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Bond behavior of self compacting concrete

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Abstract

The success of an optimum design lies in the effective load transfer done by the bond forces at the steel-concrete interface. Self Compacting Concrete, is a new innovative concrete capable of filling intrinsic reinforcement and gets compacted by itself, without the need of external mechanical vibration. For this reason, it is replacing the conventional vibrated concrete in the construction industry. The present paper outlays the materials and methods adopted for attaining the self compacting concrete and describes about the bond behavior of this concrete. The bond stress-slip curve is similar in the bottom bars for both SCC and normal concrete whereas a higher bond stress and stiffness is experienced in the top and middle bars, for SCC compared to normal concrete. Also the interfacial properties revealed that the elastic modulus and micro-strength of interfacial transition zone [ITZ] were better on the both top and bottom side of horizontal steel bar in the SCC mixes than in normal vibrated concrete. The local bond strength of top bars for SCC is about 20% less than that for NC. For the bottom bars, however, the results were almost the same.

Keywords: Self Compacting concrete, Bond force, Transfer of stress.

1 Introduction

The assumption in the design of concrete structures is that the concrete and reinforcement act together to form a composite material which is safe and durable. The transfer of the load from the steel to the surrounding concrete is done by the bond stress. This bond stress is the stress which acts at the interface between the steel and surrounding which plays a vital role in transferring the load from the steel to the surrounding. The load carrying capacity is mainly influenced by this bond mechanism.

Proper consolidation of the concrete surrounding the steel is an important factor that draws attention from the durability point of view. Particularly structures like seismic resistant incorporates heavily congested beam column joints where attaining full compaction is of utmost important for its durability. Hence for such a structure highly workable concrete is necessary. Self compacting concrete is an innovative concrete known for its excellent deformability, filling ability, and segregation resistance with the capability of consolidating itself without the need of any vibration externally. The entire voids between the reinforcements and the formworks are filled by self compacting concrete enhancing better bond and durability of the structures.

2 Bond in General

Bond in reinforced concrete refers to the adhesion between reinforcing steel and surrounding concrete. It is this bond which is responsible for the transfer of axial force from reinforcing bar to the surrounding concrete, thereby providing strain compatibility and composite action of concrete and steel. If the bond is inadequate, slipping of reinforcing bar will occur, thereby destroying full composite action. Whenever steel strain differs from concrete strain, a relative displacement between the steel and concrete (slip) occurs, but this lack of compliance is also due to highly- localized strains in the concrete layer adjacent to the reinforcement (interface). The force transferred from concrete to steel or steel to concrete, at the interface, per unit contact area is called Bond stress. When a bar stress is calculated on the basis of transfer of bar force over a finite length is called average bond stress. While the bond stress acting at a section over an infinitesimal length of a bar as a rate of change of bar stress known as local bond stress.

The main parameters that influence the bond behavior of RCC structures are the surface of the rebars, the number of load cycles, the mix design, the direction of concreting, as well as the geometry of the test specimens (pull-out test). One of the experimental conditions that have a significant influence on the bond strength is the casting process of the test specimens. First, the settlement of fresh concrete leads to the formation of voids under fixed horizontal bars, which reduces the bond strength. In addition, fresh concrete bleeding can change the physicochemical properties and increase the size of the voids at the steel-concrete interface, leading to an additional bond reduction. This phenomenon is called the top-bar effect because the horizontal reinforcements located near the top casting surface are the most affected.

3 Mechanism of Bond

For an optimum design there should be efficient transfer of load from the steel to the surrounding concrete. This transfer of load occurs by the following three components:

- Chemical adhesion between the bar and the concrete;
- Frictional forces arising from the roughness of the interface, forces transverse to the bar surface, and relative slip between the bar and the surroundings concrete; and
- Mechanical anchorage or bearing of the ribs against the concrete surface.

After initial slip of the bar, most of the force is transferred by bearing. Friction, however, especially between the concrete and the bar deformations (lugs) plays a significant role in force transfer. Friction also plays an important role for plain bars (that is, with no deformations), with slip-induced. The frictional force exerted by the lugs on to the surrounding concrete is inclined at an angle β with the axis of the bar as shown in Fig. 1. The radial component of this force causes splitting of the surrounding concrete. If the stress component along the longitudinal axis of the bar is “u”, the radial component of the bond force is $u' = u \tan \beta$.

