Effect of Embedded Bar Length on the Pull-Out Force of Steel - Concrete Bond

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Abstract

This paper investigated the effect of embedded bar length on the steel-concrete bond with a view to proposing a regression model to predict ultimate pull-out force. Concrete of mix proportion 1:2:4 (cement: sand: granite) was prepared using water-cement ratio of 0.5. Concrete cubes of sizes 150 mm were cast and cured in water for 7, 14, 21 and 28 days. Another set of concrete cubes of sizes 400 mm were cast and reinforcing steel bars were embedded up to 100, 200 and 300 mm depth at the centre of the cubes. Slump and compacting factor of the fresh concrete were determined, so also the compressive strength. The force required to pull out the bar from the concrete cube was measured at expiration of curing ages. The results showed that the concrete was of normal weight with 28-day compressive strength of 24.33 N/mm^2. Pull-out tests showed that pull-out forces (initial and ultimate) increased with increase in embedded length of the bars, the pattern was that the initial pull-out force increases about 17 – 22 % while the ultimate pull-out force increases by about 25-32 % for every 100 mm increase in the bar length. Strength relationship between compressive strength and ultimate pull-out force was linear, but not proportional. A regression model was proposed to predict the ultimate pull-out force using the age of the concrete and the embedded length of the bar as variables.

Keywords: Pull-out force, embedded length, compressive strength, strength relationship, workability.

1.   INTRODUCTION

Performance of reinforced concrete is not only dependent on each material constituent but also significantly depends on the interaction between them. Steel bars are incorporated in concrete to improve flexural strength by transferring tensile stress into the concrete through adequate bonding (ACI 408 2003). Thus, the bond between steel bars and concrete is a major factor in influencing the structural performance of reinforced concrete. Factors that influence steel-concrete bond have been subject of research. Quantification of the individual contributions of these factors has been a challenge, but extensive efforts are being made to do so (El-Hacha *et. al.,* 2006).

(Darwin *et al.,* 1996) studied, extensively, the effect of compressive strength of concrete on the steel-concrete bond. They observed that the bond strength which was traditionally accepted to be proportional to the square root of compressive strength could not accurately estimate the bond strength for high strength concrete use in modern construction. A more exact model was suggested. Effect of concrete cover on steel-concrete bond was equally studied (El-Hacha *et al.,* 2006). It was observed that when adequate cover depth is used, the splitting tensile stresses were low at the surface, limiting the development of crack during pull-out test. Conversely, they observed that, if concrete cover was insufficient, tensile stresses will spread to the surface resulting in a longitudinal crack along the bar and thus a loss of bond between the bars and concrete. They concluded that bond strength increases as concrete cover increases.

Furthermore, aggregate quantity and gradation have been identified as one of the factors that influence the concrete bond strength. In the work of Zuo and Darwin (2000) in which the effect of basalt and limestone aggregates on steel-concrete bond was studied. They reported that a higher strength coarse aggregate (basalt) contributed to higher bond strength when compared to a low aggregate type (limestone). Also, (Eligehausen *et al.,* 1983) investigated the effect of bar diameter on the concrete bond strength. In their study, they embedded a short bar length (five times the bar diameter) of different sizes in the middle of concrete cubes containing various amount of transverse reinforcement. The forces required to pull out the embedded bars were noted and plotted. Models to predict the bond stress-slip of a specimen subjected to monolithic loading was proposed. However, effect of the embedded bar length and curing age of the concrete was not reported. An experimental program investigating the bond behaviour of FRP bars indirect pull-out was conducted (Chaallal *et al.,* 1993) while the load transfer behaviour between FRP reinforcement and concrete was experimentally investigated (Nanni *et al.,* 1995).

In this paper, the effect of embedded bar length on the pull-out force is investigated and results presented. Pull-out tests was adopted to measure bond strength because of its simplicity in producing specimens and the ability of isolating the effects of different parameters on the overall bond performance. Also, a regression model was proposed to predict the steel-concrete bond behaviour for various embedded length and curing ages.

2.   MATERIALS AND METHOD

2.1   Materials

Type I ordinary Portland cement was used as binder while granite and river sand of maximum nominal sizes of 19 mm and 3.18 mm were used as coarse and fine aggregates respectively. Water-cement ratio of 0.5 was used for the concrete mixture. High yield and ribbed reinforcing steel bars of diameter 12 mm, was obtained from retail steel seller. It has an average tensile strength of 410 N/mm^2 as determined from testing 10 samples of the steel bars.

