LOAD~SLIP BEHAVIOR OF L-ANCHOR BOLTS EMBEDDED IN REINFORCED RECYCLED AGGREGATE CONCRETE

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ABSTRACT: *Load-slip behavior of cast-in place anchor-bolts in a column pedestal using concrete with Recycled Aggregates (RA), including main and confinement reinforcement, is the core research essence of this project. This study focuses on the joint formed between the steel superstructure and the reinforced concrete foundation using RA through cast-in anchor-bolts and presents the comprehensive series of experimental pull-out test results alongside their failure patterns.*

Internationally, due to environmental factors and scarcity of natural aggregate, the use of Recycled Aggregate Concrete (RAC) is gaining much structural attention and usage. RAC is currently being used in numerous engineering projects; so it has become essential to acquire accurate knowledge of the actual structural behavior of anchorages in RAC in the presence of confinement reinforcement. This study aims to explore the effects of RA usage as replacement for the crushed rock aggregates on bond behavior of anchors. The load transfer behavior between the anchor bars and the surrounding concrete through bond stress and end-anchorage plays an important role in the response of reinforced concrete structures. The guidelines of the ACI-318-11 Appendix-D [1] for anchor design in the normal concrete are checked when applied to reinforced concrete with RA. The load-slip behavior and the failure modes are also evaluated under monotonic loading.

KEYWORDS: Anchorage, Hooked Anchor, Load-Slip, Pedestal, Pullout, Recycled Aggregate Concrete

1.0 INTRODUCTION

Currently, world-wide research studies are being carried out to develop concretes constituting recycled materials i.e; Recycled Aggregates (RA). When such concrete is proposed in a civil engineering project where connection between heterogeneous structural elements is required to be developed through anchor-bolts, the structural design requires extensive experimental and theoretical knowledge of anchors-bolts in such type of concrete.

The anchors in concrete generally represent a vital transition element to join two heterogeneous construction materials - concrete and steel. The anchoring between structural steel and the reinforced concrete pedestal is of pivotal importance for structural stability. Industrial structures and commercial buildings mostly require anchored joints for load transfer.

1.1 ANCHOR-BOLTS

Anchor bolts (earlier known as Fastenings) are essential elements in most of civil structures where there is a requirement of steel structure to be fixed with concrete foundations to transfer loads or where an extension is required in concrete structure itself. The joint thus formed has to transfer the normal loads (tension or compression), self-weight and possible shear loads from one structural element to the other. The broad types of anchor-bolts are summarized in Fig 1.

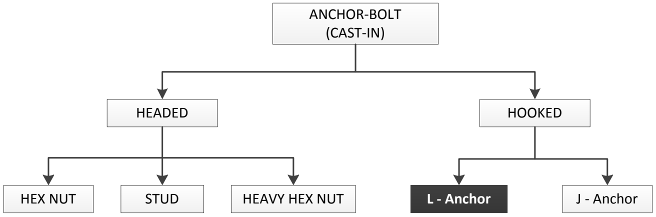

Fig: 1: General Classification of Cast-in Anchor Bolts.

This research limits itself to the study of plain anchor bolts having an end anchorage hook in the shape of 'L' embedded in reinforced concrete, as shown in Fig 2.

Fig: 2: Plain Ø25 Bar A36 Steel L-Anchors used in the Pedestal Specimen

Commercial use of L-anchor-bolts is seen in various civil structures (Fig 3), i.e; Electrical Substations, Transmission Towers, Communication Towers, Industrial Buildings, Machine Foundations, Steel Frames and Ware-houses, Lighting Poles, Airport Hangers, etc.

Fig 3: Cast-in L-Anchors supporting an industrial steel frame structure through base plate and pedestal arrangement.

1.2 RECYCLED AGGREGATE CONCRETE

Natural Aggregate (NA) used as coarse aggregate is one of the main constituent of concrete. In recent times, in some international projects the NA component is being gradually replaced with RA. The RA is obtained from the demolition of concrete elements of buildings, waste of concrete pre-fabrication factories, defective rigid pavements, abandoned bridges and other infrastructures. Due to various nature of demolished concrete and the demolishing/crushing method, the actual mechanical and physical properties of the crushed aggregate vary substantially. In fact, the crushing induces micro-cracks in recycled aggregates and it is the main cause of variation in its mechanical and physical properties. Therefore, in structural work the recycled aggregate may be used in conjunction with proportionate amount of NA so that the concrete properties may not vary considerably. To make the demolished concrete debris fit for reuse purpose it has to be crushed to a particular size and screened for gradation. Popular use of recycled aggregate concrete is in rigid pavements, temporary structures, barriers, embankment rip-rap, etc.

In this research, the RA source is a demolished precast concrete girder taken from a precast factory.