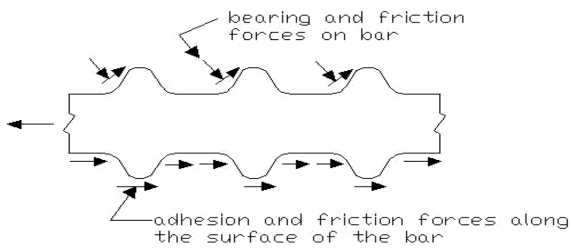

Figure 1: Bond Force Transfer Mechanism

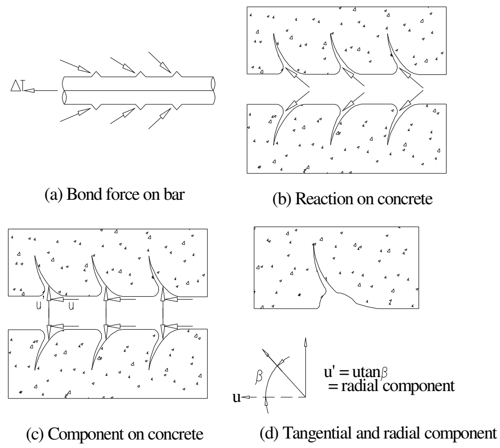

Figure 2: Force Components in Deformed Bars and Concrete

When a deformed bar moves with respect to the surrounding concrete, surface adhesion is lost, while bearing forces on the ribs and friction forces on the ribs and barrel of the bars are mobilized. The compressive bearing forces on the ribs increase the value of the friction forces. As slip increases, friction on the barrel of the reinforcing bar is reduced, leaving the forces at the contact faces between the ribs and the surrounding concrete as the principal mechanism of force transfer.

4 Bond Failure Mechanisms

The mechanisms that initiate bond failure may be any one or combination of the following:

- Break – up of adhesion between the bar and the concrete
- Longitudinal splitting of the concrete around the bar
- Crushing of the concrete in front of the bar ribs (in deformed bars) and
- Shearing of the concrete keyed between the ribs along a cylindrical surface surrounding the ribs (in deformed bars)

The ability of a deformed bar to transfer its load into the surrounding concrete is typically limited by the failure of this ring of tension when the thinnest part of the ring splits (splitting failure), as shown in figure 3. However, if a relatively small diameter bar is embedded in a large block of concrete, the bar pulls out of the concrete (pull out failure 4.) due to concrete shear failure along a cylindrical surface at the extremities of the bar deformation (see figure)

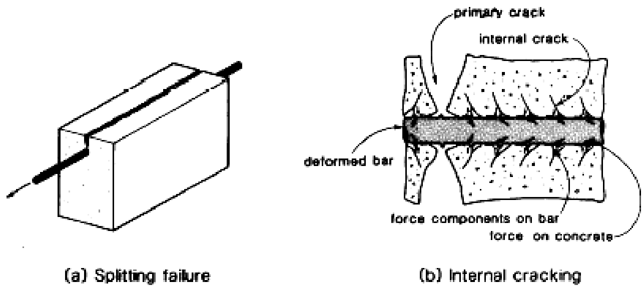

Figure 3: Splitting failure and internal cracking described by Goto

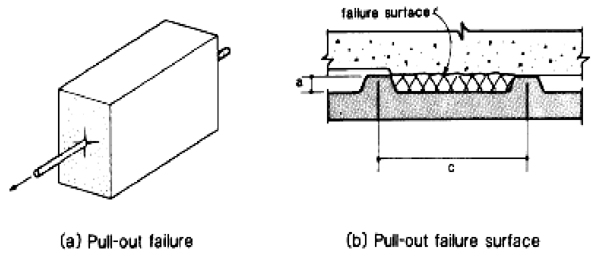

Figure 4: Pullout failure and failure surface

5 Self Compacting Concrete and its Development

As the name indicates, self compacting concrete is new evolution in the filed of concrete technology with the view of attaining full compaction with its own weight, fulfilling the main requirements, such as, filling ability, passing ability and resistance to segregation. Starting its origin in Japan during 80's to meet the durability requirements through fully compaction, now it slowly gained fame in Europe through Sweden during mid of 90's. The reason which stimulated Okamura of Japan in finding this new type of concrete is the lack of durability in their structures due to insufficient compaction of concrete attributed by the unskilled workers. He aimed to attain this durable concrete at minimum water cement ratio and hence sometimes, referred to as High Performance Self Compacting Concrete [8].

