Experimental investigation on bond of reinforcement in steel fibre-reinforced lightweight concrete

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Abstract. Bond behaviour of reinforcement is crucial parameter for load bearing reinforced concrete members. Many parameters like anchorage of reinforcement, lap splices, deflection or tension stiffening are influenced by the bond properties. It is well known that the ductility of bond can be improved by steel fibres. In this context almost innumerable experiments were performed for investigation of bond in normal weight concrete. However, the bond behaviour of reinforcement in steel fibre-reinforced lightweight concrete (SFR LWC) has received much less attention. For this reason, an experimental program dealing with bond in SFR LWC has been started at HTWK Leipzig/Germany. Main parts of the investigation were pull-out tests with various bar sizes and application of different steel fibre-reinforced lightweight and normal weight concretes. The paper reports the details of experimental investigations and evaluates the test results. As one of the most important outcomes that can be noted is that there is pronounced effect of bar size and steel fibre amount on bond properties in general. But those effects are more pronounced for SFR LWC in comparison to normal weight concrete with and without steel fibres.

1. Introduction

In a reinforced concrete member, both steel bar and concrete complement each other for better structural behavior and are therefore vital for each other to oversee the weaknesses of the other. Bond between reinforcement and surrounding concrete plays important role in structure’s overall behaviour under loading. The bond between these two materials therefore needs to be sufficiently adequate for proper interaction or transfer of stresses from one material to the other.

Since 1960, use of discrete fibres in concrete has seen significant growth [1]. Use of fibres in concrete, made from lightweight aggregates, is particularly encouraging for number of reasons; for example, compared to conventional concrete, lightweight concrete is more brittle and is therefore in more need of fibre reinforcement, also according to Balendran et al. [2] ductility improvement is more in lightweight concrete than normal weight concrete for similar amount of fibres. Additionally, adverse effect of fibres on workability is to some level reduced normal weight aggregates are replaced by lightweight aggregates of regular shape [3].

In a reinforced concrete member, sufficient level of bond strength is warranted by ensuring proper anchorage/bond length. Current design expressions for the estimation of bond strength and anchorage/bond length have been derived by statistical analysis of results that were obtained by testing
bond specimens made from conventional concrete. And improvement, if any, that can be achieved in bond performance by the addition of discrete fibres to concrete is neither reflected in these empirical expressions, nor in the bond stress-slip laws. For wider acceptability of SFRLWC, it is therefore imperative that its mechanical and structural properties not only be studied and determined, but also be compared with conventional concrete and finally encoded in building codes. Current work discussed here is the part of series of studies [3–6] that were initiated at HTWK, Leipzig to address above mentioned issues. The main target of the study was the investigation of the influence of bar size and steel fibre amount on the ultimate bond strength and the bond stress versus slip behavior in steel fibre reinforced normal weight concrete (SFRNWC) and SFRLWC.

2. Experimental Program

Experimental programmed involved studying the bond behaviour of SFRLWC and also of SFRNWC using pull-out tests. Details of materials and specimens are presented in following sections.

2.1. Materials

All the materials used for making conventional and lightweight concretes were similar except coarse aggregates. Gravel and expanded clay (see Figure 1) were used for these concretes and had size range of 2-8 mm and 2-10 mm respectively. Natural sand having size range of 0-2 mm was used as fine aggregate. As a binding material an ordinary Portland cement (CEM-1/42.5 N) was selected. Apart from the non-fibrous concretes, two fibrous mixes, each one for lightweight and normal weight concretes were prepared by adding hooked-end steel fibres (35 mm long and 0.55 mm in diameter) to the mixes in quantities of 60 kg/m³. At trial mix design stage some difficulty was faced while working with fibrous mixes and for that reason it was decided to add some quantity of superplasticizer. Table 1, presents all the material quantities that were used for all mixes. Three different bar sizes 10, 16 and 20 mm in diameter and having yield strength of 500 MPa were selected as pull-out bars.

![Figure 1. Used coarse aggregates: gravel (left), expanded clay (right).](image)

2.2. Hardened Material Properties

The main hardened material properties of the non-fibrous concretes can are summarized in the following:

- Cube compressive strength of the normal-weight concrete: 42.9 MPa
- Cube compressive strength of the lightweight concrete: 38.0 MPa
- Density of the lightweight concrete: 1716 kg/m³

More details about hardened material properties are stated in [3]
Table 1. Mix design for SFRLWC and SFRNWC.

