ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

The Effect Of Concrete Cover On Pure Torsional Resistance In Reinforced Concrete Beam:- Experimental Investigation

A Thesis in Structural Engineering

By Abdulkerim Muhdin

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A Thesis

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UNDERTAKING

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ABSTRACT

Structural elements in building and bridge construction may be subjected to the significant pure torsional moment that affects the design. As a result, in last century ,there is an enormous amount of knowledge that has been generated on the behavior, design and detailing of the reinforced concrete member. however, concrete cover spalling phenomena due to torsional moment is not adequately addressed.

In this study, Experimental investigation is conducted to study the effect of concrete cover on the behavior of reinforced concrete members subjected to pure torsion. Nine large reinforced concrete beams in three experimental sets, with three different thickness of concrete cover were tested under pure torsional load.

In all the experimental program increasing the thickness of concrete cover for equivalent sectional properties decrease its torsional capacities. Beside relatively larger transverse reinforcement diameter, which is diameter 10mm increases its ultimate torsional capacity of the beams compared to that of equivalent area of transverse reinforcement diameter dimeter 8mm in the experimental test conducted.

In the study, here also again, high strength concrete shows relateively small influence in its ultimate capacity of the member but it enhance the cracking capacity of the beam.

Since, spalling of concrete cover is critical for pure torsional resistance, it also affect the yield point of the transverse reinforcement.

Generally speaking , the thickness of concrete cover has huge impact on the ultimate strength as well as the overall behavior of reinforced concrete members.

Keywords: angle of twist; beams(support);concrete; cover;high strength concrete;pure torsion; reinforced concrete ;Spalling; strength

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LIST OF ACRONYMS

NSC_S1_C30	normal strength concrete in experiment set 1 concrete cover 30mm
NSC_S1_C40	normal strength concrete in experiment set 1 concrete cover 45mm
NSC_S1_C60	normal strength concrete in experiment set 1 concrete cover 60mm
NSC_S2_C30	normal strength concrete in experiment set 2 concrete cover 30mm
NSC_S2_C45	normal strength concrete in experiment set 2 concrete cover 45mm
NSC_S2_C30	normal strength concrete in experiment set 2 concrete cover 60mm
HSC_S3_C30	High strength concrete in experiment set 3 concrete cover 30mm
HSC_S3_C30	High strength concrete in experiment set 3 concrete cover 45mm
HSC_S3_C60	High strength concrete in experiment set 3 concrete cover 60mm

LIST OF SYMBOLS

A_ outer circumference of the cross section area

A_c _ outer area perimeter

A_k_ Area enclosed by center line of the connecting wall

A_l_ Area of longitudinal reinforcement

A_O_ Shear flow area

A_t _ Area one leg of closed strriups

C_ cover

f_{yd}_ design yield stress of longitudinal reinforcement

P_c_ Perimeter of the concrete Cross-Section

P_h_ perimeter of centerline of outer most closed strriups

q_u_ Shear flow

T_{Ed}_ Applied design torsion

T_u_ Ultimate Torque

$t_{ef,i}$_ Effective wall thickness

t_d_ Depth

U_ Perimeter in outer circumference of the cross section

U_k_ Perimeter of the area A_k

$V_{Ed,i}$_ Shear force in wall I, due to torsion.

V_{u}_ Nominal shear stress

Z_{i}_ The side length of wall i

θ_ The angle of compression strut

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Finally, “Love you mom”

Chapter 1 INTRODUCTION

1.1 General background

The Motivation in gaining a better understanding of reinforced concrete members' torsional behavior has increased in recent decades. This may be due to the increasing use of structural components in which torsion is a central behavioral feature such as curved bridge girders RC gutters, and helical slabs. However, the achievements were not as much as in those axial and bending areas, their design techniques are the same in all nations and well understood.

It is also very primitive to deal with shear and torsion in today's codes of practice and the empirical design methods used in the codes and specifications are very different around the world which does not include the more elaborate techniques.

Emphasizing for torsional effects is essential for the safe design of structural concrete members, requiring full knowledge of the torsion effects and a sound understanding of the analytical models that can be easily used for design.

Such that Analytical models based on skew bending and the truss model concept were developed. Several of these models have been developed to predict a member's full load history, while others are simplified and used for calculating torsional strength only. Since the 1980s, many models have been developed to soften diagonally cracked concrete. In all those different models do not take into account the effect of concrete cover

Following the scarcity of experimental data on the behavior of reinforced concrete in pure torsion, it is not surprising that the existing design procedure continues in question. One such post was a response to concrete cover treatment. ACI provisions, which assume that concrete cover contributes to the torsional resistance, were based on the tests conducted by Hsu, T.T.C of beams with relatively small cover (12.7mm-15.24mm). Later studies by Mitchell, D, and Collins on members in pure torsions shows relatively large concrete cover spall off under high torsional stresses. Because of this, the Canadian code neglects the contribution of the concrete cover to torsional resistance.

This research describes an experimental program that tested nine reinforced concrete beams in three different categories. The study was conducted

- To investigate the effectiveness of concrete cover in pure torsion resistance.
- To see the formation of splitting to the effect of stirrups diameter with the different concrete cover on its torsional resistance
- To state the contribution of high strength concrete grade with altered concrete cover

And to provide experimental background for a theoretical model for concrete cover spall checking to be published in confidant researches.

1.2 Significance of the research

Design codes have a different approach on the pure torsional capacity of the RC beam in relating to the member concrete cover. Fairly, large concrete covers are required to protect reinforcement against threats of fire and corrosion. It is important to be able to assess the effectiveness of concrete cover in resisting the applied pure torsional moment and its effect on the loading history of the member and also should state the codes weakness in the approach of concrete cover.

1.3 The objective of the research

1.3.1 General Objective

The General objective of the research is to experimentally investigate the effect of concrete cover on pure torsional resistance of RC beam.

1.3.2 Specific objective

The specific objective of the research includes:-

- ✓ To visualize the concrete cover effect on its torsional resistance
- ✓ To state the influence of transverse reinforcement diameter with an equivalent area on its ultimate resistance.
- ✓ To illustrate the role of high concrete grade in its torsional resistance.
- ✓ To determine the effect of concrete cover spalling on the yield point of transverse reinforcement.

1.4 Scope of the research

The research will focus only on reinforced concrete beams that are susceptible to pure torsion. Shear force and flexural effects were neglected.

1.5 Methodology

Besides reviewing significant literature, the study is carried out in three stages, examining the general role of concrete cover in RC beam in the first stage. In the second stage, the design approach of various codes with regard to concrete covers in pure torsional resistance. Finally, the experimental program will be carried out to investigate the effect of concrete cover variation in its torsional resistance of RC beams.

1.6 Overview of The research content

Chapter two provides a valid literature review. On the top of the line, deep attention is set on filling in the practice of different design consideration of pure torsional resistance code based and unlike theoretical models attitude to capture the specimen's general behavioral history.

Chapter three is knee on the general experimental package in AAiT material laboratory. Type of material used, checking the availability of material, testing used material, preparation of the specimen (beam), arranging test set up instrumentation used, and conducting experimental test were covered in this portion.

Chapter four state the result and discussion in the output of the experimental result and Comparing with different code approach in pure torsional resistance.

Chapter five dealt with the conclusion of the research and recommendation for the future study depending on this research.

Chapter 2 LITERATURE REVIEW

2.1 General background

A clear understanding of the effects of pure torsion on Reinforced concrete members is essential to the safe, economical design of reinforced concrete members.

This report begins with a brief and systematic summary of the 180-year history of torsion of structural concrete members, new and updated theories and their applications, and a historical overview outlining the development of research on torsion of structural concrete members.

2.1.1 The behavior of beams in pure torsion

Prior to cracking, a torsional moment applied to a concrete member is resisted by internal shear stresses. The largest shear stresses occur in the middle of the outside faces or perimeter of the cross-section. Shear stresses lead to diagonal principal tensile and compressive stresses. When the diagonal tension exceeds the tensile strength of the concrete, diagonal cracking occurs.

It has been observed in experiments on beams subject to torsion that once the crack initiates, it spirals around the perimeter of the member. Simultaneously, the beam torsional stiffness drops significantly. It takes significant twisting before recovering the cracking torque. Upon further torsional loading, excessive twisting deformations lead to spalling of the concrete cover over the transverse reinforcement. Hence, transverse reinforcement must be properly anchored with 135-degree hooks.

Lampert, P., and Thurlimann, B., Torsionsversuch anStahlbetonbalken (Torsion Tests of Reinforced Concrete Beams), Bericht Nr. 6506-2, 101 pages, they observed experimentally that solid and hollow beams of similar external cross section and with similar longitudinal and transverse reinforcement achieve comparable torsional strength. Thus, in a solid beam, part of the concrete core separates from the outer shell (inside the transverse reinforcement) and becomes inefficient. Therefore, when the torsional strength of a beam is reached, a solid section can be represented by a hollow section of the same external dimensions.

Before the concrete cracks, a member under pure torsion is assumed to behave elastically with a nearly linear torque-twist curve. After cracking, the resistance mechanism changes and stirrups and longitudinal reinforcement carry most of the tensile load whereas the concrete carries the compression. The longitudinal reinforcement tensile strains cause the member to lengthen. Increased torque causes the nearly linear increase in the beam length. A longitudinal restraint acts as a compressive prestress force and increases the torsional strength.

2.1.2 Equilibrium versus compatibility torsion

Kamara, M.E., and Rabbat, B.G., editors, Notes on ACI 318- 05 - It is important for designers to distinguish between two types of torsions: equilibrium torsion and compatibility torsion.

Torsion of equilibrium occurs when the resistance of the torsion is required to maintain a static balance. In this case, the structure will become unstable and collapse if there is not sufficient torsional resistance. There is no alternative load path for external loads and torsion must be resisted.

Compatibility torsion develops where torsional moments may be redistributed to adjacent members. The term compatibility refers to deformation compatibility between adjacent parts of a structure. Consider, for example, a spandrel beam that supports an external slab.

Lampert, Farmington Hills, Mich., 1973 The negative slab end moment, which induces torsion in the spandrel beam, also increases as the load on the slab increases. The negative slab end moment is proportional to the spandrel beam's torsional stiffness. When the magnitude of the torsional moment exceeds the cracking torque, the torsional spiral cracks around the member and the spandrel beam's cracked torsional stiffness is significantly reduced

2.2 Overview of torsional Theories and Theoretical Models

2.2.1 Navier's theory

A theory for torsion of elastic homogeneous members was first developed by C. L. Navier (1826) for circular cross-sections. His theory, which was based on equilibrium conditions, compatibility conditions, and a linear stress-strain a relationship like Hooke's Law, has guided the development of various theories about the behavior of reinforced concrete members subjected to torsion after cracking.

2.2.2 Hollow tube analogy

Experimental testing by Hsu (1968) showed that hollow and solid beams have a similar ultimate torsional strength. This indicates that the contribution of the inside core of the concrete to the capacity of the section is negligible. Similarly, measurements by Mitchell and Collins (1974) showed that near ultimate conditions the principal compressive strains between the cracks vary in a linear manner, with the maximum near the surface and zero at a distance t_d below the surface. This reinforces the conclusion from Hsu's tests regarding the contribution of the inside core of concrete. Hsu, T.T.C. 1968(Torsion of structural concrete, SP-18, American Concrete Institute, Detroit, Mich. pp. 261–306.)

The hollow tube analogy assumes that near ultimate conditions a concrete beam can be idealized as a hollow tube with the same outer dimensions and with a thickness t_d. See Fig. 1*b*. A field of shearing stresses n circulating in the tubular section resists the torsional moment. These stresses vary from zero on the inside face to a maximum at the outer face of the tube, as shown in Figure 1-1. An equivalent field of constant shear flow *q* acting over a thickness a_o can be obtained (Collins and Mitchell 1991). Collins, M.P., and Mitchell, D. 1991 "Prestressed concrete structures. Prentice Hall, Inc., Englewood Cliffs, N.J.."

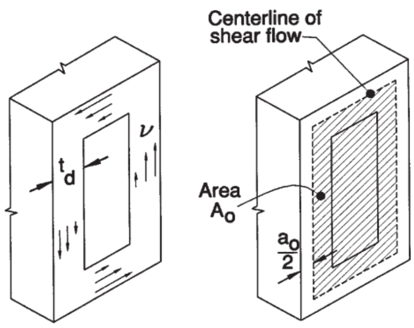


Figure 2-1 Equivalent hollow tube and centerline of shear flow

The area enclosed by the centerline of the shear flow is named shear flow area A_o. For thin-walled closed sections, the relationship among the ultimate torque T_u, the shear flow q_u, and the shear flow area A_o is given by

$$T_u = 2q_u * A_o \qquad (2.1)$$

The shear flow q_u can be related to a nominal shear stress V_u by

$$q_u = a_o * V_u \qquad (2.2)$$

The thickness of the diagonal depends on the amount of longitudinal and transverse reinforcement, the concrete strength, and the geometry of the section. Based on a simplified model, Rahal and Collins (1996) found that the average value of the thickness of the concrete that is effective in resisting the torsional moment was

$$t_d = 0.5\, {}^{A_c}/_{p_c} \qquad (2.3)$$

Where *A*c and *p*c are, respectively, the outer area and perimeter of the concrete cross section. This relationship is also found in the Canadian code (CSA 1994) as the minimum required thickness of hollow sections for which the presence of the core does not reduce the torsional capacity. For concrete strengths below 50 MPa, a parabola can be used to represent the stress-strain relationship of concrete in compression. Based on a linear variation of the concrete principle compressive stress along t_d, and the parabolic stress-strain relationship of concrete in compression, the depth of the equivalent stress block *a*o can be taken as (Collins and Mitchell 1991).

$$a_o = 0.833t_d \qquad (2.4)$$

Equation (2.4) is based on the assumption the at the principal compressive strain varies linearly from a maximum at the surface to zero at a depth t_d. Mitchell and Collines (1974) proposed this assumption in their compression field theory(CFT).based on the results of Rahal and Collins(1996, the area enclosed by the centerline of the shear flow A_o Can be approximated as

$$A_o \cong 0.8A_c \qquad (2.5)$$

Combining Eqs (2.1) to (2.5) gives the following relationship between the ultimate torsional moment T_U and the ultimate shearing stress in the wall of the equivalent tube.

$$T_u = 0.67(\frac{A^2{}_c}{P_c})V_c \qquad (2.6)$$

The walls of the section can be idealized as reinforced concrete membrane elements subjected to pure in-plane shearing stresses. If the nominal shearing capacity of the reinforced concrete in the walls of the tubular section is known, the ultimate torsional moment can be easily calculated using Eq (2.6). It is to be noted that because of the simplified assumptions in Eqs. (2.3)– (2.5), the equation for torsional strength (eq. (2.6)) does not depend on the shape of the cross-section. Consequently, the method can be applied to a wide range of cross-sectional shapes such as square, rectangular, circular, and T-section.

