STUDIES ON TORSIONAL BEHAVIOUR OF RECYCLED AGGREGATE BASED STEEL FIBER REINFORCED SELF COMPACTING CONCRETE

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by

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CERTIFICATE

This is to certify that the thesis entitled "**STUDIES ON TORSIONAL BEHAVIOUR OF RECYCLED AGGREGATE BASED STEEL FIBER REINFORCED SELF COMPACTING CONCRETE"** being submitted by **Mr. K J N SAI NITESH** for the award of the degree of **DOCTOR OF PHILOSOPHY** to the Faculty of **Civil Engineering** of **NATIONAL INSTITUTE OF TECHNOLOGY, WARANGAL** is a record of bonafide research work carried out by him under my supervision and it has not been submitted elsewhere for award of any degree.

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This Thesis entitled "**STUDIES ON TORSIONAL BEHAVIOUR OF RECYCLED AGGREGATE BASED STEEL FIBER REINFORCED SELF COMPACTING CONCRETE**" by **Mr. K J N SAI NITESH** is approved for the degree of Doctor of Philosophy.

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DECLARATION

This is to certify that the work presented in the thesis entitled **"STUDIES ON TORSIONAL BEHAVIOUR OF RECYCLED AGGREGATE BASED STEEL FIBER REINFORCED SELF COMPACTING CONCRETE"** is a bonafide work done by me under the supervision of **Dr. S. VENKATESWARA RAO** and was not submitted elsewhere for the award of any degree. I declare that this written submission represents my ideas in my own words and where others ideas or words have been included, I have adequately cited and referenced the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea / data / fact /source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the Institute and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been taken when needed.

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Dedicated to

My Beloved Family

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ABSTRACT

Any complex force system can be defined in terms of five basic actions viz. axial compression, tension, bending moment, shear force and a torsional moment. Torsion is one of the basic structural action which is low prioritized though very essential in analyzing the structures subjected to earthquake and wind loads. Torsion failure is mainly due to inherent weakness of concrete in tensile strength. In spite of all the various kinds of failures in concrete, torsional failure is brittle and sudden which occurs abruptly without any prior warning. This failure is magnified if concrete has inherent voids due to improper compaction in members such as columns, beams and slabs due to closer spacing of reinforcement

Unoccupied voids and macro-pores inside concrete arise from inappropriate vibration and compaction might affect the mechanical strength and durability of the concrete and possible reasons of deterioration in concrete. Self-Compacting Concrete (SCC), originally established by Okamura in 1986 is a well thought-out solution to solve the above stated problems. Self-Compacting Concrete as the name itself indicates, no external effort in compacting the concrete, it compacts itself under its own weight.

Tensile properties of concrete can be significantly improved with addition of various fibers such as glass, steel, polypropylene etc. From literature review, it was found that tensile properties of concrete can be significantly enhanced with the inclusion of steel fibers. The difference between Steel Fiber Reinforced SCC (SFRSCC) and traditional Fiber Reinforced Concrete (FRC) is that the fiber content of FRC is mainly determined by the post-cracking behaviour, whereas the effect of fibers is mainly limited to fresh properties of SCC.

The nature of the construction industry is not environmentally friendly and the need for sustainable methods in construction is very crucial to ensure that natural materials are not depleted for future. The usage of cement and natural aggregate has increased drastically over the past few years in the construction industry. Due to depletion of natural resource such as lime stone and natural aggregates, there is an urgent requirement of replacing the main ingredients in concrete like cement and natural aggregates with locally available waste byproducts like mineral admixtures (flyash, GGBS, silica fume) as

substitute to cement and recycled concrete aggregates to natural coarse aggregates. The use of mineral admixtures as partial replacement to cement is a well-established fact that its helps in improving the strength and durability performance of concrete and it is used by many researchers and by construction organizations. Although, the use of recycled concrete aggregate is well recognized as a sustainable material that can replace the natural coarse aggregates and offers solutions to this problem, but it is still considered as inferior to natural aggregate in terms of its structural properties.

There are various softwares available to perform nonlinear analysis on reinforced concrete and to study the behaviour of fiber reinforced concrete (FRC). ATENA Gid is one such software developed exclusively to perform non-liner analysis on reinforced concrete. ATENA is a finite element based software used for nonlinear analysis of reinforced concrete structures**.** By using Atena software, the actual behaviour of reinforced concrete structures, such as concrete crushing, cracking and yielding of reinforcing can be analyzed.

Combining the above and from a detailed literature review, the following points were observed.

- It is evident that use of steel fibers in SCC significantly improve the load carrying capacity and also changes the failure pattern from a brittle behaviour to ductile mode.
- Effect of steel fibers on torsional behaviour of self compacting concrete needs to be investigated.
- Effect of shape and aspect ratio of steel fiber on torsional behaviour of SFRSCC can be studied.
- The performance of SCC need to be evaluated with respect to vibrated concrete under all structural actions and verify the applicability of existing theories of vibrated concrete towards self compacting concrete.
- Effect of aspect ratio of steel fiber and its dosage in self compacting concrete needs to be investigated.
- The torsional behaviour of SCC with use of recycled coarse aggregates as replacement for natural aggregates is to be investigated.

- Analytical modelling using a Finite element based software can be used in studying the torsional behaviour of SCC and VC beams with and without steel fibers.

The scope of the present investigation includes:

- Evaluation of fresh and mechanical properties of steel fiber reinforced self compacting concrete for various dosages of steel fibers for low, medium and high-strength of SCC and thus maximizing the dosage of steel fibers.
- Develop analytical model for predicting torsional strength of steel fiber reinforced self compacting concrete (SFSCC) and Vibrated concrete (SFVC) with natural aggregates.
- Develop analytical model for predicting torsional strength of recycled aggregate based steel fiber reinforced self compacting concrete (RSFSCC) and vibrated concrete (RSFVC).
- Numerical modelling of steel fiber reinforced concrete using a finite element software ATENA for both SCC and VC for 20 MPa, 50 MPa and 80 MPa concrete strength and validate based on experimental results.
- To establish an equation to predict the torsional strength for SCC and VC with and without recycled aggregates.

The following objectives have been formulated to study and validate the use of steel fibers in SCC to evaluate the torsional behaviour.

1. To evaluate the fresh and hardened properties of natural aggregate and recycled aggregate based steel fiber reinforced SCC.
2. To predict the torsional behaviour of natural aggregate based steel fiber reinforced SCC and VC.
3. To propose the torsional behaviour of recycled aggregate based steel fiber reinforced SCC and VC.
4. To validate the experimental results with those obtained from finite element software ATENA.

To achieve the above objectives and keeping in view the scope of the research work, a detailed experimental program was planned and the work was divided into four phases.

Phase: I

Studies were carried out on fresh and hardened properties of steel fiber reinforced self compacting concrete for various dosages of hooked end steel fibers (0 %, 0.25 %, 0.5 %, 0.75 % and 1 % by volume of concrete) for three strengths i.e. 20 MPa, 50 MPa and 80 MPa. The effect of steel fibers on fresh and mechanical properties are studied with aspect ratio 50, 70 and 100. The various tests were conducted to evaluate the fresh properties of SCC included slump flow test, V-funnel test, V-funnel at T_{5min} and J-ring test .The mechanical properties included compressive strength, split tensile strength and flexural strength.The mix proportions for SCC mixes were designed by using Nansu method of mix design.

Phase - II:

Studies on torsional behaviour of natural aggregate based self-compacting concrete for three aspect ratios (l/d= 50, 70 and 100) for 20 MPa, 50 MPa and 80 MPa strengths for both SCC and Vibrated Concrete. To correlate the experimental results with various models available in literature for vibrated concrete.

Phase - III:

Studies on torsional behaviour of recycled aggregate based self-compacting concrete for three aspect ratios (l/d= 50, 70 and 100) for 20 MPa, 50 MPa and 80 MPa strengths for both SCC and Vibrated Concrete. To correlate the experimental results with various models available in literature for vibrated concrete.

Phase - IV:

Analytical modelling of steel fiber reinforced self-competing concrete using both natural and recycled aggregates and to evaluate the effect of aspect ratio of steel fibers and strength of concrete using a finite element software ATENA. Compare the experimental results with results obtained through analytical modelling for 20 MPa, 50 MPa and 80 MPa strength SCC and VC.

The parameters of investigation include

Type of concrete	-	Self-Compacting Concrete (SCC) and Vibrated Concrete (VC).
Strength of concrete	-	20 MPa, 50 MPa and 80 MPa.
Dosage of steel fibers	-	0%, 0.25%, 0.5%, 0.75% and 1 % by volume of concrete- for maximizing fiber dosage
Aspect ratio of steel fibers	-	50 (length= 25 mm, diameter = 0.5 mm), 70 (length= 35 mm, diameter = 0.5 mm) and 100 (length= 50 mm, diameter = 0.5 mm).
Type of aggregate	-	Natural aggregate (NA) and Recycled Coarse Aggregate (25 % replacement) (RCA).
Dosage of steel fiber	-	0 % and 0.5 % (maximum dosage of fiber)-adopted for casting of beams.

From a detailed experimental study on Torsional behaviour of Steel Fiber Reinforced Recycled Aggregate based Self Compacting Concrete, the following conclusions have been drawn.

1. Based on Fresh properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is maximum for all three grades. All the aspect ratios of fibers could not achieve the fresh properties of EFNARC specifications for dosages 0.75 % and 1 %.
2. Based on hardened properties also it can be inferred that 0.5 % dosage of steel fibers by volume of concrete is the maximum dosage for self compacting concrete of three strengths. There is a good increase in the split and flexural strengths due to the fibers bridging the crack propagation and resulted in increased ultimate load carrying capacity of the specimens.
3. It can be concluded that steel fibers with aspect ratio 70 has significant contribution towards increase in mechanical properties of SCC compared to low (50) and high (100) aspect ratios with 0.5 % dosage of steel fibers. It is true for all strengths of SCC.

4. Due to addition of steel fibers, the ultimate torsional strength and angle of twist increased by 18.40 %, 24.77 % in A-VC-70 and 20.77 %, 31.39 % respectively in A-SCC-70 compared to plain beams.
5. In case of B-VC-70 and B-SCC-70, the increase in ultimate torsional strength and angle of twist was 16.22 %, 30.77 % and 17.06 %, 37.31 % respectively.
6. Due to addition of steel fibers, the ultimate torsional strength and angle of twist increased by 14.28 %, 57.75 % in C-VC-70 and 18.38 %, 83.02 % respectively in C-SCC-70 compared to plain beams.
7. The torsional strength of beams using recycled aggregates reduced by 8.59 %, 5.56 % and 8.96 % for plain VC beams of strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
8. The torsional strength of beams using recycled aggregates reduced by 7.69 %, 5.28 % and 5.95 % for plain SCC beams of strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
9. Similarly, a comparison was made between experimental and existing theories of torsion on vibrated concrete. It can be noticed that the ultimate torsional strength was under estimated by elastic analysis and was over estimated by plastic analysis.

