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Research Article

PERFORMANCE OF CHEMICAL ANCHORS AND APPLICATIONS IN STRENGTHENING OF RC STRUCTURAL SYSTEMS

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ABSTRACT
This paper reports on some experimental investigations on performance of chemical anchors in concrete controlled by lateral reinforcement. Other parameters varied in this study include; strength of concrete, and embedment depth of rebars. Three different grades of concrete to achieve compressive strengths of 25, 40 and 60MPa were adopted with three embedment depths of 150mm, 200mm and 250mm. The strength of chemical anchors increases as the compressive strength of concrete and embedment length of anchor increase. The strength of adhesive anchors coincides with the estimated strength of post installed anchors as per both CCD and ACI 349. Concrete cone failure was predominantly observed in all the tested plain concrete specimens. However, the concrete provided with confinement reinforcement alters the mode of failure from concrete cone type to more ductile failure with uniformly distributed circular and radial cracking. The ductility and strength of adhesive anchors under direct tensile loading has been improved significantly with confinement lateral reinforcement. Further, as the volume of lateral reinforcement increases, the strength and ductility in-terms of long post-peak response have been improved significantly. Application of bonded anchors in various structural applications has been demonstrated.

Keywords: *Bonded Anchors, Confinement, Embedment Length, Compressive Strength, Ductility*

INTRODUCTION
Anchorage in concrete can be adopted as (i). cast-in-place and (ii). post-installed. In the post-installed method, anchors can be classified as mechanical or bonded. Use of such anchors in connection of structural system is of recent origin and promising in the future construction activities as the precast construction is going to play key role due to its advantages. The anchors transfer the loads to concrete through mechanical interlock, friction, chemical bond or combination thereof. Use of mechanical anchors in concrete construction is well known. Bonded anchors are used in several civil engineering applications, whose performance needs to be investigated. Though, the adhesive (bonded) anchors are being used extensively in practice, their design guidelines are not yet available. The anchorages may be adopted for attachment of piping systems, lightweight suspended ceilings, etc., and are also widely employed for the attachment of metal deck to steel framing or connecting concrete to concrete. Fastenings may be used for less critical applications such as securing lightweight duct, lighting, and wiring, can be selected based on the function without serious analysis or structural review. Anchorage system needs to be studied to ensure durability and robustness, and with sufficient load carrying capacity and deformability.

1. Review of Literature
Eligehausen and Clausnitzer (1983) investigated the tensile behavior of expansion anchors, considering nonlinear behavior of smeared cracks in concrete over finite width. The behavior of concrete in tension, size of element and number of load increments up to ultimate load has been studied. The ultimate load increases as the element size increases with decrease in number of load increments. Fuchs *et al.*, (1995) reported concrete capacity design (CCD) approach for design of post-installed mechanical anchors, and cast-in-place headed studs or bolts. A data base containing 1200 European and American tests was evaluated. Cook *et al.*, (1998) reported that a constant bond stress was developed over the embedment length, and the bond strength is independent of the embedment length. Cook and Kunz (2001) investigated the factors influencing the bond strength of adhesive anchors; installation conditions of hole (wet, damp, cleaned, uncleaned), difference of concrete strength, difference in aggregate, and in post-

installation process include curing and loading at elevated temperature. Eligehausen *et al.*, (2006) validated the model proposed for concrete cone breakout failure by Fuchs *et al.*, (1995) for single cast-in-anchors and post-installed mechanical anchors with that of Cook *et al.*, (1998) using uniform bond stress model. The failure of adhesive anchors can be compared to the concrete cone break out failure of post-installed mechanical anchors. The actual bond stress distribution at the peak load along the embedment length seems to be nonlinear with low bond stress at the concrete surface, whereas high bond stress developed at the embedded end of anchor. Comparison of the proposed models with the database for single adhesive anchor indicates that the failure load is reasonably described using uniform bond stress model by incorporating nominal anchor diameter, d with mean bond stress, τ associated with the adhesive (Cook *et al.*, 1998). Eligehausen *et al.*, (2006) described that the failure load of a single adhesive anchor is limited to load corresponding to concrete cone break out failure. The uniform bond stress model for adhesive anchors is as follows,

$$N_u = \tau \pi d\, h_{ef} \qquad (1)$$

Where

d =diameter of anchor rod, mm,

τ= average bond stress, and

h_{ef}= embedment depth, mm,

According to *ACI 349*, a 45° failure cone and a constant tensile stress over the projected surface area are adopted. The calculated failure loads correlate with the test results with a limited range of embedment depths. In CCD Method (Fuchs *et al.*, 1995), the capacity of a single anchor in tension is calculated based on 45^0 inclination of the failure surface of concrete. This corresponds to the assumption that the failure surface is twice that of the effective embedment depth of the anchor. The failure load, N (kN), corresponding to concrete cone breakout of a single anchor is as follows

$$N_u = k\ f_{cc}^{'0.5}\ h_{ef}^{1.5} \qquad (2)$$

Where

k = 13.5 for post-installed anchors, and

= 15.5 for cast-in situ headed anchor bolts,

f_{cc}' = concrete cube compressive strength and

h_{ef}= effective embedment depth, mm.