2 SCOPE OF STUDY

The bond behavior of anchor-bolts in ordinary concrete is already well known but when anchor-bolts are to be embedded in a concrete other than ordinary concrete, a detailed study is very much required to establish a behavioral analysis of these anchor-bolts in a confined reinforced concrete environment. The findings of this research will enable a much enhanced insight into the pull-out behavior of the anchor-bolts in reinforced concrete pedestals made using recycled aggregates.

2.1 OBJECTIVE

The primary objective of this research project is to analyze the load-slip behavior and performance of cast-in steel L-anchors bolts embedded in RAC in the presence of usual pedestal reinforcement.

The anchors proposed for study are ASTM F1554 Grade-36 of 250MPa (36 ksi) capacity having diameters of Ø19 (#6) and Ø25 (#8) with L-hook end anchorage. The embedment of the anchor-bolts is kept constant for a specific bolt size. The RAC is made using varying percentages of RA.

Specifically, following objectives are proposed for this experimental exploration:

1. To experimentally study load-slip relationship of the cast-in anchor-bolts in the RAC pedestals through a series of concentric (monotonic) pull-out tests.
2. To experimentally inquire the failure modes of anchor-bolts embedded in RAC during tension pull-out mechanism.
3. To investigate the effect of the varying percentages of recycled aggregate on the pull-out behavior of the anchor-bolts.
4. To check whether ACI-318 Appendix-D anchor design guidelines can be used for RAC.

Two types of full-scale reinforced concrete column pedestals with cast-in anchor-bolts essentially subjected to vertical pull-out load are tested as part of the experimental program. In order to keep the loads and the boundary conditions of the specimens as close to the real structural support system as possible, a computer-controlled testing system with displacement measuring device was used and the data was automatically recorded.

2.2 RESEARCH SIGNIFICANCE

The research work on the RAC is rather a new discipline and therefore the findings of this research will enable a better understanding of the Steel-Concrete combined interaction through anchor-bolts. Further, the potential benefit of adding reinforcement around anchors-bolts has not been fully understood, though some efforts have been invested to test anchors with confinement reinforcement. Thus this study will give more insight on use of confinement reinforcement.

3 LITERATURE REVIEW

The design of anchor bolts in concrete has been addressed in numerous building codes. The ACI-318 (2011) is a standard building code and it includes provisions for major aspects of the design and structural behavior of anchor-bolts embedded in concrete structures. Within it [1], the design of anchor bolts has been discussed thoroughly in its Appendix D. ACI 318 Appendix D is the standard for anchor bolt design in general and the design industry and all other codes refer to the recommendations within it.

The American Institute of Steel Construction (AISC) [2] has also published numerous design guides that deal with many distinct features of the construction of steel structures and their anchoring to concrete structures in detail.

ACI 355.3R11 [3] code explains the practical implementation of the ACI-318 Appendix D, which contains design provisions for determining the strength of cast-in anchors based on the Concrete Capacity Design (CCD) method for concrete breakout failure. The CCD method calculates the concrete breakout strength using a model that is based on a breakout prism having an angle of approximately 35^o. The code also states that when the capacity of the anchorage is controlled by the strength of concrete, it is generally the tensile properties of the concrete which control cone failures, and crushing strength that controls slip failures. The tensile properties of concrete vary more than compressive properties.

In the study by [4], it was found that under the equivalent mix proportion, the bond strength between the RAC and the plain rebar decreases with an increase of the RA replacement percentage, whereas the bond strength between the RAC and the deformed rebar has no obvious relation with the RA replacement percentage. Moreover, it was also concluded that the general shape of the load-slip curve between RAC and steel rebars is similar to the one for NA and steel rebars, which includes micro-slip, internal cracking, pullout, descending and residual stages.

When supplementary reinforcement is used to transfer the full design load from the anchors, it is generally referred to as anchor reinforcement. Even though the Appendix D of the ACI 318 permits the use of supplementary reinforcement to restrain concrete breakout, it does not provide specific guidelines in designing such reinforcement. The anchor tension and shear forces are assumed to be resisted by the vertical reinforcing bars and ties, respectively. The vertical reinforcement intersects potential crack planes adjacent to the anchor head thus transferring the tension load from the anchor to the reinforcement as long as proper development length is provided to develop the required strength, both above and below the intersection between the assumed failure plane [5].

The research of Eligehausen and Mallée [6] states that, cast-in-place systems transfer external tension loads into the base material by means of a mechanical interlock between the embedded component and the concrete. During pull-out test the tensile load is transferred initially through a bond between the steel anchor bolt and the adjacent concrete, and later through the end-anchorage embedded in concrete.

The research of Rao and Arora [7] presents that the lateral reinforcement enhances the confinement of the anchor block thereby preventing the cracking of concrete leading to cone failure. As the quantity of lateral reinforcement is increased, the load carrying capacity of the anchor also increases. In reinforced concrete, the load increases proportionately with the increase in the slip. As soon as the load reaches its ultimate value, there is a marginal drop in the load up to the ultimate deformation followed by a sudden drop in the load in all the cases due to concrete splitting. The behavior is virtually linear elastic up to ultimate load, however, following the peak load, a ductile behavior is observed up to the ultimate deformation.

