# Slippage of Steel in High and Normal Strength Concrete

K. Ahmed[1], Z. A. Siddiqi[1] & M. Yousaf [1]

[1] *Assistant Professor, Civil Engineering Department, University of Engineering & Technology, Lahore, Pakistan.*

## Abstract

*Composite action of any reinforced concrete member is only possible if sufficient bond strength exists between steel reinforcing bars and concrete, which can adequately transfer shear stress between them. Bond strength is a function of compressive strength of concrete and hence high strength concrete has higher bond strength [1-2]. Therefore required development length can be reduced. In order to investigate the effect of development length on bond stress and slip relationships, experimental investigation was carried out. In this experimentation 24 pull-out samples of high strength concrete and normal strength concrete were casted and tested. The results of this investigation revealed that by increasing the development length from $5d_b$ to $10d_b$ bond strength increases for both high and normal strength concrete as shown in Figure 11, 12 and 13. However incase of normal strength concrete increase in bond strength is more compared to that in high strength concrete as it is clear from Figure 11 and Figure 13. The increase in bond strength is observed even at $10d_b$ development length but the extent is less for 19 mm than 16 mm bars as shown in Figure 12 and Figure 13. This is in agreement with the earlier findings of Chen et al [3] and Harajli et al [1]. However incase of HSC the total slippage at $10d_b$ is 50% greater than at $5d_b$. This may be due to the fact that more no of concrete keys participate in resisting the slippage.*

**Key words:** Bond stress; Slippage of reinforcement; high strength concrete

## 1. Introduction

With the use of High strength concrete cross-sectional dimensions of columns and beams can be significantly reduced compared to normal strength concrete offering saving of space, time and cost of materials. High strength concrete is more durable than normal strength concrete due to very small number and evenly spaced voids of gel pore size. Therefore water transportation co-efficient and permeability are also small compared to normal strength concrete [4].

When any reinforced concrete member is subjected to flexure beyond the cracking state of concrete in tension, steel reinforcement gets tensile stresses. Hence reinforcement must be anchored at the ends by the bond between steel bars and concrete. In case of plain bars this bond is developed only through adhesion and friction between steel and concrete. [3]

As soon as the interface cohesive crack and radial cracks form and propagate, the bond strength diminishes rapidly and slip increases. However in case of deformed steel bars, bond strength is a function of adhesion and friction between steel and concrete, bearing resistance offered by concrete against the reinforcing steel bar ribs and friction between concrete keys and surrounding concrete as can be seen from the Figure 1. When structural member is loaded and adhesion between steel and concrete is broken then slip occurs and bond strength reduces. Further resistance is provided by the friction between broken concrete particles and concrete. [1] However, major contribution of bond strength is provided by bearing strength of concrete in front of bar ribs. The ultimate bond failure is a function of concrete compressive strength, cover to the reinforcement or confinement, reinforcing bar profile, its diameter and development length.[5-7] Many researchers, as mentioned in the reference, studied the various aspects of bond stress and slippage of reinforcement. Only a few worked for high strength concrete.

## 2. Types of failure

There are two main types of bond failure; pull out failure and splitting failure.[8,13] Pull out failure is likely to occur when the concrete in between the reinforcing steel bar ribs known as concrete key, is weak and surrounding concrete is strong; as shown in Figure 2 [9]. The concrete key will be heavily stressed due to

Corresponding Author: K. Ahmad (Kafeel91@hotmail.com)

relatively high rib height a/d >0.1, small rib spacing a/c > 0.5 and high rib angle (greater than 70°). [9] In case of splitting type of failure there can be two further types. In first type due to rib angle between 40° to 70°, concrete in front of the keys is crushed and forms a wedge on which concrete key slips outwards along the side of the wedge as shown in Figure 3 & its circumference increases generating radial tensile stresses and longitudinal splitting cracks. In the second type of splitting failure, rib angle is so small even less than 40°, that concrete key slips without crushing and longitudinal splitting cracks are formed under the action of radial component of bond stress. This type of failure is more brittle as compared to the first type of splitting failure and undesirable. [10]