The strength of a single anchor in tension as per ACI 318 is given below

$$N_u = (4\ f_c^{'0.5})\ A_N \qquad (3)$$

Where A_N= projected area of a single anchor = $A_N = \pi h_{ef}^2 \left(1 + \frac{d}{h_{ef}}\right)$

In SI units, the capacity of the anchor is given by

$$N_u = 0.96 f_c^{'0.5}\ h_{ef}^2 (1 + \frac{d_u}{h_{ef}})\ , N \qquad (4)$$

The splitting of concrete occurs when the size of concrete block is small, in which the anchor is installed very close to an edge or when the line of anchors is installed in close proximity to each other. The load at failure associated with splitting of concrete is reduced relative to that of the corresponding concrete cone break-out failure. The failure of steel bolt or stud represents an upper value of the highest load carried by an anchor. The fracture of steel bar rarely occurs in conventional concretes except in high-strength concretes. The splitting of concrete during anchor installation can be avoided by providing minimum spacing between anchors, and minimum edge distance

$$N_u = \frac{\pi d^2}{4}\ f_y \qquad (5)$$

Where d is the diameter of the anchor, and f_y is the yield strength of steel.

Table 1: Strength of Post installed anchors, in tons, based on CCD /ACI 349

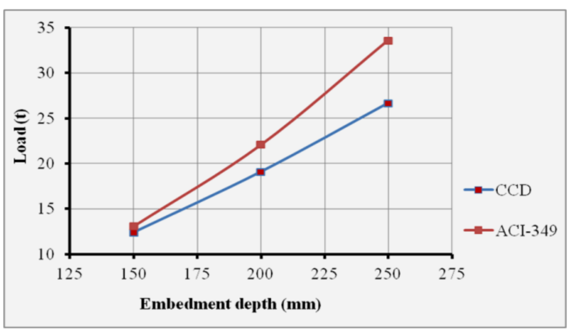
S. No	Embedment Depth (mm)	Grade of Concrete (MPa)		
		25	40	60
1	150	12.4/13.0	16.0/16.7	19.2/20.1
2	200	19.1/22.0	24.7/28.6	29.6/34.2
3	250	26.7/33.6	34.5/43.6	41.3/52.0

2. Determination of Strength

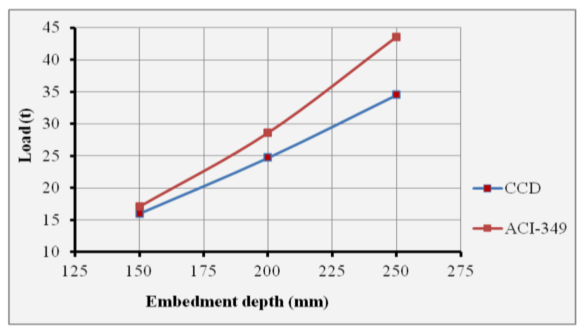
According to the previously mentioned methods of calculating the capacity of anchors based on capacity of concrete, strength of steel and bond strength areshown in Table 2. The relationship between load capacity of anchor with embedment depth as per the concrete cone design (CCD) method and ACI-318 is shown in the Figures 1 with different concretes.

Table 2: Bond strength of Anchors

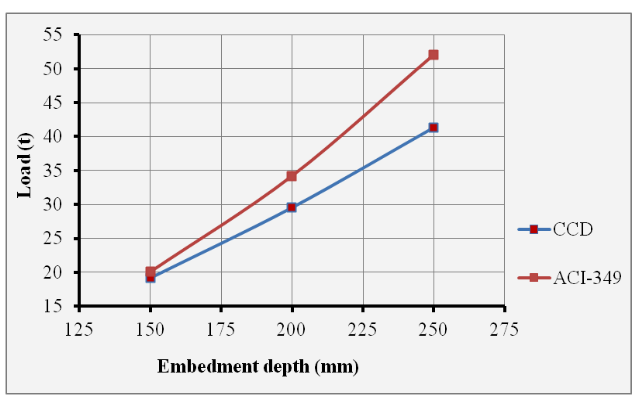
S. No	Embedment Length, H_{ef} (mm)	Bond Capacity (tons)
1	150	21.20
2	200	28.27
3	250	35.34



(a). 25 MPa Concrete,



(b). 40 MPa Concrete,



(c). 60 MPa Concrete

Figure 1: Load vs. Embedment Depth

The failure of steel is well understood. In this, an attempt has been made to achieve the concrete cone failure. In order to avoid steel failure, 30mm diameter steel anchors were used.The capacity of steel anchor bar = f_y. A_{st} and the capacity of bond, $N_u = \tau \pi d h_{ef}$. The design strength of anchors is to be determined experimentally and the relationship between the load and displacement to be established. In this study, the effect of embedment depth, and strength of concrete on the capacity of anchors is undertaken.