2.2.3 Thin-tube theory

Navier's torsion theory for members of circular sections was followed by Saint-Venant's (1856) solution for rectangular sections. Saint-Venant's torsional constants considered warping of rectangular cross section. According to SaintVenant's circulatory shear flow theory, the most efficient cross section to resist torsion is a thin tube. His thin-tube theory states that the shear stress multiplied by wall thickness has a constant value around the perimeter and that this enclosed by the shear flow path. Bredt's theory has served as the basis for modern theories of cracked reinforced concrete members subjected to saint-venanat torsion. (Report on torsion joint ACI-ASCE Comittee 445)

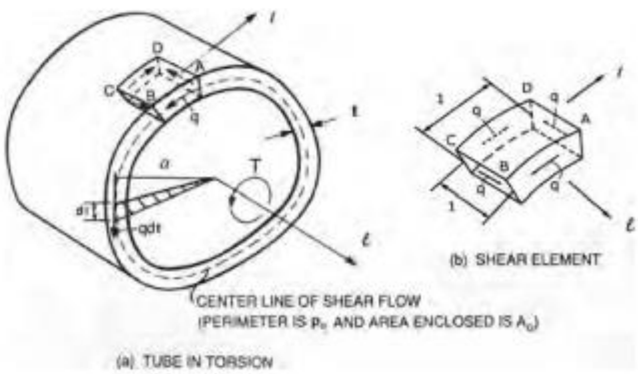
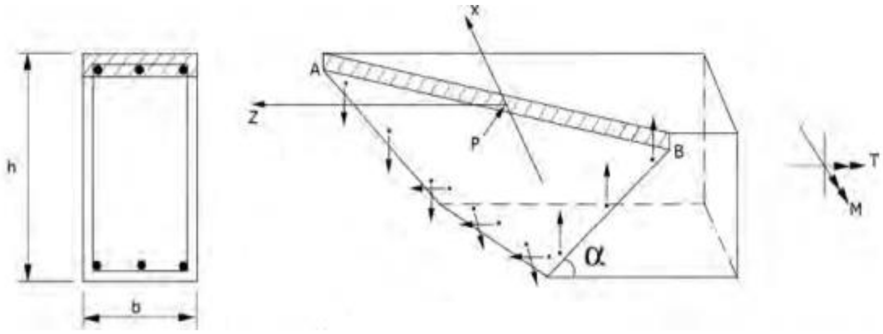


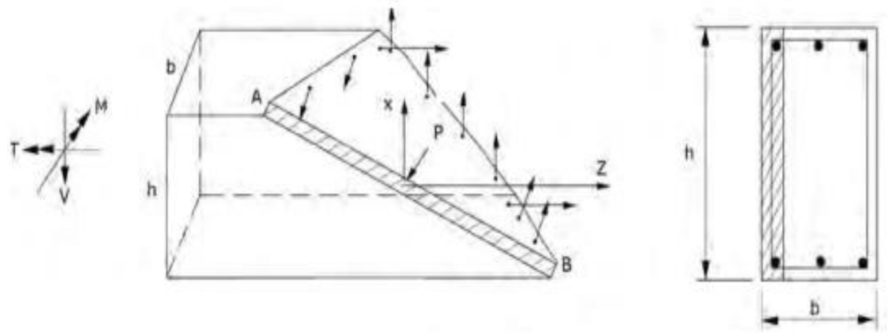
Figure 2-2 Torsion of thin tube and lever arm area A_o (Hsu 1993 after bredt 1986

2.2.4 Skew-bending and space truss theories

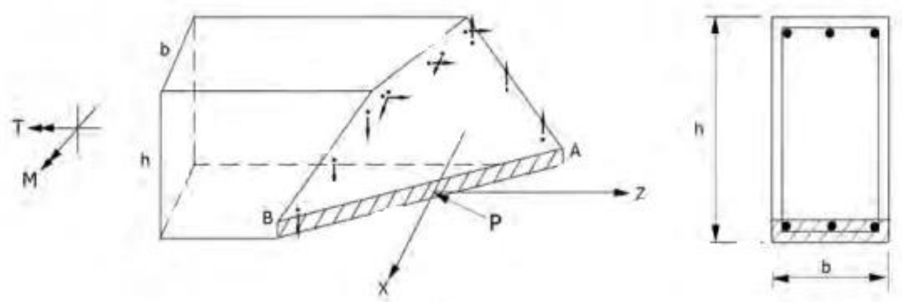
In later years, research on pure torsion followed two theoretical tracks skew-bending and space truss Lessig (1959) first proposed a skew-bending theory for reinforced concrete members with two modes of failure. The first mode has a compression zone along the top face and failure is caused by the yielding of the bottom longitudinal reinforcement and transverse reinforcement along with three remaining faces. The second mode has a compression zone along the face and failure is caused by the yielding of the longitudinal reinforcement on the opposite side face, and in the transverse reinforcement along the three face in tension. Figure 2-2 shows mode1 and mode 2 failures. Lessig, N. N., 1959, "Determination of Load-Carrying Capacity of Rectangular Reinforced Concrete Elements Subjected to Flexure and Torsion,



(a) Mode 1 failure



(b) Mode 2 failure



(c) Mode 3 failure

Figure 2-3 failure mode in skew- bending theories a) mode 1 b) mode 2 c) mode 3

The third mode has a compression zone along the bottom face where failure is caused by yielding along with longitudinal reinforcement and transverse reinforcement along the three remaining faces.

2.2.5 Compression field theories (CFT)

The truss model with linear elements developed by Rausch was replaced in the 1960s by a new type of truss model with membrane elements that were subjected to in-place normal and shearing stresses. In determining the torsional strength of members where some reinforcement does not yield, consider compatibility conditions. Such conditions were introduced by Baumann (1972) for shear and by Collins (1973) for torsion. Mitchell and Collins (1974). Incorporated compatibility conditions in their CFT, which also relied on equilibrium equations and nonlinear material models for concrete and reinforcement. Unlike previous models, the CFT calculates cracked member torsional behavior up to the peak torque. A compatibility condition derived by minimizing the strain energy in the system is used to calculate the angle of inclination in truss model struts.

2.2.6 Softened truss model (STM)

In 1985, Hsu and Mo (1985a,b,c) proposed the STM by softening the concrete stress-strain curve. All of the aforementioned models satisfy Navier's theory.Earlier models overestimated test strengths (Hsu 1968c), whereas the CFT, which uses spalling of concrete cover, and STM, which uses softening of concrete, have been shown to predict test results accurately (McMullen and EL-Degwy 1985)

2.3 Different design codes statements on pure torsion

2.3.1 EBCS EN 1992-1-1:2014

A section's torsional resistance can be calculated on the basis of a thin-walled closed section in which shear flow satisfies the balance. Equivalent thin-walled sections can model solid sections. Complex shapes, such as T-sections, can be divided into a series of sub-sections, each of which is modelled as the equivalent thin-walled section, and the total resistance taken as the sum of the individual element capacities.

Where a structure's static equilibrium depends on the torsional resistance of structural elements, a complete torsion design shall be made that covers both the ultimate and the limiting states of serviceability.

In proportion to their un cracked torsional moments over the sub-sections, the distribution of acting torsional moments over the sub-sections should be proportional to their un cracked torsional stiffness. For non-solid sections the equivalent wall thickness should not exceed the actual wall thickness.

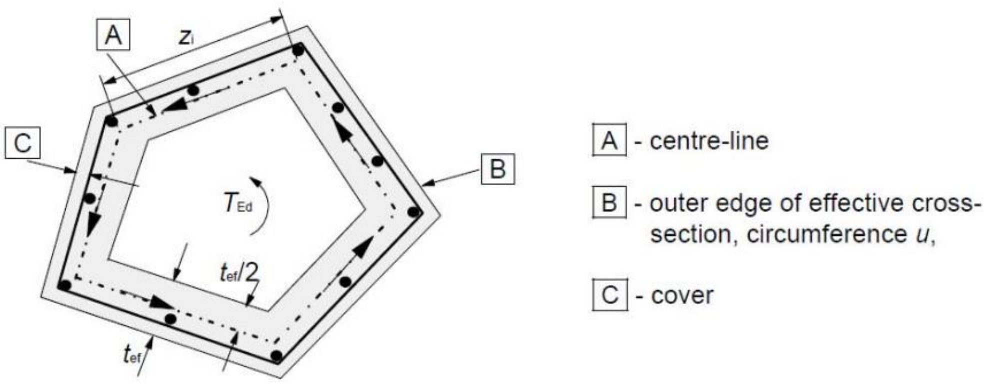


Figure 2-4 Notation and definition used in thin-walled cross section

Design statement by the EBCS EN 1992-1-1:2014

- ✓ The shear stress in a wall of section subjected to pure torsional moment is

$$\tau_{t,i} * t_{ef,i} = \frac{T_{ed}}{2A_k} \qquad (2\text{-}7)$$

- ✓ The shear force in the wall

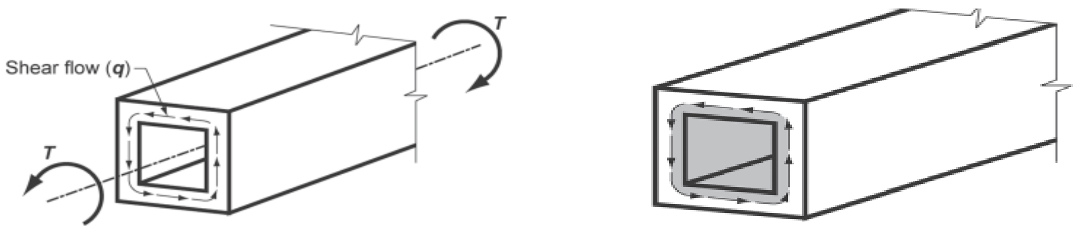
$$V_{ed,i} = \tau_{t,i} * t_{ef,i} * z_i \qquad (2\text{-}8)$$

- ✓ The required cross-sectional area of the longitudinal reinforcement for torsion:

$$\Sigma \frac{A_{sf} f_{yd}}{U_k} = \frac{T_{ed}}{2A_k} cot\theta \qquad (2\text{-}9)$$

2.3.2 ACI 318R-14

The torsion design in this section is based on a thin-walled tube space truss analogy. A torsion beam is idealized in a solid beam as a thin-walled tube with the core concrete cross section neglected as shown in figure 2-4.



a) b)

Figure 2-5 a) Thin wall tube; b) Area enclosed by shear flow path

Once a reinforced concrete beam has cracked in torsion, it mainly provides its torsional strength through closed stirrups and longitudinal bars located near the member's surface.

In the thin-walled tube analogy, the outer skin of the cross-section approximately centered on the closed stirrups assumes the strength. Both hollow and solid sections are idealized before and after cracking as thin-walled tubes.

The concrete contribution to torsional strength is ignored, and in cases of combined shear and torsion, the concrete contribution to shear strength does not need to be reduced.

The design procedure is derived and compared with test results in MacGregor and Ghoneim (1995) and Hsu (1997).

Torsional strength

The torsional design strength ϕTn must equal or exceed the torsional moment Tu due to factored loads. In the calculation of Tn, all the torsion is assumed to be resisted by stirrups and longitudinal reinforcement, neglecting any concrete contribution to torsional strength. At the same time, the nominal shear strength provided by concrete, Vc, is assumed to be unchanged by the presence of torsion.

The code states:

$$T_n = \frac{2A_o A_t f_{yt}}{s} cot\theta \qquad (2\text{-}10)$$

$$T_n = \frac{2A_o A_l f_y}{s} cot\theta \qquad (2\text{-}11)$$

2.4 Researches related to concrete cover spalling

High concrete shearing stresses outside of the stirrups create the potential for concrete spalling under high torques. To satisfy equilibrium, the concrete compressive stress that resists torsion after cracking changes directions at the outside corners of the beam. When the tensile stress is high enough, the resulting tensile stress in the concrete causes the concrete cover to spill off. The spall typically occurs in the stirrups. The resulting section is smaller and the torsional strength is reduced (Mitchell and Collins 1974). Mitchell and Collins (1974) tested two beams, PT5 and PT6, to investigate the effects of spalling. The beams had similar reinforcing cages and concrete strength, but PT5 had a cover of 1.5 mm (1/16 in.) and PT6 had a cover of 40 mm (1-9/16 in.). The results of the tests showed that, although the concrete outside the hoop reinforcement had a significant effect on the cracking torque, it had little effect on the peak torque after significant spalling occurred (Figure. 2-6)

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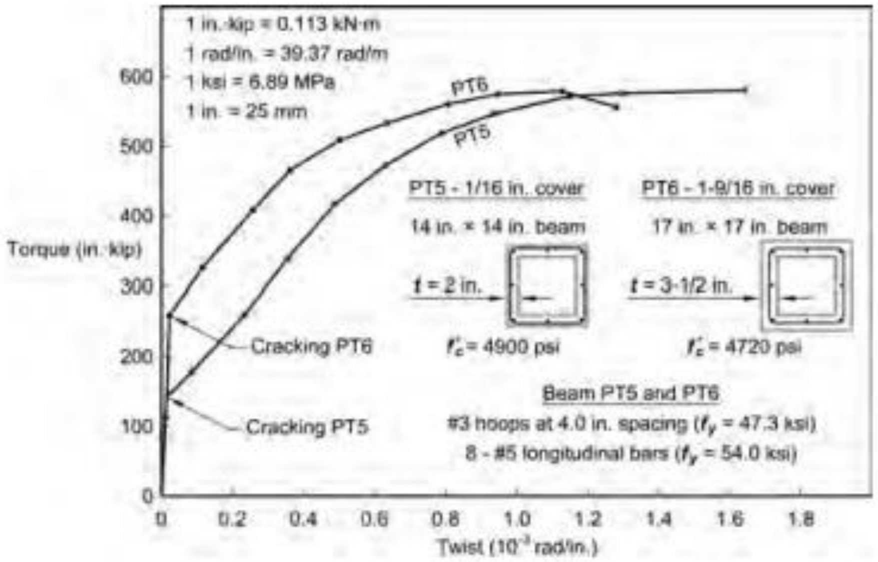

Figure 2-6 **Effect of concrete cover on torque-twist behavior (Mitchell and Collins 1974). (Note:1 in-kip=0.113kN.m)**

In tests performed by Rahal and Collins (1995b), specimens with small covers did not experience spalling until after the torsional strength had been reached. Beams with large cover spalled before reaching torsional strength.

2.5 High-Strength Concrete

In the case of pure torsion, the use of HSC allows higher service stress in the reinforcing bars and produces a higher stiffness in the structure, enhancing both the strength and stiffness of a member. For a given amount of reinforcement, the initial crack width is larger for HSC because larger reinforcement strains are induced at cracking, but the number of cracks is fewer in HSC. (Report on torsion joint ACI-ASCE Committee 445)

Chapter 3 EXPERIMENTAL PROGRAM

3.1 Introduction

This section describes the experimental program completed at the Construction Materials Laboratory, Addis Ababa Institute of Technology to study the effect of concrete cover in pure torsional resistance of reinforced concrete beams. In this experimental program, nine reinforced concrete beams in three sets were cast.

In the first set of experiment three reinforced concrete beams were casted. The main variable of the beams were concrete cover, with cover thickness 30mm, 45mm and 60mm for each three beams.

In the second set of experiment here also three reinforce concrete beams were casted. The main variable of the beams were the diameter of transverse reinforcement. Here, diameter 10 strriups is used. For this set, Experimental set one is the control Specimen for Experimental set two, and also the objective of set one can be captured.

In the third set of experiment here also again three reinforced concrete beams were casted. The main variable of the beams were high strength concrete. The selected concrete strength were C-60. Once more for this set of experiment, set one is the control Specimen, in addition, the objective of set one also can capture here.

All nine rectangular reinforced beam has a width of 300mm and a depth of 200mm. At both edges of the specimen for loading purpose reinforced concrete wing attached in the opposite direction. The total length of the specimen is 1.5m and the critical region where in a uniform pure torsion.

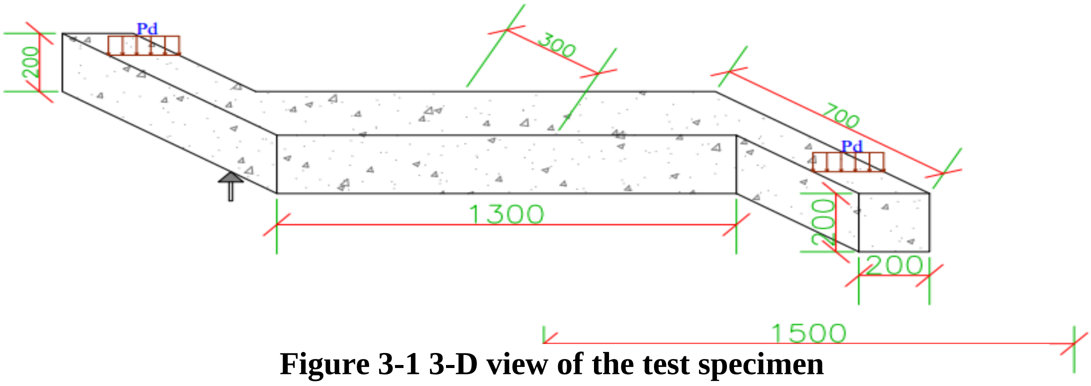

Figure 3-1 3-D view of the test specimen

3.2 Test setup and testing procedure

The experimental investigation is carried out in the following three phases:

- Material mobilization
- Specimen preparation
- Specimen fabrication
- Instrumentation
- Specimen investigation

3.2.1 Material mobilization

All the necessary material required for the preparation of specimen were collected. This includes sand from river, aggregate from quarry site, cement and reinforcement bar from the factory are collected And place in a proper manner. For the support condition to be roller and the specimen to rotate freely, additional material which provide roller support fabricated using sheet metal.

3.2.2 Specimen preparation

3.2.2.1 Concrete

Concrete is a construction material composed of cement, fine aggregate (sand) and coarse aggregate with water which harden with time.

