International Journal of Scientific Engineering and Science
Volume 3, Issue 4, pp. 18-25, 2019 ISSN (Online): 2456-7361

Pull-out Behavior of Conventional Steel Reinforcement in Normal and High Strength Concrete

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Abstract— *Strength incorporating properties in reinforced concrete are cardinally dependent on the bond strength developed between concrete matrix and the steel reinforcement bars. In matrix-reinforcement composite, bond strength depends on essentially two material properties, i.e., factors related to concrete matrix and the factors related to the reinforcement used. Therefore, such an investigation has been carried out in this research which determines the effectiveness of bond strength based on variations developed due to type of concrete and steel reinforcement bars. Experimental investigations were carried out to observe the effectiveness of bar diameter and embedded length on the pull-out strength of reinforced normal strength concrete (R-NSC) and reinforced high strength concrete (R-HSC). Concrete cylinders having dimensions* 12" *height and 6"dia. were casted for the pull-out tests using steel bars of different types i.e. plain, deformed and tor bars of Grade-40 and -60, of imperial bar sizes of* #3, #4 *and* #5 *having embedment lengths of* 4", *8"and* 12", *each. Curried reinforced normal and high strength concrete specimens were tested for pull-out test after 28-days of curing. Pull-out test results showed that for the larger dia. steel reinforcement bars i.e #5 bar, having any embedment length gives equal bond strength for varying grades i.e. Grade-40 & -60 steel bars; while, yielding was observed for #3 and #4 bars at an embedment length of* 12". *Steel bars of* #5 *cause splitting of concrete cylinders both in R-NSC and R-HSC, depicting that pull-out strength decreases as the bar diameter increases. Moreover, the increase in the embedded length decreased the bond strength of concrete as well as bars having smaller dia, shoed enhanced bond strengths.*

Keywords— *Bond-Strength, Bar pull-out, Grade-40 and -60 steel bars, Normal and high strength concrete, Reinforcing steel bar.*

I. INTRODUCTION

Utilization of Reinforced-Normal Strength Concrete (R-NSC) and Reinforced-High Strength Concrete (R-HSC) significantly depends on the behavior of bond strength of steel reinforcement bars in Reinforced Concrete (RC) structures and has a significant effect on the overall design and structural ductility [1–3]. R-NSC are suitable for conventional constructions which are cost-effective, requiring lesser labor skills and is commonly in existences globally. While, R-HSC is suitable material in developed countries, imparting higher strengths and durability into the structures. Higher bond strength between the concrete matrix and primary reinforcement, i.e., steel reinforcement bars is essential for challenging locations like off-shore constructions, construction of bridges, high-rise buildings, structures on weak or saline soils or incorporated in parts of hydraulic structures [1, 4]. Development in the design and mechanics of RC composite structures is possible today due to higher bond strengths or more effectiveness of interfacial transition zones (ITZs) [5, 6]. Research is being carried out on the densification of ITZs. The greater the density of the ITZs, the greater will be the bond strength between the concrete matrix and the steel reinforcement. Many other factors affect the properties of the steel-concrete bond, which include density of concrete [7], type of aggregates [8], strength of concrete [9], shape of reinforcement bars [10], embedment length and orientation of the reinforcement bars [11].

Apart from densification of concrete matrix at the ITZs for better RC-bond strength, which is decisively determined for high strength concrete (HSC), unlike normal strength concrete (NSC), only by refined choice of the type of steel reinforcement being used, engineers can obtain the similar or maybe better results regarding RC-bond strength. Subsequently, it may minimize the concrete mixing time for producing a denser matrix, and much labor efforts could also be reduced [12]. R-HSC with the incorporation of the correct choice of steel reinforcement bars could result in a further enhancement in overall design and structural ductility. Bond behavior can be determined by evaluating the ITZs. Bond strength is usually the measurement of bond stress at the interface of the steel reinforcement bar and concrete along the total embedment of reinforcement bar [18-19]. Cairns redefines *bond stress* as the ratio of applied force to the reinforcement bar area. The embedded reinforcement bar area is the total surface area over which the axial force is applied [15].

Steel-concrete bond strength can be achieved due to the following mechanisms [1, 9, 13, 15–17].

