failure Pattern

The pull out of steel bars accompanied with splitting cracks is the failure pattern of all tested specimens. For normal weight concrete and lightweight concrete specimens, the splitting cracks are extended with a direction of the bar ribs as a result of good mechanical interaction between concrete and steel bar by ribs, the bar ribs apply high bearing pressure on contact concrete surface, see Plate (2) and (3).

Through observation, it can be noted that the failure in lightweight concrete specimens was characterized by brittleness, in addition to spalling pieces of concrete from the surface. The normal weight specimens have ductility more than the lightweight concrete specimens.

Plate 2. Failure Mode of Lightweight Specimens
7.2. Ultimate Bond Strength

The experimental results of tested specimens in terms of bond strength are listed in Table (7). The bond strength is calculated by dividing the pull-out force by contact area between steel bar and concrete \( U = \frac{P}{A} \).

Where:
- \( U \) = Bond strength (MPa).
- \( P \) = Pull-out Force (N).
- \( A \) = Area (mm\(^2\)).

7.2.1. Effect of Concrete Type

The test results for normal weight and lightweight concretes are presented in Table (11). It is obvious that the bond strength for normal weight concrete specimens \( N_1, N_2, N_3 \) and \( N_4 \) is larger than that of light weight concrete specimens \( L_1, L_2, L_3 \) and \( L_4 \) by about (61.26)\%, (64.32)\%, (61)\% and (62)\% respectively. This is due to lower concrete shear strength of the lightweight concrete made the concrete beneath ribs ease to crush.

In addition to increase the possibility of creation the micro-cracks at the interface between lightweight concrete and bar ribs.

The shear strength of lightweight concrete was improved through increase its tensile strength by using steel fibers. Consequently, the bond strength was increased in lightweight concrete specimens \( LS_1, LS_2 \) and \( LS_3 \) about (75.45)\%, (126.36)\% and (174.54)\% respectively in comparison with lightweight concrete specimen \( L_1 \), the specimens \( LS_1, LS_2 \) and \( LS_3 \) contain steel fibers 0.5\%, 1\% and 1.5\% of the total volume respectively, see Table (7).

7.2.2. Effect of Bar Diameter

Two bars diameters (10mm and 16mm) were used as variables. In normal weight concrete specimens, the specimens with (10mm) bar diameter achieved bond strength
about (2.74) MPa. In comparison, the specimens with (16mm) bar diameter recorded a reduction in bond strength about (7.67)% with respect to specimen with (10mm) bar diameter.

On the other hand, the lightweight concrete specimens L_3 and L_2 (with 16mm bar diameter) recorded a reduction in bond strength about (4.6)% and (2.32)% in comparison with lightweight concrete specimen L_1 and L_4 (with 10mm bar diameter) respectively, see Table (7).

From the results of tested specimens, it is clear that the increasing in reinforcing bar diameter results a decrease in the bond strength, which may be attributed to the splitting failure of concrete within the specimens.

| Table 7. Bond strength of Tested Specimens |
|-------------------------------------------|
| Specimens No. | Pull-out Force (kN) | Bond Strength (MPa) | Variation (%) |
|---------------|---------------------|---------------------|---------------|
| **Effect of Embedded Length**             |                     |                     |               |
| N1            | 17.83               | 2.84                | R             |
| N2            | 55.76               | 3.7                 | 30.2          |
| N3            | 29.64               | 2.95                | R             |
| N4            | 32.02               | 3.4                 | 15.25         |
| L1            | 6.9                 | 1.1                 | R             |
| L2            | 19.89               | 1.32                | 20            |
| L3            | 11.55               | 1.15                | R             |
| L4            | 11.96               | 1.27                | 12.2          |
| **Effect of Bar Diameter**                |                     |                     |               |
| N1            | 17.83               | 2.84                | R             |
| N3            | 29.64               | 2.95                | 7.67          |
| N4            | 32.02               | 3.4                 | R             |
| N2            | 55.76               | 3.7                 | 8.8           |
| L1            | 6.9                 | 1.1                 | R             |
| L3            | 11.55               | 1.15                | 4.6           |
| L4            | 11.96               | 1.27                | R             |
| L2            | 19.89               | 1.32                | 2.32          |
| **Effect of Cover Thickness**             |                     |                     |               |
| N1            | 17.83               | 2.84                | R             |
| N5            | 19.78               | 3.15                | 10.92         |
| N4            | 32.02               | 3.4                 | R             |
| N6            | 23.86               | 3.8                 | 11.76         |
| L1            | 6.9                 | 1.1                 | R             |
| L5            | 7.97                | 1.27                | 15.45         |
| L4            | 11.96               | 1.27                | R             |
| L6            | 9.35                | 1.49                | 17.3          |
| **Effect of Steel Fibers Ratio**          |                     |                     |               |
| L1            | 6.9                 | 1.1                 | R             |
| LS1           | 12.12               | 1.93                | 75.45         |
| LS2           | 15.63               | 2.49                | 126.36        |
| LS3           | 18.96               | 3.02                | 174.54        |

7.2.3. Effect of Concrete Cover

The experiments indicate that specimen with large cover tend to fail in bond strength larger than those of with small cover, see Table (7).