In this research two kinds of targeted cylindrical compressive strength needed to be 40Mpa and 60Mpa.The mix design follows the ACI mix design and construction laboratory manual by Abebe Dinku (2002) used.

Coarse Aggregate

Coarse aggregate is a portion of concrete which made up large stone embedded in the mix. Concrete production is very much subjective by the properties of Coarse aggregate. To remove any impurities the coarse aggregate has been washed with pure water.

Aggregate grain size distribution or gradiation is among those properties that the researcher give due consideration.

According to Ethiopian standard Coarse Aggregate are those between 75 and 4.75mm in size. Gravel, crushed rock and blast furnace slag are generally used as aggregate. For this research sieve analysis is done to determine the nominal size of aggregate as indicated in table 3-1.

Table 3-1 Gradation of Coarse Aggregate

Sieve size (mm)	Weight of Sieve (gm)	Wt. of sieve and Retained (gm)	Weight Retained (gm)	Percentage Retained (gm)	Cumulative Coarser (%)	Cumulative passing (%)
37.5	1.085	1.085	0.000	0.000	0.000	100
19	1.390	4.21	2.82	56.627	56.627	43.373
9.5	1.160	2.70	1.54	30.924	87.550	12.45
4.75	1.175	1.43	0.255	5.12	92.671	7.329
Pan	0.735	1.10	0.365	7.329	100	0.000

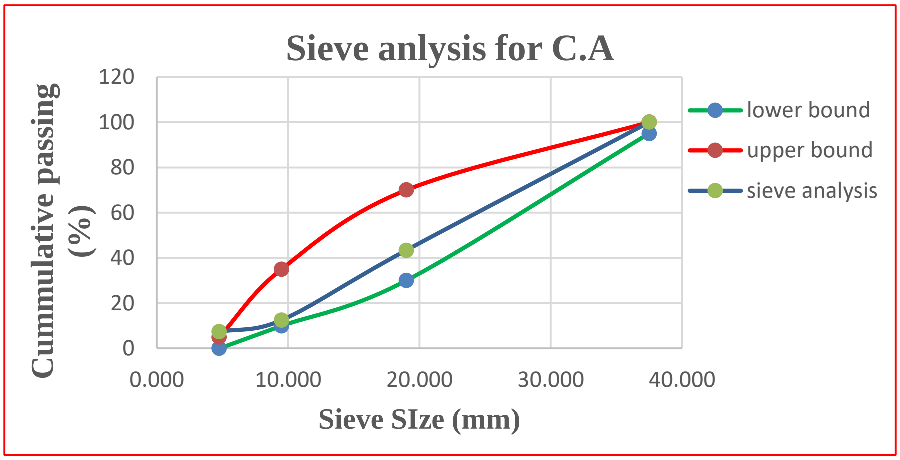

Figure 3-2 Coarse aggregate Gradation curve in the limit

Fine Aggregate

Sand is a product of natural artificial disintegration of rocks and minerals, which obtained from deposits of river, Lake Marine …etc. these deposits, however, do not provide pure sand. They may contain dust and clay which are finer than sand. The presence of such material affects the material concrete. Which reduce the strength. Therefore for this research, it is necessary to check the silt content against the permissible limit to the Ethiopian standard silt content 6%.

To test the silt content of the fine aggregate, the researcher takes graduated cylinder having a capacity of greater than 100ml and pour 30ml of sand to the cylinder and after that ¾ of fill, the cylinder with water and shake vigorously, table 3-2 shows the silt content results.

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Figure 3-3 Silt content test

Table 3-2 Silt content results

Cylinder	Silt Content(ml)	Pure Sand (ml)	% Silt Content $=\frac{silt}{pure\ sand} * 100$
1	17	376	4.52
2	18	361	4.9

The same thing as done in coarse aggregate, the gradation of fine aggregate has to be within the permissible limit.

Table 3-3 Gradation of Coarse Aggregate

Sieve size (mm)	Weight of Sieve (gm)	Wt. of sieve and Retained (gm)	Weight Retained (gm)	Percentage Retained (gm)	Cumulative Coarser (%)	Cumulative passing (%)
9.5	0.585	0.585	0.000	0.000	0.000	100
4.75	0.43	0.435	0.005	1.136	1.1361	98.864
2.36	0.385	0.445	0.06	13.636	14.773	85.227
1.180	0.355	0.460	0.105	23.864	38.636	64.364
0.6	0.335	0.470	0.135	30.682	69.318	30.682
0.3	0.350	0.410	0.060	13.636	82.995	17.045
0.15	0.270	0.320	0.050	11.364	94.318	5.682
pan	0.335	0.360	0.025	5.682	100	0.000

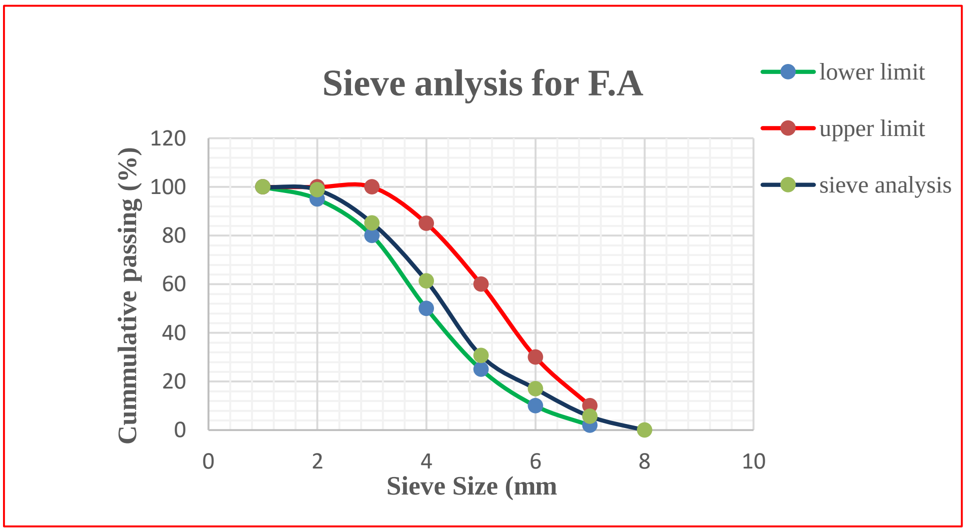

Figure 3-4 Fine aggregate gradation curve in the limit

Cement

For this research ordinary Portland cement has been used.

And finally, for the study two kind of concrete mix proportion is need, the targeted cylindrical compressive strength were 40Mpa and 60Mpa, which is a random selection, table 3-4 shows the mix proportion used in both case.

Table 3-4 Mix proportion of Concrete

Material	Targeted C-40	Targeted C-60
Nominal aggregate size(mm)	25	25
Cement content (Kg/m^3)	459.52	540.15
Coarse aggregate (Kg/m^3)	1132.916	1211.86
Fine aggregate (Kg/m^3)	838.98	550.68
Water (Kg/m^3)	182.32	210.33
Water- Cement ratio	0.47	0.37
Slump (mm)	45	60

In order to keep the consistency of concrete strength in each specimen, 350kg concrete mixer has been used as shown in figure 3-4 a). In each concrete mix a single specimen was casted and in all specimen casting the mixing process were controled by doing the slump uniform.

a) b)

Figure 3-5 a) Concrete mixing b) cylinder and cube taken

During the process of casting 4 samples (150mm X 150mm X 150mm) of concrete cube and 3 samples of cylinder 150mm diameter with 300mm height for tensile splitting test taken figure 3-4 b). Table 3-5 and Table 3-6 shows tensile and compressive test result.

Table 3-5 Compressive strength of each sample

Specimen sets	Naming of the Specimen	Cube designation	Mass (Kg)	Compressive strength (Mpa)	Mean strength (Mpa)
SET 1	NSC_S1_C30	S1A	7.7	42.56	42.125
		S1B	7.82	42.1	
		S1C	7.81	44.24	
		S1D	7.83	39.6	
	NSC_S1_C45	S1A'	7.82	36.82	40.51
		S1B'	7.8	40.86	
		S1C'	7.79	40.5	
		S1D'	7.8	43.86	
	NSC_S1_C60	S1A"	7.815	36.82	40.645
		S1B"	7.8	40.86	
		S1C"	7.75	44.44	
		S1D"	7.77	40.46	
SET 2	NSC_S2_C30	S2A	7.82	36.43	41.0375
		S2B	7.815	41.23	
		S2C	7.76	42.25	
		S2D	7.81	44.24	
	NSC_S2_C45	S2A'	7.81	36.43	40.48
		S2B'	7.815	41.23	
		S2C'	7.76	42.25	
		S2D'	7.81	42.01	
	NSC_S2_C60	S2A"	7.79	36.82	41.4775
		S2B"	7.8	40.86	
		S2C"	7.82	46.75	
		S2D"	7.8	41.48	
SET 3	NSC_S3_C30	S3A	8.39	62.4	60.75
		S3B	8.27	59.6	
		S3C	8.205	58.3	
		S3D	8.23	62.7	
	NSC_S3_C45	S3A'	8.39	62.4	60.75
		S3B'	8.27	59.6	
		S3C'	8.205	58.3	
		S3D'	8.23	62.7	
	NSC_S3_C60	S3A"	8.22	59.86	59.79
		S3B"	8.17	61.8	
		S3C"	8.15	58.9	
		S3D"	8.2	58.6	

Table 3-6 each tensile strength of the sample

Specimen sets	Naming of the Specimen	Cylinder designation	Tensile strength (Mpa)	Mean strength (Mpa)
SET 1	NSC_S1_C30	S1A	3.7	3.873
		S1B	4.02	
		S1C	3.9	
	NSC_S1_C45	S1A'	3.92	3.753
		S1B'	3.61	
		S1C'	3.73	
	NSC_S1_C60	S1A"	3.3	3.466
		S1B"	3.4	
		S1C"	3.7	
SET 2	NSC_S2_C30	S2A	3.4	3.503
		S2B	3.61	
		S2C	3.5	
	NSC_S2_C45	S2A'	3.12	3.513
		S2B'	3.74	
		S2C'	3.68	
	NSC_S2_C60	S2A"	3.432	3.410
		S2B"	3.47	
		S2C"	3.33	
SET 3	NSC_S3_C30	S3A	4.9	5.103
		S3B	5.21	
		S3C	5.2	
	NSC_S3_C45	S3A'	5.1	4.613
		S3B'	4.3	
		S3C'	4.44	
	NSC_S3_C60	S3A"	3.7	4.333
		S3B"	3.6	
		S3C"	5.7	

3.2.2.2 Reinforcement

In this experimental program deformed bar from diameter 8 to diameter 14 used. Diameter 8 and 12 are used as transverse reinforcement for experimental set 1,3 and set 2 respectively. For longitudinal reinforcement diameter 12 and for wing beam to resist flexure diameter 14 has been used.

In all case three sample were taken to test the mechanical properties of the reinforcement. A uniaxial tensile test was conducted using universal tensile strength test machine UTM. The properties of a material is given in table 3-7.

Table 3-7 Mechanical properties of reinforcement

Tensile strength of steel							
Diameter	**Area**	**Yield load**	**yield stress**	**failure load**	**failure stress**	**Average yield stress**	**Average failure stress**
8	50.24	26.9	535.429	33.7	670.780	534.102	659.501
		27.2	541.401	32.8	652.86		
		26.4	525.477	32.9	654.856		
10	78.5	40.3	513.375	50.4	642.038	521.019	647.133
		41.5	528.662	51.2	652.229		
		40.9	521.019	50.8	647.133		
12	113.0	76.2	674.097	92.8	820.948	689.726	817.409
		78.4	693.559	91.3	807.678		
		79.3	701.521	93.1	823.602		
14	153.8	87.4	568.048	105.3	684.388	575.631	692.620
		88.9	577.798	106.5	692.187		
		89.4	581.047	107.9	701.286		

3.2.3 Specimen fabrication

3.2.3.1 Formwork

For this experiment the peripheral support used was plywood, which is made from sawn zigba as shown in figure 3-7. The reason behind plywood was chosen is that when the concrete vibrates it doesn’t burst easily.

After the formwork was erected, form releasing agent was applied on the inner surface of the forms for easy stripping of formwork.

Figure 3-7 plywood formwork preparation

3.2.3.2 Reinforcement

The reinforcement cage preparation was based on the euro code reinforcement detailing for torsion recommendation. For both top and bottom, diameter 12 longitudinal reinforcement used. And the top bar hooks 90° in both edges of the specimen from top to bottom. The bottom reinforcement was aline throughout the specimen length.

For transverse reinforcement in experimental set 1 and set 3 diameter 8 center to center spacing of 80mm used and for the experimental set 2 diameter 10 center to center spacing of 130mm. In all cases, 135° hook used as shown in the figure and maintained the desirable concrete cover in all side or the specimen clearly stated in the figure.

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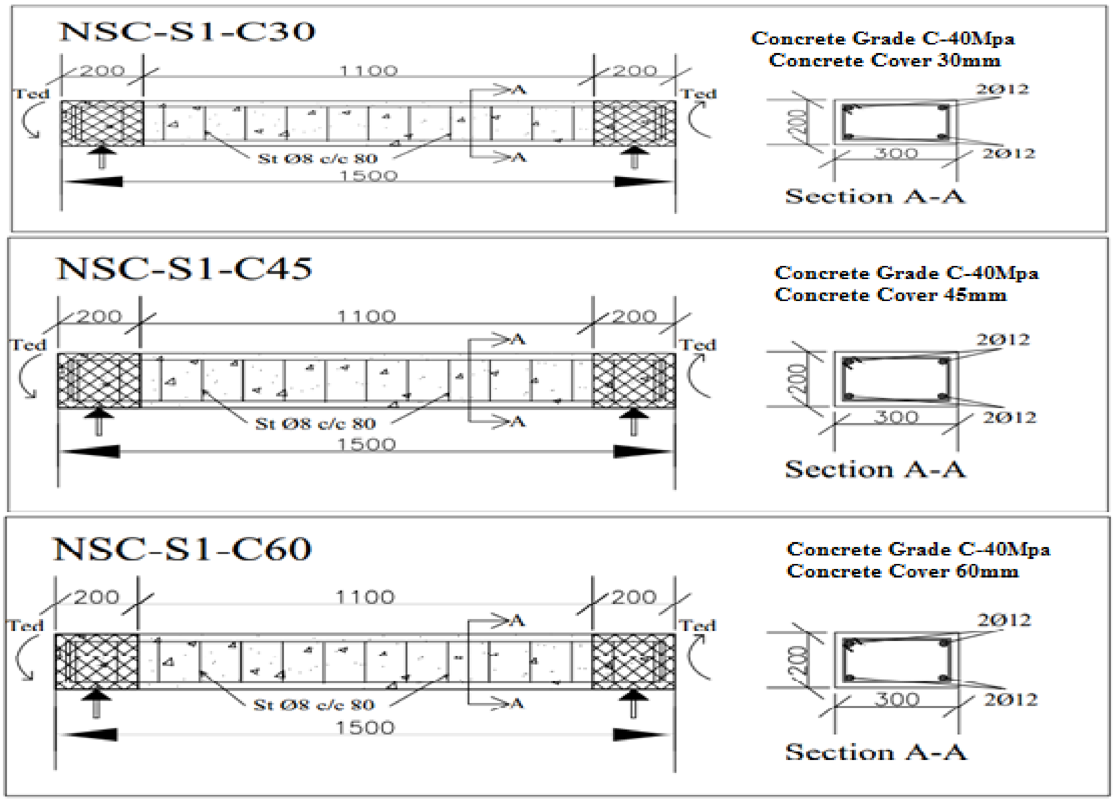
Figure 3-8 Specimen reinforcement preparation

a) **b)**

Figure 3-9 Transverse reinforcement hooked 135° a) side view b)Top view

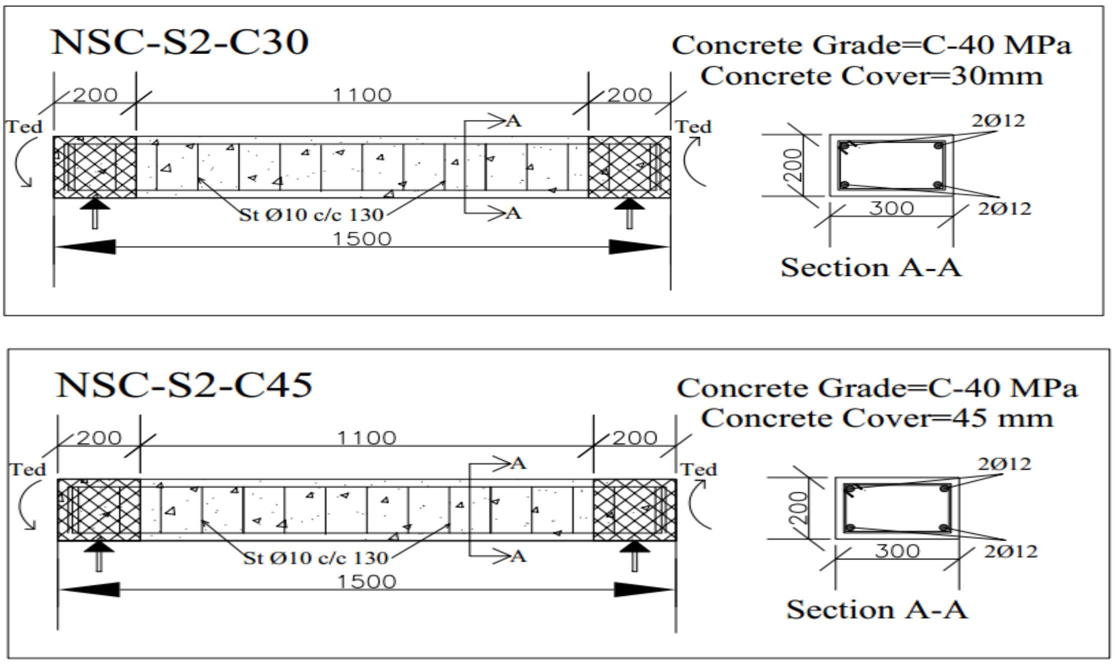
Longitudinal and transverse reinforcement detailing with the desire concrete cover is stated in figure 3-10.