1. Friction between the composite of hardened concrete and the reinforcement bar,
2. Mechanical interlocking between the reinforcement bar and concrete,
3. The adhesion between the composites, i.e., concrete to steel, which is due to the chemical bonding or adhesion of cement particles to the embedded reinforcement

Presently, the advancement in the production of different strengths of concrete, application, and usage of reinforced concrete has led to the development of R-HSC. Elfgren and Noghabai [18] and Hamad et al. [19] recorded no precise results about the influence of the reinforcement bar size in concrete on its bond strengths. According to Gambarova [20] bond strength is mainly associated with:

- The stiffening of structural members after the initial cracking in the tension zone,

- The attainment of tensile strength in the structure,
- The achievement of specified ductility,
- The cracking limitations.

Moreover, in reinforced concrete member, the measurement of bond between the reinforcement and concrete is carried out by measuring the shear stress or bond stress, which takes place at the periphery of embedded length of reinforcement bars [21]. In case of deformed bars, some other parameters such as Normal Stresses (NS) and Radial Shear Stresses(RSS) also contribute to the bond strength of concrete [22–24]. Normal shear stresses take place along the length of the bars when a tensile load applied to it. Normal shear stresses are always parallel to the bar surface; whereas, the radial shear stresses take place along the ribs of the deformed reinforcement bars as shown in Fig. 1 [25]. In case of deformed bars, multi-axial stresses are produced within the ribs which increases the possibility of the pull-out load for the reinforced steel reinforcement bars [24]. The ribs provide wedging action which causes the crushing of concrete when the pull-out load is applied. Pull-out load produces micro- as well as macro-cracks in the concrete. The production of micro- cracks in concrete causes the loss of strain compatibility in reinforced concrete [23]. In the presence of these micro- cracks and with the further increase in the axial loads, slippage of the reinforcement bar occurs which initiate the friction bond strength of concrete [12].

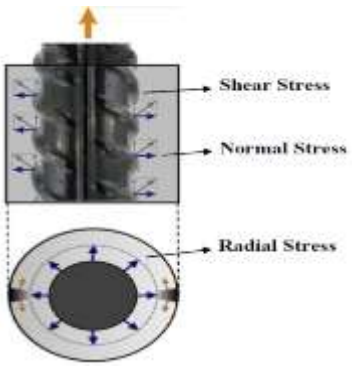

Fig. 1. Bond Stresses (Normal, Shear & Radial Stresses) produced at the Interface Transition Zones (ITZs) of twisted reinforcement bar.

There are three main techniques to determine the steel-concrete bond strength between the neighboring ribs of the reinforcement bar. These are the bearing stresses as opposed to the interfaces of ribs (mechanical interlock), the shear stresses due to physical or chemical adhesion along the reinforcement bar surface, and the static friction between the surrounding concrete and reinforcement bars [26]. Concisely, higher adhesion and friction forces between concrete and steel reinforcement bars can be anticipated for concrete with higher compressive strengths which is basically dependent on the higher density of the composite matrix [26].

The magnitude of the steel-concrete bond is significantly increased by the use of deformed reinforcing bars particularly due to additional radial stresses produced at the ribs of the reinforcement bar. The utmost influence of bond strength comes from mechanical interlocking [27]. The main features of the steel to concrete bond-stress vs. slip evolution and the maximum bond-stress are clearly dependent on properties like material properties, geometrical properties or loading conditions [24, 28, 29]. Viriyametanont and François studied the effect of reinforcing bars orientation within the concrete composite with different casting conditions and directed positive relationship between the height of reinforcement ribs and spacing and the steel-concrete bond strength [30].

The bond stresses between reinforcement bars and the concrete matrix is transferred by the adhesion between them before slip occurs and by the action produced by the splitting particles which are breaking free from the concrete during slipping [19, 31]. Arrangement of smooth reinforcing bars along each of two sides of the precast concrete joint can enhance joint resistance against reinforcement slippage during dynamic loading and will make the joint ductile. However, to use plain steel reinforcement bars as a reinforcing material in the reinforced concrete members some perspective of their behavior have to be determined including bond-strength and anchorage in concrete [32]. The stress and slip model of bond strength have been proposed, that the load-slip and anchorage length of the reinforcing bars extended from the interconnecting beams into external columns under large nonlinear actions, suggesting that such proposed models are overly simplified compared to the real behavior of structures [33, 34].