   Empirical formula is proposed to estimate the ultimate torsional strength of the member (T_{SCC}) for SCC. This is given by

   $$T_{SCC} = (0.5-0.092(b/d))\ (b^2 d f_{t1}) + \left(\frac{l}{dia}\right)*f_{t2}$$

   Similarly, an empirical formula proposed to estimate the ultimate torsional strength of the member (T_{VC}) for VC.

   $$T_{VC} = (0.5-0.118(b/d))\ (b^2 d f_{t1}) + \left(\frac{l}{dia}\right)*f_{t2}$$

   $$1/ f_t = (1/ f_c) + (1/ f_{spt})$$

10. Where, f_{t1} = Tensile strength of plain concrete; f_{t2} = Tensile strength of fiber reinforced concrete; f_c = Compressive strength of concrete; f_{spt} = Split tensile strength; b = width of beam; d = depth of beam; l = length of steel fiber; dia= diameter of steel fiber.
11. The Numerical results obtained are compared well those with experimental results and maximum values are within 85-90 % level of confidence and with an average error of 9.54 %.

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Abbreviations

SCC	:	Self compacting concrete
VC	:	Vibrated concrete
FA	:	Fine aggregate
CA	:	Coarse aggregate
SP	:	Super plasticizer
SF	:	Steel fibers
RAC	:	Recycled aggregate concrete
ITZ	:	Interfacial transition zone
RCA	:	Recycled coarse aggregate
FRC	:	Fiber reinforced concrete
NASCC	:	Natural aggregate based Self compacting concrete
RASCC	:	Recycled aggregate based self compacting concrete
SFSCC	:	Steel fiber reinforced Self compacting concrete
RSFSCC	:	Recycled aggregate based steel fiber reinforced self compacting concrete
SFVC	:	Steel fiber reinforced Vibrated concrete
RSFVC	:	Recycled aggregated based steel fiber reinforced Vibrated concrete

Chapter 1 Introduction

1.0 General:

Concrete is the most consumed artificial product on earth with an average of 3.5 tons per human in this world. Concrete production and its construction has an enormous influence on human life due to its capability of formation into different shapes, dimensions and aesthetic designs. Therefore, it considered to be the versatile materials used in construction industry. The performance of concrete is highly influenced by its compaction integrity and brittle nature. Improper compaction effects the hardened properties such as strength and durability. Whereas, brittle nature of high strength concrete leads to sudden failure in all structural actions. Swift progress in the field of construction technology has led concrete structures to be more massive and taller, which require high performing concrete in terms of strength and durability. It has led to increase in reinforcement volume and compulsion of closely spaced reinforcing bars. Overcrowded arrangement of rebars in Reinforcement Concrete (RC) members, such as beams, column and slabs, creates it problematic to compact concrete properly with usage of any mechanical vibrator. Unoccupied voids and micro pores arise in concrete creates due to inappropriate compacting in concrete, which effects the strength and durability of the concrete and possible reasons of deterioration in concrete **(Bouzoubaa 2003).** The operation of compaction becomes more complicated when form configuration has long inclined components such as inclined columns, very high casting heights, long cantilever access area, etc. Additionally, the noise generated from use of these vibrators would sometimes restrict the working hours for precast concreting process and cast-in-situations. It also demands extra workforces at every discharge point to confirm proper compaction, especially in space congested with reinforcing bars.

Conventional concretes used in construction and civil engineering applications requires compaction to attain required compressive strength there by increase the life of the structure. To overcome aforementioned difficulties **Okumura** in Japan in the year 1986 developed a new type of concrete which can compact under its own weight and also address the problems involving strength and durability. This new type of concrete is named as Self Compacting Concrete (SCC). SCC is cohesive enough to handle without segregation or bleeding **(Ozawa et al., 1989; Okamura, 1997; Goodier, 2003; Oliverira et al., 2015).**

Self Compacting Concrete (SCC) as the name itself indicates, that it does not require any external compaction, it compact itself under its own weight only. Due to the above property it need no vibration, subsequently no noise pollution and also reduces the labour cost and can compact to every corner of the form by means of its self-weight without undergoing any significant segregation, predominantly in heavy congested reinforcement.

Generally, diagonal cracks in beams arise when the principal tensile stress of concrete exceeds the tensile strength of concrete in structural members subjected to pure torsion or torsion along with bending/shear. **(Seshu et al., 2003)**. As we know that torsional failure is sudden and brittle arise without any prior warning. To overcome these type of failures in beams are to be reinforced to increase its tensile strength.

Torsion is the one of the important design criteria in limit state of collapse. The exact analysis of torsion in reinforced beams is quite complex. Torsion is one of the basic structural action which is low prioritized though very essential in analyzing the structures subjected to earthquake and wind loads. It is predominant in many structural members such as space frames, inverted L-beams as in supporting sunshades, curved beams in water tanks, edge beams of slab, spandrel beams etc. Generally, part of torsion in reinforced concrete member is contributed by concrete which is a fraction of the torsional strength of a corresponding plain concrete member. Torsion test on plain concrete members are helpful in understanding the more complex problem of torsion of reinforced concrete members. It is used as prelude study of reinforced concrete. Nowadays usage of short steel fiber in concrete has gained importance. The major advantages of using steel fibers are, it enhances the flexural tensile strength and also improves the ultimate load carrying capacity of the concrete beam by means of arresting and bridging the cracked surfaces. So, the effect of steel fibers in resisting torsion can be understood when added to plain concrete members. The concrete reinforced internally by means of short and discrete steel fibers is known as Steel fiber Reinforced Concrete (SFRC).

Torsion failure is mainly due to inherent weakness of concrete in tensile strength. The presence of the cracks both in interfacial transition zone and the mortar matrix of concrete is the factor responsible for insignificant strength. Tensile properties of concrete can be significantly improved with addition of various fibers such as glass, steel, polypropylene etc. From literature review, it was found that tensile properties of concrete can be significantly enhanced with the inclusion of steel fibers. However, steel fibers are most commonly used because of its low cost and easy availability. Steel fibers in reinforced concrete helps in bridging crack faces, delaying the failure of specimen and increase the ultimate load carrying capacity. **(Darwish, I.Y.S, 1987; Hanai, 1997; Yang, 2014; Arslan et al., 2017)**. If steel fibers are added in sufficient amount, brittle torsional failure can be modified to a ductile behavior, also with reduced crack widths **(Kishor et al., 2012).**

Steel Fiber Reinforced Concrete (SFRC) is a composite material that is characterized by enhanced post-cracking behavior due to the capacity of fibers to bridge the crack faces if they are present in sufficient amount **(Cucchiara et al., 2004)**. The significance of steel fibers varies with the shape, aspect ratio (length/diameter) and dosage in concrete. Steel fibers are used to increase the tensile strength and torsional capacity of concrete **(T.D.G. et al, 2003)**. Researchers attempted to improve tensile and torsional strength of plain concrete by adding discrete fibers, thoroughly dispersed across the matrix **(Mansur et.al 1982, Narayan et al, 1983-1986, Hsu et.al, 1985-1988, T.D.G et al 2003-2005, Behra 2006).**

1.1 Self Compacting Concrete:

Self compacting concrete (SCC), a composite material with ability to flow under its own weight without segregation over long distances. It is a solution to all compaction related problems and can achieve consolidation without the use of vibrators. SCC can fill the formwork whilst maintaining integrity, homogeneity even at places of congested reinforcement without any use of external energy and attain full compaction without any segregation in its ingredients **(Day et al, 2005; EFNARC, 2005)**. Self Compacting Concrete (SCC), was originally established by **Okamura** in 1986, which is a well thought-out answer to solve the difficulties involved in placing and compaction of conventional concrete. Conventional concrete used in civil engineering applications and construction require external compaction to attain strength and durability. Self compacting concrete is cohesive enough to handle without segregation or bleeding **(Ozawa et al., 1989; Okamura, 1997; Goodier, 2003; Oliverira et al., 2015)**. As it requires no vibration, hence no sound pollution and also reduces the cost of vibration equipment required, labor cost and can be compacted to every place of the congested reinforcements without undergoing any significant segregation **(Ouchi et.al, 1996)**. The constituent materials in SCC differ from conventional concrete only in case of imparting high workability with Viscosity Modifying Agents (VMA) and High Range Water Reducing (HRWR) admixtures. The cement content in SCC is relatively high compared to conventional concrete. Fine fillers can be used in addition to cement to achieve required fresh and hardened properties. The amount of fine aggregate is often greater than 50% in the total aggregate fraction. In despite of all these SCC has several advantages as follows.

- Ability to flow in complex reinforcements.
- Quick placement of concrete without vibration or conventional consolidation.
- Enhancement in construction ability.
- Higher performance in terms of workability, durability and strength.
- Improvement in structural integrity.
- Adequate bond between reinforcing steel and concrete.
- Reduction of voids in highly reinforced areas.
- Minimization in requirement of labour.
- Reduces noise levels produced by conventional vibrators.
- Superior surface with uniform finishing can be achieved.
- Construction period can be decreased.

The property of compaction by its own weight in SCC is attained by reducing the content of coarse aggregate and using higher powder content. The cement content in SCC is relatively high compared to conventional concrete. Fine fillers can be used in addition to cement to achieve required fresh and hardened properties. The amount of fine aggregate is often greater than 50% in the total aggregate fraction. The inter particle friction between aggregates is minimized by limiting the size of aggregate content, which helps in increasing the flow ability of SCC **(Ozawa, et al., 1995)**. In SCC, fracture plane is relatively smooth due to the presence of lesser amount and small size of coarse aggregate as compared to vibrated concrete. The addition of steel fiber in SCC combines the benefits of fresh properties and enhances the tensile properties in the hardened state. The difference between Steel Fibre Reinforced Self Compacting Concrete (SFRSCC) and traditional Fibre Reinforced Concrete (FRC) is that the fibre content of FRC is mainly determined by the post-cracking behaviour, and the fibre content of SFRSCC is mainly restricted by the workability of fresh SCC. SFRSCC combines the advantages of both SCC and FRC **(Cuenca, et al., 2015)**. However, research work on the study of SFRSCC beams, specifically on the torsional behaviour of SFRSCC, is still limited.

Some of the limitations in using of SCC are:

- Due to use of higher power content and super plasticizers, the cost of SCC is relatively higher compared to normal concrete.
- Due to low water to binder ratio, plastic shrinkage cracks may occur but these can be avoided by curing the concrete properly.
- Highly skilled and experienced workers are required for production of SCC on the site.
- In hot climatic conditions SCC cannot be produced.

SCC should satisfy the vital physical properties in fresh state such as flowability, resistance to segregation, passing ability and viscosity. The consistency of fresh state of SCC is checked by Slump-flow value which describes the flowability. Additional information regarding resistance to segregation and uniformity is obtained by visual observations and measurement of T_{500mm} time. V-funnel flow time and V-funnel 5 min-time assess the viscosity and segregation resistance of SCC in fresh state respectively. Resistance to segregation is rudimentary for SCC in-situ quality and homogeneity. The ability of fresh mix to flow through areas of congested reinforcements and confined spaces without losing uniformity, resistance to segregation is described as passing ability. J-ring and L box tests are used to evaluate the passing ability of SCC as per guidelines of **EFNARC (2005)**.

SCC is wide range of applications in tunnel constructions, earth retaining systems, bridges, drilled shafts, columns and areas with high amount of reinforcements. It has achieved wide spread in precast industry, where all its advantages are verified under skilled labour and put to a profitable use. It also enhances aesthetics and durability performance of precast elements **(D'Souza et al., 2012)**.

1.2 Fiber Reinforced Concrete:

Over the years, various attempts were made to improve the tensile properties of concrete by way of using conventional steel bars and also by pre tensioning techniques. Although both these methods improve the tensile strength of concrete members, however they do not increase the inherited tensile strength of concrete. Under loading, micro cracks present inside the concrete propagate and open up and results in early failure of the RC member. In the past few years, use of short and randomly disturbed fibers in concrete has gained attention which helps in resolving in arresting these micro cracks and thereby improving the flexural and tensile strength of concrete. The use of fiber in concrete is termed as Fiber reinforced concrete.