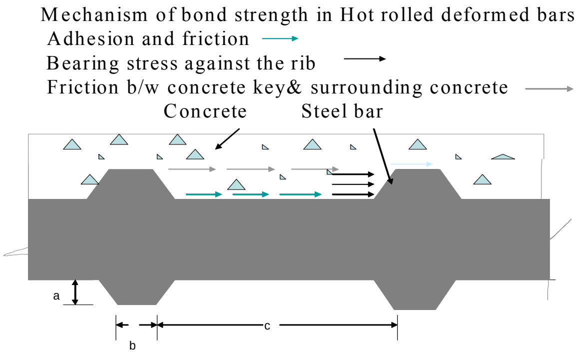

**Figure 1:** Mechanism of bond strength development.

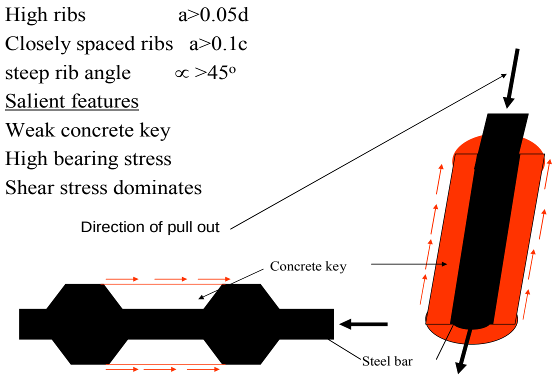

**Figure 2:** Pull out failure of samples.

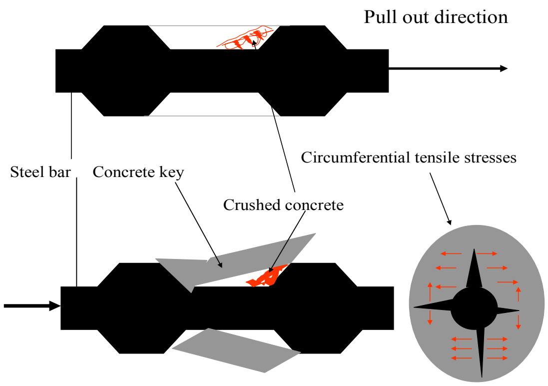

**Figure 3**: Longitudinal splitting failure.

## 3. Development length

In case of high strength concrete, concrete key is sufficiently strong and has high bearing resistance against bar ribs increasing the bond strength of concrete. Hence required development length can be reduced as compared to normal strength concrete. Earlier researchers like Harajli [1] carried out experimentation using $5d_b$ as the development length. Nygun Viet Tue [3] used 2.5 to 3 $d_b$ as the development length. The authors planned experimentation using $5d_b$ and 10 $d_b$ as the development length for both normal and high strength concretes using 16 mm and 19 mm diameter reinforcing bars.

## 4. Experimentation

High strength concrete using silica fume and normal strength concrete were used for the study [11]. Hot rolled deformed steel bars having yield strength of 415 MPa were used in pull-out samples consisting of 150mmØ and 300 mm high concrete cylinders.

## 5. Material

Ordinary Portland cement conforming to EN 196, silica fume of particle size 0.1 to 1 micron, Quatz sand 200 to 500 micron, Lawrencepur sand of 4.00mm maximum size, Sargodha crush in two fractions 9.5mm to 8.0mm and 6.7mm to 5.6 mm, third generation superplasticizer polycarboxylate ether were used for high strength concrete.

In order to control the temperature of concrete, chilled water and ice cooled aggregates were used in saturated surface dry conditions. Laboratory temperature was kept at 30$^o$C and relative humidity at 75%. PVC pipes were used to debond the steel from concrete in order to achieve the desired development lengths as shown in Figure 4. Immediately after pouring the moulds were covered with polyethelyne sheets and tightly tied with thread to stop the loss of water due to evaporation as shown in Figure 5 [12-14]**.** After 24 hours, de-molding was carried out and all the specimens were placed in curing water tank making sure that projecting bars should not be submerged. The samples for compressive strength were tested at 3, 7, 14 and 28 days. The pull-out test was performed at the age of 28 days.