2.2   Preparation of Specimens and Testing

Aggregate characterization was conducted and tensile strength of the steel bars was determined. Concrete of mix ratio 1:2:4 was batched by weight. Concrete cubes of sizes 150 mm were cast and cured in water for 7, 14, 21 and 28 days. The compressive strength was determined at the expiration of curing age. Another set of concrete cubes of sizes 400 mm were cast and reinforcing steel bars were embedded up to 100, 200 and 300 mm depth at the centre of the cubes as shown in Figure 1. The cubes containing steel bars were also cured in water for similar periods. Care was taken to ensure that un-embedded part of the reinforcement was covered with polythene to prevent water from reaching it during curing. Pull-out test was conducted in accordance with ASTM C192. Average of three readings was noted for all the parameters measured. All the tests were conducted in the Structural Laboratory of the Department of Civil Engineering, University of Lagos, Nigeria.
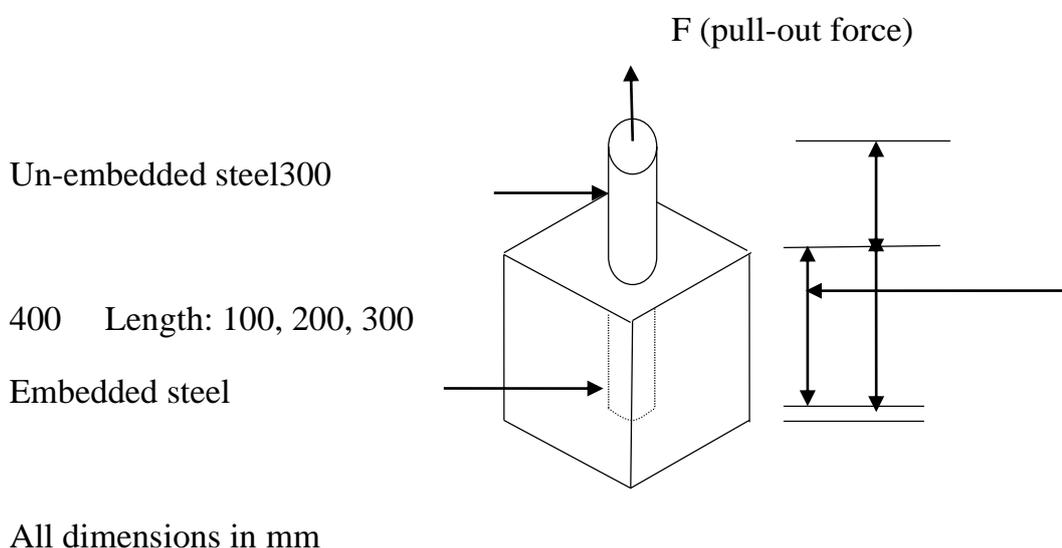
F (pull-out force)

Un-embedded steel300

400   Length: 100, 200, 300

Embedded steel

All dimensions in mm

Figure 1: Specimen for pull-out testing

3.   RESULTS AND DISCUSSION

3.1   Aggregate Characteristics

Figure 2 shows the particle-size distribution curves for the fine and coarse aggregates. It indicates that about 95.4 % of sand particles passed through sieve size 3.18 mm and less than 5 % was retained on 150 μm size (No. 200). This shows that the sand is within the fine aggregate limits for concrete production. In the case of the granite, the particle size distribution shows that 100 % of the particles passed through sieve size 25 mm, 98.82 passed through 19 mm while only 10.66 % was retained on sieve No. 4 (4.75 mm) showing that the granite can be categorized as coarse aggregate suitable for concreting. Gradation coefficients of the aggregates, as determined from the curves (Figure 2) shows that the coefficient of uniformity

(C_u) of the sand and granite are 3 and 2.02 while their curvature coefficient (C_c) are 0.75 and 0.97 respectively. The import of these is that the aggregates were well sorted. Both the granite and sand have bulk densities of 2655 and 2680 kg/m^3, indicating they are within the normal weight of aggregates.