Fiber is small piece of reinforcing material possessing certain characteristic properties. The geometry of the fiber can be flat or rounded and are describe by a parameter “aspect ratio”. It is defined as the ratio of length to diameter of the fiber. Fiber generally used in concrete are made of steel, glass, polypropylene, carbon and basalt. Each type of fiber has its characteristics and limitations **(Mehmet C 2007)**.

Fiber reinforced concrete is a composite material containing fiber in cement matrix, in orderly manner or randomly distributed manner. The major properties of fiber are: fiber geometry, fiber volume fraction, fiber orientation and distribution. Fiber have widespread application in concrete like, bridging the crack surfaces, crack arresting and controlling and also to modify the behaviour of RC member.

1.2.1 Steel fiber reinforced Concrete:

Over the past few years studies on Fiber reinforced concrete (FRC) have dealt with use of steel fiber in concrete, since then Steel Fiber Reinforced Concrete (SFRC) has most commonly used fibrous concrete. Steel fibers in concrete greatly improves the toughness and also increases the post cracking behaviour of concrete. Initially steel fibers are normally used to passive reinforcement to increase the post cracking behaviour and also increase the flexural toughness of reinforced concrete. Currently, steel fibers are used to substitute the secondary reinforcement in flat slabs, beams, tunnel lining and pavement as well as in various repair applications. These days steel fiber are also progressively used either to replace conventional reinforcement or to balance it. Some of the commonly used steel fibers are shown in Figure 1.1.

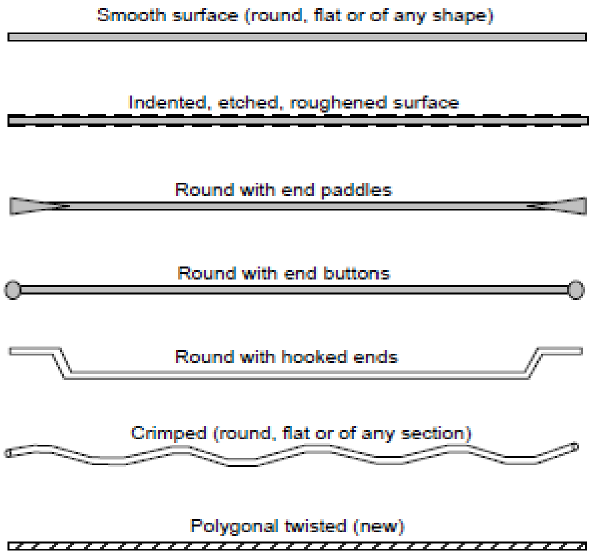


Figure 1.1 Commonly available deformed steel fiber

Steel used for preparing fiber are of normally carbon steel or stainless steel alloys. The manufacture process of steel fibers may be done in numerous ways based on the desired geometry, size and length. Depending upon the specific making process and the nature of steel, the tensile strength of steel fiber ranges in between 450-2100 MPa. Typically, flat surfaced fibers do not have enough bond with concrete matrix, whereas crimped or hooked end fiber have perfect bond with concrete matrix.

1.2.2 Factors effecting the properties of steel fiber reinforced concrete:

Steel fiber reinforced concrete is a composite material, comprising of steel fiber in cement concrete matrix in an arranged or randomly distributed manner. The properties of steel fiber reinforced concrete generally depend upon on the effective stress transfer mechanism of concrete matrix and steel fibers which are primarily depend upon: type of fiber, fiber geometry, aspect ratio of fibers, fiber volume fraction, orientation and distribution of fibers and similarly on compaction methods and shape and size of aggregates. Fiber action occurs through stress transfer of concrete matrix to fiber by combination of interfacial shear and mechanical interlock among fiber and concrete matrix. Up to the point of concrete cracking, the load is supported equally by fiber and concrete, after cracking arises, fibers acts completely by connecting the cracked surfaces of concrete matrix thereby delaying the failure of the member.

While fibers enhances the properties of concrete matrix, under all categories of loading, but they are primarily effective only under direct tensile stresses and also they are equally effective when the members are subjected to flexure, shear, impact and fatigue loading and they are less active under compressive loading **(Arnon et al., 2013)**.

1.2.3 Steel fiber reinforced self compacting concrete:

Generally plain unreinforced concrete is brittle material under low tensile load and strain capacities. Self compacting concrete (SCC) remains to be brittle and fails under low tensile stresses. This behaviour of brittleness can be overcome by using randomly distributed short steel fibers. Steel fiber not only subdue the crack development but also subsides the propagation of crack growth. Steel fiber reinforced self compacting concrete is made from cement, various sizes of aggregates, which combines with discrete and discontinuous fibers **(Sable et al., 2012)**.

Addition of steel fibers in self compacting concrete (SCC) combines the benefits of both FRC and SCC. The main disadvantage of using steel fibers in SCC is reducing the fresh properties. The major constraints that effects the fresh properties of SCC are fiber aspect ratio, fiber volume fraction and fiber geometry (shape, size and length). Typically, the same parameters which influence the performance of fiber reinforced concrete (FRC) will affect the fresh properties of SCC **(Abbas et al., 2013)**.

1.3 Torsion:

Any complex force system can be defined in terms of six basic actions viz. axial force, two shear forces, two bending moments and a torsional moment. These actions may exist independently or in combination. A torsional moment usually occurs along with bending and/or shear. The interaction between these aforementioned actions is usually defined in terms of strength of element under individual actions. This necessitates the study of behaviour of a given element under pure bending, pure shear and pure torsion.

An applied torsion can be of primary or secondary nature. It occurs as a primary action when external load has no other alternative but to be resisted by the torsional resistance of section only, e.g. a lintel beam carrying a canopy slab. A neglect of primary torsion in design may lead to collapse. The magnitude of primary torque can be determined by static equilibrium conditions. Therefore, such torsion is also called as equilibrium torsion. The example for behaviour of equilibrium torsion is shown in Figure 1.2.

A torsional moment required to maintain the compatibility of deformation in a continuous structure is defined as secondary torsion e.g. main beam supporting a secondary beam in a grid structure. As this torsion is required for the compatibility of deformation, it is termed as compatibility torsion. If such torsional action is not accounted in structural design, the structure may still be safe but will show large deformations and cracking. The magnitude of this torsion can be calculated by accounting the compatibility and equilibrium conditions. The example for behaviour of compatibility torsion is shown in figure 1.3.

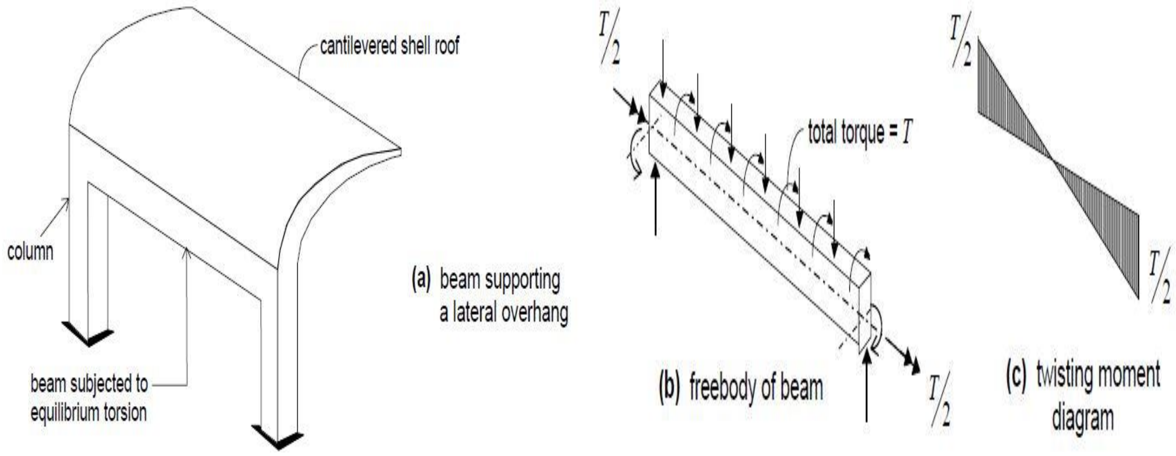


Figure 1.2 Structural members subjected to equilibrium torsion

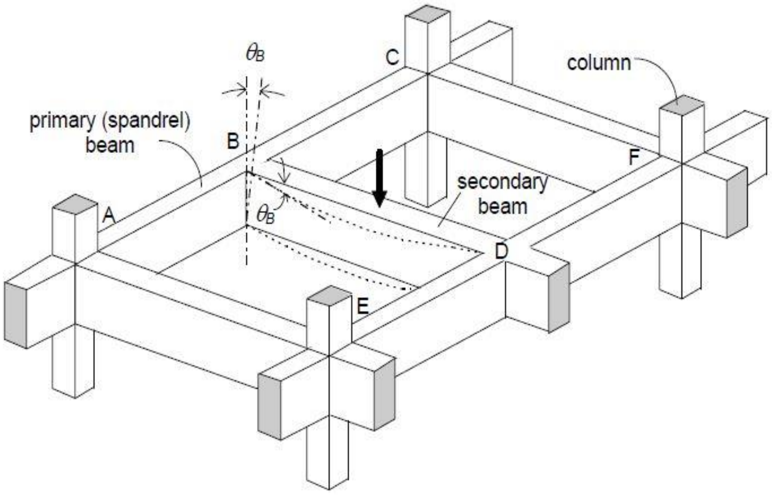


Figure 1.3 Structural members subjected to compatibility torsion

When a torsional moment is applied to a non-circular element, it induces twisting and warping. An applied torsional moment is therefore resisted by the torsional as well as warping rigidity. In case of open thin walled sections, e.g. channel and T-sections, warping rigidity plays a dominant role in resisting torsion, hence cannot be neglected in analysis. However, warping is usually neglected in case of analysis of solid sections or thin walled close sections e.g. tubes, hollow box etc. This is due to the substantially large torsional rigidity of these sections in comparison to their warping rigidity.

1.3.1 Historical Background:

Most of the classical theories describing structural behaviour of material under different loading conditions were developed during industrial revolution. As torsion plays a significant role in design of industrial parts, substantial research efforts were put-in to study their torsional behaviour. However, research during initial phase, was confined to elastic, homogeneous and isotropic materials only. **Navier (1826)** proposed an expression for pure torsion, which was analogous to expression given for pure bending. It indicates zero intensity of shear stress at centre of rotation and maximum intensity at maximum distant fiber. However, this expression could not define torsional behaviour of non-circular sections. Later, **St. Venant (1856)** proposed expressions to calculate torque and twist of a rectangular section using semi-inverse approach. It represents maximum shear stress at centre of long face, and zero at corners. **Nadai (1923)** proposed a methodology to calculate the torsional strength of plastic materials.

1.3.2 Structural response of concrete under pure torsion:

A torsional moment induces pure shear condition in a structural member, known as torsional shear. A pure shear condition results in a biaxial compression-tension condition along diagonal directions. The intensity of compressive and tensile stress acting along these diagonals is same as that of applied torsional shear stress. Across the section, magnitude of these stresses is maximum at the surface, which reduces to zero at center of rotation. As the stress intensity is less near center of rotation, the peripheral tubular section provides majority of torsional resistance.