| Material         | Unit          | SFRLWC | SFRNWC |
|------------------|---------------|--------|--------|
| Cement           | [kg/m$^3$]    | 360    | 350    |
| Coarse aggregate | [kg/m$^3$]    | 472    | 884    |
| Fine aggregate   | [kg/m$^3$]    | 772    | 955    |
| Total water      | [kg/m$^3$]    | 205    | 180    |
| Superplasticizer | [% wt. of cement] | 0.5   | 0.5    |
| Fibre volume, $f_v$ | [kg/m$^3$] | 0, 60  | 0, 60  |
| Effective $w/c$  |               | 0.35   | 0.45   |

2.3. Specimens and Test Setup

Most of the RILEM [7] guidelines were followed for fabrication of specimens except few. For example, as per guidelines, for all sizes of pull-out bars, specimens’ dimensions are fixed at 200 x 200 x 200 mm. This approach results in higher bond strength values for smaller bars, as these bars receive higher confinement effect from larger concrete cover compared to the higher bar sizes. In modified pull-out specimens bar size to cover ratio was kept constant to see if higher diameter bars are able to achieve bond strength greater than the smaller bars. Dimensions of all the test specimens were 10 times the bar diameter, whereas, bonded and un-bonded lengths of the pull-out bar were 5 times the bar diameter. As an example, bond specimens with 16 mm pull-out bars have dimensions equal to 160 mm, other details are shown in Figure 2. Contact of the bar with concrete for un-bonded length portion was made possible by using PVC tube. There were three (03) specimens for each bar size in every concrete mix i.e. nine (09) specimens for every mix and total 36 specimens for all the four concrete mixes.

Testing of specimens was carried out in a displacement controlled machine with maximum load application capacity of 600 kN. Specimens during testing rested on steel plates which were supported by four steel rods with the help of screws. Bar was pulled out of the bond specimens at constant rate of 0.005 mm/s and displacement of pull-out bar was recorded with the help of linear variable displacement transducers, these were placed on both the loading side (bottom) and on the free end side (top) of specimens as shown in Figure 2.

![Figure 2. Details of specimen with 16 mm pull-out bar (left), specimen ready for testing (right).](image-url)
3. Test Results

Three modes of failure are expected during testing of a bond specimens depending upon the matrix composition and boundary conditions, namely splitting, pull-out and yielding of pull-out bars. For current experimental work, all the specimens tested had splitting mode of failure. Besides 28-days cylindrical compressive strength ($f'_c$) and maximum force applied during testing, Table 2 also shows the ultimate bond strength of all the 36 specimens calculated using following expression.

$$\tau_u = \frac{P_{\text{max}}}{\pi \cdot l_b \cdot d_b}$$

Where, $\tau_u$ is ultimate bond strength, $P_{\text{max}}$ the maximum applied pull-out force, $d_b$ the bar diameter and $l_b$ the bond length respectively.

Table 2. Pull-out test results of SFRLWC and SFRNWC.

| S. No. | $f_v$ (kg/m³) | $d_b$ (mm) | $f'_c$ (MPa) | $P_{\text{max}}$ (kN) | $\tau_u$ (MPa) | $f'_c$ (MPa) | $P_{\text{max}}$ (kN) | $\tau_u$ (MPa) |
|--------|--------------|------------|--------------|-----------------------|---------------|--------------|-----------------------|---------------|
| 1      | 100          | 10         | 21.63        | 13.77                 |               | 37.25        | 22.96                 | 14.62         |
| 2      | 10           | 10         | 24.52        | 15.61                 |               | 20.26        | 12.90                 |               |
| 3      | 10           | 10         | 19.72        | 12.55                 |               | 26.52        | 11.61                 |               |
| 4      | 16           | 16         | 55.38        | 13.77                 |               | 43.48        | 10.81                 |               |
| 5      | 100          | 10         | 37.52        | 11.99                 | 49.56         | 12.32        |                       |               |
| 6      | 16           | 16         | 41.11        | 10.22                 | 46.45         | 11.55        |                       |               |
| 7      | 20           | 20         | 48.72        | 7.75                  | 66.39         | 10.57        |                       |               |
| 8      | 20           | 20         | 57.47        | 9.15                  | 56.37         | 8.97         |                       |               |
| 9      | 20           | 20         | 41.64        | 6.63                  | 79.70         | 12.68        |                       |               |
| 10     | 10           | 10         | 22.62        | 14.4                  | 28.56         | 14.62        |                       |               |
| 11     | 10           | 10         | 21.89        | 13.94                 | 25.25         | 16.07        |                       |               |
| 12     | 10           | 10         | 25.56        | 16.27                 | 28.67         | 18.25        |                       |               |
| 13     | 16           | 16         | 46.63        | 11.59                 | 56.69         | 14.10        |                       |               |
| 14     | 60           | 16         | 35.41        | 10.95                 | 35.07         | 13.78        |                       |               |
| 15     | 16           | 16         | 48.86        | 12.15                 | 58.53         | 14.56        |                       |               |
| 16     | 20           | 20         | 72.68        | 11.57                 | 92.21         | 14.68        |                       |               |
| 17     | 20           | 20         | 72.85        | 11.59                 | 86.14         | 13.71        |                       |               |
| 18     | 20           | 20         | 80.35        | 12.79                 | 86.15         | 13.71        |                       |               |

3.1. Effect of bar and specimen size

Compared to conventional concrete, brittleness of lightweight concrete was evident, as specimens of this mix completely split at the end of test. This is because, normal weight aggregates have higher values of density, particle strength and elastic modulus, therefore these act as an obstacle to further propagation of cracks, whereas lightweight aggregate being lighter and porous offer less resistance.