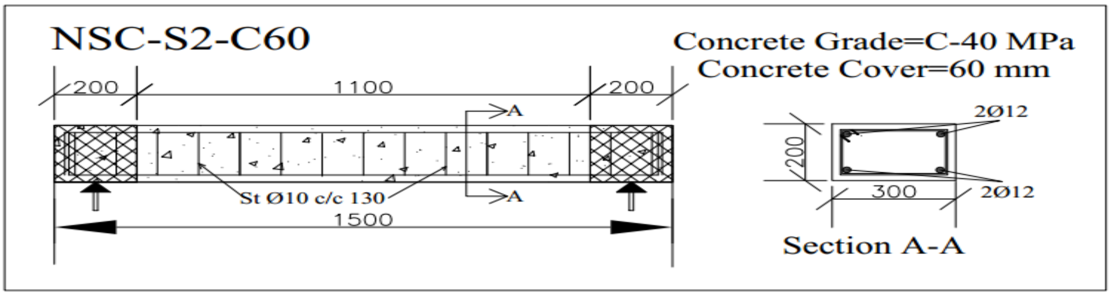
Experimental Set 1



a)

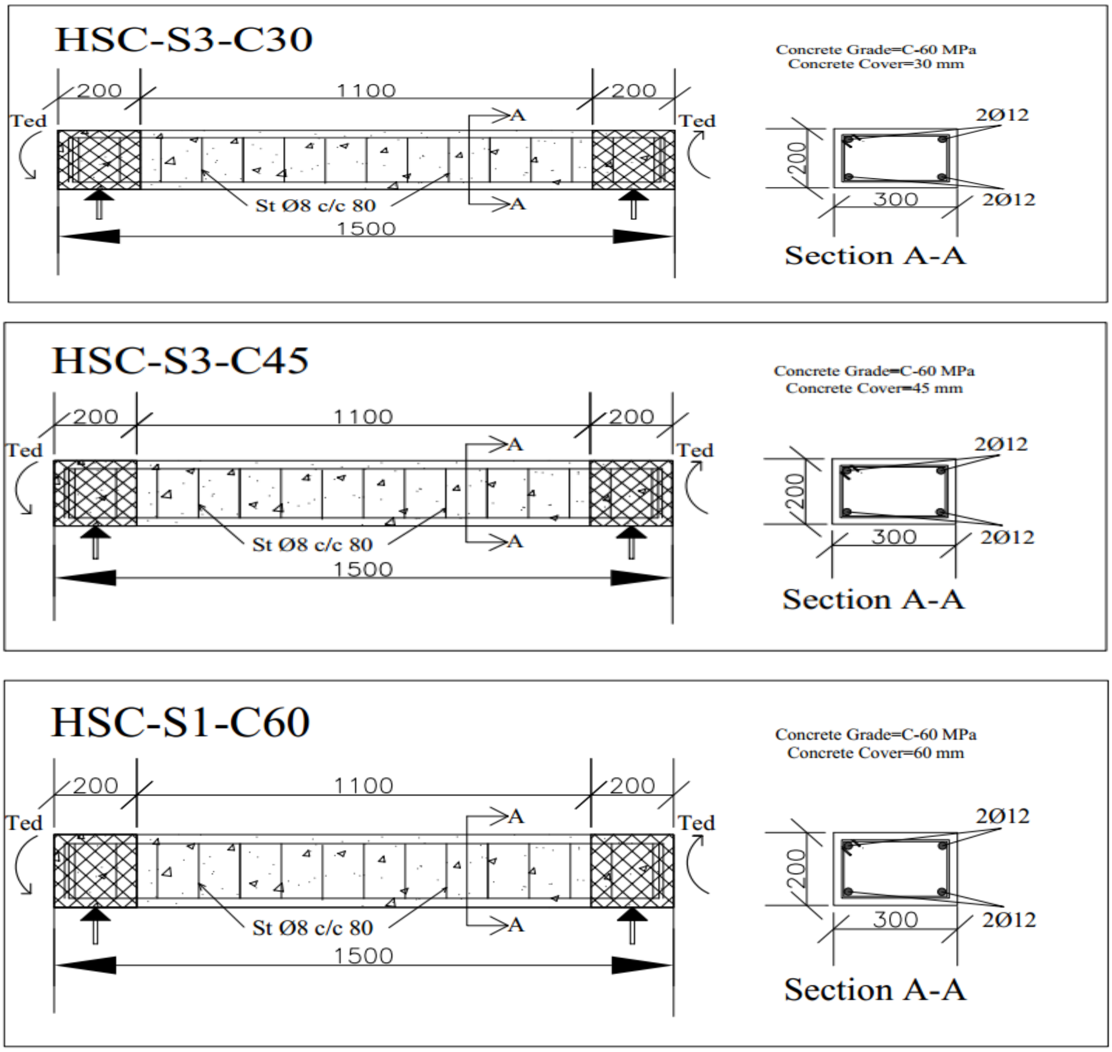
Experimental Set 2





b)

Experimental Set 3



c)

Figure 3-10 Reinforcement cage detailing

The fabricated reinforcement specimen has placed inside the plywood formwork and stiffen at the mid to avoid bulging of concrete during casting, in addition, the steel strain gauge attached to the transverse reinforcement using super glue and gum as shown in Figure 3-11.

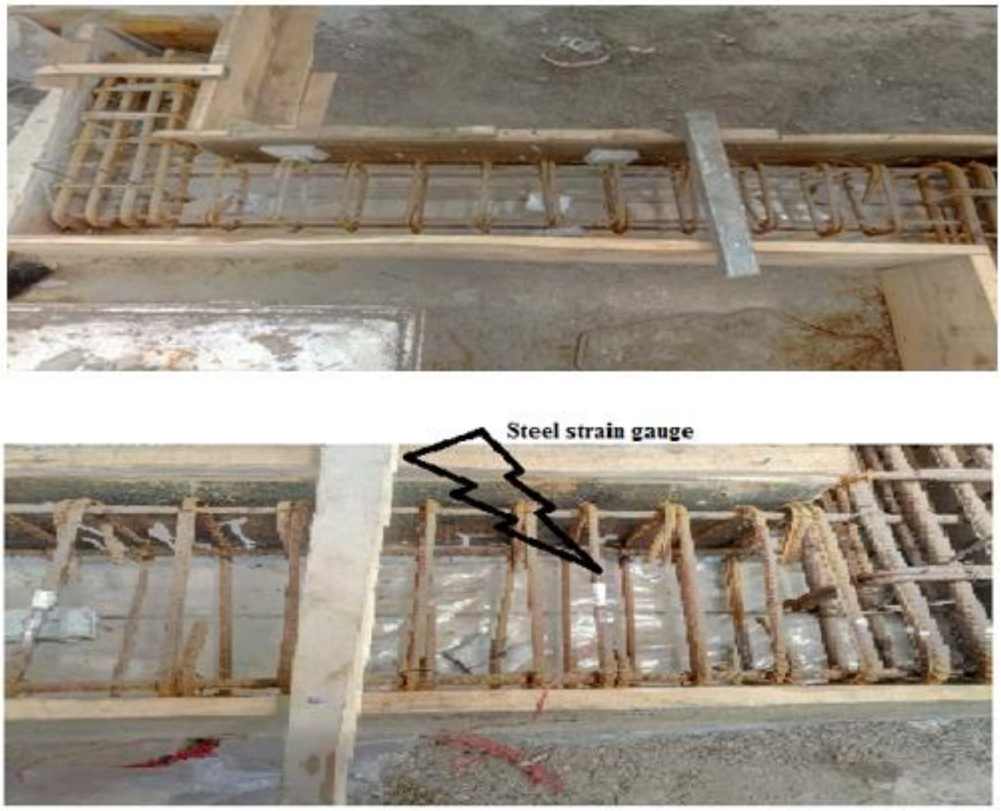


Figure 3-11 Reinforcement cage and formwork of the specimen with attached strain gauge

Concrete was cast outside the laboratory and vibrator was used to consolidate the concrete. The concrete surface exposed to air was moist cured by covering the beams with wet cotton to absorb water as shown in Figure 3-12.

Figure 3-12 Concrete casting outside laboratory

Figure 3-13 curing with covering wet cotton sack

Roller support

Providing free rotation was very essential for the specimen. For such case roller support has fabricated using sheet metal figure 3-13 shows the clear image of the support and for the safety of the support, the voids filled by concrete.

Figure 3-14 specimen free rotation provider roller support

3.2.4 Instrumentation

The instrumentation was mainly designed to capture torsion to the angle of twist behavior of the beam.

Comprehensively the apparatus used for the test set up consist of:

- ✓ Hydraulic jack: which used to apply a load;
- ✓ load cell: measures the applied load from the hydraulic jack;
- ✓ Transducer: reads the specimen's displacement which placed far away from the center of the beam to create a large angel of twist. This reading includes both translation and rotation;
- ✓ Dial gauge: help us to capture specimen centroidal translation and the reading is with post test video investigation;
- ✓ I-section steel: provide a pure torsional moment;
- ✓ Data logger: receive different datas, load from a load cell, displacement from the transducer, and strain from the attached strain gauge. After that it record and store in every second of the test;

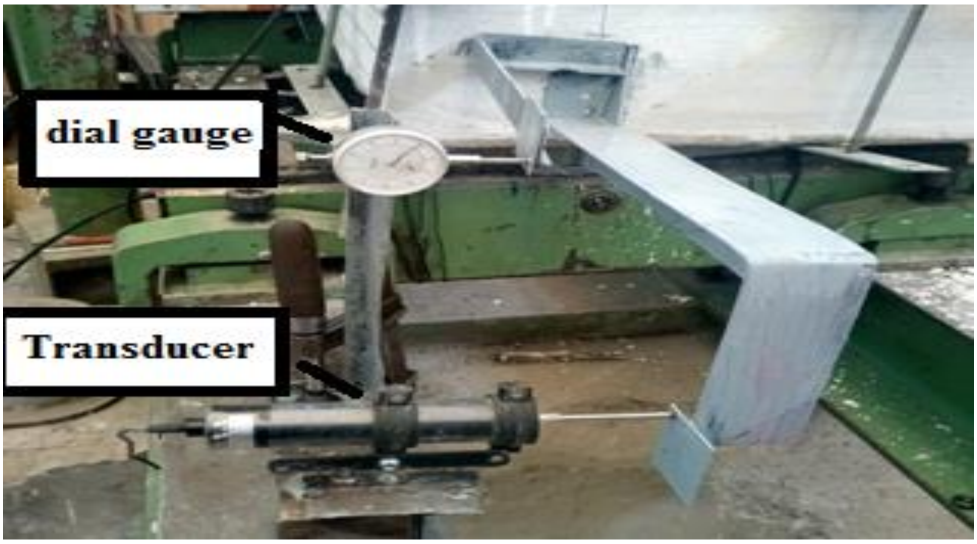


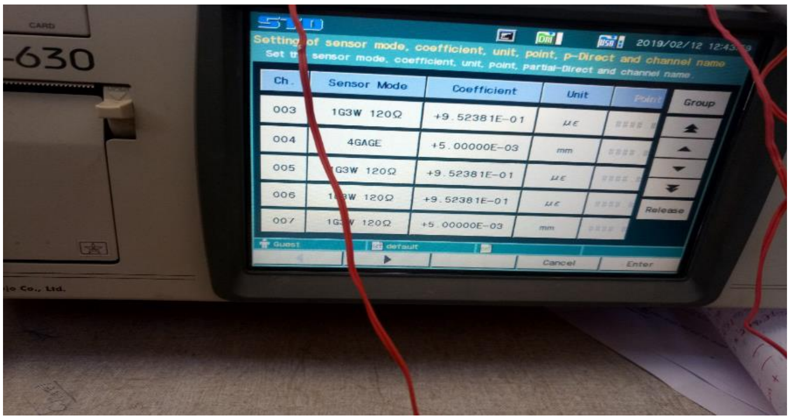
Figure 3-15 Angle of twist measurement using transducer and dial gauge

Displacement measurement transducers were systematically used to capture the angle of twist. The angle of twist due to the pure torsional moment was measured at both ends of the test specimen shown in figure 3-15. The angle of twist is computed with tan function.

$$Angle\ of\ twist\ \theta = tan^{-1}(\frac{the\ transducer\ distance\ position}{deflection\ reading})$$

a)

b)



c)

Figure 3-16 a) Hydraulic jack b) load cell c) data logger

As shown in figure 3-17, a concentrated load was applied to the mid-point of the I-section steel using a hydraulic jack and continues monitoring of the applied load through the use of load cell. The load cell the displacement transducers and the strain gauge were connected to the data logger and then all the data accessed through USB flash disk in excel format.

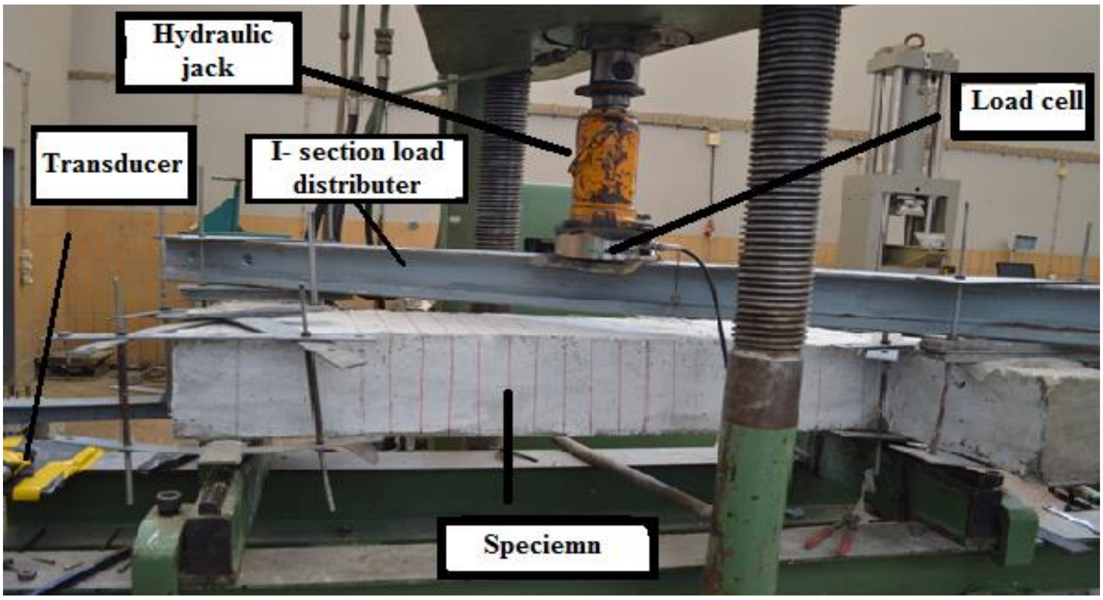


Figure 3-17 Test set up

Chapter 4 Result and Discussion

4.1 Result of the Experiment conducted

4.1.1 Set 1 (C-40, longitudinal reinforcement dia 12, stirrups dia 8 C/C 80mm)

This sets of experiments were essentially needed to see the effect of concrete cover variation on its torsional resistance. All the properties: concrete grade, specimen size, and area of reinforcement used to be similar but a different concrete cover.