3. Applications of Anchors

Figure 2 demonstrates the applications of bonded anchors in strengthening of structural systems.

(a). Strengthening of column base

(b). Connection of steel with Concrete

(c). Connection of steel with Concrete

Figure 2: Bonded anchors in strengthening of structures

Experimental Programme

4.1. Design of Concrete Mixes

In this experimental investigation, to understand the influence of compressive strength of concrete on behavior of adhesive/bonded anchors three different strengths of concrete were adopted. A 43 grade ordinary Portland cement was used for this programme. 20mm nominal maximum size of coarse aggregate was used. The three different compressive strengths of concrete achieved were 25, 40 and 60 MPa. The details of the design concrete mix proportions are as follows.

a. Mix Proportion 25MPa Strength
CementContent = 360 kg
Mix Proportion = 1: 1.70: 3.15: 0.48

b. Mix Proportion for 40MPaStrength
Cement Content= 420 kg
Mix Proportion = 1: 1.45: 2.65: 0.42

c. Mix Proportion for 60MPaStrength
Cement Content = 450 kg
Mix Proportion = 1: 1.33: 2.44: 0.36

4.2. Steel

The steel anchor rods were supplied by M/s. Hilti (P) Ltd. One diameter of anchornamely 30mm was used with nominal yield strength of 640 N/mm^2.

4.3. Adhesive

Adhesive was used to bond the anchors with the surrounding concrete. An injection type RE500 adhesive was used with mean bond strength of 15.0 N/mm^2. Plastic cartridges containing pre-measured quantities of resin and hardener facilitate controlled mixing of polymer components. These components are typically mixed through a special mixing nozzle, as they are dispensed, or are completely mixed within the cartridge immediately before injection.

4.4. Parametersof Study

To study the influence of various factors on the strength and behavior of bonded anchors, thirty RC anchorage specimens embedded with steel high strength anchors were cast. The actual strengths of concrete achieved in the laboratory were 25 MPa, 42 MPa, 60 MPa. Three specimens for each parameter were cast and the average of the three is considered. The failure of anchor (steel failure) was avoided by selecting the diameter of anchors in all the specimens as 30 mm. Parameters varied in this study are:

a) Concrete Grades = M25, M40 and M60
b) Embedment depth = 150mm, 200mm and 250mm
c) Lateral reinforcement= 8mm diameter bar spaced at 60mm,90mm & 120mm

4.5. Preparation of Anchorage Specimens

The moulds were prepared using steel channels placed back-to-back with required dimensions. Three different sizes with three different embedment depths were prepared. The reinforcement as per the calculations was provided by carrying out bar-bending as shown in Figure 3. The mould inner walls were lubricated with oil for easy detachment of concrete. Fresh concrete was poured vertically from the top without segregation. Needle vibrator was used to achieve proper compaction. After 24 hours the concrete specimens were demolded from the formwork, duly designated and cured for 28 days. Typical RC anchorage concrete specimen embedded with high strength anchor rod is shown in Figure 4.

Figure 3: Casting of anchorage Specimen,

Figure 4: Fabricated Anchorage Specimens.

After attaining adequate strength, the concrete specimens were drilled holes with designed embedment depth and diameter. Three embedment depths of 100mm, 150mm, 250mm were formed using 35mm drill bits to embed 30mm diameter anchor rods. The holes were cleaned with hand pumps to blow out the concrete dust and wire brushes were also used. Subsequently, the drill holes were washed with water and allowed cleaned drill holes to dry under shade for two days. The high strength anchor rods were mounted with electrical resistance strain gauges at about half of the embedment depth. The drill hole was filled up to2/3rd depth with RE-500 adhesive using injection type installation. Subsequently, the anchorage test

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specimens were cured. The anchorage specimens were allowed for curing for forty eight hours for adhesive to set.