The results of an experimental study carried out by Daun and Poon [8] shows that the performance of Recycled Aggregates (*RAs)* from different sources varies greatly and *RA* of good quality can be used to produce high strength concrete with hardened properties comparable to those of the corresponding natural aggregate concrete.

4 EXPERIMENTAL METHODOLOGY

4.1 PEDESTAL DESIGN

ACI 318-11 D.1 recommends reinforcement layout for tension loading to place reinforcing bars within $0.5h_{ef}$ of the anchors for maximum effectiveness and assume a 35^o concrete breakout cone formation that is restrained by the anchor reinforcement. This concept of ACI [1] became the inspirational research basis of this paper. The detailed design calculations initially made for the sizing of the pedestals having f_c' of 20.8MPa (3ksi) are briefly presented in Table 1. The concrete design of pedestal has also been consulted from literature [9].

Table 1: Calculation Results of L-Anchor in Un-confined Concrete

Anchor Design Strength	Calculated Design Strength Ø19 L-Anchor	 Ø25 L-Anchor
Steel (N_{sa})	114.1 kN	202.5 kN
Conc. Breakout (N_{cb})	73.1 kN	90.1 kN
Conc. Pullout (N_{pn})	34.7 kN	56.8 kN
Conc. Side-face Blowout (N_{sb})	N.A.	N.A.

It is evident from the calculations that concrete pullout controls the failure mode in the unconfined concrete. Siddiqi [10] also presents the same theoretical behaviour for hooked anchors. In order to attain a ductile behaviour of concrete pedestal as per ACI [4], the main reinforcement needs to be designed according to the anchor steel capacity. The detailed design calculations for the pedestal reinforcement are presented in Table 2.

Table 2: Calculation Results of L-Anchor in Confined Concrete

Anchor Reinforcement Type	Calculated Reinforcement Ø19 L-Anchor	 Ø25 L-Anchor
Main reinforcement	4 - Ø13 at least l_{dh} of 104mm (4.1”) main rebar length is required for all main rebars above and below the expected breakout cone in concrete pedestal.	4 - Ø16 at least l_{dh} of 149mm (5.86”) main rebar length is required for all main rebars above and below the expected breakout cone in concrete pedestal.
Lateral ties in pedestal top 125mm	3 – Ø10	3 – Ø10
Lateral tie in pedestal bottom	1 - Ø10	1 - Ø10

MAIN REINFORCEMENT - This research concerns adaptation of the main pedestal reinforcement to act as anchor reinforcement. In order to achieve full development capacity, 180^o bend on the top of the main rebar is provided. This bend effectively holds the 35^o breakout prism of the concrete as per CCD method. This main rebar has another anchorage at the bottom in the form of a 90^o L-bend designed to withstand the developed force of the anchor bolt that is in-turn transferred to the main reinforcement. The lengths of 180^o standard hook at top and 90^o standard hook of main reinforcement are based on the ACI-315-99 [11] recommendations. The details of rebars are shown in Fig 4.

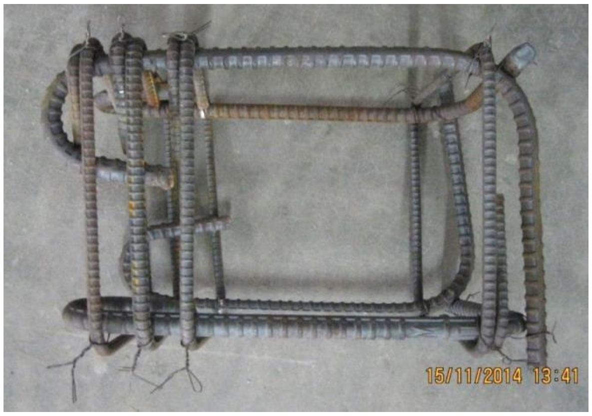

Fig 4: A reinforcement cage before the specimen casting.

CONFINEMENT REINFORCEMENT - As per ACI 355 [4], the confinement reinforcement, present in the transverse direction of the load can provide restraint and improve ductility of the anchorage. Although this supplemental reinforcement is not explicitly designed to transfer the load, it has shown to improve ductility, thereby also allowing an increase in the design strength of the connection.

The code provisions of ACI-318-11 guide the confined reinforcement in pedestal to be in the form of lateral ties surrounding the main reinforcement bars. The code clauses 7.10.5.2 and 7.10.5.7 have been applied in pedestal design and are discussed later in para 5.3(b).

4.2 PEDESTAL DESIGNATION AND SIZING PARAMETERS

The sizing of two distinct reinforced concrete pedestals is based on the L-anchor bolt diameter and its embedment (h_{ef}). The specimen comprise of longitudinal and lateral reinforcement as per the guidelines of ACI 318-11.