In 1996, several European countries formed the "Rational Production and Improved Working Environment through using SCC" project in order to explore the significance of published achievements in SCC and develop applications to take advantage of the potentials of SCC [15]. During the last few years, interest in SCC has grown in the United States, particularly within the precast concrete industry [16]. The mixes developed should meet the main three requirements for its efficient performance such as, filling ability, passing ability, and resistance to segregation [10, 19].

5.1 Materials For Making Self Compacting Concrete

Just the same materials which are used for making conventional concrete are employed for making Self Compacting Concrete, with high powder content. As it the new material there is no standard procedure for attaining the mix proportion. The mix proportion is attained only by the previous researcher works. Pioneer Okamura [14] developed a mix design method in Japan in which the coarse and fine aggregate content are fixed while the water – cementitious ratio and superplasticizers content is adjusted to achieve self consolidation. Nan Su [12] developed a mix with a view of filling the voids between the aggregate using the paste attained. He introduced a term 'Packing Factor', which influences the flowing ability, strength and self compactability. Saak et al [1] presented a new segregation-controlled design methodology. The theory assumes that for a given aggregate particle size distribution and volume fraction, the rheology and density of the cement paste matrix dictate the fluidity and segregation resistance of concrete. Authors defined a segregation-resistant and yet high workability region as rheological self-flow zone (SFZ). Brouwers et.al [4] the features of ''Japanese and Chinese Methods'' are discussed, in which the packing of sand and gravel plays a major role. Sri Ravindrarajah, attained SCC by, coarse aggregate and fine aggregate were mixed (dry mixing) and followed by addition of fly ash and cement , 80% of water is mixed with superplasticizer and mixed (Wet mixing). Domone et al. [6] attained the mix at Lower coarse aggregate content, increased paste content, higher powder content, lower water /powder ratios, and high superplasticizer dosage.

The filler materials are incorporated in great extend in making the self compacting concrete, there is variation in interfacial transition properties in SCC. This variation enhances the bonding performance and durability of SCC.

6 Interfacial Transition Zone (ITZ)

The self compacting concrete has high content of filler material, stable particle slurry and exceptional rheological properties, gives the concrete a denser microstructure than conventional concrete with the same water to cementitious ratio. The porosity is lower in SCC ensuring the fillability of self compacting concrete. The pores of size range 5 to 25 μm were more evenly distributed between the interfacial transition zone and the bulk paste in the self compacting concrete. The amount of larger unreacted cement grains (> about 25 μm) in the bulk paste was higher in the self compacting concretes. These conditions will greatly reduce the effect of internal bleeding between the aggregate thus enhancing the bonding between the cement paste and aggregates, which has greater influence on the concrete – steel bond performance. The average elastic modulus and micro-hardness of the ITZ were considerably lower on the lower side of the steel bar than on the top for both the SCC and conventional concrete mixes. For the vibrated mix, the average ITZ properties were 20-30% lower on the bottom side of the bar than those on the top. For the SCC mix, the reduction was limited to 15-20%, thus a better bond between the concrete and steel reinforcement is ensured [20,21]. Bond strength is directly affected by the quality of the interfacial transition zone (ITZ) between the paste and the embedded reinforcement [29]. If the behaviour of the material is examined at microstructure level, as done by Tragardh [30] and Zhu and Bartos [33], it becomes clear that the ITZ around coarse aggregates, which constitutes the weak point of

cement-based systems and has features in common with the ITZ that forms around the reinforcements [29], is denser, stronger and stiffer in SCC than in NVC of the same w/c ratio. Persson [32] also found that this zone is wider. The enhanced micro-mechanical properties of the ITZ and their uniformity around coarse aggregate for the SCC mixes are consistent with the result of others studies on ITZ properties around horizontal reinforcing bars [29, 31]. These results indicate that the ITZ underneath the horizontal steel reinforcement bar was weaker than that above it for both SCC and NVC. However, the difference of ITZ properties between top and bottom side of a horizontal bar appeared to be less pronounced for the SCC mixes than for the conventional mixes. Furthermore, just as it was observed in the case of the aggregates, the ITZ is stronger and stiffer in SCC [30].
The aim of this paper is to present the bond behavior of SCC performed by various researchers through pull out test, beam end bond test under different loading conditions.