4.6. Test Set-up

The load to the anchor rods was applied by an actuator through a pulling bracket which was fitted in front of the actuator. Displacement was increased incrementally to the anchors to prevent any dynamic effect. Three standard concrete cubes were tested to determine the compressive strength of concrete. The actuator was supported ona testing frame. The concrete block was fixed by a reaction frame anchored to the strong floor, preventing the pulling out of concrete block. The anchorage specimens were prepared with three embedment depths of 150mm, 200mm and 250mm. The experimental set-up was prepared for testing the anchorage specimens as shown in Figure 5. A 1000kN capacity actuator was fixed laterally with an existing A-frame which can withstand 2000 kN loading. Another frame was fabricated and anchored to the strong floor to hold the specimen and provide adequate reaction against the pulling out of the actuator. Two LVDTs were fixed at the base of the steel bolt embedded in the concrete block to monitor the slip of the anchor rod, which was connected with a data logger to continuously record the observations at a frequency of 0.5Hz. Under the monotonic loading effect, the rate of displacement control was maintained as 1.0mm/min.

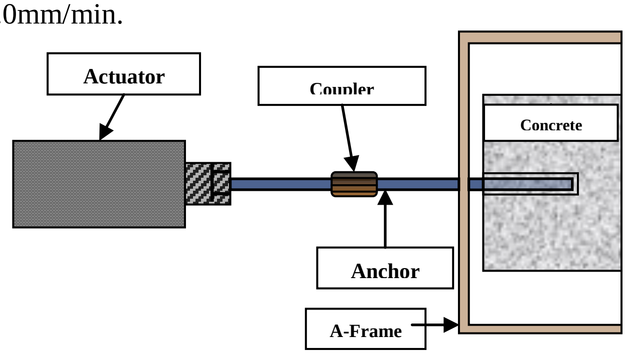

Figure 5: Experimental set-up

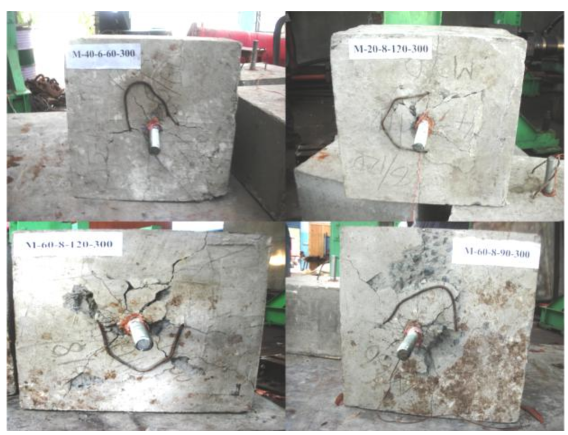

Figure 6: Typical concrete splitting failure

RESULTS AND DISCUSSION

The strengths of concrete achieved were 25 MPa, 40 MPa and 60 MPa. The three embedment depths adopted were 150mm, 200mm and 250mm with a 30mm diameter of anchor bars. Three specimens without reinforcement anchored with 250mm embedment depths were also tested in order to compare the load carrying capacity and also to understand the failure modes. The specimens were tested for the ultimate load carrying capacity under monotonic load in tension. The variation of the load carrying capacity with compressive strength and embedment depth is studied. The loads vs. displacement responses are drawn.

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Table 3: Experimental observations (Capacity in tons)

S. No	Embedment depth (mm)	Strength of concrete (MPa) 25			40			60		
1	150	25.24	25.37	18.70	32.58	29.71	28.63	37.23	37.27	33.48
2	200	28.60	26.56	25.70	33.61	31.70	29.72	407.2	37.68	34.82
3	250	29.32	29.11	28.52	36.38	32.16	300.2	489.4	38.32	35.18

6.1. Failure Modes

Under the action of monotonic tension on the anchored reinforced concrete, concrete splittingfailure, as shown in Figure 6, in most of the specimen's wasobserved. The tensile load was gradually applied under displacement control. As the load was applied, the initial load versus displacement response was appeared to be approximately linear.

As the load increased further, a reduction in stiffness was observed. In plain concrete anchor specimens, there has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking,while in RC anchor specimen, the load capacity was increased with the increase in the slip.

As soon as the load the ultimate load, there has been a marginal drop in the load up to the ultimate deformation followed by asudden drop in the load in all the cases due to concrete splitting failure. The behavior is virtually linear elastic up to ultimate load. However, in the post-peak region ductile behavior was observed up to the ultimate deformation. The ultimate load carrying capacity has been found to increase and also matched well with that of the post installed mechanical anchors in almost all the cases.

6.2. Test Results

Figures 7 show the ultimate load carrying capacity of the adhesive/bonded anchors with 30 mm diameter bars with the variation of embedment depth i.e. 150, 200and 300 mm. Table 3 shows the ultimate load carrying capacity of anchors obtained in the experiments when loaded in tension. Figures 8 show the ultimate load carrying capacity of the anchors with 30 mm diameter with various strengths of concrete i.e. 25, 40, and 60 MPa.