- The concrete pedestal specimen size for the Ø19 (#6) L-anchor bolt is 350mm x 350mm x 350mm (14"x14"x14") with reinforcement and designated as S14.
- The concrete pedestal specimen size for the Ø25 (#8) L-anchor bolt is 400mm x 400mm x 425mm (16"x16"x17") with reinforcement and designated as S16.

The specimen designation details are given in Table 3.

Table: 3: Specimen Designation Details

Concrete Type	Specimen Size	Anchor Type	Specimen Designation
Natural Aggregate Concrete (NC) (0% RA)	S14	Ø19 (#6) L Hook	14-NC-6L-1
	S16	Ø25 (#8) L Hook	16-NC-8L-1
	S14	Ø19 (#6) L Hook	14-NC-6L-2
	S16	Ø25 (#8) L Hook	16-NC-8L-2
Natural Aggregate - Recycled Aggregate Concrete (NRAC) (50% RA)	S14	Ø19 (#6) L Hook	14-NRC-6L-1
	S16	Ø25 (#8) L Hook	16-NRC-8L-1
	S14	Ø19 (#6) L Hook	14-NRC-6L-2
	S16	Ø25 (#8) L Hook	16-NRC-8L-2
Recycled Aggregate Concrete (RAC) (100% RA)	S14	Ø19 (#6) L Hook	14-RC-6L-1
	S16	Ø25 (#8) L Hook	16-RC-8L-1
	S14	Ø19 (#6) L Hook	14-RC-6L-2
	S16	Ø25 (#8) L Hook	16-RC-8L-2

4.3 DESIGN ASPECTS OF CONCRETE PEDESTALS

For experimental investigations, brief description of the major design considerations of specimens is as follows:

a. Based on earlier research information the mix design of recycled aggregate concrete is carried out to obtain compressive cylinder strength of at least 20.7 MPa (3ksi) and this minimum concrete strength of batch mixes is utilized for three % age types of RA (0%, 50%, 100%).

b. Each pedestal sample should contain 4 rebars in each corner of pedestal as main reinforcement, sufficient enough to withstand the force transfer through development length from the anchor bolt and should also have 3 – Ø10 ties in top 125mm of pedestal as lateral reinforcement according to the ACI [1].

c. The anchor-bolt embedment depth h_{ef} should be kept to 12 diameter of anchor bar, based on PIP [12].

d. For sizing the pedestal specimen S14 or S16, each pedestal height is based on h_{ef} + 125 criteria so that the main reinforcement in the pedestal could be given adequate development length and to fulfil adequate cover requirements of ACI-318. The length and width of the pedestal is kept same and is based on the main reinforcement side concrete cover, anchor dia and 0.5h_{ef} distance from anchor, as per clause RD 5.2.9 of ACI [1].

   - Specimen height = h_{ef} + 125
   - Specimen length or width =

$$2 \times \left(Side\ Cover + 0.5\, d_a + \frac{0.5h_{ef}}{\sqrt{2}}\right)$$

e. Each S14 and S16 is provided with 115mm (4.5") long plastic sleeve of inner dia 19mm and 25mm respectively, directly under the anchor sample and having Ø6 (#2) rebar pin in the concrete specimen to measure the slip through a LVDT later during testing. The specimen details are given in Table 4 and shown in Fig: 5.

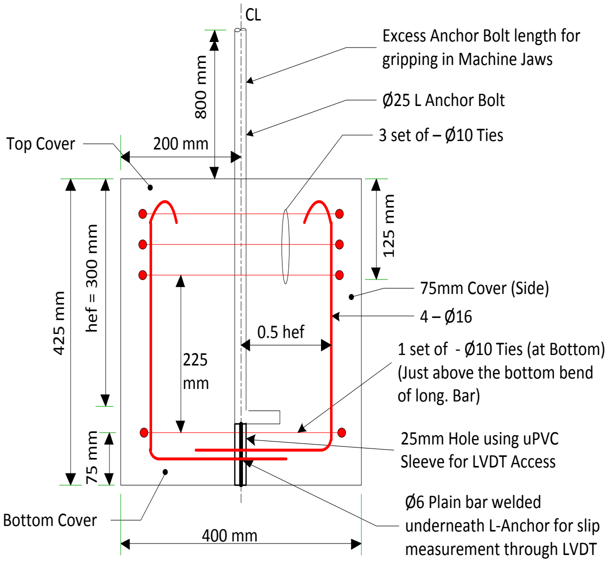

Fig 5: Specimen S16 with Ø25 (#8) L-Anchor and Reinforcement Details

Table: 4: Specimen Casting Details

Specimen Pedestal	Anchor Bolt Type	Anchor Bolt Embedment (h_{ef})	Concrete RA%	Main Reinforcement	Transverse Reinforcement	No. of Specimen
S14	Ø19 L	225mm (9")	0%	4 – Ø13	4 – Ø10 Ties	2
			50%	4 – Ø13	4 - Ø10 Ties	2
			100%	4 – Ø13	4 - Ø10 Ties	2
S16	Ø25 L	300mm (12")	0%	4 – Ø16	4 - Ø10 Ties	2
			50%	4 – Ø16	4 - Ø10 Ties	2
			100%	4 – Ø16	4 – Ø10 Ties	2

5…SPECIMEN MATERIALS

One of the main objectives of this research is that the test specimens should be constructed with construction materials that are used in general civil construction so as to make test specimens simulate the reality.