Table 1 shows the diameter, cover and development length used for various pull-out samples The measured compressive strengths of both normal and high strength concretes are given in Table 2.

**Table 1:** Properties of steel reinforcing bars, cover and development lengths.

| Sr. No | Bar No SI bar # | Bar Ø mm (in) $d_b$ | Cylinder size 150mmØ 300mm High (6"Ø 12"High) | | | |
|---|---|---|---|---|---|---|
| | | | **Cover 'c' in mm** | **$c/d_b$** | **High strength concrete Development length mm** | **Normal strength concrete Development length mm** |
| 1 | 16(5) | 16(5/8) | 67.0 | 4.18 | $02d_b$ =032 | $02d_b$ =032 |
| 2 | 16(5) | 16(5/8) | 67.0 | 4.18 | $05d_b$ =080 | $05d_b$ =080 |
| 3 | 16(5) | 16(5/8) | 67.0 | 4.18 | $10d_b$ =160 | $10d_b$ =160 |
| 4 | 19(6) | 19(3/4) | 65.5 | 3.44 | $02d_b$ =038 | $02d_b$ =038 |
| 5 | 19(6) | 19(3/4) | 65.5 | 3.44 | $05d_b$ =095 | $05d_b$ =095 |
| 6 | 19(6) | 19(3/4) | 65.5 | 3.44 | $10d_b$ =190 | $10d_b$ =190 |

**Table 2:** Properties of concrete.

| Sr. No | Specimen type 150mmØ 300mm High | High strength concrete fc' in PSI (MPa) | Normal strength concrete fc' in PSI (MPa) |
|---|---|---|---|
| 1 | Cylinders | 7133 (49.4) | 3742 (25.8) |

**Table 3:** Properties of grade 60 reinforcing steel bar 16 mm diameter.

| Bar Diameter in mm | Rib height in mm "a" | Rib width in mm "b" | | | C/C rib spacing in mm "c" | | | Clear dist. b/w ribs in mm | | | a/c |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | end | mid | End | end | mid | end | end | Mid | end | |
| 16 | 1.48 | 2.1 | 1.9 | 2.0 | 8.0 | 8.0 | 8.3 | 5.2 | 5.1 | 5.5 | 0.18 |
| | | 1.5 | 1.4 | 1.3 | 7.9 | 8.0 | 8.36 | 6.2 | 6.2 | 6.3 | |
| | | 2.1 | 2.0 | 2.0 | 7.6 | 7.6 | 8.2 | 5.2 | 5.3 | 5.3 | |
| | | 1.86 | 1.76 | 1.76 | 7.8 | 7.86 | 8.2 | 5.5 | 5.53 | 5.7 | |
| | | | 1.79 | | | 7.97 | | | 5.576 | | |
| 16 | 1.51 | 2.1 | 2.3 | 1.9 | 8.0 | 8.0 | 8.9 | 5.1 | 5.3 | 5.2 | 0.18 |
| | | 1.7 | 1.3 | 1.6 | 7.4 | 8.0 | 7.9 | 6.3 | 6.4 | 6.2 | |
| | | 2.1 | 2.0 | 1.9 | 8.0 | 8.0 | 8.0 | 5.2 | 5.0 | 5.3 | |
| | | 1.83 | 1.86 | 1.8 | 7.8 | 8.0 | 8.26 | 5.5 | 5.63 | 5.5 | |
| | | | 1.83 | | | 8.02 | | | 5.573 | | |
| 16 | 0.90 | 2.7 | 2.4 | 2.4 | 8.3 | 8.4 | 8.2 | 6.8 | 6.6 | 6.5 | 0.11 |
| | | 2.4 | 2.1 | 2.0 | 8.2 | 8.0 | 8.4 | 6.4 | 6.3 | 6.3 | |
| | | 2.7 | 2.4 | 2.3 | 8.4 | 8.0 | 8.6 | 6.7 | 6.7 | 6.6 | |
| | | 2.6 | 2.3 | 2.23 | 8.3 | 8.2 | 8.4 | 6.6 | 6.53 | 6.4 | |
| | | | 2.4 | | | 8.3 | | | 6.54 | | |