6.2.1. Influence of Strength of Concrete

Three different concrete strengths of 25MPa, 40 MPa and 60 MPa were adopted in this study. Figures 7 and Table 3 show the comparison of load carrying capacity with concrete strength at different embedment depths. As the strength of concrete increases, the load carrying capacity of the anchor increases. It can be inferred that the compressive strength of concrete is directly proportional it's tensile strength.

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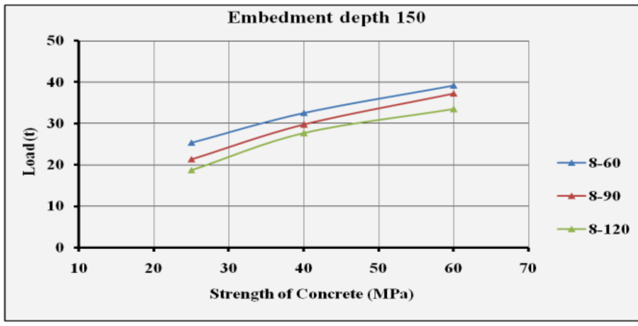
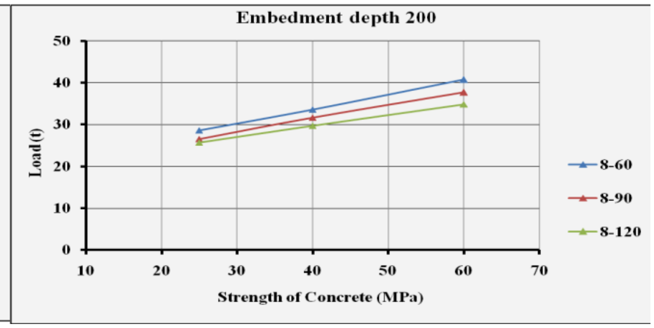
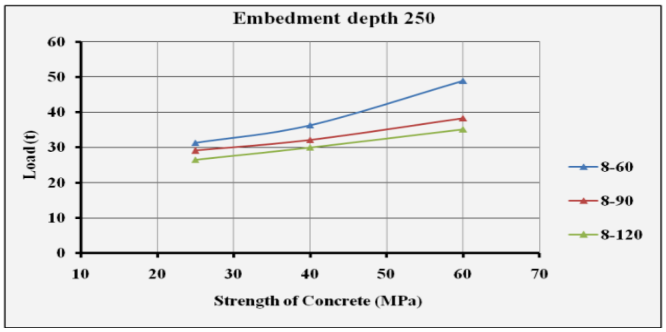


(a). Embedment depth 150mm

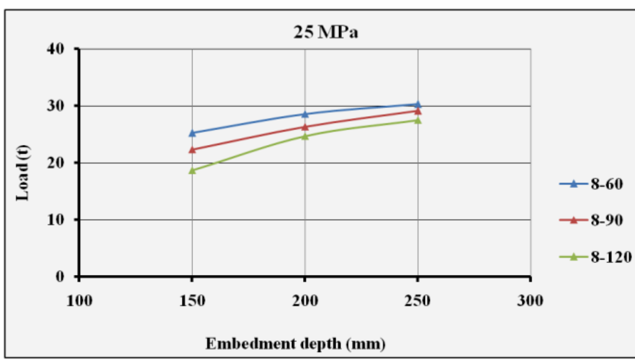


(b). Embedment depth 200mm,

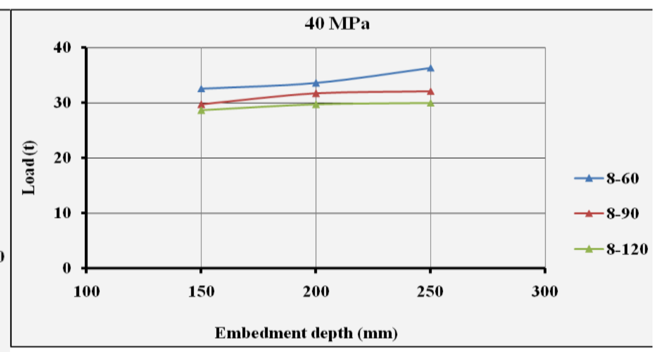


(c). Embedment depth 250mm

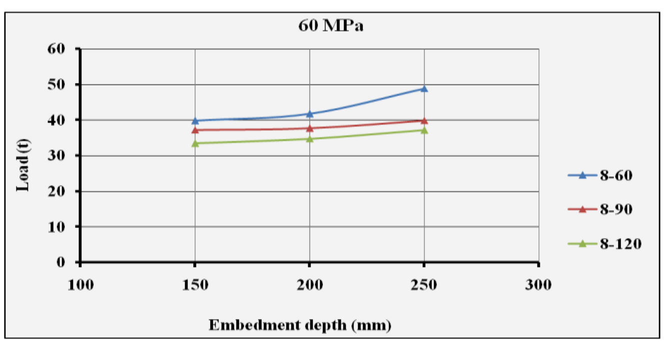
Figure 7: Load carrying capacity v/s strength of concrete