As contemporary world structures are more sophisticated and are frequently subjected to earthquake frequencies of higher magnitudes, making it mandatory for engineers to account safety enhancement in their designs and constructions. The earthquake design changed the design parameters to provide safety in the structures. An appropriate bond between the surrounding concrete and steel reinforcement bars is also essential for the long-term serviceability and lifetime strength of reinforced concrete (RC) members. These techniques usually need higher embedment lengths for the steel reinforcements. Therefore, to achieve the perfect bond strength, there was a need of research in order to investigate the bond-strength of conventional steel reinforcement within the normal and high strength concrete and to check the effect of embedment length of steel reinforcement on the bond-strength, and also to check the variation in bond-strength with the variation in bar size and bar shapes. This research investigates the effect of different types and sizes of steel reinforcement bars on the bond strength within two different types of concretes, i.e., normal strength concrete (NSC) and high strength concrete (HSC).

II. Experimental Program

There are various methods used to test the bond-strength of steel reinforcement bars with the concrete matrix and their behavior (e.g., bond-slip relationship). Here, the direct pull-out test was performed in which experimental phase consisted of 216 cylindrical specimens having dimensions 12" height and 6" dia., casted with normal and high strength concrete, in order to investigate the bond-strength under monotonic loadings. The influence of steel reinforcement bar-diameter and concrete strength were investigated for plain, deformed, and tor rebars of bar #3, #4 and #5 having diameter 3/8, 4/8 and 5/8 inches, respectively, were used to observe the

International Journal of Scientific Engineering and Science
Volume 3, Issue 4, pp. 18-25, 2019 ISSN (Online): 2456-7361

bond-strength and their stress-slip relation between the reinforcement bars and NSC and HSC.

A. Materials

a. *Super Plasticizer and Cement*

Sika Viscocrete 3110W obtained from Sika Group, Pakistan was used in HSC to achieve the specified slump range. A dosage of 0.45% by weight of cement was used in this research program. Ordinary Portland Cement (OPC) of ASTM Type-I (Grade-53) was used in this research. The freshness of cement was checked according to the standard practice of ACI, followed by the determination of chemical composition and physical properties of cement which were found as per standards recommended.

b. *Fine Aggregate and Coarse Aggregate*

Locally available fine and coarse aggregates were used for the experimentation. The properties of the fine aggregates were examined and justified according to ASTM C 33. All the required properties of the fine aggregates were checked for better results. The coarse aggregates were having a maximum size of ½ inches and lower sizes. The spherical and flakey particles were negligible in the specified coarse aggregates source. The physical properties of fine and coarse aggregates are shown in Table 1.

TABLE 1. Physical Properties of Aggregates (Fine and Coarse)

Characteristics	Fine Aggregate	Coarse Aggregate
Type	Normal	Crushed
Specific Gravity	2.54	2.64
Dry Ridded Bulk Density (lb/ft^3)	148	96.53
F.M	2.40	6.75
Absorption %	1.00	0.10

B. Steel Reinforcement

a. Plain, Deformed and Tor Steel Bars

The plain, deformed and tor steel reinforcement bars of 36" length were obtained from Steel Industries, Lahore (Pakistan) having Grade-40 and -60 as shown in Fig. 2 and details are given in Table 2.

(a) (b) (c)

Fig. 2. Types of steel reinforcement bars used. (a) Plain Steel Bar, (b) Deformed Steel Bar (c) Tor Steel Bar

C. Mix Proportions of Concrete

Concrete mix was prepared with water/cement (w/c) ratio of 0.50 and 0.35 for NSC and HSC, respectively. To observe the proper workability of concrete, slump test was performed, and the slump value within the range of specified value of 3 inches was found.

TABLE 2. Physical Properties of Plain, Deformed and Tor Bar

Reinforcement Type	Bar Number	Grade		Lengths		
				L1	L2	L3
Plain bars	# 3	40	60	24"	28"	32"
	# 4			24"	28"	32"
	# 5			24"	28"	32"
Deformed bars	# 3	40	60	24"	28"	32"
	# 4			24"	28"	32"
	# 5			24"	28"	32"
Tor bars	# 3	40	60	24"	28"	32"
	#4			24"	28"	32"
	#5			24"	28"	32"

Following standard codes of ASTM C 31, concrete cylinder of 6 inches diameter and 12 inches height were adequately filled in three layers simultaneously consolidated with a tempering rod and were tested for compressive strength according to ASTM C 39 after 28 days (Fig. 3). After 24 hours, the cylinders were demolded and then placed for curing at room temperature in curing tank for 28 days (Fig. 4).