8 Bond Strength Of SCC

8.1 Pull out tests

In a study dealing with pull-out tests on SCC, Chan et al. [22] reported that, as compared to NC, SCC exhibits higher bond to reinforcing bars and lower reduction in bond strength due to the top-bar effect. Zhu et al. [19] performed bond tests (pullout tests) with 12 and 20 mm deformed bars placed in concrete specimens of 100 × 100 × 150 mm to study the performance of SCC compared to NC. The test results showed 10%-40% higher normalized bond strength in SCC compared to NC. Dehn et al. [22] performed pull out tests with 10mm diameter bars placed centrally in the specimen of size 100 x 100 x 100 mm to investigate the bond strength of SCC. The bond behavior was measured at 1, 3, 7, and 28 days and was reported as all specimens failed from pulling out, no visible cracks in the concrete cover were monitored. Arnaud et al. [2] investigated the bond strength of SCC using 100 x 100 x 150 mm sized pull out specimens and reported that the maximum ultimate bond strengths obtained were approximately 20% higher for SCC than normal concrete, regardless of the concrete strength. Valcuende et al. [28] examined the bond strength between reinforcement steel and concrete, and the top-bar effect in self-compacting concretes through pull out test on 200 mm specimen and reported that at moderate load levels, SCC performed with more stiffness, which resulted in greater mean bond stresses. The ultimate bond stresses are also somewhat greater although, due probably to the negative effects of the bleeding having less impact on failure, the differences between SCC and NVC are reduced considerably, and even disappear completely for concretes of more than 50 MPa.

8.2 Failure Mechanism in Pull out Test

The failure occurred in two different modes for SCC. One mode consisted of splitting of the concrete surrounding the bar, and the other mode consisted of shearing of the reinforcement against the surrounding concrete. The splitting failure is caused by the wedging action of the lugs on the bars. The wedging produces confining pressure from the surrounding concrete and is balanced by circumferential tensile stresses around the bar. These stresses cause formation of radial splitting cracks that lead to a sudden loss of bond strength. The shearing failure occurs after the reinforcement lugs shear or crush the concrete in front of the lug, thus making a pull out along a cylindrical frictional surface possible. The splitting failure is obviously fracture dominated. Different though it might seem at first, the shearing failure is also of fracture mechanics type since it is propagating and progressive. The shearing failure starts from the loaded end and then propagates towards the free end as one lug after another shears or crushes the concrete in front of the lug. After the shearing has progressed over the entire length of embedment of the bar, the force drops and then the remaining pullout is resisted by the friction, which is nonsoftening in nature but occurs at a force lower than its previous maximum. Nevertheless, due to law of friction, the shearing failure is much less abrupt than the splitting failure which is almost purely of fracture mechanics type [24].

Figure 5: Splitting failure

Figure 6: Shearing failure

8.3 By Beam Tests

In the study dealing with beam test on bond in SCC, Castel et al. investigated the Bonding and cracking of SCC performing beam test in flexure. Bond properties of both types of concrete are similar. No significant difference between SCC and VC tensile strength was observed. Turk et al. [25] investigated the bond performance using beam test with varying the diameter of the bars (16 mm and 20 mm), reporting that as the diameter of the steel bar increased from 16 to 20 mm the bond strength decreased regardless of concrete type. Finally, the normalized bond strengths of the SCC mixes were about 4% higher than those of the NC mixes for both bar diameters. Pandurangan et al.[26] reported there is an increase in the bond strength when self compacting concrete is used in place of vibrated concrete. Ductility and splice strength increased as the confinement increased. When the stirrup spacing is less than

150 mm, the failure in the splice region was by yielding of steel. Chan et al. [21] investigation proved that the reduction in bond due to bleeding and inhomogeneous nature in the case of ordinary concrete was prevented in the case of SCC. Jiann et al. reported that the bond strength of SCC is more than that of high strength concrete incorporating silica fume admixture. Desnerck et al. [27] investigated bond stress—slip behavior of reinforcing bars with diameters ranging from 12 to 40 mm and concluded that the bond strength of SCC is higher than normal concrete for small bar diameters, but the difference becomes smaller for larger bar diameters.