(a). 25 MPa Concrete



(b). 40 MPa Concrete

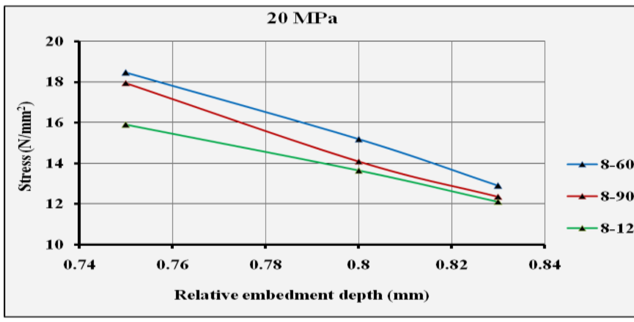


(c). 60 MPa Concrete

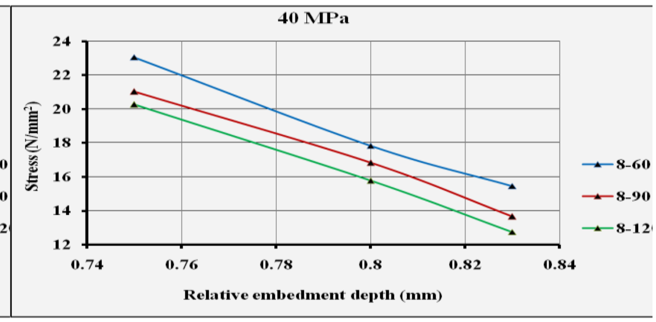
Figures 8: Effect of embedment depth with compressive strength of concrete

6.2.2. Influence of Embedment Depth

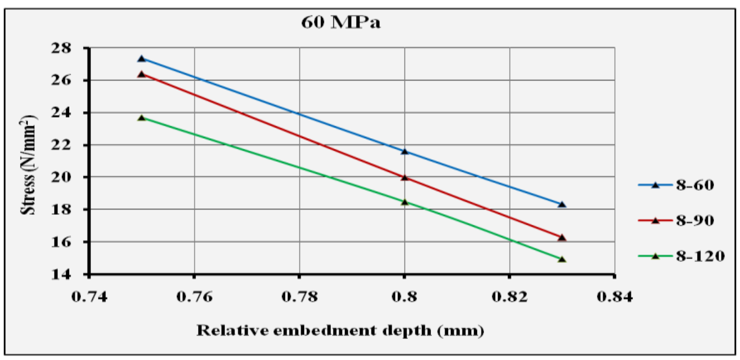
The embedment depthsadopted were 150mm, 200mm and 250mm. As the embedment depth increases so does the magnitude of tensile load that can be resisted increases, and therefore the load carrying capacity of the anchor increases. According to the CCD method, the load carrying capacity of anchors increases as a function of $h_{ef}^{1.5}$. As per ACI 349, the load carrying capacity increases as a function of h_{ef}^{2}.The comparison of experimental results with CCD method as compared with ACI code is very similar. There is no significant difference in the stiffness with regards to the embedment depth. Figures 8 show the effect of embedment depth on the load carrying capacity of adhesive anchors for a given concrete.The stress vs. relative embedment depth in different concrete is plotted as shown in Figures 9.