Fig. 3. Concrete mixing and casting of cylinder

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ISSN (Online): 2456-7361

Fig. 4. Curing of concrete cylinders in curing tank

D. *Test Specimens for Pull-out Test*

Cylindrical molds of dimensions 6" diameter and 12" height with proper arrangement for the embedment length of steel were used. Concrete mix poured adequately in three layers to the cylinders. The details of different cylindrical molds with the embedment length for different size of bars are shown in Table 3. After 24 hours, cylinders were demolded and placed for curing in the curing tank for 28 days in such a manner that only concrete portion was completely submerged in water, whereas the steel was above the water. The schematic diagram for pull out test shown in Fig. 5

TABLE 3. Specimens detail for embedment length

No. of Specimens	No. of Bar	Embedment Length		
		L1	L2	L3
2 (per embedment)	#3	$10.5d_b$ = 4"	$21.0d_b$ = 8"	31.5db = 12"
	#4	$8.0d_b$ = 4"	$16.0d_b$ = 8"	$24.0d_b$ = 12"
	#5	$6.4d_b$ = 4"	$12.8d_b$ = 8"	$19.0d_b$ = 12"

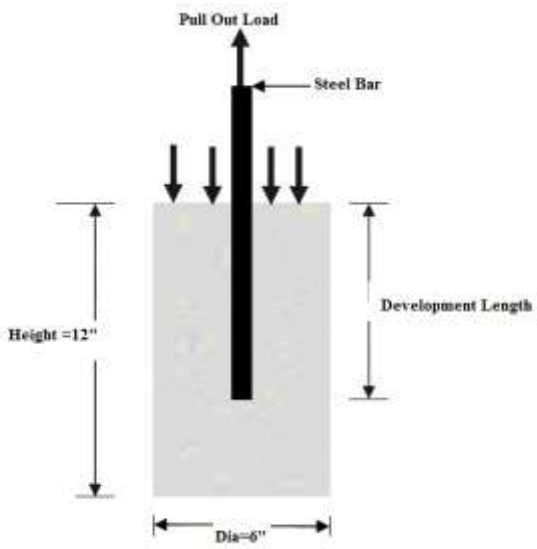

Fig. 5. Schematic diagram for pull-out test

III. Tests Result

A. *Compressive Strength*

Triple concrete-reinforcement cast cylinders were tested after 28 days curing at room temperature. An average compressive strength for NSC and HSC were achieved as 3200 psi and 6400 psi, respectively.

B. *Pull-out Load and Bond Strength*

The pullout-test specimens were loaded by the Universal Testing Machine (UTM) fitted with the assembly of bar pull-out apparatus. Specimen of different sizes of Tor (Twisted), deformed and plain rebars and different embedment lengths are shown in Table. 3, tested after 28 days of curing. The results of pull-out load obtained from the UTM and bond-strength were found by using the following formula:

$$f_b = \frac{P}{\pi d L}$$

Where, f_b = Pull-out strength of concrete (psi), P = applied pull-out load (lbs.), d = dia. of the reinforcement bars (inches), L = Embedment length of the reinforcement bars (inches)

a. *Plain Reinforcement Bars – (Steel Grade-40)*

The results of pull-out loads and bond-strengths are shown in Fig. 6 and Fig. 7, respectively.

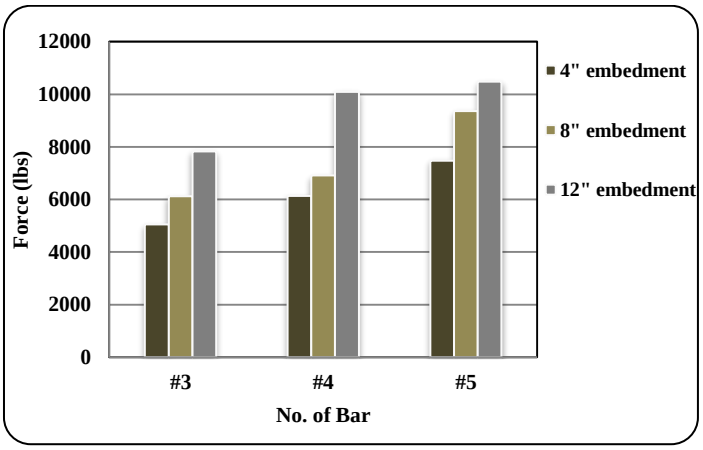

Fig. 6. Pull out load for plain steel reinforcement bars - NSC.