**Table 4:** Properties of grade 60 reinforcing steel bar 19 mm diameter

| Specimen Diameter in mm | Rib height in mm "a" | Rib width in mm "b" | | | C/C rib spacing in mm "c" | | | Clear dist. b/w ribs in mm | | | a/c |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | end | mid g | end | End | mid g | end | end | mid g | end | |
| 19 | 2.31 | 2.6 | 2.5 | 2.0 | 10.7 | 10.8 | 10.8 | 7.8 | 8.0 | 7.8 | 0.21 |
| | | 1.8 | 1.8 | 1.5 | 10.5 | 10.8 | 10.9 | 8.6 | 8.5 | 8.5 | |
| | | 1.9 | 1.9 | 1.8 | 11.0 | 10.9 | 10.6 | 7.2 | 7.1 | 7.1 | |
| | | 2.1 | 2.0 | 1.76 | 10.73 | 10.83 | 10.76 | 7.87 | 7.86 | 7.8 | |
| | | | 1.97 | | | 10.77 | | | 7.843 | | |
| 19 | 2.37 | 2.4 | 2.6 | 2.2 | 10.9 | 10.6 | 11.0 | 8.1 | 8.0 | 8.0 | 0.22 |
| | | 1.6 | 1.3 | 1.9 | 10.9 | 10.5 | 10.5 | 8.4 | 8.8 | 8.4 | |
| | | 2.0 | 2.0 | 1.8 | 10.8 | 10.8 | 10.3 | 8.3 | 8.3 | 7.6 | |
| | | 2.0 | 1.967 | 1.73 | 10.86 | 10.63 | 10.6 | 8.27 | 8.36 | 8.0 | |
| | | | 1.9 | | | 10.70 | | | 8.209 | | |
| 19 | 2.28 | 4.5 | 4.6 | 4.5 | 12.7 | 13.3 | 12.9 | 6.9 | 6.8 | 6.7 | 0.175 |
| | | 3.7 | 3.7 | 3.8 | 12.8 | 13.2 | 13.1 | 6.4 | 6.5 | 6.3 | |
| | | 4.5 | 4.3 | 4.5 | 12.9 | 13.4 | 13.3 | 6.8 | 6.9 | 6.6 | |
| | | 4.23 | 4.2 | 4.27 | 12.8 | 13.2 | 13.1 | 6.7 | 6.73 | 6.53 | |
| | | | 4.31 | | | 13.03 | | | 6.65 | | |