Research on shear took a slight lead over that on torsion. However, in spite of a slightly delayed start in the work on torsion, the understanding of the torsion phenomenon matches or even surpasses that of shear in concrete. Shear in members of skeletal structures generally arise due to the variation of bending moment and is, therefore, called flexural shear. Shear is directly related to bending moment as it equals the rate of change of bending moment. Torsion has no direct relation with either shear or flexure. Both shear and torsion produce shear stresses which in turn give rise to diagonal tension. This diagonal tension is responsible for diagonal cracking and possible distress in concrete members. While the cracks due to torsion are in the form spirals and cracks due to shear on the two vertical faces of the member are parallel and mirror images of each other. While the tensile resistance of cracked concrete is ignored in either case, it is known that aggregate interlock opposes failure in shear and torsion unless it is destroyed by repetitive reversible applications of load **(S.P. Gupta)**.

In a reinforced concrete section, plain concrete, in the form of cover, occupies a substantial part of effective peripheral section. The plain concrete provides good resistance to compressive stress component of biaxial state. However, tensile stress component of biaxial state induces cracking at the early stage of loading due to inherent weakness of plain concrete against tensile stress. This cracking makes outer peripheral section less effective against applied torsion. Therefore, a section can be made more efficient in resisting torsion by improving tensile strength of plain concrete.

Researchers attempted to improve tensile strength of plain concrete by adding discrete fibers, thoroughly dispersed across the matrix. Fibers of steel, polymer, carbon etc. are used for this purpose. However, steel fibers are most commonly used because of its low cost and easy availability.

1.3.3 Failure mode in torsion:

The skew bending theory was first developed for computing the ultimate torque of a plain concrete member of rectangular cross-section subjected to pure torsion and extended for the cases of combined torsion. Under the theory two possible modes of failure have been conceived depending upon the orientation of the failure plane. In mode-1, the failure plane is normal to the wider faces and inclined at an angle α to the shorter faces about 45 °. In combined torsion α varies from 0° to 90° depending upon the load combination. In mode-2, the failure plane is normal to the shorter faces and is inclined at an angle α to the wider faces. In case of rectangular cross-section mode-1 is always more critical than mode-2 because it gives a lower value of ultimate torque. The failure pattern of mode-1 and mode-2 is shown in figure 1.4.

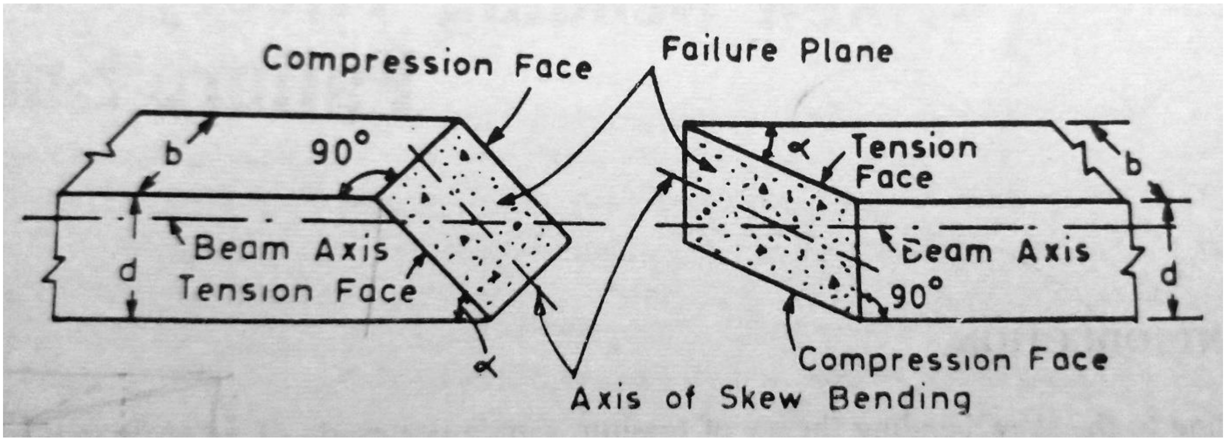


Figure 1.4 Mode-1 and Mode-2 failure pattern of skew bending failure

1.3.4 Torsional Behaviour of Fiber reinforced concrete:

Torsion is the one of major criteria in the limit sate of collapse. The exact analysis of torsion in reinforced concrete design is extremely difficult due to its various forms. It may be primary or secondary, also it may occur either alone or in combination with bending/shear. The main contents that influence the torsional behaviour of reinforced concrete beams are: tensile strength of concrete (f_t), compressive strength of concrete (f_c), aspect ratio of steel fiber (l/d) and volume fraction of fibers (V_f).

1.4 Recycled Concrete Aggregate:

As per Technology information, **Forecasting and Assessment Council (INDIA-2002)**, about 626 million tons of demolition waste is being generated in India. Massive quantities of building rubble become available by the way of demolition of old structures to make way for contemporary structures. These quantities enormously increase during high rate of reconstruction after devastating earthquakes. Due to scarcity of suitable dumping grounds and meeting the environmental requirements, disposal of these materials is being difficult. Thus, the broken concrete is increasing being recycled. The act of creating a new product by processing old concrete is known as recycling. Use of Recycled concrete Aggregates (RCA) in SCC, benefits the construction industry from the perspective of sustainability, environmental protection and in terms of economy **(Hansen, 1986; Corinaldesi et al., 2009; Reddy et al., 2013; Arezoumandi et al., 2015)**. In the view of global demand for construction aggregates, use of recycled aggregates is an alternative solution which can also be useful for sustainable environmental and economic terms. In view of the large demand for alternate aggregates, recycled aggregates from building and demolished waste are being used in large quantities. Some of the major benefits of recycled concrete aggregates (RCA) include

- Cost savings over new (virgin) aggregates.
- Reduction in the resource consumption, landfills, decreased quarrying, decrease in the greenhouse gases, water and air pollution.
- Recycled aggregate can also serve as base material for road ways.

1.4.1 Production of Concrete Aggregate from Demolition Material:

Recycled concrete aggregates are produced in aggregate crushing plants similar to those used to crush and screen conventional virgin aggregates. Jaw crushers handle residual reinforcement and large pieces of concrete. Electro-magnets are used to remove residual reinforcement. Impact crushers are used to produce higher percentage of aggregate without adhere mortar. Jaw crushers reduces material down to size 60-80 mm, which is fed to secondary crushers. Aggregates get separated into two different sizes when passed through two screens.

1.4.2 Need for the use of recycled aggregates in concrete:

Concrete is one of the most used material by mankind next only to water. The demand for concrete by way of construction material was there in past and continues to in future. Concrete uses substantial amount of non-renewable materials and resources especially natural aggregates (coarse and fine aggregates). The waste produced from construction and demolishing process is getting accumulated as landfills **(Rathish et al, 2001; Vivian et al, 2007)**. This results to ground and water pollution which is harmful to environment. Some of the matters that can help environment form this type of pollution is by usage of recycled concrete aggregates in construction process as substitute to both natural fine and coarse aggregates.

1.4.3 Recycled aggregate based self compacting concrete:

Recycled aggregates are obtained from crushing unwanted concrete and coarse fraction can be used as replacement of natural coarse aggregates. In spite of having lesser density and higher water absorption than normal aggregates, it can be used to produce concrete with good performance, if they are added in appropriate quantities. To make self compacting concrete, preferably the aggregates used for producing normal aggregates can be used for concrete making process, but in order to increase the flowing ability and also to resist segregation of aggregates, higher amounts of mineral admixtures such as fly ash, GGBS and silica fumes in addition to super plasticizers can be used.

As we recognize that self compacting concrete is highly flowable and does not require any external compaction and can also fill into every corner of the form work. The use of recycled aggregates as a partial replacement of natural coarse aggregates there is decline in mechanical properties, due to formation of second Interfacial Transition Zone (ITZ) which is the weakest link in the concrete where failure take place. Addition of steel fiber in concrete can overcome this defect and a new concrete by way of steel fiber reinforced self compacting concrete can be produced.

Steel fiber reinforced recycled aggregate based self compacting concrete (RASFRSCC) combines the benefits of SCC in the fresh state by avoiding cracking and shows an improved performance in the hardened state compared to conventional concrete. Although use of recycled concrete aggregate in place of natural aggregate has now received considerable attention as a sustainable method.

There is considerable amount of work available in the literature on the use of recycled aggregates as partial replacement of normal aggregates up to 100 %. In the present context, natural coarse aggregates are replaced 25 % by weight with recycled aggregates in SCC. The torsional behaviour of recycled aggregate based self compacting concrete is studied by adding steel fibers.

1.5 ATENA- GID:

ATENA is finite element based software, generally used for performing non-linear analysis on the Reinforced Concrete (RC) members. The behaviour of RC members such as concrete crushing, cracking and yielding of reinforcement can be performed using ATENA. It helps in visualization of crack propagation even while performing the analysis can be accomplished. GiD is an interactive graphical user interface programme used for preparation of input data for analysis, and it also used for defining, preparing and visualizing all the input data for numerical simulation **(Cervenka V)**.

In the present study a finite element model of a beam is created in ATENA and nonlinear analysis is performed to study the shear behaviour of steel fiber reinforced Self compacting concrete.

1.6 Summary:

Use of SCC has numerous advantages as it does not require any external compaction, it compacts under its own weight. Use of steel fibers in concrete not only improves the post cracking behaviour but also enhances the ultimate load carrying capacity of concrete. Addition of steel fibers help in altering the failure mode from sudden brittle failure to ductile mode. As the part of torsion in reinforced concrete member is contributed by concrete which is a fraction of the torsional strength of a corresponding plain concrete member. The effect of addition of steel fibers on torsional strength in plain concrete (SCC and VC) is studied in this investigation. In wake of sustainability in construction, use of recycled concrete aggregates as partial replacement of natural aggregates is unavoidable. The use of recycled concrete aggregates in SCC is advantage and is also sustainable way of construction. Finite element modeling using ATENA-GID software helps in understanding the behaviour of steel reinforced SCC and VC beams, such as concrete cracking, yielding of reinforcement and also supports in analyzing the behaviour of fiber reinforced concrete beams.

A literature review was planned to understand the behaviour of concrete especially in torsion and furthermore the influence of steel fiber on torsional behaviour of reinforced SCC is required. The effect of replacement of natural aggregates with recycled aggregates is also intended in the study. Finally, a thorough literature review was planned on various finite element software available in investigating the torsional behaviour of reinforced concrete is also planned in the present study.

Chapter 2 Literature Review

2.0 General

In order to understand the role of steel fibers on strength and torsional behaviour of SCC and moreover to distinguish the effect of recycled concrete aggregates on strength properties of SCC and vibrated concrete (VC), a thorough literature review is planned in the present chapter. The need for making the concrete ductile through use of steel fibers for high strength SCC have been discussed. Similarly to acquire an in-depth awareness of various software package available on the modelling of fibrous concrete and to analyse the behaviour of steel fibrous SCC a detailed literature is intended in the present chapter.

2.1 Review of literature on Self Compacting Concrete.

The necessity of SCC was proposed by Okamura in 1986 **(Okamura et al., 2003)**. For the members with congested reinforcements, this concept was used as tool to improve the long-term durability but later due to the excellent user-friendly characteristics of SCC the applications have spread slowly to conventional construction industry also. SCC has a vital role to play with substantial benefits in construction both qualitatively and quantitatively. Compared to vibrated concrete (VC), SCC can be considered as an altered approach in mix proportioning and a new type of high-performance material possessing good rheological characteristics. It can be considered as an innovative approach to casting concrete obtained by adjusting fresh concrete properties.