(a). 20 MPaConcrete



(b). 40 MPa Concrete



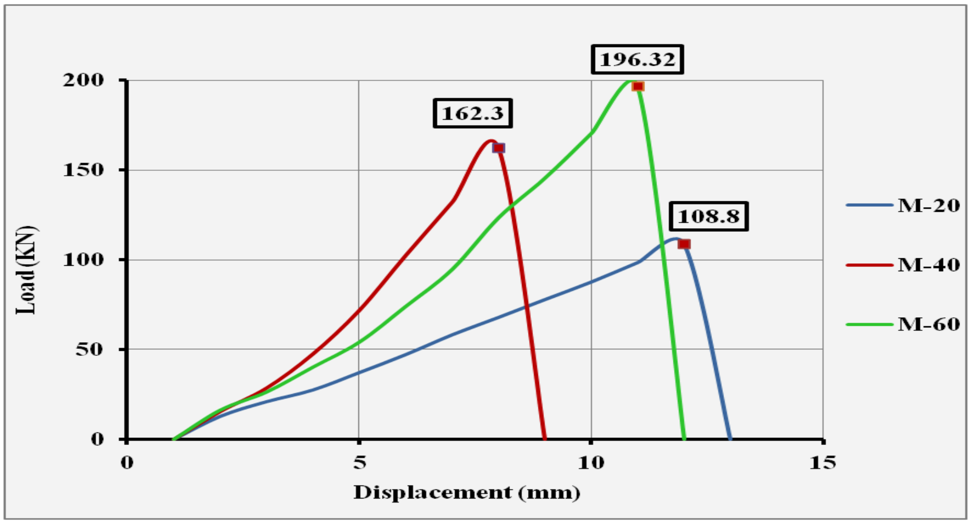
(c). 60 MPa Concrete

Figures 9: Stress v/s. Relative embedment depth

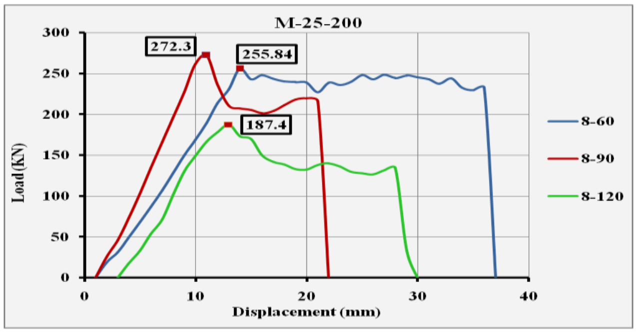
6.2.3. Effect of Lateral Reinforcement

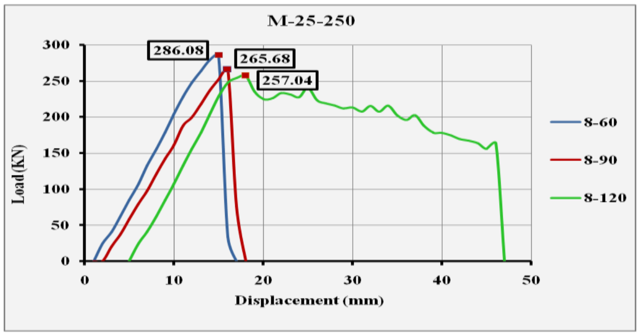
The quantity of lateral reinforcement was varied in terms of varying spacing of 8mm diameter stirrups. The three different spacing's of 8mm bars were 60mm, 90mm and 120mm. In plain concrete, there was a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking. Figure 10 shows the load vs. displacement response of the anchorage specimen in plain concrete with embedment depth 250mm loaded monotonically in tension. The lateral reinforcement enhances the confinement of the anchorage block thereby preventing the formation of cone failure. As the quantity of lateral reinforcement increases, the load carrying capacity of the anchor also increases. In reinforced concrete, the load on anchor increases proportionately with the increase in the slip.

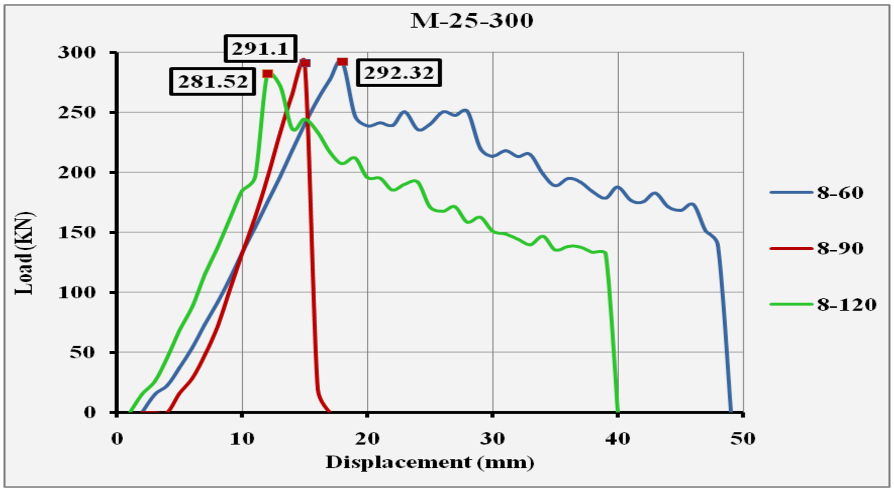
As soon as the load reaches its ultimate value, there exhibits a marginal drop in the load up to the ultimate deformation followed by a sudden drop in the load in all the specimens due to concrete splitting. The behavior is virtually linear elastic up to ultimate load. However, the peak load is followed by a ductile behavior up to the ultimate deformation. The slip-stick region in the response depicts the ductile behavior of anchorage specimens.