3.2   Workability, Density and Compressive Strength

Slump and compacting factor tests were conducted to determine the workability of the fresh concrete. Results show that the slump and compacting factor were 55 mm and 0.99 respectively, showing that the concrete was plastic and required little force for adequate compaction. Hence, the water-cement ratio of 0.5 used appears to be appropriate. The results of the density and compressive strength of the hardened concrete cubes at different curing ages are summarized in Table 1. It is observed that the density of the concrete specimen varies minimally with age without distinct pattern. This finding shows that the age of curing does not appreciably influence the density. Quantitatively, the average density is 2555.35 kg/m^3 with a standard deviation of 30.73, indicating that the concrete is normal weight concrete. The compressive strength varies with increase in age. At age 7, 14 and 21 days, the compressive strengths are 11.34, 15.34 and 18.97 N/mm^2 respectively, while 28-day strength is 24.33 N/mm^2.
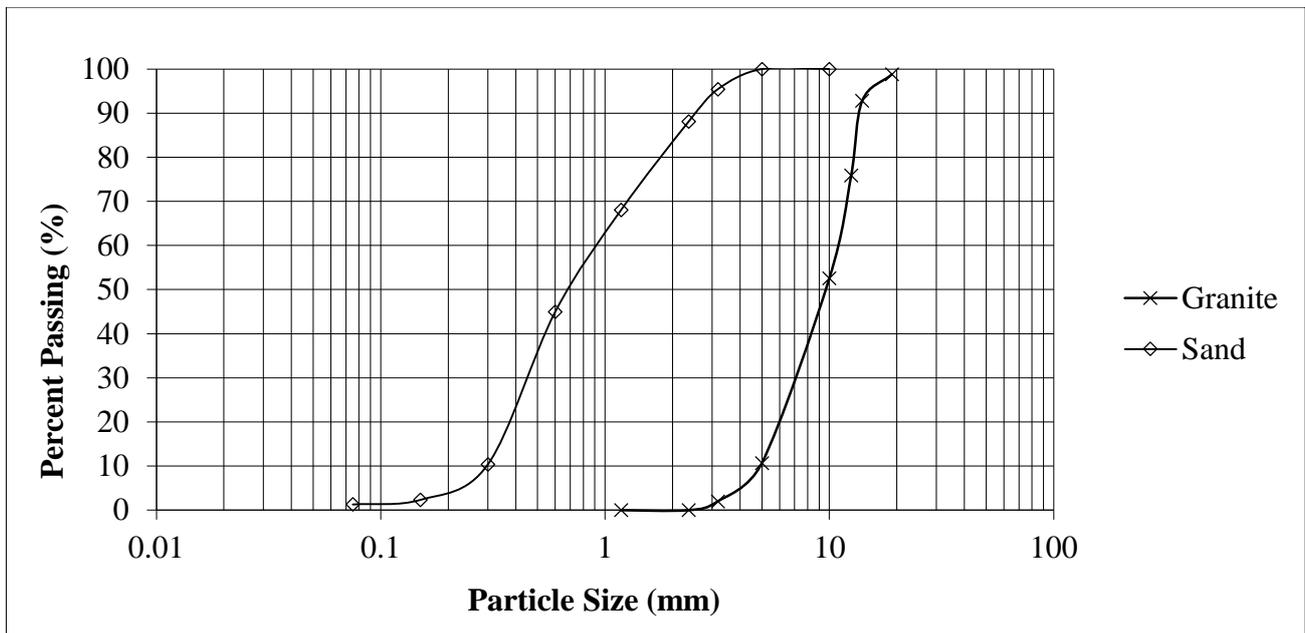

Figure 2: Particle size distribution curves of the aggregates.

Table 1: Density and compressive strength of the concrete specimen

Properties	Curing Ages (Ages)			
	7	14	21	28

Density(kg/m^3)	2558.03	2528.40	2537.43	2597.53
Compressive Strength (N/mm^2)	11.34	15.34	18.97	24.33

1.3   Effect of Embedded Length on Pull-Out Force at Different Curing Ages

Two types of forces were measured during the pull-out test. First, force required in breaking the steel-concrete bond; this is called initial pull-out force and second, the force required to pull-out the steel bar from the concrete (ultimate pull-out force). The pull-out forces (initial and ultimate) measured for different embedded steel lengths at different ages are presented in Table 2. It is observed that the pull-out force increases with increase in the embedded length and increase in age. At 28 days, for instance, the initial pull-out force is 66.55 kN for an embedded length of 100 mm, 80.51 and 91.73 kN were obtained in the case of 200 and 300 mm, respectively. If these values are compared to their corresponding ultimate pull-out forces, incremental changes of 41 % (28.52 kN), 47 % (37.5 kN) and 48 % (43.7 kN), respectively are obtained, showing that additional force is required to pull out the steel bar from the concrete after the bond had been broken. This may be attributed to friction between the steel and the concrete. It is equally observed that the change in pull-out force increases with increase in the embedded length.