Ozawa et al., (1989) completed the first prototype of SCC using materials readily available in market. By using various types of superplasticizers, a concrete with good workability was developed. It was suitable for quick placement and had very less permeability. V-funnel test was developed to measure the viscosity of concrete. The influence of mineral admixtures, on the segregation resistance and flow ability of self-compacting concrete was also investigated. It was found that the flow ability of the concrete improved remarkably with partial replacement of Portland cement with fly ash (10-20 %) and blast furnace slag (25-45 %) showed the required flowing ability and strength characteristics. Self compactability was achieved easily by altering water to cement ratio and dosage of superplasticizer by fixing coarse and fine aggregate content to 50 % and 40 % of the solid and mortar volume respectively. A summary of articles and research investigations found in the literature on mix design methods are presented in the subsequent paragraphs.

Kuroiwa (1993) has developed a special concrete using the similar materials that were used in conventional concrete. The proposed new concrete can easily flow to every corner of form work and also completely fill the dense reinforcement without any external effort. Chemical admixtures were used in order to enchase the viscosity of that new concrete. From the laboratory test it was concluded that the proposed concrete has excellent workability in fresh state and good durability in hardened state.

Considering the lack of a proper mix design for SCC, **Su et al., (2001)** proposed a simple mix design method for SCC, where a term Packing Factor was introduced to calculate the quantities of aggregates. The method involved determining the aggregate Packing Factor (PF) and influence on the strength, flowability and self-compatibility ability. The ratio of mass of fully compacted aggregates to mass of loosely compacted aggregates defines the Packing Factor. Higher the packing factor, lesser is the requirement of powder content and vice versa. Initially, the amount of aggregates required were calculated and later to fill the voids of aggregates the paste of binders is determined. Thus, the mix proportion obtained is tested for required flowability, self-compacting ability and other desired SCC properties. The major factors influencing the properties of SCC were, amount of aggregates and binders, quantity of water, as well as dosage and type of superplasticizer (SP).

EFNARC Specifications (2005), have given guidelines for SCC, material requirements, its composition and applications. EFNARC guidelines provides the detailed test procedures to check the workability of SCC. The different developed tests are Slump flow, V-funnel, J-ring, U-box and L-Box test to check the passing ability, flowability, filling ability and segregation resistance and certain acceptance criteria for these tests are also given in detail in the specifications.

Domone (2006), reviewed 68 case studies performed on SCC regarding the distribution of the constituents and the corresponding workability. It was found that the constituents and the mix proportions were spread in a relatively wide range. This indicates that a well working SCC can be produced in many different ways with various proportions between the constituents and that no unique standard rule exists. SCC comprising a wide range of mixes were investigated and it was concluded that there is a potential for optimizing SCC with higher efficiency, which can be obtained based on the type of application and properties based on locally available materials are taken into consideration.

Yazicioglu et al., (2006), examined different types of curing conditions on the engineering properties of SCC. The authors considered three curing conditions i.e. water curing, sealed curing and air curing. The properties of SCC obtained under these curing conditions were compared with vibrated concrete. It was concluded from the study that SCC containing silica fume gave higher compressive and tensile strength values than SCC containing fly ash. For similar compressive strengths of normal vibrated concrete and SCC, the tensile strength was higher in case of SCC. It was also observed from the engineering properties of SCC that SCC required proper curing in the initial days as the water-binder ratio is minimum (0.38).

Rao, et al., (2010), has developed standard and high strength SCC with different sizes of aggregates based on NanSu mix deign. The results has shown that SCC can be developed with different sizes of aggregates. The mechanical properties were evaluated at the age of 3, 7 and 28 days. From the experiential results it was found that 16 mm size and 52 % fly ash is optimal for standard strength SCC and 10 mm and 31 % fly ash is optimal for high strength SCC.

Radhika et al., (2012), developed a mix design methodology for SCC based on compressive packing model (CPM). It was noted that the CPM based optimization of aggregates considers important parameters like wall effect, loosening effect and perturbed volume that are important in deciding the aggregate portion of SCC. Three grades of SCC mixes without and with steel fiber, were developed using CPM concept and the method proved to be best suited for polydisperse mixtures and SCC applicable without and with fibers. The strength and durability properties of these mixtures were investigated and were found to be satisfactory.

Das (2012), compared the hardened properties of fly ash based Self Compacting Concrete (SCC) with normally compacting concrete (NCC) under different curing conditions. The curing conditions adopted were water curing, accelerated curing and followed by water curing. The test programme included determination of compressive strength, split tensile strength, modulus of rupture, stress-strain characteristics and Poisson's ratio of SCC and NCC subjected to different curing conditions. The correlations developed for SCC indicated a difference in the pattern of strength development and stress-strain behaviour compared to NCC. The presence of fly ash particles in SCC lowered the porosity at later ages due to pozzolanic action and improved mechanical properties as well as stress-strain relationships. It was also concluded that curing condition significantly affects the properties of concrete.

Rao, et al., (2013) their investigation includes developing a new mix design methodology for SCC by modifying the Nansu method of mix design. From the strength and workability studies carried on SCC it was noticed that there is significant change in mix proportions with respect to packing factor, size of aggregates, fine aggregates to total aggregate ratio, cement content, flyash and water content on SCC. A simplified and direct mix deign method was proposed by modifying the Nansu method of mix deign for any grade of SCC.

2.2 Review of literature on Recycled Aggregate Concrete:

The usage of recycled aggregates in concrete constructions has being carried out from past few decades. A good amount of research work has been done on the use of Construction Demolished Waste (CDW) as recycled aggregates by way of replacement of natural aggregates in concrete by many researchers. Some relevant literature on use of recycled aggregates in normal and self compacting concrete is presented in the subsequent paragraphs.

Gumaste et al., (1998), investigated the use of recycled aggregates as replacement for natural aggregates in concrete. The authors studied the effect of recycled aggregates on strength properties by replacing the normal aggregates with recycled concrete aggregate by 10 %, 20 % and 30 % by weight. The study concluded that the compressive strength of recycled aggregate concrete was relatively less and they opined that the variation of strength mainly depends on the strength of parent concrete from which the aggregates are obtained.

Limbachiya et al., (2000), determined the difference between physical and mechanical properties of natural aggregate and recycled aggregates. It was found that recycled aggregates possess 7 to 9 % lower relative density and double water absorption when compared to normal aggregate. It was also found from their experimental results that there was no effect on strength properties up to a replacement of 30 % of normal aggregates with recycled aggregates. They have also proven by widespread experimental results that by using recycled aggregates higher strength concretes can also be developed.

Rathish et al., (2001) in their research investigation, they have used construction demolished waste as partial replacement of coarse aggregates. They have also used mineral admixtures such as fly ash and silica fume as partial replacement of cement to increase the workability of fresh concrete. From their studies it was established that recycled concrete aggregate is effective materials and that can be used as replacement of coarse aggregates, also recycled aggregates are efficient and sustainable material, so the disposal of demolished waste can be reduced. They have also concluded that higher percentage of replacing normal aggregates with recycled concrete aggregates can badly effect the strength of the concrete. Therefore the replacement of normal aggregates cannot be more than 50 %. They have also achieved high strength concrete with recycled concrete aggregates by using silica fume as mineral admixture and superplasticizer. The optimal dosage of silica fume that can be substitute cement was found to be 15 %.

Guptha et al., (2002), found that a replacement of 30 % natural aggregate with recycled aggregate didn't affect the strength of concrete. The study observed that the increase in replacement of recycled aggregate has decreased the compressive strength gradually, due to inferior physical and strength characteristics of RA compared to natural aggregate. It was stated that by adjusting the water/cement ratio for the strength of recycled aggregate concrete specimens could be improved. Use of fly ash in recycled concrete aggregate improved the impermeability of concrete and thus durability.

Vivian et al., (2007), in their investigations they removed the adhered motor present on the recycled aggregates by presoaking methods. They have found that the reason for decrease in the compressive strength of concrete made by means of recycled aggregates was the presence of old cement mortar on the surface of the recycled aggregates. Due to the presence of large quantities of cement mortar on the aggregate surface it resulted in higher porosity, water absorption there by a weaker interfacial transition zone (ITZ) between new and old cement mortars was established which decreases the strength of the recycled aggregate concrete. From the experimental results, it was found that the behaviour of recycled aggregates was much improved as a result of presoaking before using in concrete making.

Etxeberria et al., (2007) in their research work, authors have examined the effect of recycled aggregates on four different compressive strengths via 20 MPa, 30 MPa, 40 MPa and 60 MPa. They have replaced the normal coarse aggregates by 25 %, 50 % and 100 % with recycled aggregates respectively. The recycled aggregates are presoaked before mixing it with other ingredients. The experimental results have proven that the standard compressive strength concrete (30-40 MPa) with replacement of normal aggregates by 25 % with recycled aggregates has displayed similar mechanical properties as that of conventional concrete. They have also found that by completely replacing the normal coarse aggregates with recycled coarse aggregates the compressive strength was reduced by 15-20 % compared with control concrete with natural aggregates.

Kumar et al., (2009), conducted experiments on the strength and performance of recycled aggregate for use in rigid pavements. Type and level of crushing and influence of old mortar adhering to the aggregate after crushing were taken up in the investigation. The study concluded that increase in replacement of recycled aggregate in natural aggregate increased the fineness modulus, water absorption, voids ratio, elongation index, angularity number, aggregate impact value, IAPST, abrasion loss and crushing value, while, the specific gravity, bulk density and flakiness index decreased. The increase in old mortar content decreased the mechanical properties of concrete.

Brito et al., (2011) investigated the use of construction demolished waste (CDW) as recycled aggregate in concrete as a replacement of normal aggregates. The study revealed that the feasibility of usage of Recycled aggregate in concrete. They also studied the effect of curing conditions on mechanical performance of concrete made with recycled aggregates. They observed that the curing conditions have greatly affects the performance of the concrete made with recycled aggregates.

Limbachiya et al., (2012) investigated the effect of replacement of normal coarse aggregates with recycled aggregates by 0 %, 30 %, 50 % and 100 % respectively. They have also replaced cement with mineral admixture flyash by 30 % in concrete production process. The studies carried on the effect of replacement of recycled aggregates with natural aggregates in flyash based concretes. The mechanical and durability studies were carried out for both normal aggregate concrete and recycled aggregate concrete with flyash as replacement of cement. The durability studies included chloride ion penetration, sulphate attack and carbonation for both types of concretes. The results showed that the use of higher percentage of replacement of normal aggregates with recycled aggregates effected the durability and strength properties. The studies also revealed that usage of fly ash as a partial replacement of cement resulted in improving the durability of normal concretes when compared with recycled aggregate concrete.

Prasad (2012), identified the importance of introducing recycled concrete aggregate as a sustainable and alternative material for natural aggregate in SCC. Two grades of concrete were considered and glass fibers were used as passive reinforcement in SCC to improve the ductility of concrete along with active tie confinement. The stress-strain behaviour of tie confined fiber reinforced SCC with natural and recycled aggregates were developed. It was observed from the investigations that RCA can be used as a potential material in Self Compacting Concrete.