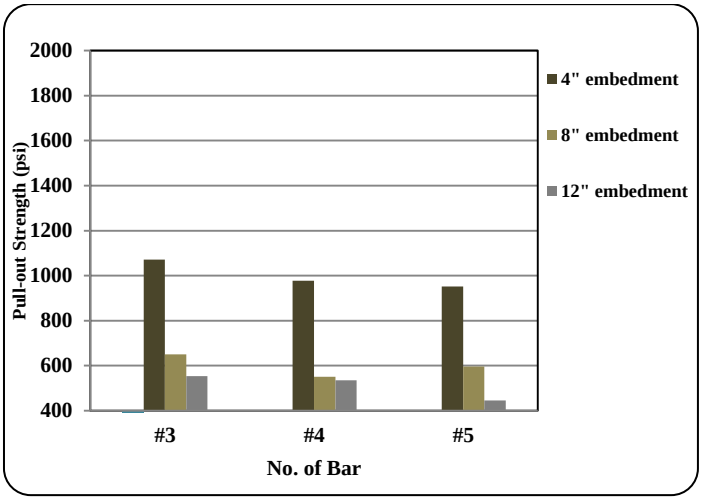

Fig. 7. Pull-out strength for plain steel reinforcement bars – NSC

The results presented in Fig. 6 shows that by increasing the dia. of the reinforcement bars, a proportional increase is observed in pull-out load for all the specimens, and with the increase in embedment similar increase is observed, i.e., linearly increases with the pull-out load. On the other hand,

the results displayed in Fig. 7 shows that with the increase in dia. of bar (or using bar of higher number) and embedment length, decrease in bond-strength was observed. Hence, greatest bond strengths were observed for smaller embedment lengths.

b. *Tor Reinforcement Bars (Steel Grade-40)*

The reflection of pull-out testing is displayed in Fig. 8 while results of pull-out load are shown in Fig. 9 and Fig. 11 for NSC and HSC, respectively; while, their bond-strengths are shown in Fig. 10 and Fig. 12 for NSC and HSC, respectively.

Fig. 8. Pull-out testing of tor steel reinforcement bars – NSC

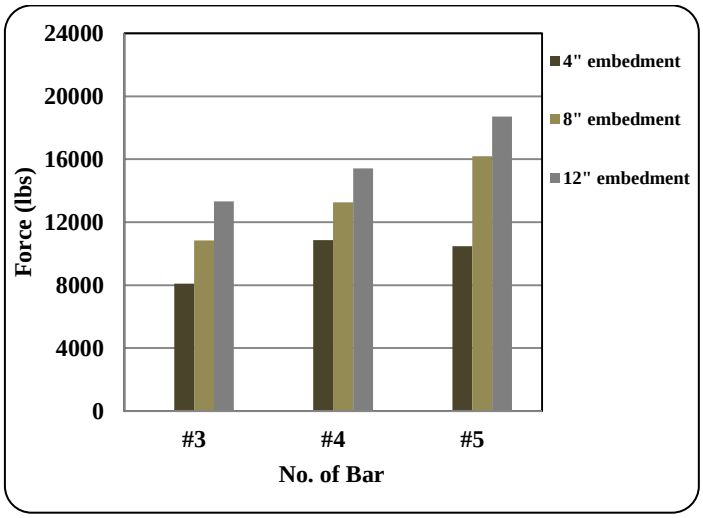

Fig. 9. Pull-out loads for different sizes of steel bars and embedment lengths (NSC) – Tor bars

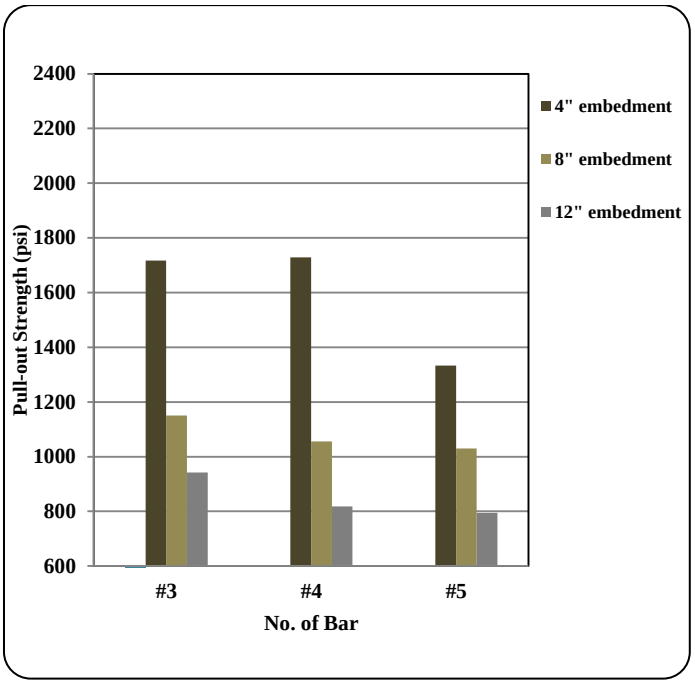

Fig. 10. Pull-out strength for different sizes of bars and embedment lengths (NSC) – Tor bars