Table 2: Effect of embedded length on pull-out force at different ages

Curing Age (Days)	Embedded Length (mm)					
	100		**200**		**300**	
	Initial Pull-Out Force (kN)	Ultimate Pull-Out Force (kN)	Initial Pull-Out Force (kN)	Ultimate Pull-Out Force (kN)	Initial Pull-Out Force (kN)	Ultimate Pull-Out Force (kN)
7	41.5	58.03	50.85	74.27	60.41	98.61
14	48.32	69.43	57.65	87.45	68.16	114.94
21	54.64	77.93	65.99	96.63	79.48	124.31
28	66.55	90.07	80.51	112.01	91.73	141.43

At the same age (28 days), it is interesting to note that about 80 % of the ultimate force required to pull out the bar with embedded length of 200 mm is needed to pull out the bar embedded up

to 100 mm into the concrete while the ultimate pull-out force for embedded length of 200 mm is about the same percentage (80 %) of the ultimate pull out force required for the bar embedded up to 300 m. Similar trend is observed for all other ages as shown in Figure 3. Critical observations of the results in Table 2 appears that whenever the embedded length increases by 100 mm, the initial pull-out force increases by between 17 – 22 % while the ultimate pull-out force increases by about 25-32 %.

3.4   Regression Model of Pull-Out Forces for different embedded length

The results of the pull-out test obtained are presented in Table 2 show that ages and embedded length of bars are major variable factors influencing the values of the pull-out forces. In order to study how these variables are related to the ultimate pull-out forces, a multiple linear model is formulated using regression analysis. The resulting model is given as follows:

$$P = 19.06 + 1.74T + 0.23D \qquad (1)$$

where:
P = ultimate pull − out force, kN
T = Age of curing, days
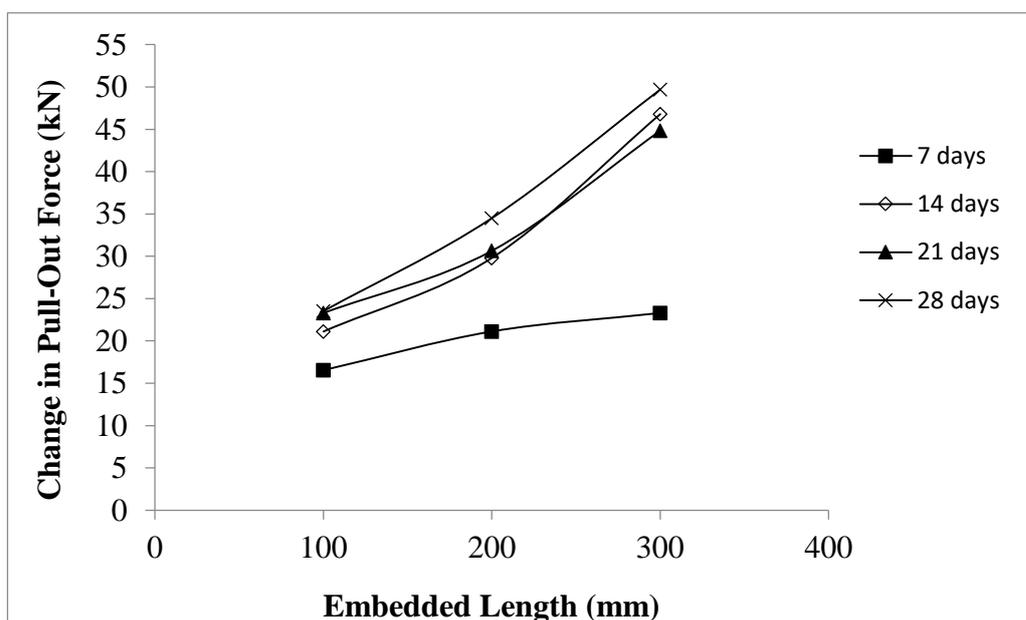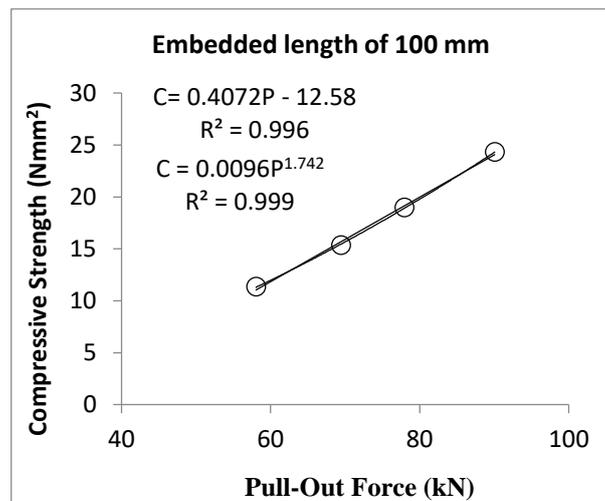D = Embedded length of bar, mm