Heeralal (2013), conducted experiments on the use of recycled concrete aggregate (RCA) for rigid pavements. The flexural fatigue behaviour of RCA was investigated without and with steel fibers. The work identified the importance of demolished concrete as aggregates in structural and non-structural applications. From a series of experiments, it was concluded that the flexural strength of concrete decreased marginally compared to natural aggregate concrete however addition of optimum dosage of steel fibers in recycled aggregate concrete improved the flexural strength at both static and fatigue loading conditions.

Arezoumandi et al., (2015) in their study they have made reinforced concrete beams with recycled aggregates as 100 % replacement of normal coarse aggregates. Flexural studies conducted on recycled aggregates beams have displayed encouraging results compared with normal aggregate beams and existing codes can be used in designing the beams with recycled aggregates.

Silva et al., (2016) established the relationship between modulus of elasticity and compressive strength of recycled aggregate concrete. A statistical analysis was performed based on the collected data to understand the loss of compressive strength and modulus of elasticity on quality and level of replacement of recycled aggregates. Furthermore, a relationship between modulus of elasticity and compressive strength was proposed in agreement with existing codes on normal concrete. The major influencing factors effecting the modulus of elasticity are found to be cement paste, interfacial transition zone (ITZ) and nature of aggregates. Finally, it was concluded that the modulus of elasticity of RCA decreases with increased content of RA. The statistical analysis performed on relationship between modulus of elasticity and compressive strength of RCA revealed that, RCA has exhibited a similar behaviour as compared with conventional concrete, but as the percentage of recycled aggregate increased there was decrease in modulus of elasticity.

There is a lot of work done in the area of SCC and using different binding materials and plasticizers. Literature also revealed the use of recycled aggregate materials for making SCC. All the authors identified the importance of Self Compacting Concrete, and that to achieve self-compactability, addition of mineral and chemical admixtures was necessitated.

2.2.1 Literature review on Recycled aggregate based SFRSCC:

Jianming et al., (1997) have investigated the effect of steel fibers on mechanical properties of high strength and light weight concrete. This investigations aims to study the influence of steel fibers on Modulus of Elasticity and Poisson's ratio of concrete along with compressive and tensile properties. The dosage of steel fibers were varied from 0 to 2 % volume of concrete with a constant increment of 0.5 %. Rectangular fibers of three different lengths were used in this investigation. It is observed there is increase in compressive strength was relatively lower compared to tensile properties of concrete with inclusion of steel fibers. It is observed rate of increase in tensile properties was upto 9-90 % depending on dosage and aspect ratio of steel fibers. The increase tensile properties due to interfacial bond between fibers and concrete. It is noted that failure of steel fiber reinforced specimens were due slow crack progress and progressive debonding of fibers. In light weight aggregate concrete the crack appears preliminarily in light weight aggregate rather than cement paste under the application of load. The increase in flexural toughness in steel fiber concrete was due to availability of number of fibers forming a bridge in the crack and a more tortuous crack propagation path. Poisson's ratio tends to decrease with increase in fiber dosage due to crack arresting property of steel fibers.

Kou et al., (2009), carried out the research work on effect of recycled aggregate on SCC. In their study, normal coarse aggregates was completely replaced with recycled aggregates and examined the fresh and hardened properties of SCC. The cement content is kept constant in all the mixes and SCC mixes were prepared by replacing normal coarse aggregates by 0 %, 25 %, 50 %, 75 % and 100 % respectively. The water to binder ratio of two SCC mixes was fixed at 0.53 and 0.44. The various test on workability of fresh SCC was evaluated and also the hardened properties like compressive, split tensile and flexural strength were performed. From the results, it reveals that SCC made with recycled aggregates performed relatively well when compared with control SCC and conventional concrete.

Zoran et al., (2010) in their research work, using the recycled coarse aggregates obtained from crushed concrete as replacement of natural aggregate in self-compacting concrete. The percentage of replacement of coarse aggregate is replaced by 50 % and 100 % with recycled coarse aggregate. The obtained results have shown that there is only a slight difference on strength properties compared with control concrete without any replacement. They have also proven that recycled aggregates can be used in SCC successfully. The experimental results shows that the density of self compacting concrete is reduced by 2.12 % and 3.40 % for replacement of normal coarse aggregates with recycled coarse aggregates by 50 % and 100 % respectively.

Prakash et al., (2011) studied the effect of manufactured sand as replacement of fine aggregate (river sand). The studies included the fresh and hardened properties of SCC made with manufactured sand (M-Sand). They have optimized the binder and aggregate combinations using particle packing approaches. The chemical admixtures like, superplasticizers and viscosity modifying admixture were used to achieve the fresh properties of SCC. The test performed on fresh SCC are slump flow, T_{500mm}, V-funnel, J-ring and L- box test to satisfy the passing ability, flowing ability, filling ability and segregation. The tests performed on hardened concrete included compressive, split tensile and flexural strength. From the experimental results, it was concluded that comparatively higher paste volume was required to achieve fresh properties of SCC using M-Sand as compared with river sand.

Experimental results also showed that only low to medium (20-60 MPa) compressive strength concrete can be achieved by using M-Sand. The results also proven that M-Sand can be used in producing SCC.

Ponikiewski et al., (2011) studied the effect of steel fibers on SCC by using three different types of steel fibers i.e. hooked end, crimped end and straight end. Fresh properties such as, Slump flow, V- funnel, J-ring and L- box test were performed on fresh concrete. It was observed that as dosage of steel fiber increased, there was drastic decrease in the fresh properties of SCC. Also studies on evaluation of compressive, split tensile, flexural strength on hardened concrete on standard concrete cubes, cylinders and prisms were carried out. From the experimental results it was found that 0.5 % dosage of steel fibers is optimal based on fresh and hardened properties of SCC.

Kishore et al., (2012) studied the use of steel fibers with different aspect ratio to increase the structural performance of SCC. The objective of the study is to determine the mechanical properties of SFRSCC with different aspect ratio of steel fibers and to perform a comparative study on the properties of SCC without and with steel fibers and to compare the effect of different types and aspect ratio of steel fibers on SCC. From the experimental results, it was found that all the SCC mixes are satisfying the lower and upper limits suggested by EFNARC. It was also observed that for same aspect ratio hookend steel fibers has shown better properties compared to crimped and straight end steel fibers. Due to the shape of fiber, crimped end fiber has shown better bonding with straight end fibers. Also it was proved that by replacing cement with flyash, the durability and microstructure of SCC has improved.

Panda et al., (2012), carried the research work on influence of recycled concrete aggregates (RCA) obtained from demolishing old concrete on fresh and hardened properties of SCC and the results are compared with normal vibrated concrete containing 100 % natural coarse aggregates (NCA). The percentage replacement of normal coarse aggregate was varied from 10 % to 40 %. The grade of concrete considered was M25. The experimental results indicated that the mechanical properties of SCC with usage of recycled aggregates decreased with increase in percentage replacement of RCA with NCA. The study also suggested that the 30 %

replacement of natural coarse aggregates with recycled concrete aggregates produces better results.

Olivera et al., (2013) studied the permeability properties of SCC made with recycled coarse aggregate. The percentage replacement of normal coarse aggregate with recycled aggregates is by 20 %, 40 % and 100 %. The studies included strength and durability properties of SCC made with recycled aggregates. The results from the fresh and hardened properties revealed that it was realistic to replace the normal aggregate with recycled concrete aggregates. From the experimental results, it was also found that the compressive strength of SCC with RCA is decreased by 3.3 % while dynamic modulus of elasticity is reduced by 8.0 % when compared with natural coarse self-compacting concrete. The results have also proven that the permeability of SCC with RCA didn't effect much when compared with SCC with natural coarse aggregates.

Arjun et al., (2014) studied the behaviour of SCC with recycled aggregates. The study includes that evaluating the fresh and hardened properties of SCC by replacing normal aggregates with recycled coarse aggregates by 25-60 % with an interval of 5 %. From the experimental results, it was concluded that with replacement of recycled aggregates there was slight decrease in fresh properties. The studies on hardened properties concluded that there was no effect on strength of SCC with recycled aggregates up to a replacement of 40 % as the percentage of coarse aggregate, replacement beyond 40 % there was reduction in compressive strength of SCC.

Deng et al., (2016) carried out the work on replacement of recycled aggregates in self compacting concrete by using construction demolished waste (CDW) as a replacement of coarse aggregates in concrete making process. The percentage replacement varied by 25 %, 50 %, 75 %, and 100 %. It was reported that the compressive and split tensile strengths were decreased as the percentage replacement of recycled aggregates increased. From the experimental results, it was concluded that the usage of recycled aggregates beyond the 50-100 % replacement there was drastically decrease in the strength properties.

Yazici et al., (2017) have investigated the effect of recycled coarse aggregate on SCC at various replacement levels. Recycled coarse aggregate was used in water saturated surface dry (SSD) state. Fresh and hardened properties were evaluated for SCC mixes with replacement of coarse aggregate from 0-100 % with an increment of 25 %. Impact resistance of SCC mixes was evaluated along with mechanical properties. It was stated that with the increase of replacement of recycle coarse aggregate there was a decrease in density of SCC mixes. But all the fresh properties were observed to be in accordance with EFNARC specifications. It was reported that relative strength mixes were not significantly affected by recycled coarse aggregate. The decrease in strength was observed to be more in case of compressive strength than compared to split tensile and flexural strength. It was stated that fracture energy of concrete is significantly reduced by recycle coarse aggregate upto 60 % with 100 % replacement.

2.3 Literature review on Torsional behaviour:

2.3.1 Classical Torsion Theories:

A brief review of classical theories, applicable to the homogeneous material, has been made in following section to get a proper insight of the basic behavior of an element under pure torsion.

First expression to relate applied torque and resulting angle of rotation was reported by **Coloumb (1794)**. Author reported that the ratio of applied torque and resulting angle of rotation was directly proportional to the fourth power of the diameter of wire and inversely proportional to its length whereas, the proportionality constant was found to be a function of material properties.

Navier (1826) derived an expression to relate torsional moment, polar moment of inertia, resulting shear stress and angle of rotation per unit length and the modulus of rigidity. It was based on the following assumptions a) Material is homogeneous and elastic b) Plain section remains plain after twisting c) Deformation due to the applied torque is very small d) Shape of section remains unchanged after twisting. The theoretical modulus of rigidity using Navier’s expression was found different for the different cross sections, though the material of the specimens was same. Hence, the Navier’s expression was found unsuitable to define the torsional behaviour of rectangular sections.

St.Venant (1856) proposed a semi-inverse approach to solve the torsional problem of a rectangular section. It was based on the experimental observations that a rectangular section shows warping as well as twisting whereas a circular cross-section shows only twisting under pure torsion. St.Venant pointed out that the assumption “Plane section remains plane after twisting” was true for the circular sections only. Therefore, the predicted torsional behaviour of a rectangular section by the Navier’s equation was not correct. St.Venant assumed constant warping along the length of the rectangular section. Following expressions were proposed to calculate torsional moment,

$$T= \beta_e X^3 Y \theta \quad (2.1)$$

$$T= \alpha_e X^2 Y \tau_{max} \quad (2.2)$$

Where α_e and β_e are the coefficients, departing on aspect ratio Y/X

X and Y are smaller and larger dimensions of the cross section

T is the applied torque

θ is the angle of rotation per unit length

τ_{max} is the maximum shear stress

Prandtl (1903), found an analogy between the stress function defining torsion and the deflection of the membrane under uniform load, stretched over the cross section. This analogy helped in visualizing the direction of torsional shear stresses produced in any arbitrary cross-section. **Nadai (1923)** extended the Prandtl’s membrane analogy to the plastic materials. Nadai considered a sand heap over the cross-section of element instead of a membrane.