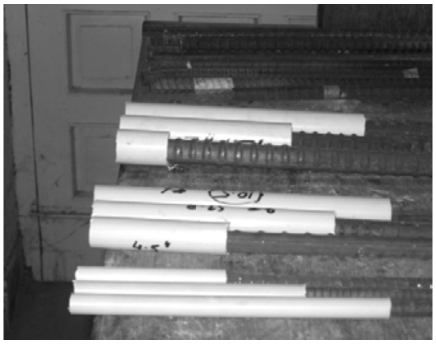

**Figure 4:** Steel bars for pull out samples.

**Figure 5:** Pullout sample immediately after casting..

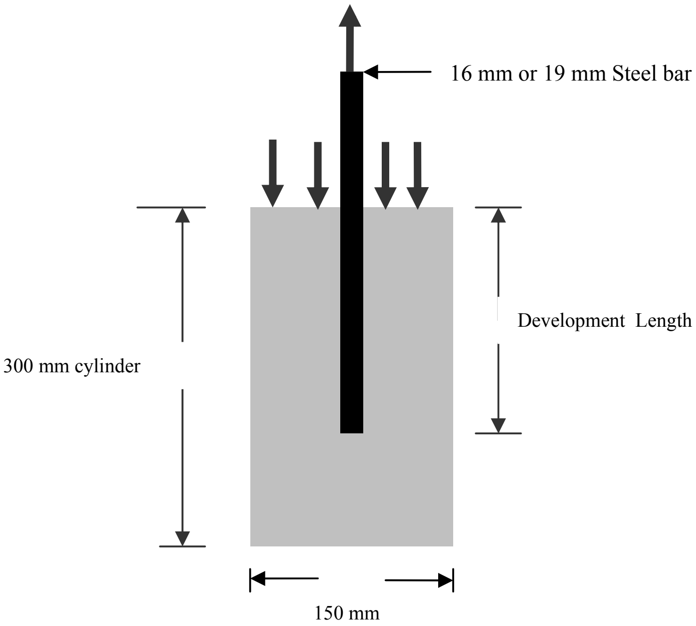

**Figure 6:** Schematic diagram for pullout test. [10]

## 6. Testing

Pullout samples were tested in a pullout assembly specially designed for the said purpose having hinge on one side to neutralize the effect of eccentricity developed during fixing of sample in the machine. The load was applied through 2000KN capacity high precision UTM and slip was recorded with the help of displacement gauge. The loading for pull-out test is represented in Figure 6 and the samples, ready to be tested, are shown in Figure 7.

**Figure 7:** Samples ready for pullout test.

## 7. Test Results and Discussion

### *7.1. Effect of compressive strength of concrete on slippage*

The failure mode of pull-out samples is shown in Figure 8. The relationships between slip of steel bar and corresponding stress level for 16mm diameter bars are shown in Figure 9 for 5$d_b$ development length and in Figure 10 for 10$d_b$ development length. It is clear from the Graphs in Figure 9 and Figure 10 that maximum noted slippage of steel relative to concrete is 29% reduced when high strength concrete is used for