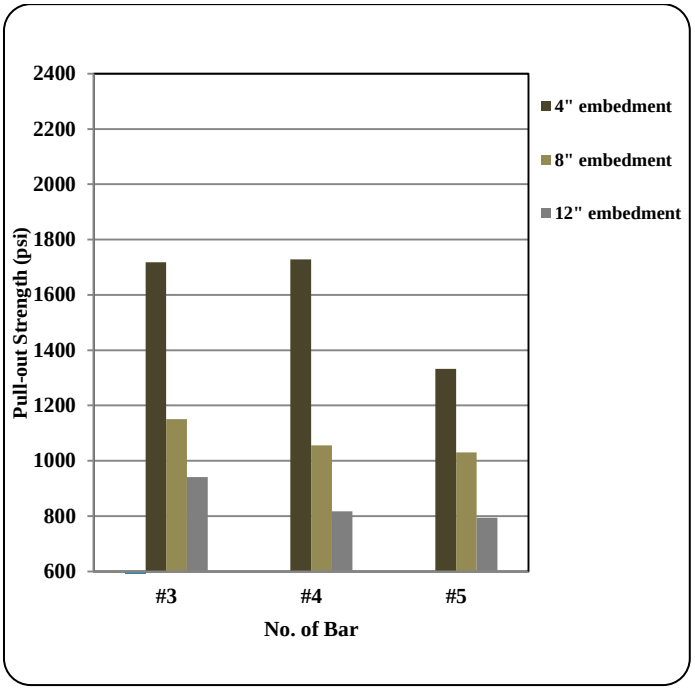

Fig. 11. Pull-out loads for different sizes of steel bars and embedment (HSC) – Tor bars

The results of the pull-out load for tor bars are shown in Fig. 9 and Fig. 11 for NSC and HSC, respectively, representing a proportional increase in pull-out load with the increase in embedment length or by increase in the dia of the bar. In other words, increasing the number (size) of tor bars; while, bond-strengths shown in Fig. 10 and Fig. 12 as well as Table 4 for NSC and HSC, revealed that the maximum bond-stress for high strength concrete is 15% to 28% higher than the corresponding one for normal strength concrete (NSC).

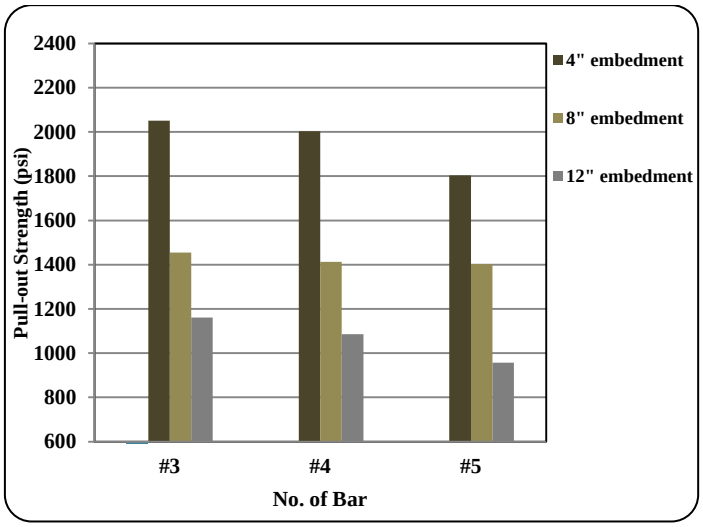

Fig. 12. Pull-out strength for different sizes bars and embedment (HSC) – Tor bars

TABLE 4. Comparison of bond-strength of NSC and HSC – Tor bars

No. of Bar	Bar Type	Grade	Embedment Lengths (inches)	Bond-Strength NSC (psi)	Bond-Strength HSC (psi)	% Increase in Bond strength
#3	Tor	40	4	1690.22	2028.51	16.68
#4				1683.93	1987.098	15.26
#5				1314.17	1796.632	26.85
#3	Tor	40	8	1138.53	1413.563	19.46
#4				1034.43	1399.066	26.06
#5				1002.45	1395.42	28.16
#3	Tor	40	12	925.68	1132.409	18.26
#4				809.46	1075.558	24.74
#5				775.81	940.4033	17.50

c. *Deformed Bars – Grade 40 & 60 Reinforcements*

The results of the pull-out load are shown in Fig. 13 and bond-strengths in Fig. 14