2.3.2 Review of literature on torsional behaviour of fiber reinforced concrete:

Hsu (1988) redefined softened truss model proposed by **Hsu et al., (1985)** in generalized terms. Author explained the applicability of this model to describe the behavior of a reinforced concrete section under shear and torsion. The proposed method was then extended to model the behaviour of reinforced concrete deep beam, shear transfer strength of concrete, low-rise shear wall and framed wall panel under shear load. A new algorithm was also proposed to solve the equations of softened truss model by iterative method.

Mansur et al., (1982) tested plain SFRC specimens under torsion by varying aspect ratio and volume fraction. Authors used plastic theory to predict the ultimate torsional strength which was close to the results. Unaffected torsional stiffness and increase in torsional strength, torsional toughness and ductility with the inclusion of steel fibers was reported.

Palanjan et al., (1983) proposed an equation to predict torsional strength of SFRC elements by modifying the expression of torsional strength of plain concrete. In this expression authors accounted the characteristics of fiber such as aspect ratio, volume fraction and bond. The effect of bond was included in terms of pull out characteristics of steel fibers. Authors reported that SFRC beams have significant reserve strength after formation of first crack.

Narayan et al., (1986) calculated the torsional strength of a reinforced-SFRC specimen by adding the resistance provided by the concrete, fibers and conventional steel. The contribution of concrete was calculated by the skew bending theory whereas, the contribution of fibers was derived from the space truss analogy. Authors suggested that the contribution of conventional steel can be calculated by any established method. The theoretical prediction of torsional strength of reinforced-SFRC elements was in good agreement with the test results. Authors reported that there is increase in the ultimate torque by the partial or full replacement of stirrups by an equivalent volume fraction of fibers.

Rahal et al., (1996) proposed a non-iterative torsion model for the reinforced as well as prestressed concrete section under pure torsion by introducing few empirical terms in softened truss model. The softening coefficients proposed by **Vecchio et al., (1996)** were used. Authors proposed an expression to calculate the balanced steel. An equation for the effective thickness at ultimate stage was also proposed by assuming the softening coefficient as 0.55 and perimeter of shear flow as 90 % of outer perimeter. The test results of specimens available in the literature and their predicted torsional strength were in good agreement. However, the predicted value of angle of twist at ultimate differed by an average of 27 % from the actual test results.

Ali et al., (1999) pointed out the empiricism in the formulation proposed for the minimum torsional reinforcement content in the ACI-318-1995. Author suggested calculation of minimum reinforcement by equating the cracking torque and steel contribution proposed by the space truss analogy.

KoutchouKali et al., (2001) tested high strength reinforced concrete specimens to investigate the effect of concrete strength and amount of reinforcement on the torsional strength of section. All the specimens were torsionally under-reinforced. Authors made a special arrangement to measure the strain across the depth of the concrete. This was planned to verify the bending action of struts under pure torsion. The specimens with low concrete strength showed large post peak response in comparison to the specimens having high concrete strength, indicating change in failure mode from ductile to brittle. Authors reported that the ultimate strength of under-reinforced specimens with same amount of steel but different concrete strength was almost same. This indicated that there was no effect of concrete strength on the ultimate torsional strength of under-reinforced sections. Authors observed that in pre-cracking stage, the strains across the depth were of compressive nature. However in post cracking stage, the strain near the surface remained compressive but its magnitude started reducing in the depth direction. The nature of strain was then changed to the tensile at certain depth. This confirmed the bending action assumed in the softened truss model for the concrete struts under warping action.

Tavio et al., (2004) proposed a methodology to calculate the effective torsional rigidity at any intermediate stage of loading. Authors used elastic modulus of rigidity for pre-cracking stage. Sudden increase in the twist angle at the cracking was accounted by considering the post cracking torsional rigidity proposed by **Hsu (1973)**. Authors modified the same equation to represent the torsional rigidity at ultimate. The equation for the effective torsional rigidity between the cracking and ultimate was obtained by interpolation. To draw a complete torque-twist diagram, the cracking torque was calculated by ACI-318-02 with modification in the value of constant. The ultimate strength was calculated by the simplified softened truss model **(Hsu, 1990)**. The torque-twist diagram between the ultimate and cracking load was drawn by calculating the effective torsional rigidity at the intermediate torque values. Authors compared with the predicted angle of twist at 60 %, 70 %, 80 % and 90 % of the ultimate torque with the test results of 76 specimens available in the literature. The average of ratios of experimental to the predicted values of angle of twist was close to 1 at all load levels. However, the coefficient of variation and standard deviation were of order 0.2.

Fang et al., (2004) compared the torsional behavior of reinforced concrete sections having high strength concrete and normal strength concrete. Sixteen test specimens were cast by varying the amount of reinforcement and compressive strength of concrete. Authors showed that the ACI-318-02 and elastic theory underestimated the cracking strength whereas the skew bending theory overestimated its value. The ultimate torque predicted by the 'Compression Field

Theory' and 'Softened Truss Theory' were in good agreement with the test results whereas ACI-318-02 overestimated in few cases. Contrary to the observation of other researchers **(Rasmussen et al., 1995, Koutchoukali et al., 2001)** in many cases, there was an increase in the ultimate torsional strength with the increase in compressive strength of concrete although, the specimens were under-reinforced. Authors reported that the compressive strain at given torque in HSC was less than the NSC specimens but at the ultimate stage, the compressive strain was generally more for the HSC specimens.

2.3.3 Research Works on Torsional Behaviour of Steel Fiber Reinforced Concrete (SFRC):

A reinforced concrete section cracks under torsional load when the tensile stress component of biaxial tension-compression state exceeds the tensile strength of the plain concrete. Researchers attempted to improve the tensile strength of a concrete by adding steel fibers. Such a concrete is known as steel fiber reinforced concrete (SFRC). The fibers in mortar changes the cracking characteristics and prolongs the initial elastic stage of a reinforced concrete section under torsion. The spalling of cover was also expected to be less in the presence of fibers. There are good number of research reports on torsional behavior of steel fiber reinforced concrete **(ACI Committee 544, 1982**), (**Hoff, 1987)**. Few important research works on the behavior of SFRC under torsion are briefly reviewed here.

Khan et al., (1976) tested plain SFRC specimens under pure torsion. The specimens were cast by varying the volume fraction and aspect ratio of fibers. The ultimate torsional strength increased with the increase in volume fraction of fibers and was reported as a function of fiber aspect ratio. The increase in toughness with the increase in volume fraction and aspect ratio of fibers was also reported.

Narayanan et al., (1981) tested plain SFRC specimens under the combined bending and torsion with crimped fibers. Twelve specimens were tested under pure torsion. An expression relating the split tensile strength and cube strength was derived from the test data. Authors proposed an equation to predict the ultimate torsion. An increase in the ductility with the increase in volume fraction was reported.

Mansur et al., (1982) tested plain SFRC specimens under the torsion by varying fiber aspect ratio and volume fraction. Authors used plastic theory to predict the ultimate torsional strength which was close to the test results.

Narayanan et al., (1983) proposed an equation to predict torsional strength of plain SFRC elements by modifying the expression of torsional strength of plain concrete. In this expression authors accounted the characteristics of fiber such as aspect ratio, volume fraction and bond. The effect of bond was included in terms of pull out characteristics of steel fibers.

Kareem et al., (1985, 1986) calculated the torsional strength of a reinforced-SFRC specimen by adding the resistance provided by the concrete, fibers and conventional steel. The contribution of concrete was calculated by the skew bending theory whereas the contribution of fibers was derived from the space truss analogy. Authors suggested that the contribution of conventional steel can be calculated by any established method. The theoretical prediction of torsional strength of reinforced-SFRC elements was in good agreement with the test results.

Mansur et al., (1989) tested few reinforced-SFRC specimens by varying the amount of longitudinal steel, transverse steel and fibers. Authors modified the softened truss model **(Hsu, 1988)** by incorporating the material properties of SFRC, to predict the torsional strength. Authors also accounted the tensile strength of matrix by including the constitutive relationship of SFRC in tension. An algorithm was proposed to calculate the torque-twist response of the reinforced SFRC specimens. The predicted and experimental ultimate torque and corresponding angle were close. Author reported improvement in the torsional strength and change in cracking characteristics due to the inclusion of fibers in a reinforced concrete section.

Till 1990, most of the investigations regarding SFRC under torsional actions were related to its behavioral aspects. There were no clear-cut design stipulations for the SFRC elements under torsional loads. **Nanni (1990)** proposed a design approach based on available literature. In the first part of paper, literature available on the torsional behavior of plain SFRC and reinforced SFRC was presented. The behavioral response of these elements was critically reviewed by the author. In second part, the design stipulations for rectangular reinforced-SFRC section were proposed. It was based on the observed behavior and torsion design stipulation proposed by ACI 318-89. The proposed design procedure was then compared with available test results. The design solution was found upper bound.

T.D.Get al., (2002) presented a thorough investigation of reinforced- SFRC elements under pure torsion. Plain and reinforced-SFRC elements were cast by varying the concrete strength, cross-sectional aspect ratio and volume fraction of fibers. An expression for the ultimate strength of plain- SFRC was proposed by the author. The torsional rigidity in pre-cracking stage of reinforced-SFRC specimen was assumed same as that of the plain-SFRC elements. The cracking torque of reinforced-SFRC elements was assumed equal to the ultimate torsional capacity of the plain-SFRC elements. Author used softened truss model to define the post-cracking behavior of reinforced- SFRC elements. A design methodology was proposed for the reinforced-SFRC elements to resist the torsional load. Author also presented failure mode diagrams and strength contours for reinforced-SFRC section as a design aid.

Seshu et al., (2003) studied the behavioural aspect of the steel fiber reinforced concrete by testing twenty plain SFRC specimens under pure torsion. The cross-sectional dimension of the specimens was kept same whereas the volume fraction of the fibers and compressive strength of concrete were varied. Authors reported an increase in ultimate torsional strength, torsional toughness and torsional stiffness with increase in fiber content. A prediction equation similar to the elastic theory was forwarded. Coefficient ‘α’ of proposed equation was calculated by an empirical equation.

T.D.G et al., (2005) presented an analytical model for the torsional strength of reinforced-SFRC elements under pure torsion. St. Venant’s equations were adopted to derive the torque-twist response in the pre-cracking stage. The cracking strength of a reinforced SFRC section was assumed to be equal to the ultimate strength of plain-SFRC. In posting-cracking range, the behaviour was predicted by the softened truss model. The equilibrium and compatibility equations were same as proposed by the **Hsu (1988)**, however, the material properties were modified to include the SFRC characteristics. The tensile strength of SFRC was included by considered the constitutive law. The softening coefficient proposed by **Veechio et al., (1996)** was used. Authors validated the proposed model by testing fifteen reinforced-SFRC specimens.

Chalioris et al., (2006) have studied the torsional behaviour of RC members with behaviour model and experimental study. To predict torsional behaviour in this investigation author had a combined approach of smeared crack analysis and softened truss model. In experimental study, author has varied the spacing of transverse reinforcement and height to width ratio of the beam. A good agreement was observed between experimental results and predicted approach.