For normal weight concrete specimens with (92) mm and (117) mm concrete cover, it is clearly seen that the bond strength is higher for larger thickness cover ;(10.92)%
and (11.76)% amount of increasing in bond strength of specimens (N₁) and (N₄) with 92 mm cover thickness over reference specimens (N₅) and (N₆) with 117 mm cover thickness.

The same result can be seen in lightweight concrete specimens (L₁) and (L₄) with 92 mm cover thickness if compared with specimens (L₅) and (L₆) with 117 mm cover thickness respectively; the improvement in bond strength due to increase the cover thickness reached to about (15.45)% and (17.3)% respectively.

7.2.4. Effect of Embedded Length

In general, the bond strength was increased by increasing the embedded length of reinforcing bar; resulting from increasing the frictional contact area and increasing the number of ribs, consequently, increasing the mechanical interlocking between steel bar and concrete then decrease the relative slip between them, see Table (4).

The lightweight concrete specimens (L₁) and (L₃) with 300 mm embedded lengths were achieved improvements in bond strengths about (20)% and (12.2)% respectively in comparison with 200mm embedded length specimen in specimens (L₂) and (L₄).

Also, the normal weight concrete specimens (N₁) and (N₃) with embedded length 300 mm achieved an increase in bond strengths about (30.2)% and (15.25)% respectively in comparison with specimens (N₂) and (N₄) with embedded length 200 mm.

8. Comparison with ACI 318 M-14

Following equation is adopted by ACI 318 M-14 to calculate the bond strength between reinforcing steel bar and concrete:

\[
U = \frac{1}{3.6} \sqrt{f'c} \left( \frac{C + k_{tr}}{d_b} \right) \frac{1}{\alpha \beta \gamma} \]

Where:
\( \alpha = 1 \)
\( \beta = 1 \) for normal and LWC.
\( \beta = 1.2 \) for grouted LWC.
\( \gamma = 0.8 \) where No.6 and smaller
\( \gamma = 1.0 \) where No.7 and larger bars
\( \lambda = 1 \) for normal weight and (1.3) for light-weight and grouted.

\[
K_{tr} = \left( \frac{A_{tr} f_{tr}}{10SN} \right)
\]

\( \alpha = \) reinforcement location factor.
\( \beta = \) coating factor
\( \lambda = \) light-weight aggregate concrete factor.
\[ \gamma = \text{reinforcement size factor.} \]

\[ N = \text{number of bars or wires being developed along the plane of splitting.} \]

As shown in Table (8), which contains a comparison between the bond strength of the tested specimens and calculated bond strength by ACI 318 M-14, it is clear that the amount of convergence between the experimental and theoretical results for normal weight concrete is greater than the amount of convergence between them in case of lightweight concrete and fibrous lightweight concrete.

| Specimen No. | Present Work Bond Strength | ACI-318M-14 Bond Strength |
|--------------|----------------------------|---------------------------|
| N1           | 2.84                       | 3.86                      |
| N2           | 3.7                        | 5.80                      |
| N3           | 2.95                       | 3.86                      |
| N4           | 3.4                        | 5.80                      |
| N5           | 3.15                       | 3.86                      |
| N6           | 3.8                        | 3.86                      |
| L1           | 1.1                        | 2.72                      |
| L2           | 1.27                       | 4.08                      |
| L3           | 1.27                       | 2.72                      |
| L4           | 1.49                       | 4.08                      |
| L5           | 1.27                       | 2.72                      |
| L6           | 1.49                       | 2.70                      |
| LS1          | 1.93                       | 2.72                      |
| LS2          | 2.49                       | 2.70                      |
| LS3          | 3.02                       | 2.72                      |

9. Conclusions

The main conclusions that are drawn from the present investigation:

1- Specimens that are casted with normal weight concrete have bond strength higher than that with lightweight concrete.
2- Steel fibers specimens exhibited increase in bond strength due to restriction of cracks by bridging effect.
3- The (300mm) embedded length in all concrete specimens has shown better bond strength when compared with smaller embedded length (200mm).
4- The increase of embedded length in lightweight concrete is less efficiency than that in normal weight concrete.
5- The specimens that are poured with (16mm) bar diameter have bond strength lower than that of smaller bar diameter.
6- The (1.5%) of total volume steel fibers ratio have shown better bond strength and restored the bond strength of normal weight concrete specimens.
7- It was also observed that in all concrete types, there is an improvement in bond strength through variation in cover thickness from (92)mm to (117) mm

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