Figure 3: Change in pull-out forces vs. embedded lengths at different ages

It is evident from the equation that coefficients of curing ages (T) and embedded length (D) are non-zero positive values, 1.74 and 0.23, respectively, indicating that they are positively related to the ultimate pull-out force. The output of the regression analysis further shows that each of the predictor variables (T and D) are statistically significant ($p<0.005$), while the regression coefficient (R^2) is about 0.985. This means that about 99 % of the variation in the dependent variables (ultimate pull-out force) is accounted for (or predicted by) the independent
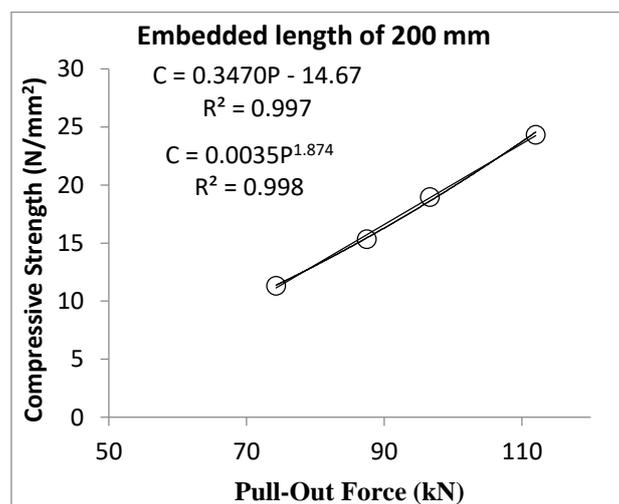
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variables (age and embedded length). This further buttress the fact that embedded length has positive effect in predicting the ultimate pull-out force of embedded bar.

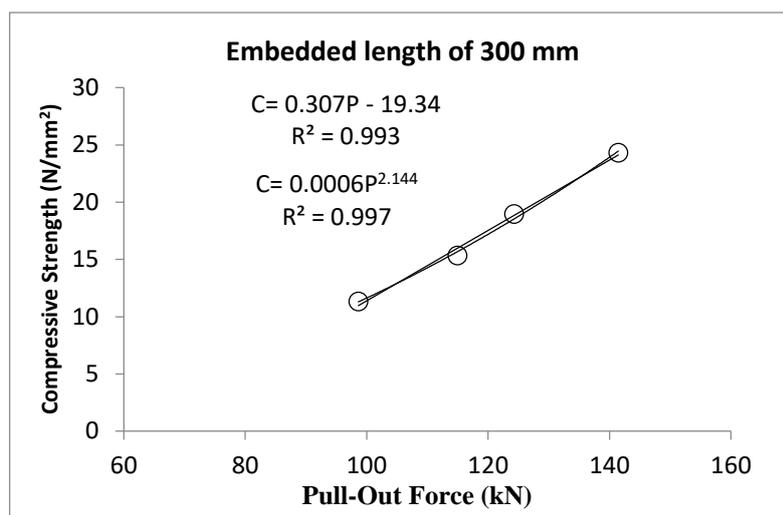## 3.5   Effect of Embedded Length on Strength Relationship

In order to compare the ultimate pull-out forces and compressive strength, a strength relationship is established using regression analysis. Strength relationship is often used to predict the compressive strength of an in-situ concrete from its ultimate pull-out force. The compressive strength is plotted against ultimate pull-out forces obtained for each of the embedded length as shown in Figure 4(a-c). It is shown that the relationship depended on the embedded length.