4.1.1.1 NSC_S1_C30 (Specimen 1-1)

The experimental investigated result is shown in figure 4-1 below. For the test conducted the first specimen of set 1 NSC_S1_C30, In this experiment a linear relationship between torsion to angle of twist have been noticed until the torsional moments reach approximately 9KN.m, which is practically the cracking torsional load but when the experiment is taken the first crack was observed at 56kN Figure 4-2 which indicats 11.2kN.m torsional moment, that can state us there were micro cracks in the member at the cracking moment of 9kN.m, afterward the member become soften and the angle of twist increment was high as compared to linear relation.

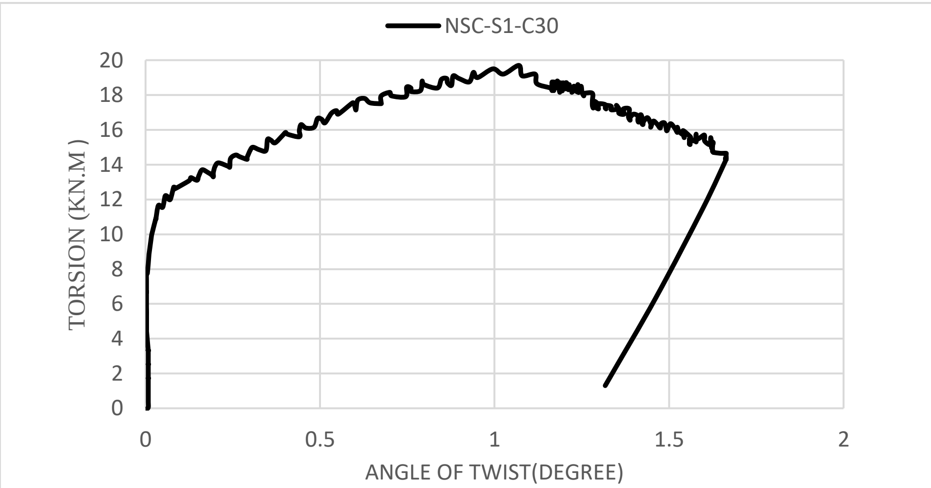


Figure 4-1 Torsion-Angle of Twist for NSC_S1_C30

During the experiment taken, the researcher has pictured the ultimate pure torsional carrying capacity of the specimen was not controlled by the concrete spalling, and at the point where the concrete spalling starts, the member were in its post-peak behavior. Small covers did not experience spalling until after the torsional strength had been reached. In this case, the contribution of transverse reinforcement was high.

After that, the member ranges its ultimate torsional moment capacity which was 19.38kN.m or from Data logger 96.9 kN. Later, the post-peak torque decrease till the test stops at (1.6635°, 14.456kN.m) and once more after the specimen unloaded, again from Figure 4-1 the observation remarked that the member was in a permanent damage stage of 1.2° angle of twist.

Figure 4-2 NSC_S1_C30 initial to post-peak cracks

In deep observation of the specimes behaviour, both end angle of twist characters were similar until its peak strength (see Figure 4-3); later, the transducer reads the higher angle of twist increment in the right side of the specimens located in transducer 1.

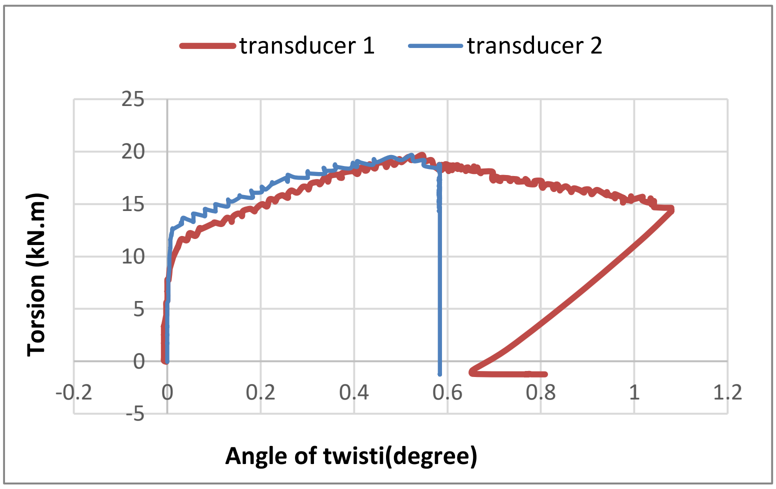


Figure 4-3 NSC_S1_C30 both ends torsion to the angle of twist

When one side of the beam has a higher angle of twist, the member tends to indicate localized damage after the peak strength on that area (see Figure 4-4); such effect is also captured from the visual inspection of the final state of the beam.

Figure 4-4 post peak cracks of Set-1 specimen 1

In this set of Experiments, the ultimate pure torsional resistance of the beam as per Euro code and ACI 318-14 was minimum of 10kN.m. but the test shows us the failure pure torsional moment were 19.38kN.m which approximately increased by 100% from the actual capacity.

This is because from visual inspection during the test was conducted the peak capacity of the beam were not controlled by the spalling of concrete cover, so this shows, the smaller the concrete cover is the higher ultimate resistance.

4.1.1.2 NSC_S1_C45 – (Specimen 1-2)

The RC beam test conducted secondly have the material properties of as used in NSC_S1_C30. But the only difference is their concrete cover, to be 45mm.

In this set of experiment similar general behavior have been a notice from that of NSC_S1_C30. But there is a slight difference in its pre-peak character. Figure 4-5 shows the pre-peak behavior is too stiff, cracking and ultimate torsional capacity almost is almost identical. The reason behind is identified during taking experimentation.

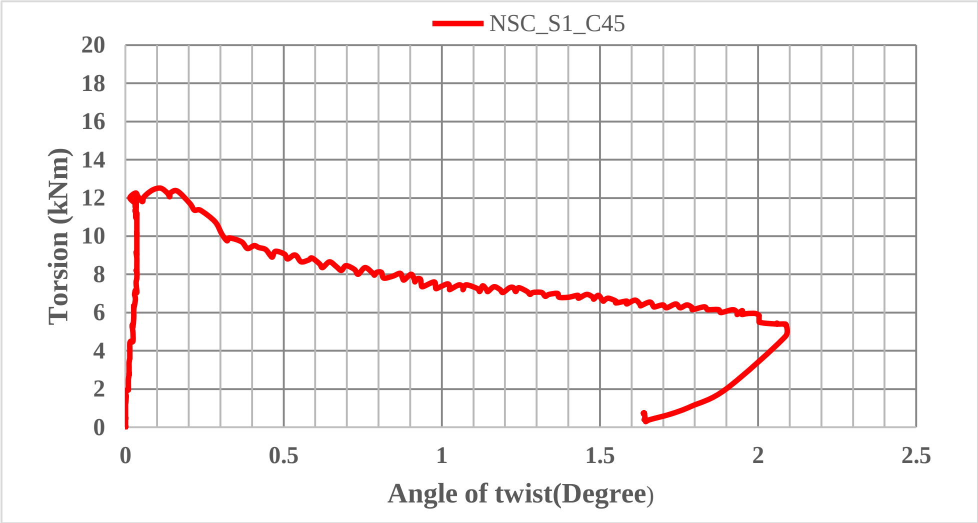


Figure 4-5 Torsion-Angle of Twist for NSC_S1_C45

As the Figure 4-6 clearly shows the first visible crack was captured at the load of 52KN from load cell reading which approximately 10.4kN.m torsional moment loss of stiffness in the member. NSC_S1_45 have relatively large concrete cover, Visual inspection and Figure 4-6 states the concrete cover starts to spall before the torsional strength had been reached. So the ultimate torsional resistance of the NSC_S1_C45 was controlled by concrete cover spalling. The contribution of transverse reinforcement were significant.

Figure 4-6 Visualized first cracks of NSC-S1-C45

This test has the ultimate torsional resistance of 12.3kN.m and post-peak character shows the steady loss of torsional carrying capacity until the test stops at a point (2.09°, 4.52kN.m). After unloading, the member returns some angles and it was in permanent damage state of 1.66°.

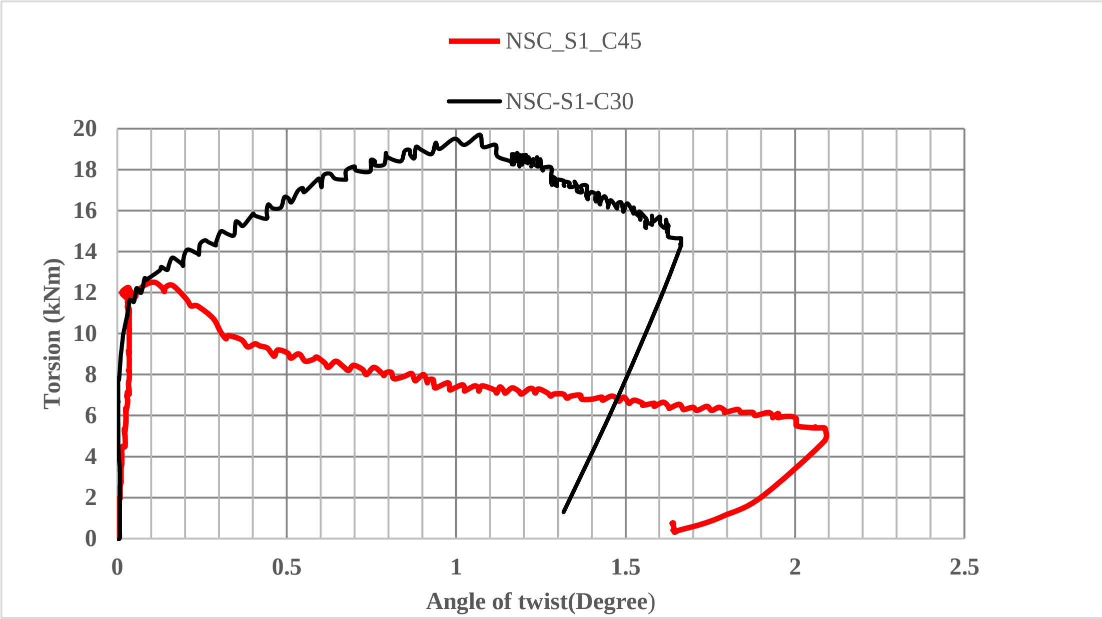


Figure 4-7 Torsion-Angle of Twist for NSC_S1_C30 and NSC_S1_C45

In the first two tests all the material, sectional and loading properties were the same, only differ in concrete cover. As the result shown figure 4-7, in NSC_S1_C30 small concrete cover the peak torsional resistance was not controlled by the spalling of concrete and the reinforcement contribution after a concrete crack was high, also slightly ductile post-crack behavior captured. But in the case of NSC S1-C45 relatively larger concrete cover 45mm used for specimen 2, the observation was absolutely reverse from that of NSC_S1_C30. Its peak resistance was governed by spalling of concrete with significant contribution of reinforcement after the concrete cracks which shows post-crack relativly brittle behavior.

Both specimens NSC_S1_C30 and NSC_S2_C45 have ultimate resistance of 19.38kN.m and 12.61kN.m respectively. In two cases, the codes state ultimate resistance were 10kN.m, so NSC S1-C45 increase by only 26.1% there was 73.9% loss of actual ultimate resistance capacity from NSC S1-C30.

Such a large difference in actual resistance within 15mm concrete cover difference is insignificant due to this further investigation on the specimen is done. Because of this as figure 4-8 shown the exact concrete cover used was 55mm.

a)

b)

Figure 4-8 Center to center core concrete dimension a) top view 190mm b) Side view 90mm

5.1.1.3 NSC_S1_C60 – (Specimen 1-3)

NSC_S1_C60 also has the same sectional, material and loading properties with different concrete cove to be 60mm. The behavior captured in the previous tests were also accounted for in Figure 4-9.

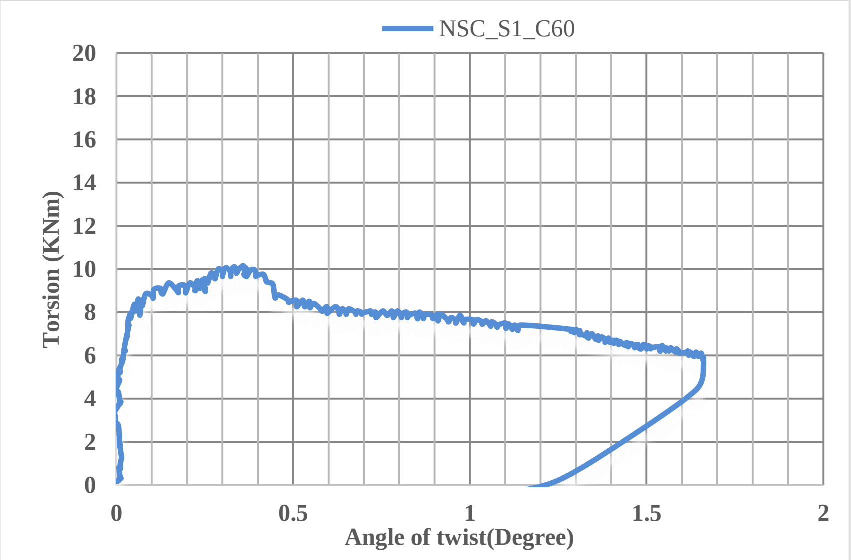


Figure 4-9 Torsion-Angle of Twist for NSC_S1_C60

Here, the elastic behavior of the specimen goes until the member starts to cracks in the early stage of testing, at the cracking torsional moment of 5.202kN.m the member shows its plastic behavior and the ultimate sectional capacity were almost the same as the Euro code and ACI 318-14 state 10kN.m. with the experimental result 10.154kN.m.

In this test, the steel strain gauge in the transverse reinforcement as shown in figure 4-10 were attached.

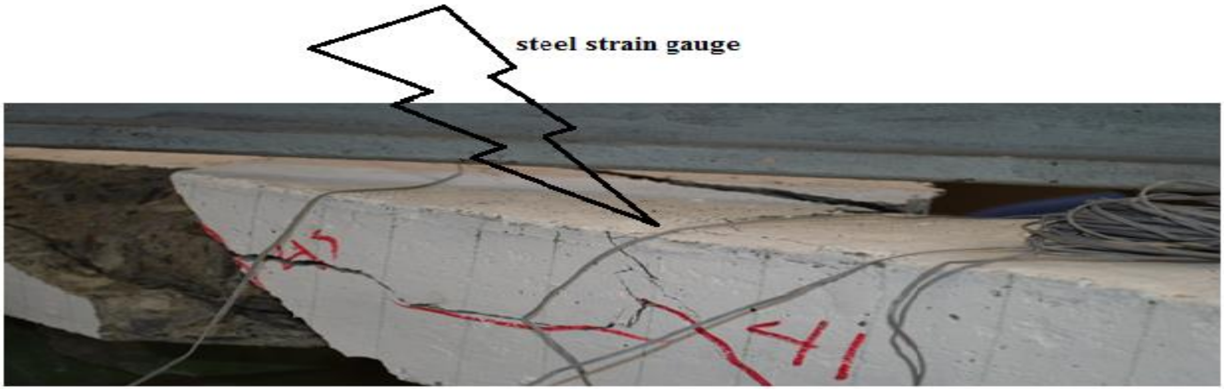


Figure 4-10 Attached steel strain gauge

The result of NSC_S1_C60 member's transverse reinforcement strain in the figure 4-11 clearly shows the effect of the concrete cover spalling on the ultimate strength and throughout the behavior of the member. Such that, approximately the strain point 1086 με directly to the point where the concrete spalling occurs 10.154kN.m torsional moments suddenly change the behavior of transverse reinforcement and its strain was below yield level strain.