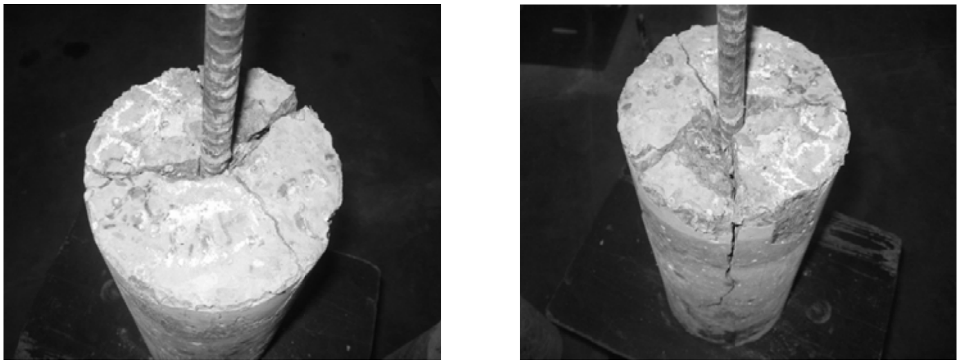

**Figure 8:** Longitudinal splitting failure of HSC(Left) and NSC(Right)samples .

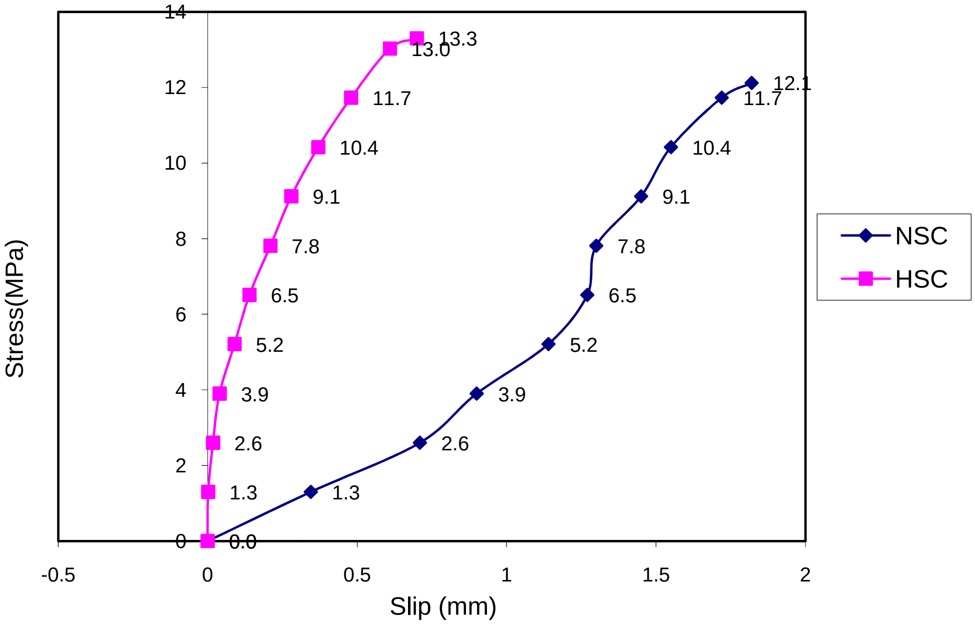

**Figure 9:** Comparison of bond stress and slip in HSC and NSC for 16mm bar with '5$d_b$' development length.

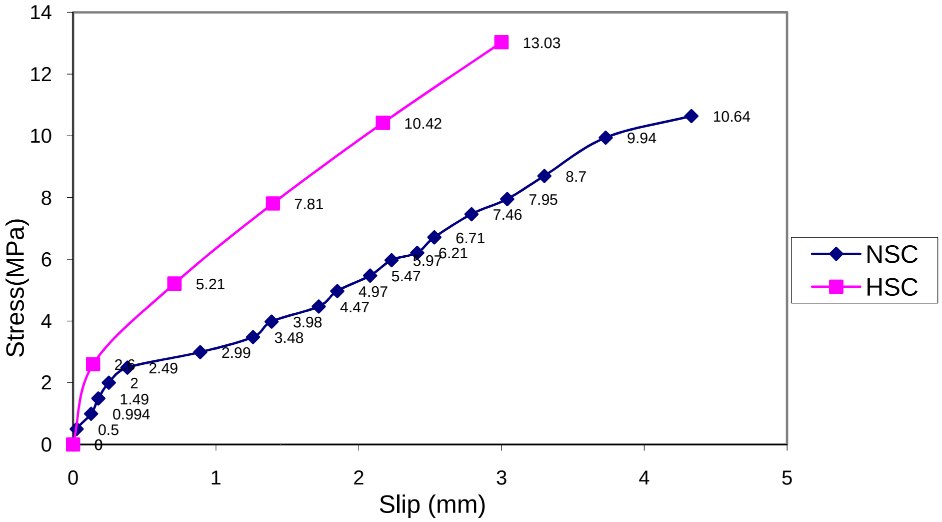

**Figure 10:** Comparison of bond stress and slip in HSC and NSC for 16mm bar with '10$d_b$' development length

$5d_b$ development length. However, it is reduced by 68% for $10d_b$ development length. This drastic decrease for high strength concrete can be attributed to increased compressive strength of concrete keys which offer greater bearing resistance against slippage. Moreover incase of longer development length there are more number of keys that resist the slippage and cumulative slippage of all keys increases the total slippage. [1,15]

Using the least square method of curve fitting resulting (from Graph) mathematical relationship of bond stress and slip for high and normal strength concrete is as follows [16]

**$U=-26.47\,\delta^2+34.833\,\delta+1.59$** for High Strength Concrete.

Co-efficient of correlation = $R^2 = 0.978$

**$U=\ 2.8\,\delta^2+1.91\,\delta+0.03$** for Normal Strength Concrete

Co-efficient of correlation = $R^2 = 0.988$

Where U is the bond stress, δ is the slip.