8.4 Failure Mechanism in Beam Test

From the experimental results, beam bond failures are as a result of concrete crushing at the bearing face of the deformations (is., lugs); shearing of the concrete around the outer perimeter of the bar; longitudinal splitting of the concrete cover in the vicinity of the bar; or a combination of these three failure modes. The beam specimens presented linear behavior until the ductile branch. After this value (which represents the ultimate bond strength) the tests continued with the yielding of the steel bar, until failure of the steel bar or the suspension of the test due to high-vertical displacement. This ductile behavior was caused by the yielding of the steel bar, which, in some cases, resulted in rupture at the middle of the bar.

With little confinement, the bond failure of large deformed bars may manifest itself by splitting of the concrete along the plane of the bar. As confinement around a bar improves, by virtue of increased cover or transverse reinforcement, the ultimate load depends increasingly on the bar diameter (perimeter). Therefore, small bars, top cast bars, or bars that are confined to the extent that bond failure occurs by shear failure of the concrete lugs (between bar deformations) instead of splitting, will carry a maximum unit load proportional to the bar perimeter. Failures of the non-splitting type are to be localized [23, 28, 29 &30].

9 Top Bar Effect in SCC

Yin-Wen Chan et al [22] investigated the bond strengths of deformed horizontal reinforcing bars located in SCC specimen and compared the results with the results of a similar conventional concrete specimen. The compressive strength and the top-bar effect were considered, the normalized bond strength of SCC ranged between 1.72 and 1.97, while that of ordinary concrete ranged between 1.18 and 1.59 according to the ACI Code provisions. This indicates that, as compared with ordinary concrete, SCC exhibits significantly higher bond strength and less significant top bar effect. Hassan et al [34] investigated the effect of positioning of bars in the SCC specimen and reported that the bond stress was slightly higher in the bottom bars than that in the top and middle bars at all ages. Also, no significant difference was detected between the top and middle bars at all ages. Valcuende et al [28] examined and compared the top-bar effect in self-compacting concretes and normal vibrated concrete. It was found that, at moderate load levels, SCC performed with more stiffness, which resulted in greater mean bond stresses. For concretes of more than 50 MPa, these differences virtually disappear (less than 2%). SCC behaves more homogeneously than NVC, as the top-bar effect was much more pronounced in the latter. Esfahani et al [35] reported that the local bond strength of top bars for SCC is about 20% less than that for NC.

10 Conclusions

Based on the extensive study made on Self Compacting Concrete and its Bond Behavior the following conclusions are made

1. The performed test shows that the bond behavior of SCC is more than the Normal Concrete. The reduction in bond due to bleeding and inhomogeneous nature in the case of ordinary concrete was prevented in the case of SCC. The bond stress slip curve is similar for both SCC and normal concrete for the bottom bars, yet higher bond stress and stiffness in the top and middle bars were observed in SCC compared to normal concrete.
2. There is decrease in bond strength when there is increase in diameter of bars. The normalized bond strength of the SCC mixes was found to be about 10-40% higher than those of normal vibrated concrete. Also the interfacial properties revealed that the elastic modulus and micro-strength of interfacial transition zone [ITZ] were better on the both top and bottom side of horizontal steel bar in the SCC mixes than in normal vibrated concrete. Generally, the bond strength between the SCC and the steel were higher than that of vibrated concrete.
3. SCC exhibits significantly higher bond strength and less significant top bar effect compared to that of conventional concrete. SCC behaves more homogeneously than NVC, as the top-bar effect was much more pronounced in the latter. The local bond strength of top bars for SCC is about 20% less than that for NC. For the bottom bars, however, the results were almost the same.

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