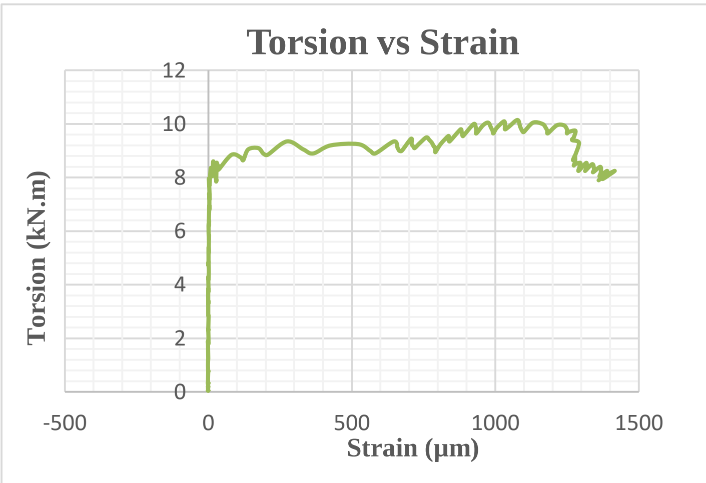


Figure 4-11 Transverse reinforcement strain for NSC_S1_C60

5.1.1.3 General comparison for set 1 of the three tests

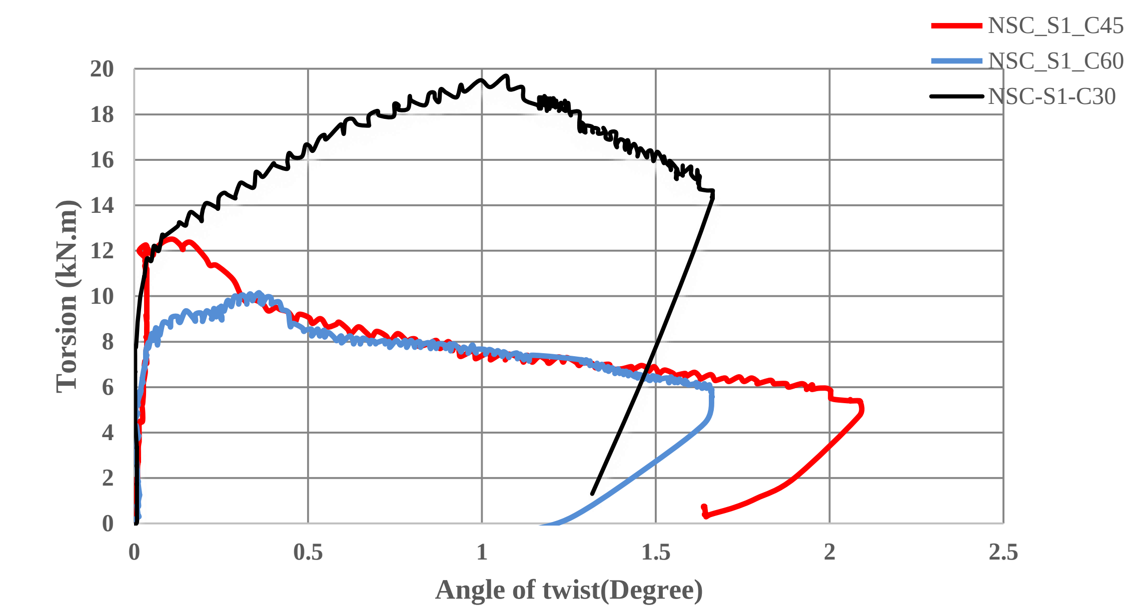


Figure 4-12 Torsion-Angle of Twist for - NSC_S1_C30, NSC_S1_C45, and NSC_S1_C60

In the last two specimens, the ultimate sectional capacity was controlled by the spalling of concrete and in the first specimen spalling occurs after reaching peak resistance.

Their pre-peak, peak and post-peak behaviors were almost similar. The pre-peak behavior states both elastic until the members' starts to crack and plastic range to the specimen reaches its peak strength.

As the figure 4-12 and experimental visualization indicate their post-crack behavior relies on the concrete cover. The smaller the concrete C30mm the ductile failure whereas larger concrete cover shows relativly brittle behavior.

As per Euro Code and ACI318-14 in the figure 4-12 cases, the ultimate capacity was 10KN.m torsional moments but the investigated result shows the smaller concrete cover (**NSC_S1_C30)** has the highest ultimate capacity 19.78kN.m nearly increased by 100% stated by the codes. But for the test specimen **NSC_S1_C45,** the peak resistance increased by 26% and that of the larger concrete cover **NSC_S1_C60** has exactly as the two codes recommended.

4.1.2 (C-40, longitudinal reinforcement dia12, stirrups dia10 C/C 130mm)

This sets of experiments were essentially needed to see the effect of transverse reinforcement diameter variation with equivalent area from that of a set of experiment 1

NSC_S2_C30 (Specimen 2-1)

NSC_S2_C30 is a set of experiment category 2 which have the similar sectional, material and loading property with that of set 1 NSC_S1_C30, which differ in the diameter of transverse reinforcement to be 10mm with the spacing of 130mm.

During taking the experimentation we have faced a critical problem that the RHS section used were fail before noticing further member behaviors as shown in Figure 4-13

Figure 4-13 Failed RHS section during taking test NSC_S2_C30

4.1.2.2 NSC_S2_C45 (Specimen 2-2)

The general behavior captured in experimental set1 also have been seen in this set experiment NSC_S2_C45. Figure 4-14 clarifies linear behavior to the point where the specimen starts to crack and gradually the member loss its stiffness until it reaches its ultimate strength of 14.65kN.m torsional moments. And its post-peak character shows the ductile behavior of the specimens.

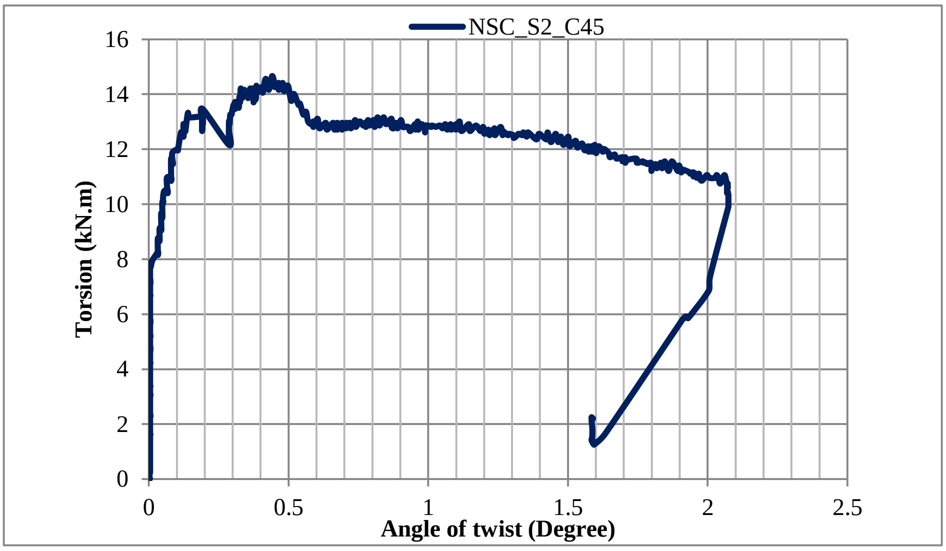


Figure 5-14 Torsion-Angle of Twist NSC_S2_C45

Form results captured in NSC_S2_C45 and NSC_S1_45 even if their general behavior similar, but the study clearly justifies how the influence of transverse reinforcement spacing increment with equivalent area increases the cracking and ultimate pure torsional resistance.

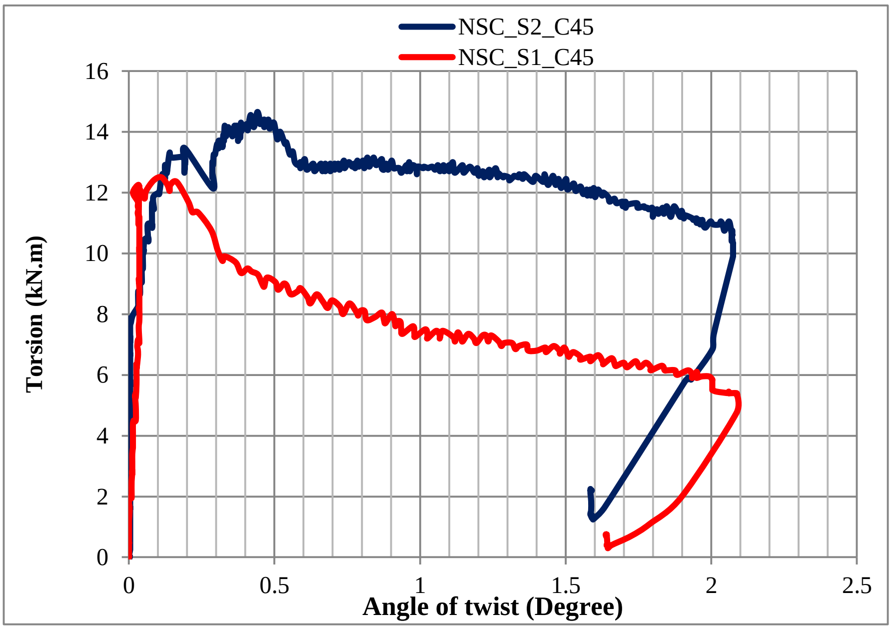


Figure 4-14 **Torsion-Angle of Twist NSC_S1_C45 and NSC_S2_C45**

As stated earlier that when the concrete cover spalling occurs the member reaches its ultimate pure torsional capacity for large concrete cover, the main question is what factors let the concrete cover spalls? Further investigations allow as to predict the condense transverse reinforcement spacing let the member spall early, due to this NSC_S2_C45's ultimate pure torsional resistance increase by 15% (12.404kN.m to 14.656kN.m) to that of NSC_S2_C45.

5.1.2.3 NSC_S2_C60 (Specimen 2-3)

The test specimen NSC_S2_C60 is provided with the same fixture transverse reinforcement spacing of 130mm with a diameter of 10mm. Figure 4-15 shows a very stiff member in its elastic behavior and the contribution of reinforcement were significant, in the early stage, it reaches its ultimate strength.

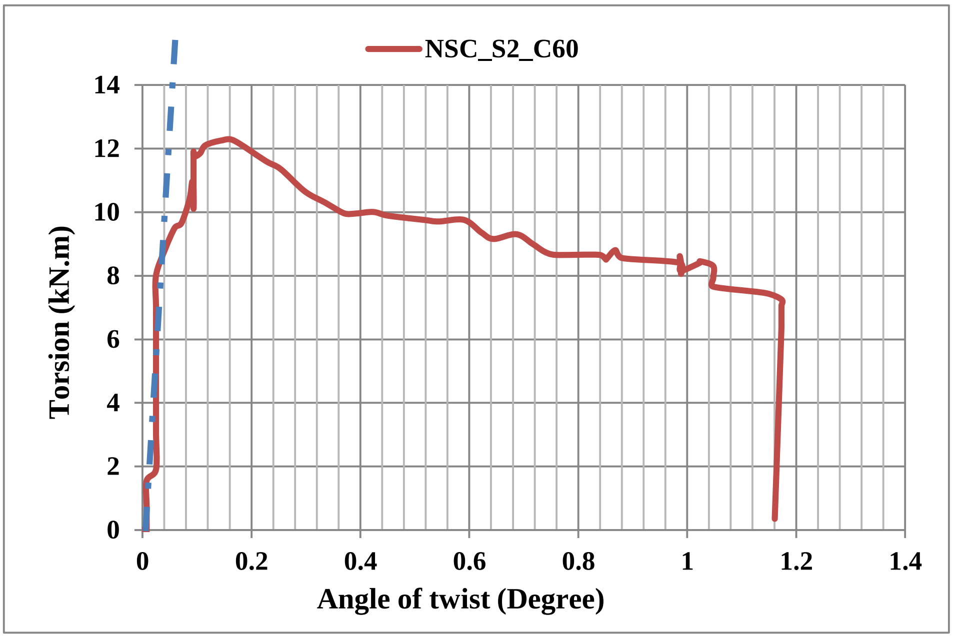


Figure 4-15 Torsion-Angle of Twist NSC_S2_C60

In this case figure 4-16 clearly shows as the number of discontinuity reduce it increase the pure torsional capacity of the specimen. The ultimate pure torsional resistance for the test specimen NSC_S2_C60 increased by 19.2% from that of NSC_S1_C60 (10.15kN.m to 12.254kN.m).

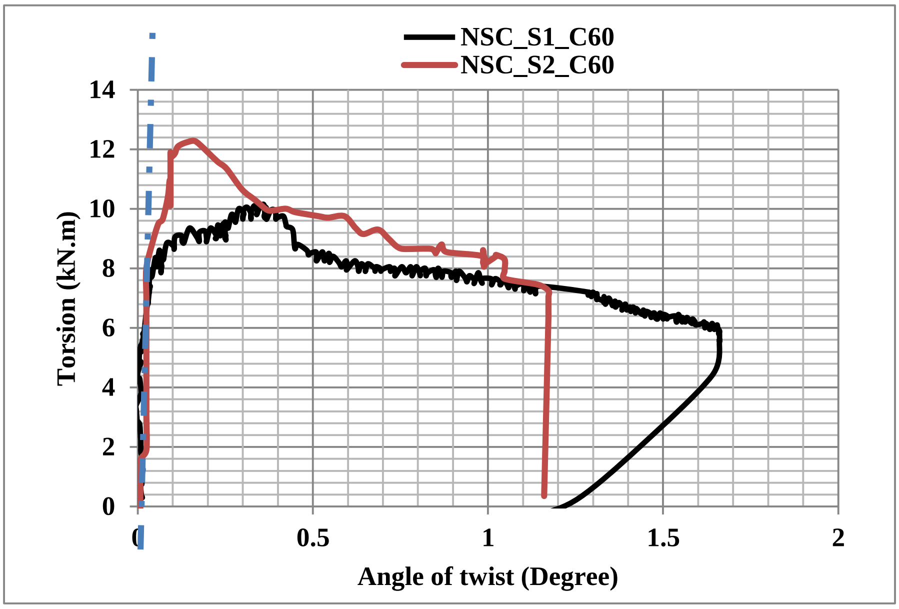


Figure 4-16 Torsion-Angle of Twist NSC_S1_C60 and NSC_S2_C60

Finally the effect of concrete cover on torsional resistance was also seen in this set of the experiment as shown in figure 4-17.

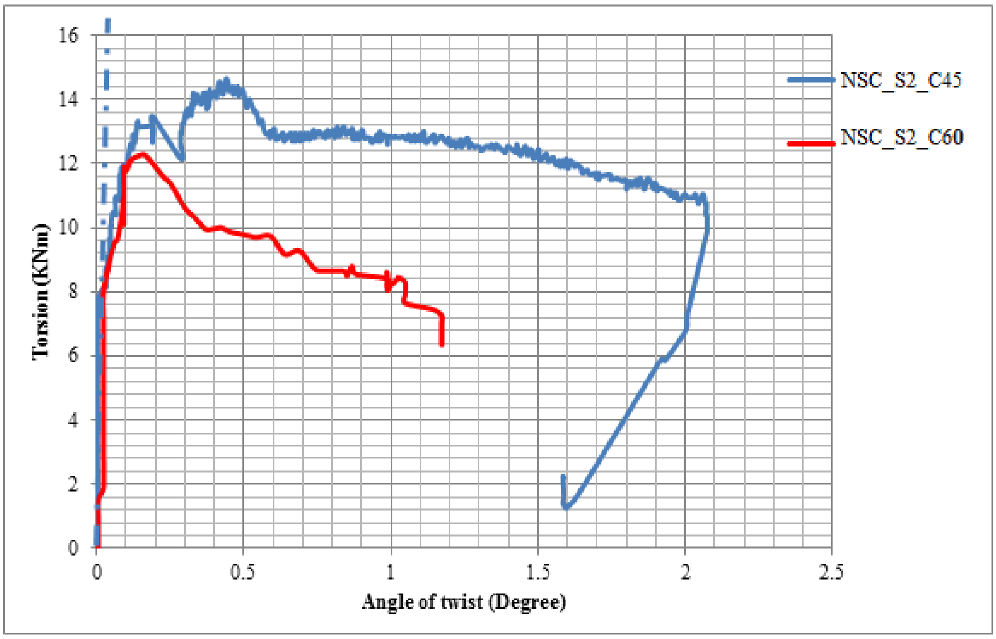


Figure 4-17 Effect of concrete cover in experimental set 2

5.1.3 Set 3 (C-60, longitudinal reinforcement dia12, stirrups dia8 C/C 80mm)

The desire for experimental set 3 is to state the concept of pure torsional resistance design theories. In the late 90s most of the design codes follow skew bending theory for the design of pure torsional resistance but after a research made by Macgregor on torsional resistance which introduces truss analogy concept in early 90s different codes Euro code, ACI 318-14 and CSA adopted its concept which ignores the role of concrete grade in its ultimate torsional resistance.