CEMENT (C) - Ordinary Portland Cement designated according to ASTM C150 has been selected for use in the test specimens. The make of the cement is Maple Leaf.

FINE AGGREGATES - SAND (S) - Lawrencepur sand has been used for all test specimens. Sand from Lawrencepur, is cleaner, coarser and more angular as compared to any other local sand.

NATURAL COARSE AGGREGATES (NA) - The Margalla crush has been used in the 0% and 50% Recycled Aggregate Concretes. The natural coarse aggregate (NA) is the common crushed stone readily available in construction market and transported from the Margalla Hills near the Islamabad city. The max crushed aggregate size used is 19mm (3/4”). The crush used is well-graded and contains particles upto to 3mm (1/8”) sieve retained with very low amount of pan particles.

RECYCLED COARSE AGGREGATES (RA) - The recycled coarse aggregate (RA) have been obtained by crushing the waste concrete of a demolished precast concrete girder. A factory crusher is used to crush the concrete into required size aggregates and the product is then properly screened for gradation. The RA gradation size used was passing 19mm (3/4”) sieve and retaining on 3mm (1/8”) sieve. The designed strength of 21MPa (3 ksi) was obtained with a nominal mix ratio of concrete, using this aggregate size (The designed strength is based on 28 Days Compressive Cylinder Strength). A number of aggregate properties namely; particle size distribution, density, water absorption and compressive strength are investigated before use in concrete casting of the pedestal specimen. The physical properties of NA and RA are presented in Table 5.

Table 5 : Physical properties of NA and RA

Coarse Aggregates	Bulk density kg/m^3 (lb/ft^3)	Water absorption (%)
Natural	1539 (96.1)	1.6
Recycled	1349 (84.2)	6.5

WATER (W) - Clean drinkable tap water has been used for the casting of the test specimens. The w/c ratio has been used in the range of 0.505 - 0.55 depending on the water absorption tests of the recycled aggregate percentage usage before each casting.

ADMIXTURE - A Type-G admixture was used in the test specimens to control the concrete workability only. Calculated amount of the admixture has been used in all the casting of the test specimens was in the range between 9ml - 10ml per kg of cement. Sikament 520BA is manufacturer designation of admixture and it complies with ASTM C-494 Type G.

REINFORCEMENT REBARS - Deformed Grade 60 low-carbon steel ribbed rebars with yield strength of 414MPa (60 ksi) were used as the main rebars and transverse ties in the specimen pedestals. The general physical properties of rebars are described in Tables 6 and 7.

Table: 6 Physical properties of Reinforcement Bar

Designation	Diameter	Type	Grade
Ø10	10mm (3/8”)	Deformed Steel	60
Ø13	13mm (1/2”)	Deformed Steel	60
Ø16	16mm (5/8”)	Deformed Steel	60

Table: 7 Tensile Properties of Reinforcement Bar

Designation	Rebar Area (mm^2)	Yield Load (Kg)	Ultimate Load (Kg)	Yield Stress (MPa)	Ultimate Stress (MPa)
Ø10	78	3200	5500	442	760
Ø13	113	5500	8500	418	646
Ø16	201	8800	14400	432	706

ANCHOR BOLTS - Two sizes of cast-in L-anchor-bolts were selected as anchors. The anchors have been taken from a steel manufacturing factory having Grade designation equivalent to A36 with yield strength of 250MPa (36 ksi). The physical properties of the anchor-bolts are presented in Table 8.

SPECIMEN STEEL MOULDS - To cast the concrete specimens in precise size; two separate customized steel moulds were prepared to carry out the concrete casting. The mould sizes were 350mm x 350mm x 350mm (14”x14”x14”) and 400mm x 400mm x 425mm (16”x16”x17”) inner volume and were designated as Mould-14 and Mould-16. The specimen thus formed will contain Ø19 (#6) anchor in Mould-14 and Ø25 (#8) anchor in Mould-16.

CONCRETE MIX PROPORTION - The batching of the dry material was based on the weight of the construction material. The concrete mix proportion is strength based and the target strength is not less than 21MPa (3 ksi) 28 days compressive cylinder strength. The concrete mix proportion used in this study is varied based on RA %age as shown in Table 10 and the corresponding f_c’ are tabulated in Table 9.