Figures 10: Load versus displacement different grades of concrete







Figures 11: Load vs. displacement inM25 grade concrete with different embedment depths

Figures 11 show the load vs. displacement response of anchor loaded in tension with variation in quantity of lateral reinforcement in 25 MPa concrete. Figures 12 show the load vs. displacement response of the anchorage loaded monotonically in tension with variation in the quantity of lateral reinforcement in 60 MPa concrete. As the quantity of lateral reinforcement increases, the load carrying capacity increases and ductility also increases. The failure becomes more ductile and gradual with increase in the lateral reinforcement.

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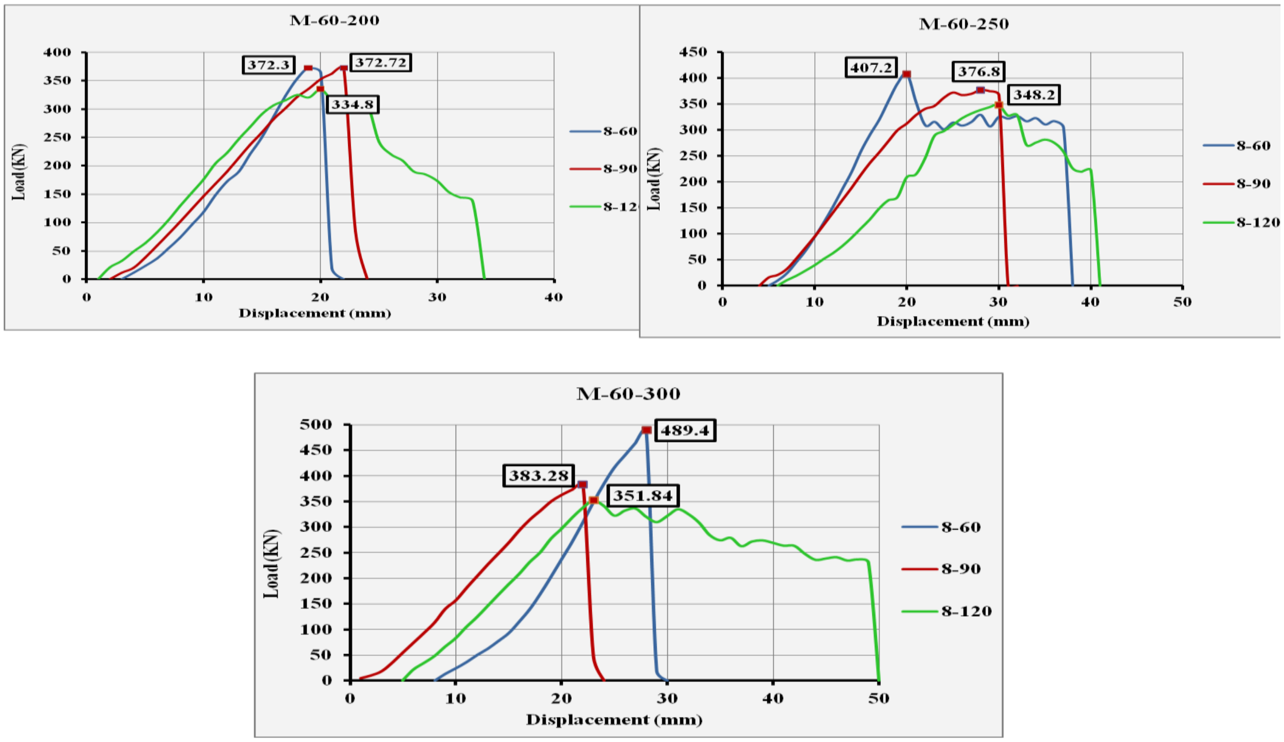

Figure 12: Load vs. displacement in 60MPa at different embedment depths in M60 concrete

Conclusion

Following conclusions can be drawn from the experimental studies.

1. In plain concrete anchorage specimens, there has been a sudden drop in the load carrying capacity due to sudden failure of concrete along the plane of cone cracking.
2. Lateral reinforcement improves the confinement thereby increases the load carrying capacity of reinforced adhesive anchors to about 250% as compared to the adhesive anchors in plain concrete.
3. Under monotonic tensile loading on the anchored reinforced concrete, concrete splitting failure in most of the specimens was observed.
4. Load carrying capacity increases proportionately with the increase in the slip. As soon as the load reaches its ultimate stage, there exhibits a marginal drop in the load up to the ultimate deformation following by a sudden drop in the load in all the cases due to concrete splitting.
5. The reinforced anchorage specimen shows increase in the load carrying capacity with the increase in the strength of concrete and embedment depth.
6. The experimental observations are very close with the CCD design method as compared to the ACI-349 Code method with regards to the tensile load carrying capacity.

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