This sets of experiments try to show what major role can the concrete grade plays in pure torsional resistance. Three specimens were cast with the same material, sectional and loading properties in set 1, with only differ in the concrete grade to be C-60.

5.1.3.1 HSC_S3_C30 (Specimen 3-1)

The test set up 3 specimens 1 as shown in fig 5-15 the member has cracking torsional strength of 13.56kN.m of elastic behavior and the more reinforcement involvement clearly notice until it reaches its ultimate pure torsional strength of 19.558kN.m. And it has undoubtedly ductile post-crack behavior.

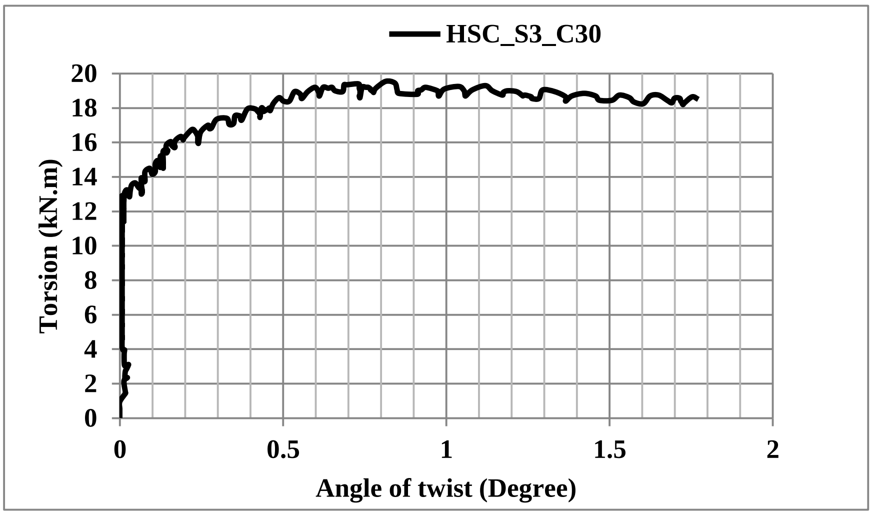


Figure 4-18 Torsion-Angle of Twist HSC_S3_C30

As mentioned earlier truss analogy concept on torsional resistance does not rely on concrete grade. clearly, from figure 4-19 test specimen NSC_S1_C30 and HSC_S3_C30 prove such phenomena, the influence of concrete grade contribution was can capture in its cracking torsional strength due to the increasing of tensile strength of concrete.

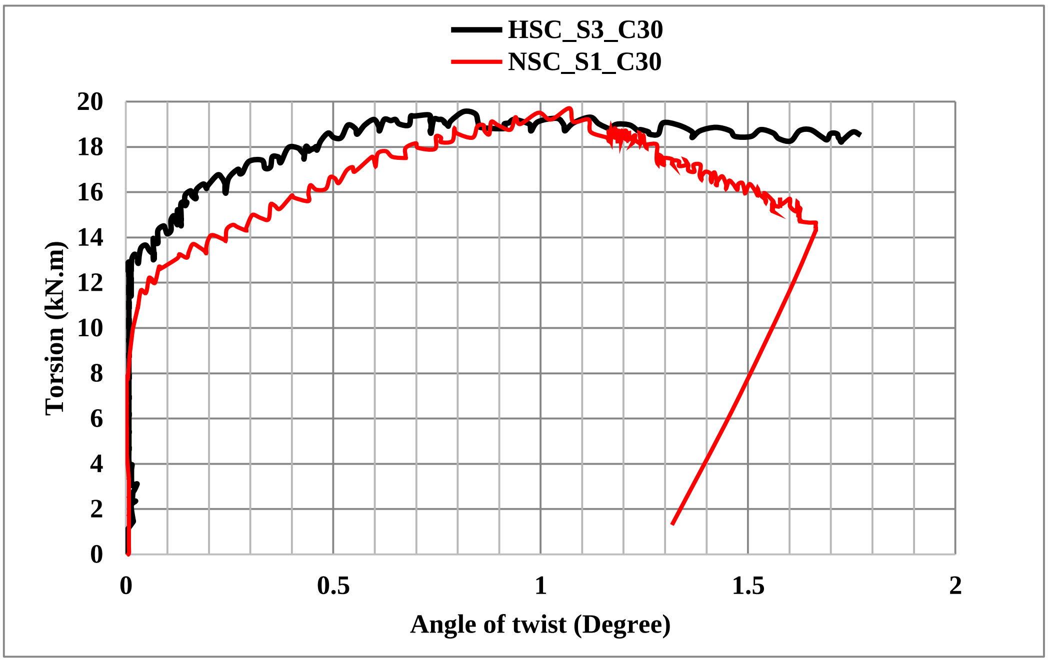


Figure 4-19 Torsion-Angle of Twist HSC_S3_C30 and NSC_S1_C30

5.1.3.2 HSC_S3_C45 (Specimen 3-2)

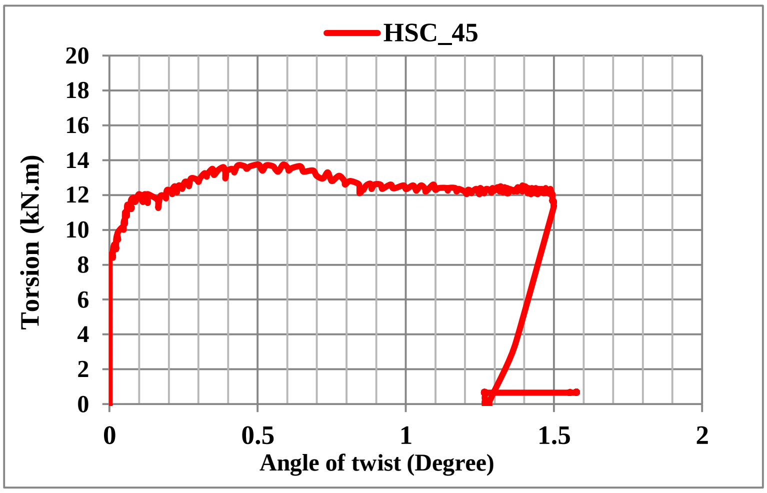


Figure 4-20 Torsion-Angle of Twist HSC_S3_C45

Similar behavior captured in this set of the experiment from that of NSC_S1_C45. Their post-peak behavior is ductile, since it has been indicated that concrete grade roll in its ultimate resistance. The contribution of transverse reinforcement is significant after the concrete cracks.

5.1.3.3 HSC_S3_C60 (Specimen 3-3)

This set of experiment is also the same in geometry, concrete cover, reinforcement type with differ in concrete strength from NSC_S1_C60. Figure 4-21 shows the general behavior of the specimen under pure torsion.

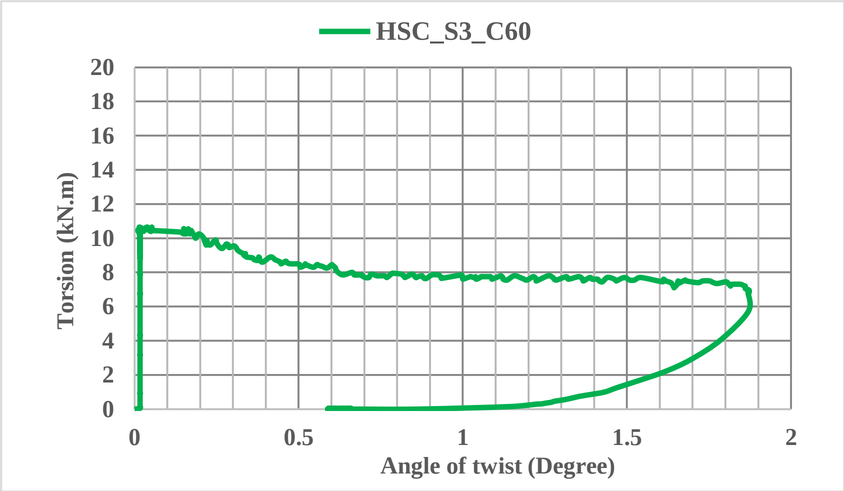


Figure 4-21 Torsion-Angle of Twist HSC_S3_C60

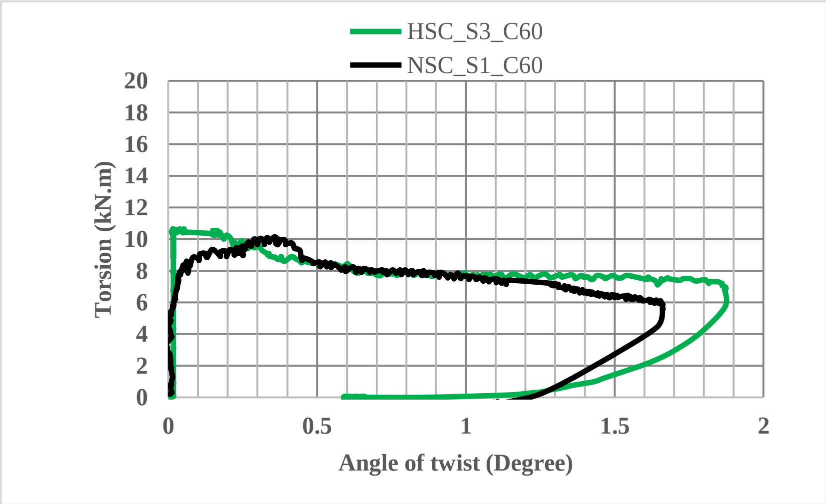


Figure 4-22 behavior of NSC_S1_C60 and NSC_S3_C60

Figure 4-22 for the two specimens their ultimate pure torsional resistance is almost similar and HSC_S3_C60 the concrete role clearly enhance torsional cracking resistance of the specimen. Both specimens shows identical ductile post peak behavior.

Here also finally, for the Experimental set 3 specimens' the concrete cover effect clearly visualize in figure 4-23 below.

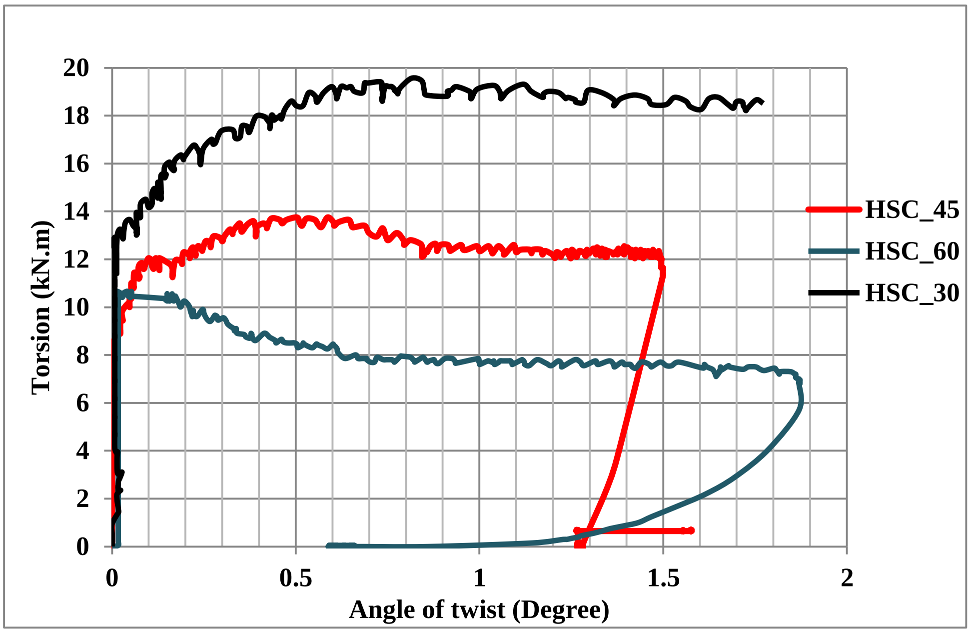


Figure 4-23 Expermental set 3 specimens behaviour

Chapter 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This research presented experimental investigation on the effect of concrete cover in pure torsional resistance of reinforced beam. In the study, nine specimens were used with three different categories for the experimental program. Besides, the study includes the state of art in well-known building codes approach in concrete cover for pure torsional resistance. After examining this analysis, the following points are put forward.

- Relatively small cover (30mm) beams did not spall until the peak load was achieved.
- Beams with relatively large covers (45mm-60mm) the peak load of the specimens were controlled by the concrete cover spalling.
- Transverse reinforcement contribution in the post crack to peak behavior of the specimen in pure torsional resistance is high, for beams with small concrete cover (30mm).
- For relatively large concrete cover (45mm-60mm) impact of transverse reinforcement in post crack behavior of the specimen was minor.
- Wider spacing of transverse reinforcement, increase its torsional capacity of the specimen with equivalent area from that of condense transverse reinforcement.
- High strength concrete has no influence in its ultimate pure torsional capacity of the specimen but it increases the cracking pure torsional capacity of the beam.
- Normal strength concrete beams with relatively small cover shows a seemingly ductile post-peak behavior.
- Concrete cover spalling radically change the behavior of transverse reinforcement the strain level.

5.2 Recommendation

- Several experiments needed to be taken to study the effect of concrete cover since it is unaddressable section.
- Since torsion behavior of beams is affected by different factors, this study should be further expanded to see the effect of web reinforcement at different stages from non web reinforcement to the limit stated by the design codes.
- The effect of aggregate shall be considered in prediction of pure torsional capacity of beams.
- Different stage of concrete grade strength for pure torsional resistance has to be conducted;
- Several experiments needed to be taken with different aspect ratio of cross section regaring different concrete cover thickness.

REFERENCES

Khaldoun. N. Rahal and MichaeL P.Collins (1995) "The effect of cover thickness on the shear and torsion interaction — An experimental investigation." ACI Structural Journal, 92(3): 334–342.

Rahal, K.N., and Collins, M.P. Khaldoun. N. Rahal (1999)"Torsional strength of reinforced concrete beams".] Can. J. Civ. Eng. Vol. 27, 2000

Keddar KIrane, Koniengbam Darunkumar Singh, and Zdenek P. Bazant. (1988) "Size effect in torsional strength of plain and Reinforced concrete". ACI structural Journal tittle no 113-s107

Thomas T.C.HSc (2009) "Softend truss model theory for shear and torsion." ACI structural Journal tittle no 85-s56

ACI. Building code requirements for reinforced concrete (ACI 318-14) and commentary (ACI318 R-14). Committee 318, American Concrete Institute (ACI),

EBCS EN 1992_1_1:2014. Ethiopian Building code standard-Based on europian norme, "Design of concrete Structures"

Thesis by mohammed siraj (2018). " strengthening torsion critical reinforced concrete beam by externaly bonded fiber reinforced polymer.: Analytical to Expermental investigation

Report on torsion in structural concrete. Reported by joint ACI-ASCE Comittee 445.

Raid I.Khalel (1999) " Torsional behavior of Normal strength Reinforced concrete beam." Journal of engineering and development VOL.19,NO.05,

Rahal, K.N., And Collins, M.P.(1996) " Simple Model For Predicting Torsional Strength Of Reinforced And Prestressed Concrete Sections". Aci Structural Journal, 93(6): 658–666, 1996.

Construction Lboratory manual by Abebe Dinku.(2002)

Lampert, Paul,(1973) "Post-cracking Stiffness of Reinforced Concrete Beams in Torsion and Bending". ACI Special Publication SP- 35, pages 385-433, American Concrete Institute, Farmington Hills, Mich.,

Lampert, P., and Thurlimann, B., Torsionsversuch an Stahlbetonbalken (1968) "Torsion Tests of Reinforced Concrete Beams", Bericht Nr. 6506-2, 101 pages, Institute of Baustatik, ETH, Zurich, Switzerland (in German).

MacGregor, J. G., and Ghoneim, M. G., (1995)"Design for Torsion," ACI Structural Journal, V. 92, No. 2, pages 211-218, Mar.- Apr. 1995.

Kamara, M.E., and Rabbat, B.G., editors, Notes on ACI 318- 05 Building Code Requirements for Structural Concrete with Design Applications, Portland Cement Association, Skokie, Ill., EB705, 2005

Hsu, T.T.C. (1968). "Torsion of structural concrete-behavior of reinforced concrete rectangular members". orsion of structural concrete, SP-18, American Concrete Institute, Detroit, Mich. pp. 261–306.