Embedded length of 100 mm

$C = 0.4072P - 12.58$
$R^2 = 0.996$
$C = 0.0096P^{1.742}$
$R^2 = 0.999$

Compressive Strength (Nmm²)
Pull-Out Force (kN)

(a)

Embedded length of 200 mm

$C = 0.3470P - 14.67$
$R^2 = 0.997$
$C = 0.0035P^{1.874}$
$R^2 = 0.998$

Compressive Strength (N/mm²)
Pull-Out Force (kN)

(b)

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Embedded length of 300 mm

C= 0.307P - 19.34
R^2 = 0.993

C= 0.0006P$^{2.144}$
R^2 = 0.997

(c)

Effect of Compressure Strength Vs Pull Out forces at different Embeded lengths.

Figure 4: Strength relationships for concrete with different embedded bar length (a) 100 mm embedded length (b) 200 mm embedded length (c) 300 mm embedded length

The equations of the linear relationships are given in Equations 2 - 4 as follows:

$C = -12.58 + 0.407P$ $\qquad$ (R = 0.998) $\qquad$ (100 mm embedded length) $\qquad$ (2)
$C = -14.67 + 0.347P$ $\qquad$ (R = 0.998) $\qquad$ (200 mm embedded length) $\qquad$ (3)
$C = -19.34 + 0.307P$ $\qquad$ (R = 0.996) $\qquad$ (300 mm embedded length) $\qquad$ (4)

where:
C = Compressive strength (N/mm^2)
P = Ultimate pull-out force (kN)

It is observed that the coefficients of P reduced from 0.407 to 0.307 as the embedded length of bar increased from 100 mm to 300 mm while the constant portion of the equations ranged from 12.58 to 19.34. The negative intercept in the Equations 2 to 4 indicates that there is different curvature. One important point to note is that the slopes for all the strength relationships (Equations 2-4) are not statistically significant, which indicates that the relationship is linear but not proportional because of non-zero intercept. But, the values of the correlation coefficients (R) are each close to unity.
The strength relationship could also be considered using power function relationship.

The power function relationships for different embedded length are equally shown in Figure 4(a-c), which is represented by the following relationships:

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$$C = 0.0096P^{1.742} \quad (R = 0.999) \quad (100 \text{ mm embedded length}) \quad (5)$$
$$C = 0.0035P^{1.874} \quad (R = 0.999) \quad (200 \text{ mm embedded length}) \quad (6)$$
$$C = 0.0006P^{2.144} \quad (R = 0.998) \quad (300 \text{ mm embedded length}) \quad (7)$$

It appears that power function relationship is best fit than its corresponding linear function relationship as indicated by their correlation coefficient which is about 0.999. However, it is observed that the coefficients of P reduce with increase in embedded length, as observed in the linear relationship, while the exponents of the power functions increase as embedded length increases and each is greater than one, showing that the relationship differs from being proportional but approximately linear. This is evidence if the log of each side of the Equations (5-7) is taken and log C is plotted against log P, a linear relationship is obtained. Taking the log of both sides of Equations (5) and resolve mathematically gives:

$$\log C = \log 0.0096 + 1.742 \log P \quad (8)$$

The graph of log C against lop P is linear but not proportional. What can be deduced from the forgoing is that the embedded length tends to influence the relationship between compressive strength (C) and pull-out force (P) and that the strength relationship is linear but not necessarily proportional.

2. CONCLUSIONS

The effect of different embedded bar length on the pull-out force is investigated and the following conclusions were reached:

i. The pull-out forces increase with increase in length of bar embedded in the concrete; the trend is that about an incremental of 17 – 22 % and 25-32 % of the initial pull-out and ultimate pull-out forces respectively are required for every 100 mm increase in embedded length.

ii. Strength relationship between the compressive strength and ultimate pull-out force was established; the relationship shows that it was linear but not proportional.

iii. Regression analysis suggests that embedded length and concrete age contribute about 99 % in predicting the ultimate pull-out force.

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