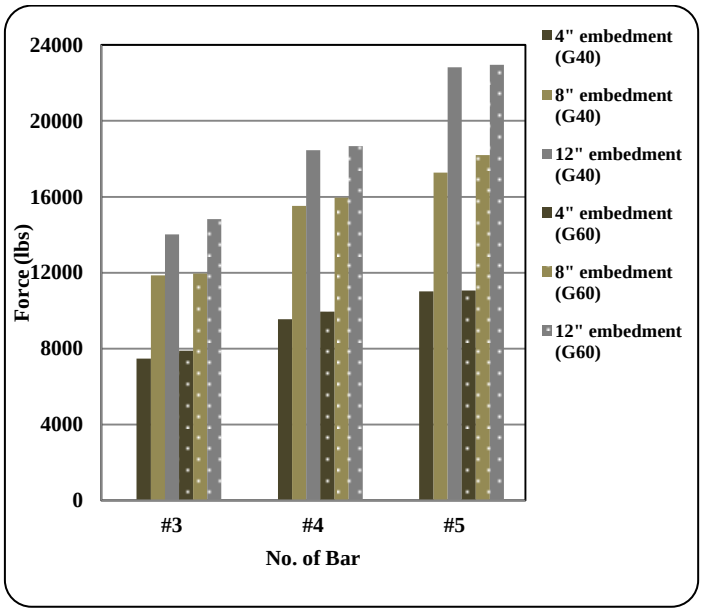

Fig. 13. Pull-out load for different sizes of bars and embedment lengths (Grade 40 & 60) – Deformed bars

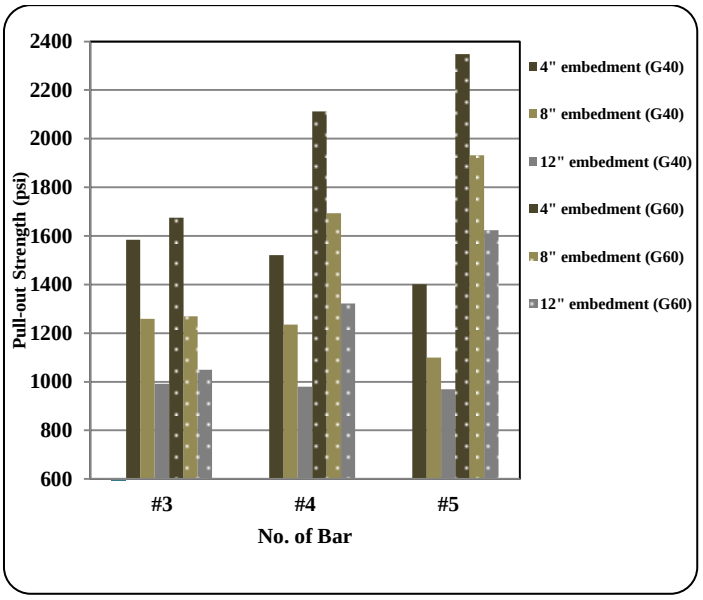

Fig. 14. Bond strength for different sizes of steel bars and embedment lengths (Grade-40 & Grade-60) – Deformed bars

Pull-out load for different sizes of steel reinforcement bars and their embedment lengths results are presented in Fig. 13 depicting similar trend in results as for plain and tor steel reinforcement bars i.e. proportional increase in pull-out force against size and embedment lengths; while negligible increase in pull-out load were observed against different grades of steel reinforcement bars. Fig. 14 shows that utilization of smaller diameter of deformed reinforcing bar bond strength between the interfaces of reinforcement bar and concrete increases. Similarly, concrete-steel bonding also depends on yielding strength of steel, i.e., greater the yield strength greater will be the bond strengths. It clearly seen from Fig. 14 that steel reinforcement of Grade-60 has more pull-out strength than steel reinforcement of Grade 40.