## 8. Effect of development length on slippage

The stress slip relationship for 16 mm diameter bars embedded in high strength concrete for the selected development lengths are shown in Figure 11 whereas the same relationship for 19 mm bar is shown in Figure 12. For normal strength concrete, the effect of development length on stress slip relationship is given in Figure 13. It is clearly evident from the Graphs that by increasing the development length slippage increases for high strength concrete. One probable reason for this is that in case of high strength concrete due to delayed failure of concrete keys more are effective in providing bond strength and resisting the slip near ultimate failure. However this trend is not present in case of normal strength concrete. This may be due to the reason that failure of one key causes the stress concentration on remaining keys that leads to rapid failure without adequate slippage as concrete keys are not so strong to resist the stress concentrations. Using the least square method of curve fitting Graph shows the following mathematical relationship of bond stress and slip for $10d_b$ development length in high strength concrete

## 9. Effect of compressive strength on slippage

The stress slip relationships for 16 mm diameter bars embedded in high and normal strength concrete for the selected development lengths are shown in Figure 9 and Figure 10. It is clear from these graphs that by increasing the compressive strength bond strength increases and sip reduces. This may be due to more bearing resistance of concrete keys which offer more resistance to slip and increase the bond strength.

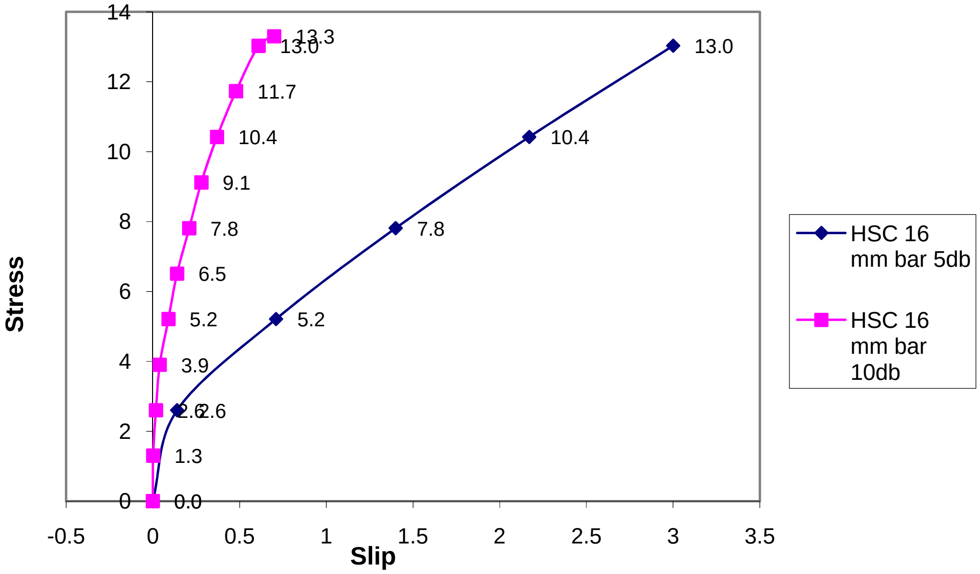

**Figure 11:** Comparison of bond stress-slip(HSC,16mm diameter).

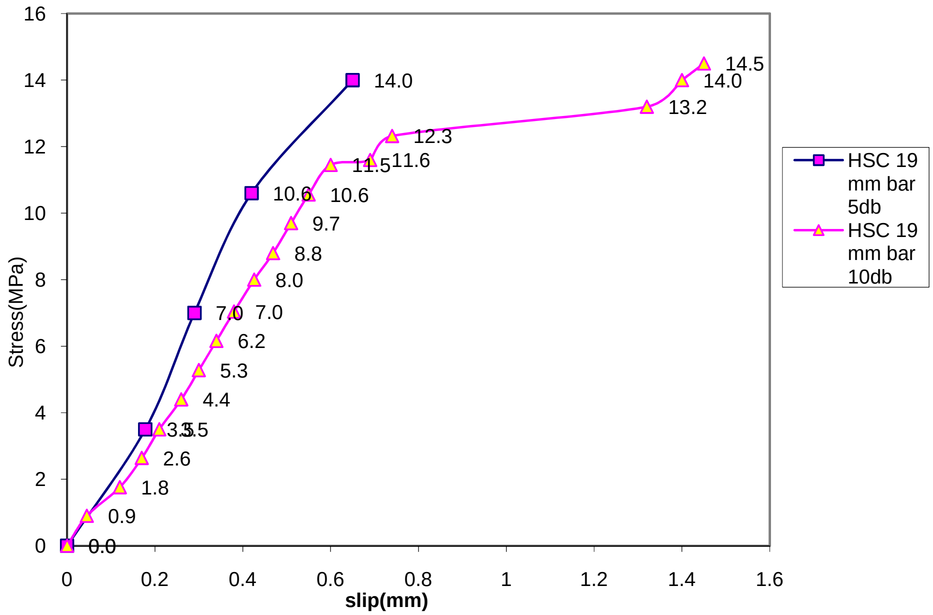

**Figure 12:** Comparison of bond stress-slip(HSC,19 mm diameter).

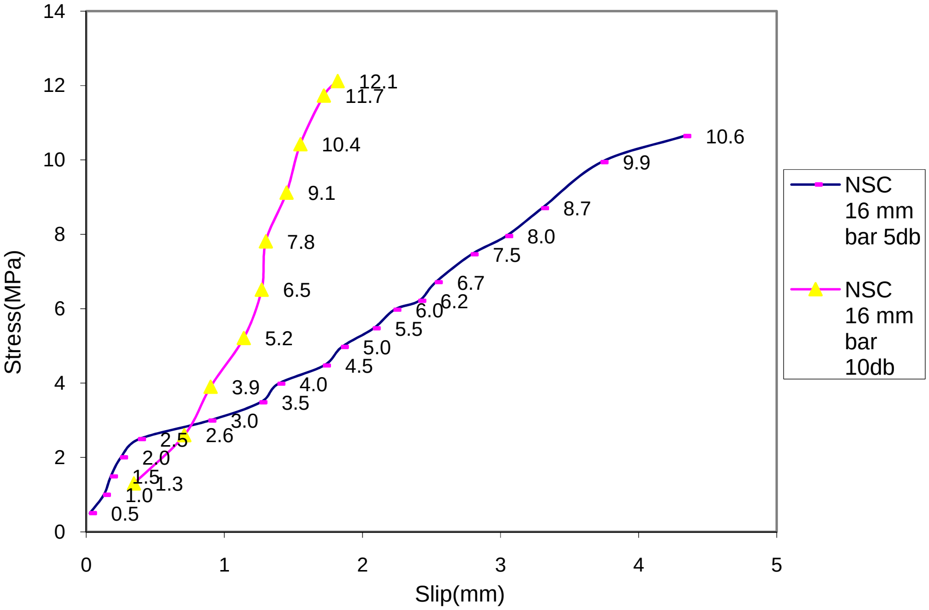

**Figure 13:** Comparison of bond stress-slip (NSC, 16mm diameter).

## 10. Conclusion

1. Observing the trends of graphs in Figure 9 and Figure 10, it is evident that when compressive strength of concrete is increased, bond strength increases but relative slippage between steel and concrete decreases for same development length, same diameter of bar and same c/$d_b$ value. This may be due to high bearing resistance of concrete keys that offer more resistance to slippage than normal strength concrete.

2. A comparison of graphs in Figure 11 and Figure 12 shows that for HSC by increasing the development length of steel reinforcement from 5$d_b$ to 10 $d_b$ for high strength concrete, slippage also increases. This may be due to presence of more no of concrete keys which resist

the slippage and cumulative slippage of all keys increases the total slippage.

3. However there seems to be no direct relationship between development length and slippage for normal strength concrete as is evident from Figure 13.

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