Effect of bar size and specimen size in different concretes on bond has been reported in earlier literature [8, 9]. These reports suggest decrease in bond strength as the bar size/specimen size increase.
This decrease is attributed to the fact that there is increase in circumferential shearing area as the bar diameter increases. Even with same cover to bar size ratio, results for all the mixes of current experimental work show that 10 mm bar size attained highest bond strength. For SFRNWC, on an average bond strength of specimens with 20 mm bar and 16 mm bar were found to be 81% and 84.7% respectively of the bond strength of 10 mm bar. Whereas for SFRLWC bond strength of 16 mm and 20 mm bars were 81.7% and 68% respectively of the bond strength of 10 mm bar.

Lightweight concrete has lower bond strength than normal weight concrete due to the lower particle strength [10]. This trend was also observed in current experimental work as shown in Figure 3. Results show that, except 10 mm bar size specimens at 0% fibre volume fraction, bond strength of SFRLWC was lower than that of SFRNWC as shown in Figure 3.

3.2. Effect of fibres

Effect of fibre addition on bond strength can also be seen in Figure 3. Bond strength for all the bar sizes is improved. For SFRNWC, average of the three test results, for each bar indicates an improvement of 34%, 22% and 30.6% for 10 mm, 16 mm and 20 mm bars respectively. Due to lower particle strength and higher brittleness of SFRLWC, non-uniform results are obtained. For example, an improvement of only 6% was recorded for 10 mm bar sized improvement, whereas for 20 mm bar sized specimen bond strength improved by 52.8%.

In non-fibrous mixes of lightweight concrete, the descending branch of bonds stress-slip profile is very steep and short when compared with the NWC as can be seen (see Figure 4 (a)) in the bond stress-slip plot of 10 mm bar size specimens of both the Lightweight and normal weight concretes. It can be inferred from this behaviour that failure occurred suddenly in the aggregates due to their lower strength. This kind of behaviour started to change with the subsequent addition of steel fibres and more consistent softening branch was observed in the post splitting region of bond slip plots. Compared to the abrupt dipping of bond force the descent was more gradual and smooth as the fibre quantity in the mix increased, indicating the effectiveness of fibres in trapping the progressing cracks (see Figure 4 (b)).

Almost similar behaviour is observed in higher diameter bar specimens of non-fibrous mixes of SFRLWC; i.e. failure also occurred in aggregates with sharp dipping of bond stress. However, because of better confinement due to larger concrete cover, resistance to slip was noted with higher bond stresses. Bond stress-slip profiles of SFRNWC have well defined descending branch without any sharp peaks (see Figure 4 (c)), which suggests that in case of normal weight concrete, aggregates did not fail, but the failure initiated in the cement paste. Overview of non-fibrous bond specimens after testing confirms this observation in comparison to normal weight aggregates, lightweight aggregates particles can be seen completely fractured in Figure 5.
Figure 4. Bond stress-slip profiles of SFRNWC and SFRLWC for 10 mm and 20 mm bar size.

Figure 5. Overview of non-fibrous bond specimens after bond test (a) LWC, (b) NWC.

4. Conclusions
Bond specimens of SFRLWC and SFRNWC were tested and compared for understanding the effect of fibres and bar sizes on bond strength. Following conclusions can be drawn from the work.

- Smaller bars attain higher bond strength compared to the larger bar sizes. RILEM specimens favour the smaller bars in terms of confinement, so it was decided to enhance the cover of higher diameter bars. But even a concrete cover of 72 mm for 16 mm bar and 90 mm for 20 mm bar was not enough to achieve bond strength higher than the smaller bars.
• Despite having similar compressive strength, bond strength of SFRLWC is lower than SFRNWC.
• For the selected amount of fibres i.e. 60 kg/m$^3$, improvement of 22% and higher for bond strength can be achieved in case of SFRNWC. However for SFRLWC this improvement was not uniform and therefore needs further experimental investigation.
• Besides improvement in ultimate bond strength, addition of fibres also positively affects the bond stress-slip behaviour.

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