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Table 8: Physical Properties of L - Anchors

Anchor Designation	Diameter (mm)	Type	Grade	Total Length (mm)	h_{ef} (mm)	Hook Length (mm)	End Anchorage Type
Ø19 (#6)	19	Plain Bar	36	1067	225	70	90^o L at Anchorage End
Ø25 (#8)	25	Plain Bar	36	1143	300	85	90^o L at Anchorage End

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Table: 9 Compressive Properties of Concrete (f_c')

Concrete Type	RA %	Average fc' (MPa)
NC	0%	27.37
NRAC	50%	25.92
RAC	100%	23.44

Table 10: Concrete Mix Proportions (in terms of Ratio by weight)

Concrete Type	RA %	Cement	Sand	Natural Aggregate	Recycled Aggregate	W/C Ratio	Admixture
NC	0%	1	2	4	----	0.550	10 ml / kg of cement
NRAC	50%	1	1.95	1.95	1.95	0.520	9 ml / kg of cement
RAC	100%	1	1.95	----	3.9	0.505	9 ml / kg of cement

SPECIMEN CASTING - The concrete of specimens is casted following the latest ASTM specifications. After preparation of the moulds for concreting, the steel anchor bars are placed in the center and hold in place using a template. Main reinforcement and transverse reinforcement are fixed in a cage form and placed with cover adjustment. The concrete is poured in the moulds and each specimen is mechanically vibrated for concrete homogeneity. Curing commenced after specimen casting and continued at least for 28 Days. Fig 6 presents the details of the concrete casting.

Fig 6: Specimen just after concrete casting

6….EXPERIMENTAL TESTING

The importance of experimental simulation in the engineering field is extremely acknowledged to gain an in-depth insight into the fundamental behavior of either a structural component or a structural system.

6.1 TEST PREPARATION

After curing, the pedestal specimens were tested under concentric monotonic vertical pull-out force applied to the anchor-bolt.

TEST SETUP - The specimen sizes were large having weight upto 175kg (385 lb), so there has been a tricky question – how to test such heavy samples precisely? It was decided to launch the specimen in Shimadzu 1000 kN (225 kip) UTM which can be set to precise stroke-controlled, strain-controlled or stress-controlled testing mode. Fig 7 presents the schematic diagram of test setup.

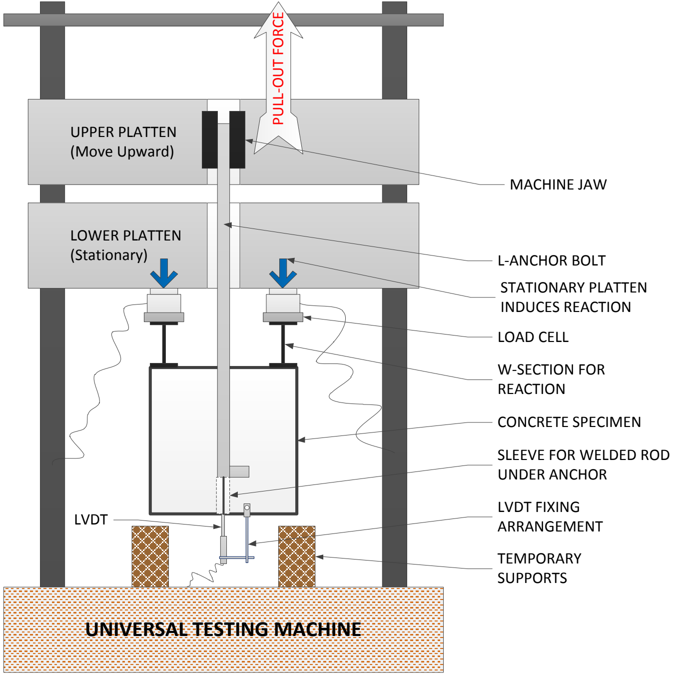

Fig 7: General Test Arrangement

TEST ARRANGEMENTS - Following test preparation steps were taken to perform the pull-out test on the test specimens. As there were 2 different sizes of the specimens S14 and S16, so the test arrangement was such managed to adapt similar test mechanism for both S14 and S16 specimens.

- After initial preparation, the specimen was lifted through slings with an electric crane and shifted to the test machine. After placement of the specimen in the test machine the upper platen of the machine was adjusted to appropriate height for the pull-out test. Specimen anchor bar was gripped through the upper platen of the machine and pedestal specimen was tested in hanging condition.
- At center of each test specimen there was a plastic sleeve at under-side of anchor bar. Each anchor bar was welded with a Ø6 (#2) rebar pin of length 115mm (4.5”) at bottom tip embedded in concrete. The tip of LVDT pin was positioned to touch the under-side of this welded pin to measure the slip during the pull-out. LVDT was fitted in a specially manufactured gripper and is fixed on

specimen precisely under the anchor bar with gripper screws.