IV. Discussions

In reinforced concrete structures, the measurement of bond between the reinforcement and concrete is carried out by measuring the bond-stress which takes place at the periphery of embedded length of rebar. Benefits of reinforced composite members' construction can be achieved only when there is sufficient bond between steel reinforcing bars and the peripheral concrete matrixes or the developed ITZs which could easily transfer the load to the adjoining composite; thus, lowering the bond stress or reinforcement pull-out stresses by transferring the load to the greater area surrounding the reinforcement bars. The bond-strength of reinforcement-concrete is dependent upon the compressive strength of concrete, hence, HSC has higher bond-strengths compared to the NSC whose compressive strengths are lower the HSC [25-26].

Test results shown in Fig. 7, Fig. 10, Fig. 12, Fig. 14 depicts that bond-strength between concrete and steel reinforcement bars decreases as the bar size or dia. increases and causes the splitting of concrete cylinders [17]. Also, with the increase in the embedded length of steel reinforcement bars, there is seen a decrease in the bond-strength of concrete

(Fig. 7, Fig. 10, Fig. 12, Fig. 14). Moreover, increase in the embedment length, increased the surface area of the reinforcing bar which is inserted in cylindrical molds of 6 inches' diameter and 12 inches' height. Bond-strength between steel reinforcement and concrete is the measure of stress at the interface of steel reinforcement bar which further depends on the strength of the ITZs of the peripheral concrete [35].

Tests result shown in Fig. 13 and Fig. 14 revealed that the reinforcement bars of larger diameter, i.e., # 5 for all the embedment lengths (i.e., same for 4, 8 and 12") give comparatively equal strengths irrespective of the grade of steel reinforcement bars used, i.e., either Grade 40 or Grade 60; but, yielding was observed for #3 and #4 reinforcement bars at an embedment length of 12". This might be due to the elongated embedment length of the reinforcement bar having the higher stiffness might be attracting higher pull-out strengths; when the strength of pull-out increases the yield-strength of the concrete or specifically the ITZs, the weaker element will yield; hence, #3 and #4 bars having embedment lengths of 12" yielded [36- 37]. Also, reinforcement bars of higher grades, i.e., Grade-60 gives better pull-out strength results than Grade-40 reinforcement bars [3, 38].

Tests results also demonstrate that the use of HSC increases the bond-strength of concrete-steel primarily due to densification of the ITZs which produce higher normal and shear stress components. Concrete compressive strength can enhance the bond performance of reinforced concrete. Moreover, higher the adhesion forces and static friction forces between the concrete and reinforcement bars greater will be the compressive strength [18]. The bond-strength is increased in HSC as compared to NSC and lesser embedment length is required as compared to normal strength concrete.

Tor bar of #5 caused splitting of concrete cylinders both in NSC and HSC. This showed that pull-out strength decreased as the steel reinforcement bar diameter increased. Additionally, the pull-out strength increased with the increase in embedment length for NSC and HSC. The bond strengths that were measured in current experimentations were in congruence with the design bond-strengths specified in ACI318-05 and the European code EC2.

V. Conclusions

The conclusions that can be drawn from this research are as follows:

- To get better pull-out load, more embedment length of steel bars is required.
- To get good bond-strength for reinforced concrete (both R-NSC and R-HSC) embedment length of 4" gives better result.
- Increase in grade of steel bars causes a slight increase in the pull-out load but considerably increase the bond-strength as compared to Grade-40.
- Increase in embedment length significantly decreases the bond-strength.
- Increase in diameter of steel reinforcement bars decreases the bond-strength between steel bars and the concrete.
- The pull-out force increases as the diameter of steel reinforcement bar and embedment length of reinforcement bar in concrete increases for both R-NSC and R-HSC.
- The bond-strength decreases as the diameter of steel reinforcement bar and embedment length increases in both cases of concrete, i.e., NSC and HSC.
- The R-HSC gives more bond-strength as compared to R-NSC. An increase in bond strength of 15% to 28% observed for HSC.

Recommendations

This research paved the path for following recommendations:

- More embedment length is recommended for resisting higher pull-out loads.
- Less embedment length is recommended for good bond-strength.
- Reinforcement bars of Grade-60 are preferable compared to the Grade-40 as it gives better results in bond-strength of concrete.
- Small diameter bars with less embedment length of 4" recommended for effective bond strength between steel and concrete.
- HSC should be used for good bond-strength of concrete with larger size of bar and with a least embedment length of 4 inches.
- For better bond-strength in the case of R-NSC, an embedment length of 4 inches for a bar size of 5/8 inches is recommended.
- R-HSC is preferred over R-NSC for better bond-strength.

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