Fanella, D. A. and Rabbat, B.G., (1997) "Design of Concrete Beams for Torsion", Engineering Bulletin EB106.02D, Portland Cement Association, Skokie, Ill., 1997.

Collins, M.P., and Mitchell, D. (1991). " Prestressed concrete structures". Prentice Hall, Inc., Englewood Cliffs, N.J..

Lessig, N. N., (1959), "Determination of Load-Carrying Capacity of Rectangular Reinforced Concrete Elements Subjected to Flexure and Torsion," Trudy No. 5, Institut Betona i Zhelezobetona (Concrete and Reinforced Concrete Institute), Moscow, pp. 5-28 (in Russian). Translated by Portland Cement Association, Foreign Literature Study No. 371 (Available from S. L. A. Translation Center, John Crerar Library Translation Center, Chicago, IL).

ANNEX-A

Design of the test specimens as per design codes

The beam is design to carry a design load of 10kN.m torsional moment.

Sectional properties: b=300mm, D=200mm, Cover= 30mm, 45mm, 60mm

Material proterties: Steel : S-460 , $f_{yd} = \frac{460}{1.15} = 400$

Concrete: C40 and C60

Solution:

<u>For cover 30mm</u>

A=b*D=300*200=6000mm^2

U=2(b+D)=2(300+200)=1000mm

$$t_{eff} = \begin{cases} 2C & = 2*30 = 60 \\ A/_U & = 60000/_{1000} \end{cases} = 60mm$$

$U_k = 2((b - t_{eff}) + (D - t_{eff}))$, $A_K = (b - t_{eff}) * (D - t_{eff})$

=2((300-60)+(200-60))=760mm = (300-60) * (200-60)=33,660mm^2

$\frac{\Sigma A_s f_{yd}}{U_k} = \frac{T_{Ed}}{2A_k} \cot\theta$, $\sum A_s = \frac{U_k T_{Ed}}{2_{fyd} A_k} Cot\theta$

$\frac{\sum A_s = (760mm*1000N.mm)}{2*400*33,600mm2} * \cot(45°)$ =282.74mm^2

Shear stress due to pure torsion

$\tau_{t,i} t_{ef,i} = \frac{T_{Ed}}{2A_k}$, $\tau_{t,i} = \frac{T_{Ed}}{t_{ef,i} 2A_K} = \frac{10,000N.mm}{2*60mm*33,600mm2}$ =2.48kN/m^2

$V_{Ed} = \tau_{t,i} t_{ef,i} z_i = 2.48 * 60 * (300 - 60) = 35,714.28N$

Provide strriups use Ø8 rebar

$$\boldsymbol{s = \frac{a_{sv} * f_{yd} * d}{V_{Ed}}, = \frac{50.24*400*270}{35{,}714.28} = 151.98mm}$$

<u>For cover 45mm</u>

A=b*D=300*200=6000mm^2

U=2(b+D)=2(300+200)=1000mm

$$t_{eff} = max \begin{cases} 2C & 2*45 = 90 \\ A/_U = & 60000/_{1000} \end{cases} = 90mm$$

$$U_k = 2((b - t_{eff}) + (D - t_{eff})), \qquad A_K = (b - t_{eff}) * (D - t_{eff})$$

=2((300-90)+(200-90))=640mm = (300-90) * (200-90)=23,100mm^2

$$\frac{\Sigma A_s f_{yd}}{U_k} = \frac{T_{Ed}}{2A_k} \cot\theta, \quad \sum A_s = \frac{U_k T_{Ed}}{2_{fyd} A_k} Cot\theta$$

$$\frac{\sum A_s = (640mm*1000N.mm)}{2*400*23{,}100mm2} * \cot(45°) = 346.32mm^2$$

Shear stress due to pure torsion

$$\tau_{t,i} t_{ef,i} = \frac{T_{Ed}}{2A_k}, \qquad \tau_{t,i} = \frac{T_{Ed}}{t_{ef,i} 2A_K} = \frac{10{,}000N.mm}{2*90mm*23{,}100mm2} = 2.405kN/m^2$$

$$V_{Ed} = \tau_{t,i} t_{ef,i} z_i = 2.405 * 90 * (300 - 90) = 45{,}454.54N$$

Provide strriups use Ø8 rebar

$$\boldsymbol{s = \frac{a_{sv} * f_{yd} * d}{V_{Ed}}, = \frac{50.24*400*270}{45{,}454.54} = 112.73mm}$$

For cover 60mm

A=b*D=300*200=6000mm^2

U=2(b+D)=2(300+200)=1000mm

$$t_{eff} = max\begin{cases} 2C & 2*60=120 \\ A/_U = & 60000/_{1000} \end{cases} = 120mm$$

$$U_k = 2((b - t_{eff}) + (D - t_{eff})), \qquad A_K = (b - t_{eff}) * (D - t_{eff})$$

=2((300-120)+(200-120))=5200mm = (300-120) * (200-120)=14,400mm^2

$$\frac{\Sigma A_s f_{yd}}{U_k} = \frac{T_{Ed}}{2A_k}\cot\theta\ , \ \sum A_s = \frac{U_k T_{Ed}}{2_{fyd}A_k}Cot\theta$$

$$\frac{\sum A_s = (520mm*1000N.mm)}{2*400*14{,}400mm2} * \cot(45°)$$ =451.39mm^2

Shear stress due to pure torsion

$$\tau_{t,i}t_{ef,i} = \frac{T_{Ed}}{2A_k}, \qquad \tau_{t,i} = \frac{T_{Ed}}{t_{ef,i}2A_K} = \frac{10{,}000N.mm}{2*120mm*14{,}00mm2}$$ =2.89kN/m^2

$$V_{Ed} = \tau_{t,i}t_{ef,i}z_i = 2.89 * 120 * (300 - 120) = 62{,}500N$$

Provide strriups use Ø8 rebar

$$\boldsymbol{s = \frac{a_{sv}*f_{yd}*d}{V_{Ed}}, = \frac{50.24*400*270}{62{,}500} = 87.16mm}$$

For all the specimen logtiudinal reinforcement to be 4Ø12

Transverse reinforcement Ø8 c/c 80mm used for experiment set 1 and experiment set 3

Transverse reinforcement Ø10 c/c 130mm used for experiment set 2

ANNEX-B

Mix-design procedure of concrete

A complete proportioning of constitutes of concrete for the intended compressive strength of concrete were held before the commencement of experimental work. It constitutes;

1. Determining properties of the constitute components of concrete (i.e. cement, course aggregate, fine aggregate and water.
2. Proportioning of constitutes by mass.

Properly proportioned concrete is expressed in the following qualities;

a. Acceptable workability of the freshly mixed concrete
b. Durability, strength and uniform appearance of the hardened concrete and
c. Economy

Trail Mix- Design Using ACI Methods for Conventional Concrete (C40 with a Maximum size of aggregate=25mm).

Materials properties:-

Concrete with compressive strength of 40 MPa (C-40) is required to be produced.

- From materials quality test we have the following result based on construction material laboratory manual test by Abebe Dinku.

a. Cement type 1; specific gravity=3.15
b. Course aggregates';
   - Bulk specific gravity=2.822
   - Absorption capacity=1.41%
   - Moisture content= 1.62%
   - Compacted unit weight=1716.54KN/m^3
c. Fine aggregate
   - Bulk specific gravity=2.514
   - Absorption capacity=0.956%
   - Moisture content=2.35%
   - Fines modules=2.9

- Based on this the mix design procedures are as follows.

1. Choice of the slump

Table 1 Recommended slumps for various types of construction (ACI-2111_91)

Types of construction	Maximum slump(mm)	Minimum slump(mm)
Reinforced foundation walls and footings	75	25
Plain footings, caissons, and substructure walls	75	25
Beams and reinforced walls	100	25
Building columns	100	25
Pavements and slabs	75	25
Mass concrete	75	25

From table 1, take that a type of construction is beams and reinforced wall.

This implies, maximum slump= 100mm and minimum slump= 25mm.

2. Maximum size of aggregate
   - ✓ Fine aggregate=4.75mm
   - ✓ Course aggregate=25mm
3. Estimation of mixing water and air content
   Assume non air entrained concrete

Table 2 Approximate Mixing Water and Air Content Requirements for Different Slumps and Nominal Sizes of Aggregates (ACI-2111_91)

NON-AIR-ENTRAINED CONCRETE								
Slump (mm)	**9.5mm**	**12.5mm**	**19mm**	**25mm**	**37.5mm**	**50mm**	**75mm**	**150mm**
25 to 50	207	199	190	179	166	154	130	113
75 to 100	228	216	205	193	181	169	145	124
150 to 175	243	228	216	202	190	178	160	-
More than 175	-	-	-	-	-	-	-	-
Approximate amount of entrapped air in non-air-entrained concrete (%)								

Slump (mm)	9.5mm	12.5mm	19mm	25mm	37.5mm	50mm	75mm	150mm
All	3.0	2.5	2	1.5	1	0.5	0.3	0.2

From table 2 of ACI standards, for non-air entrained and slump of 75-100, the water in 1m³ of concrete is 193Kg.

4. Water to cement selection table 3

Table 3 Relationship between water-cement or water-cementations materials ratio and Compressive strength of concrete (ACI-2111_91)

Compressive strength at 28 days (MPa)	Water-cement ratio by weight (Non-air-entrained concrete)
40	0.42
35	0.47
30	0.54
25	0.61
20	0.69
15	0.79

From table 3, for C -40 and non-air entrained concrete water to cement ratio is 0.42.

5. Cement content calculation

For slump of 75-100

Water content=193Kg/m³

Water/cement=0.42

$$cementcontent = \frac{watercontent}{\frac{w}{c}}$$

$$= \frac{193}{0.42}$$

$$\mathbf{=459.52 kg/m^3}$$

6. Estimation of course aggregates content (table 4)

Table 4 Volume of oven-dry-rodded coarse aggregate per unit volume of concrete for different fineness moduli of fine aggregate.(ACI -2111_91)

Nominal maximum size of aggregate (mm)	2.4	2.6	2.8	3.0
9.5	0.50	0.48	0.46	0.44
12.5	0.59	0.57	0.55	0.53
19	0.66	0.64	0.62	0.60
25	0.71	0.69	0.67	0.65
37.5	0.75	0.73	0.71	0.69
50	0.78	0.76	0.74	0.72
75	0.82	0.80	0.78	0.76
150	0.87	0.85	0.83	0.81

From table 4 of ACI, for maximum size of aggregate= 25mm and fines modules for sand = 2.9, the volume of course aggregate per unit volume of concrete is

$$= 0.66$$

$$Required\ dry\ mass\ of C.A = 0.66 * 1716.54$$

$$\mathbf{= 1132.916 kg/m3}$$

7. Estimation of fine aggregates content

At the end of Step 6, all ingredients of the concrete have been estimated except the fine aggregate. Its quantity is determined by making difference. For this process either of the two procedures may be employed:

- the weight method
- the absolute volume method

If the weight of the concrete per unit volume is assumed or can be estimated from experience, the required weight of fine aggregate is simply the difference between the weight of fresh concrete and the total weight of the other ingredients. Therefore, In this paper the weight method preferred.

Fine aggregate content (F.A)=unit weight of concrete-(C.A+cement+water)

First estimate the unit weight of fresh concretes from table 5.

Table 5 First estimate of concrete weight (kg/m3)

Nominal maximum size of aggregate (mm)	Non-air-entrained concrete
9.5	2280
12.5	2310
19	2345
25	2380
37.5	2410
50	2445
75	2490
150	2530

From the table 5 the unit weight of fresh concrete corresponding to max. Aggregate size of 25mm and non- air entrained is **2380kg/m^3**.

Fine aggregate content (F.A)=2380-(1132.916+459.52+193)=**594.564kg/m^3**

8. moisture adjustment

Absorbed water does not become part of the mixing water and it must be removed from the mixing water, if moisture content is greater than absorption capacity. But, if absorption capacity is greater than moisture content of aggregate, we need to add water up to its moisture capacity. Therefore, in this case since the moisture content of the aggregates are greater than their absorption capacity, water should be deducted from the mixing water.

Removed water from C.A=1.62+1.41=**0.21%**

Removed water from F.A=2.35-0.956=**1.394%**

$$total\ water\ required = 193 - \left[1132.916 * \left(\frac{0.21}{100}\right) + 594.564 * \left(\frac{1.394}{100}\right)\right]$$

=182.332kg/m^3

The estimated ingredient of concrete for nominal aggregate size of 25mm in one meter cube are summarized as follows.

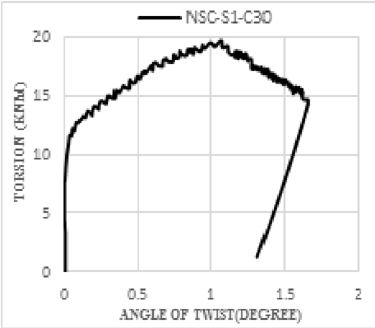
Ingredients	Weight per meter cube(kg/m^3)
Course aggregate	1132.916
Fine aggregate	594.564
Cement	459.52
Water	182.332
Concrete unit weight.	**2369.332**

ANNEX-C

5.1.3. General description of the result

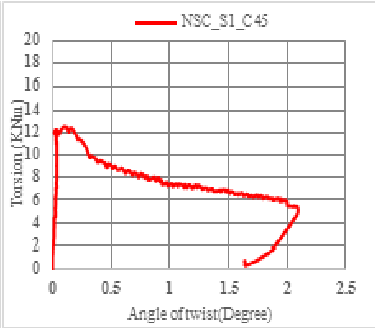
Experimental Set 1

1-1)



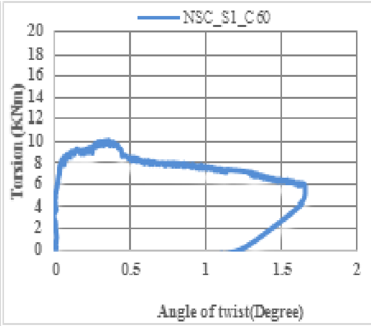
NSC_S1_C30

1-2)



NSC_S1_C45

1-3)



NSC_S1_C60

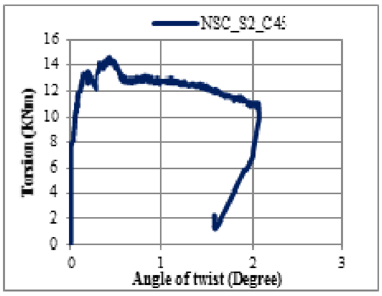
Experimental Set 2

2-1)

During taking the test, load distributer RHS sectiom fails

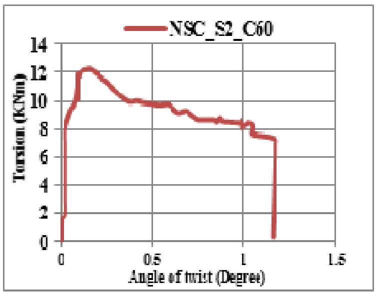
NSC_S2_C30

2-2)



NSC_S2_C45

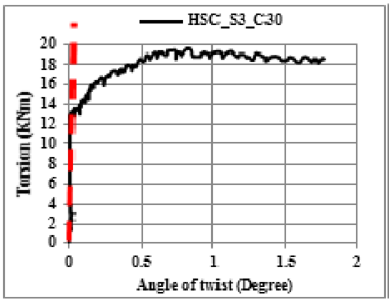
2-3)



NSC_S2_C60

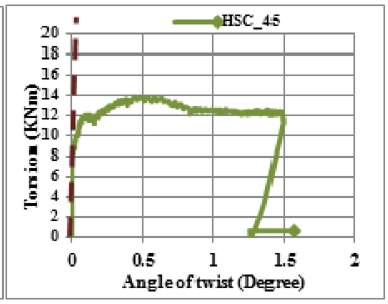
Experimental set 3

3-1)



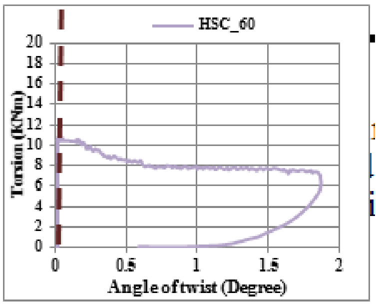
HSC_S3_C30

3-2)



HSC_S3_C45

3-3)



HSC_S3_C60

Figure 5-1 General Torsion to angle of twist