- Next, two W-sections with specimen contact width of 75mm (3”) were placed directly on the specimen. Over these W–sections, two load cells of 50 Ton (110 kip) capacity each were centered and placed precisely. Each load cell had an independent hinge, so the load transfer remained uniform during test.
- The lower platen of the machine was then moved to be just touching the top plate of the load cell.

SPECIMENS TESTING - To initiate the testing of the specimen following general steps were taken for each test:

- The UTM was started and stroke-rate control was set to 4.0 mm/min (0.066 mm/sec) loading. The graph parameters on the machine monitor were adjusted according to the expected load and slip with some extra margin. Next the data-logger software *StrainSmart 4.01* on a desktop computer was initiated to record load-cells and LVDT data. Relevant zero corrections were applied accordingly.
- The LVDT was connected with the data logger to continuously record the slip at the bottom of anchor w.r.t the surrounding concrete at a time interval of 0.2 sec.
- As soon as the load reached ‘in-elastic’ range, a slight chipping started in concrete adjacent to anchor bar. In the meantime, the slip measurement at LVDT was seen to increase gradually. After the initial occurrence of slight chipping on the top surface of the specimen, the chipping grew and became more evident all around the anchor bar. This initial chipping was seen to occur only in the top cover of each specimen.
- Later, in the ‘residual’ range, the load on the anchor became almost stationary but the slip in the LVDT continued to increase speedily. The test was halted in this stage, due to the safety of sensitive test equipment.
- The load-cell and LVDT data readings recorded in *StrainSmart* software were then processed and saved in computer files to perform further analysis of the results.

6.2 TEST RESULTS AND DISCUSSION

To access the anchor-bolt strength in concrete a load-slip relationship is evaluated, therefore a related graph is plotted.

The experimental results in graphical form of the load-slip tests are plotted for specimens S14 and S16. Each particular type of test specimen is made in duplicate, so in order to achieve meaningful information a representative pull-out test curve of a single specimen is selected for presentation in this paper.

LOAD~SLIP GRAPHICAL CURVES - Figures: 8 and 9 represent the pull-out behavior of the test specimens under the monotonic strain-controlled load. Following inferences have been deduced from the load-slip graphs of the pedestal specimen testing:

- As A36 steel anchor bar is used with confinement reinforcement so yielding of the anchor steel is expected beforehand. Due to this reason, the slip at top of specimen close to the anchor bar is not measured.
- The load borne by the Ø25 L-Anchor is almost twice as compared to Ø19 L-Anchor due to its proportionately large x-sectional area and its corresponding design.
- All the load-slip curves may be divided into three parts, namely, linear un-cracked part, non-linear part and a residual part. The cracking load for the NC, NRAC and RAC is individually same for both the anchor diameters.
- In the in-elastic region, the load deflection curve of NC, NRAC and RAC changes behavior randomly. However, in the residual portion RAC and NRAC behave slightly better than NC.
- It is further noted that the difference in the curvature of graphs is more after the bond strength between anchor and concrete surface has been consumed.
- It is evident from the results that anchor reinforcement is fully activated after the formation of a concrete internal failure.

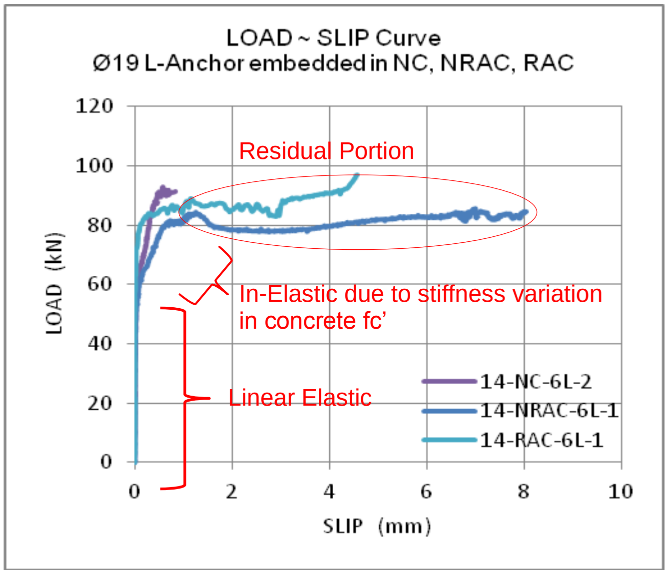

Fig 8: Load~Slip Curve of Ø19 L-Anchor Bolt in NC, NRAC and RAC.

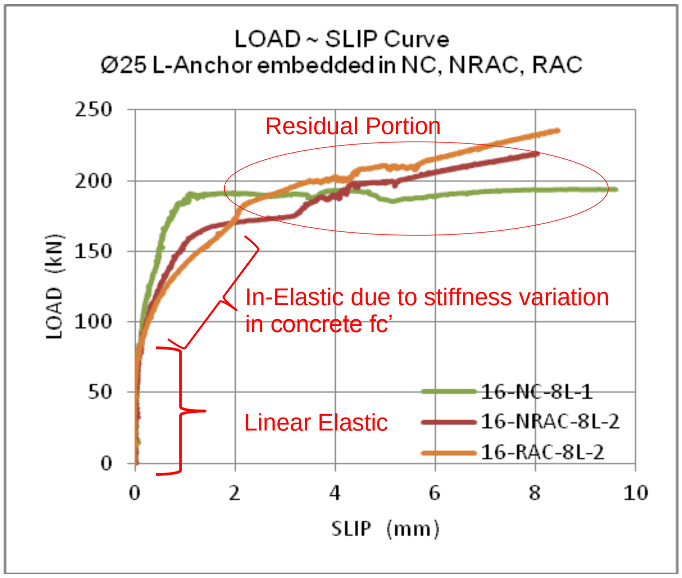

Fig 9: Load~Slip Curve of Ø25 L-Anchor Bolt in NC, NRAC and RAC.

ULTIMATE LOAD CHARACTERISTICS – After the initial phase of load-slip test measurements, the specimens were finally subjected to ultimate load to discover the failure pattern of the concrete and the steel anchor. A brief account of the failure pattern is presented in Table 11.

Table 11: Specimen Ultimate Load Characteristics

Specimen ID	Ultimate Load	Specimen Failure
14-NC-6L-1	124.6 kN	- Anchor Bar Cup and Cone Failure - Concrete Top Surface Chipping with Cracks
14-NRAC-6L-2	122.6 kN	- Anchor Bar Slippage - Concrete Top Surface Chipping with Cracks
14-RAC-6L-2	118.7 kN	- Anchor Bar Slippage - Concrete Top Surface Chipping with large Radial Cracks

SPECIMEN FAILURE DISCUSSION All specimens during and after testing are observed for the failure cracks. Following are the details of the observations:

- In the initial linear portion, the bond of anchors with the concrete is intact and major resistance is provided by the bond strength.
- Top surface concrete chipping initiated on the specimen near the anchor bar when the applied load exceeds the linear elastic limit of load-slip curve, Fig 10 depicts the initial cracking.
- In the in-elastic range, the visible cracks increase in size on the top surface in the form of chipping regardless of the concrete type or anchor diameter.
- At the ultimate load, the specimen failure is witnessed either in anchor bar slippage though 'pull-out failure' pattern in RAC or through the anchor bar failure through 'cup and cone failure' in NC.
- The earlier formed chips are cracked radially. The chips further increase in size and in appearance when the applied load enters the 'residual' portion of load~slip curve in all specimens and in this range the load become almost constant whereas slip continue to increase. Figures 11 and 12 show the distinct crack pattern.
-

Fig 10: Initial chipping and top surface cracking in surrounding of L-Anchor bolt as the load is entering in-elastic range during testing.

Fig 11: The normal concrete Ø19 L-Anchor of S14 specimen after test. The cracks on top surface and the anchor-bolt steel failure is evident at the rupture load.

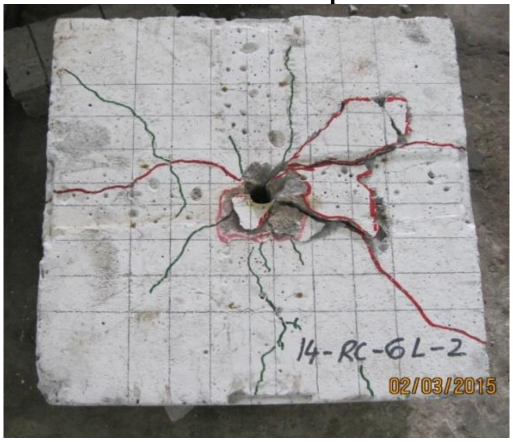

Fig 12: The Ø19 L-Anchor of RAC S14 specimen after test. The crack due to chipping and the radial cracks on top surface are marked for clarity after the ultimate load.

7 CONCLUSIONS AND RECOMMENDATIONS

Following conclusions have been inferred from this research:

- The concrete using recycled aggregate for pedestals to hold steel anchors performs like the concrete using normal aggregate. In fact, the ductility is somewhat improved. Therefore, the use of ACI-318-11 Appendix-D guidelines can be followed in the same manner as that of the NC keeping the strength of the concrete same.
- Properly designed anchor reinforcement can induce a 'ductile steel failure' instead of brittle concrete failure mode.
- The confining reinforcement protects concrete around anchors from splitting, breaking out, and side face blowout.

Further studies could analyze the behavior of the RAC in numerous other types of the cast-in anchor bolts i.e; hex, heavy hex, stud and J-bolt. Also there is a room for behavioral analysis on the group of anchors casted in the RAC. The embedment depth h_{ef} of anchor-bolt can be varied and the effect of the same can be experimentally studied in detail.

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