Reza et al., (2009) have investigated the torsional behaviour of concrete with carbon fiber reinforced polymer. Carbon fiber reinforced polymer (CFRP) sheet wrappings were used in different configurations in full and strip wrappings. The contribution of CFRP towards the strengthening of torsional behavioral of concrete is been studied. Three different ratios of longitudinal to transverse reinforcements were used in this investigation. The authors reported that the torsional behaviour of beams strengthened by one ply and two plies of CFRP sheet was close to various steel reinforcements ratios, in comparison to increase with amount of steel reinforcement. The beams with higher amount of total torsional reinforcement had higher torsional capacity for a given twist angle. The beams with higher amount of torsional reinforcements failed at higher levels of ultimate torque and strain.

Eisa et al., (2014) have investigated the effect of hooked steel fiber on SCC under combined bending and torsion. Six beams were cast and tested by varying dosage of steel fiber and longitudinal reinforcement. Significant increase in ductility and toughness was observed in post-cracking zone of beams with steel fibers. Torsional capacity of high strength SCC with fibre volume fraction of 1.5 % has increased upto 30 % in comparison to beams without steel fibers. The validation of experimental results is done using finite element analysis in ANSYS software. The results of FEM analysis have underestimated ultimate loads of experimentally tested beams by 7-13 %. This closeness of results between FEM and experiments indicate that ANSYS software can be used to predict the load carrying capacity of high strength steel fiber reinforced SCC.

Behara et al., (2015) have studied the torsional behaviour of concrete by providing ferrocement U-Jacketing experimentally. The parametric variation in this investigation is the number of mesh layers with four possible cases of torsion by varying longitudinal and transverse reinforcements. The experimental results have shown that the effect of three mesh layers on ultimate torque was nearly equal to four and five mesh layers. It was noted in all states of torsion U warps have provided better torque carrying capacity. Better rotation capacity was shown by under reinforced beams whereas, completely over-reinforced beams had effective resistance towards torque.

Lokesh et al., (2015) have studied the torsional behaviour of recycled aggregate concrete beams experimentally. Recycled aggregate is obtained from demolished building waste of 35 year old. The percentage of replacement is varied from 0 to 100 % with a regular increment of 25 %. The experimental results showed that uniaxial compression strength decrease with the increase of RA dosage. It was also noted that, coarse aggregate replacement of 50 % doesn't affect the torsional strength more than 10 % whereas, complete replacement of recycled aggregates adversely affect torsional behaviour of concrete.

Abdelrazik et al., (2016) have investigated the effect of types of fibers on mechanical and crack resistance of super workable concrete (SWC). The enhancement of crack resistance is studied for two different fiber volumes. Hook end steel fibers of 3D, 4D, 5D and polypropylene fibers were added in different combinations. Mixtures with low fiber factor possessed lower flow and passing ability than similar mixtures with higher fiber factor. Hookend 5D with 0.75 % dosage by volume of concrete had significant performance in all nine mixes of different fiber combinations. Significant increase is observed in toughness of SWC mixes with 5D hookend fibers in all dosages of fiber volume.

2.4 Summary of Literature Review:

From a detailed literature review on SCC, it was evident that SCC is new type of concrete can compact in to every corner of formwork by means of its self-weight. There is abundant amount of literature available on SCC. Usage of recycled aggregates in concrete as a replacement of natural aggregates is now gaining importance especially in SCC. From the review of literature, it was found that the use of recycled aggregates as substitute to natural aggregates is an effective way of handling disposal of waste concrete when used at proper replacement proportions, and also influence of steel fibers on SCC was studied. The literature available on the torsional behaviour of steel fiber reinforced SCC is very limited. The studies on the torsional behaviour of recycled aggregates based steel fiber reinforced SCC are very less. The validation of torsional behaviour of fiber reinforced SCC and VC using FEM is scant.

Based on the detailed literature review, scope and objectives are formulated along with detailed research methodology and is presented in the chapter-3

Chapter 3 Scope and Objectives

3.0 General

A detailed literature review has been carried out with an aim to study the influence of steel fibers on improving the torsional behaviour of both natural aggregate and recycled aggregate based SCC. The following points were observed.

- The use of steel fibers in concrete can greatly enhance the tensile and torsional strength and also change the sudden brittle failure mode to a ductile mode.
- SCC has numerous advantages including concreting in difficult environments and congested reinforcements. This type of special concrete has large scope in structural applications.
- Hooked end steel fibers can improve the mechanical properties of concrete significantly better than straight and crimped steel fibers.
- Effect of steel fibers on torsional behaviour of SCC needs to be investigated.
- Effect of shape and aspect ratio of steel fiber on torsional behaviour of Steel fiber reinforced Self Compacting Concrete (SFRSCC) can be studied.
- The torsional behaviour of SFRSCC with the usage of recycled coarse aggregates as partial replacement for natural aggregates has to be investigated.
- Analytical modelling using a Finite element based software can be used in studying the torsional behaviour of SCC and vibrated concrete (VC) for both natural and recycled aggregates.
- Studies on torsional behaviour of steel fibers are limited to vibrated concrete only. Studies on torsional behaviour of SCC and SFRSCC is scant and the available models in the literature on vibrated concretes needs to be complemented and supplemented for SCC based on experimental work.

3.1 Scope and Objectives of the Investigation

The scope of the present investigation includes:

- Evaluation of fresh and hardened properties of steel fiber reinforced SCC for various dosages of steel fibers and thus maximizing the dosage of steel fibers.
- Develop an analytical model for predicting the torsional strength of steel fiber reinforced self compacting concrete (SFSCC) and Vibrated concrete (SFVC) with natural aggregates.
- Develop analytical model for predicting the torsional strength of steel fiber reinforced vibrated concrete (SFVC) with natural aggregates and recycled coarse aggregates.
- Numerical modelling of steel fiber reinforced using a finite element software ATENA doe both SCC, VC and validate based on experimental results.
- To establish an equation to predict the torsional strength for SCC and VC with and without recycled aggregates.

The following objectives have been formulated to study and validate the use of steel fibers reinforced SCC to evaluate the torsional behaviour.

1. To evaluate the fresh and hardened properties of natural aggregate and recycled aggregate based steel fiber reinforced SCC.
2. To predict the torsional behaviour of natural aggregate based steel fiber reinforced SCC and VC.
3. To enumerate the torsional behaviour of recycled aggregate based steel fiber reinforced SCC and VC.
4. To validate the experimental results with those obtained from finite element software ATENA.

3.2 Research Methodology

To achieve the above objectives and keeping in view the scope of the research work, a detailed experimental program was planned and the work was divided into four phases.

The parameters of investigation include

Type of concrete	-	Self-Compacting Concrete (SCC) and Vibrated Concrete (VC).
Strength of concrete	-	20 MPa, 50 MPa and 80 MPa.
Dosage of steel fibers	-	0%, 0.25%, 0.5%, 0.75% and 1% by volume of concrete- for maximizing fiber dosage
Aspect ratio of steel fibers	-	50 (length= 25 mm, diameter = 0.5 mm), 70 (length= 35 mm, diameter = 0.5 mm) and 100 (length= 50 mm, diameter = 0.5 mm).
Type of aggregate	-	Natural aggregate (NA) and Recycled Coarse Aggregate (25% replacement) (RCA).
Dosage of steel fiber	-	0 % and 0.5 % (maximum dosage of fiber)-adopted for casting of beams.

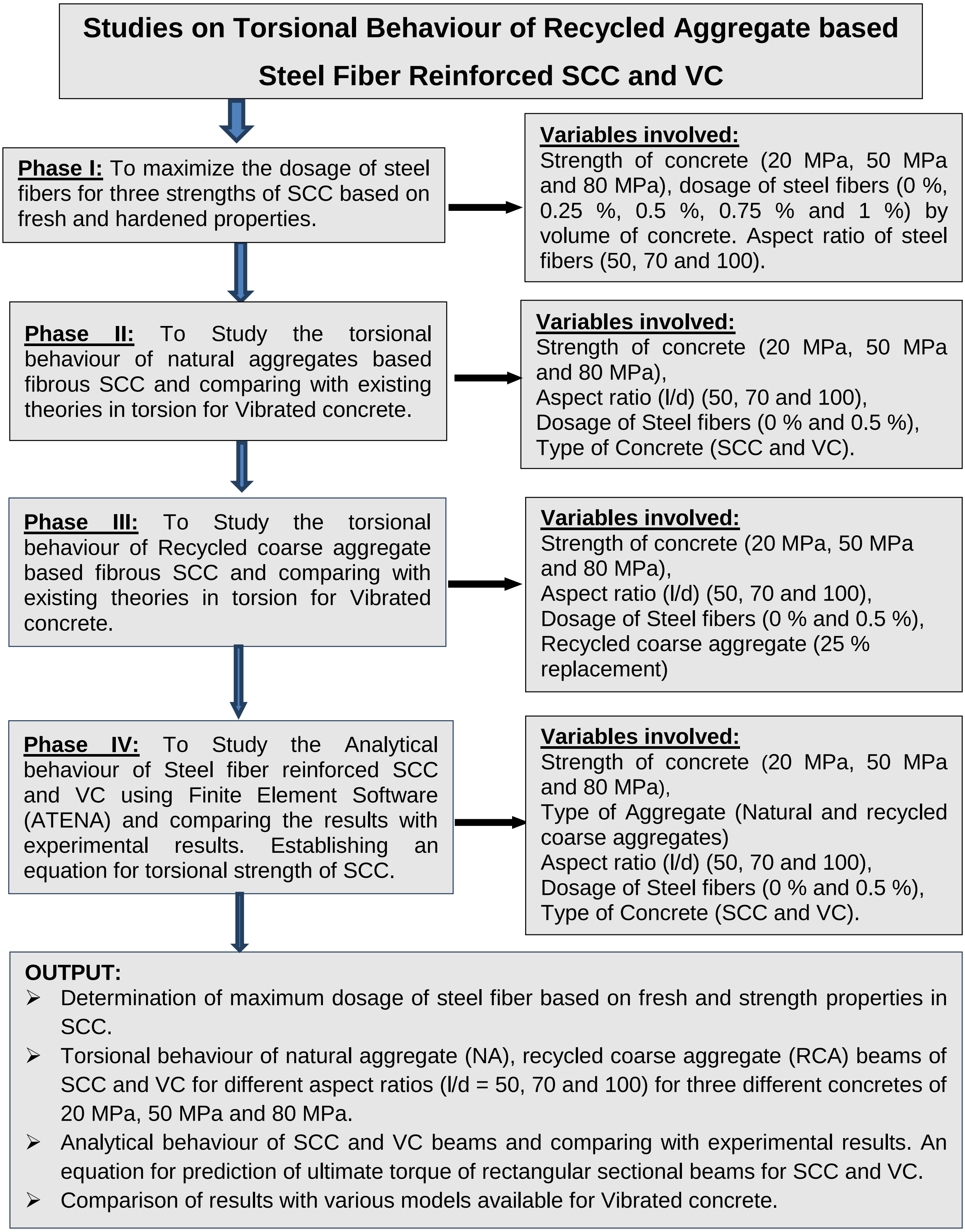


Figure 3.1 Schematic Diagram of the Research work

3.3 Detailed Research Methodology

3.3.1 Phase - I:

Studies were carried out on fresh and hardened properties of steel fiber reinforced self-compacting concrete for various dosages of hooked end steel fibers (0 %, 0.25 %, 0.5 %, 0.75 % and 1 % by volume of concrete) for three strengths i.e. 20 MPa, 50 MPa and 80 MPa with fiber aspect ratio 50, 70 and 100. Based on the fresh and hardened properties of SCC, maximum dosage of steel fibers was determined. Various tests were conducted to evaluate the fresh properties of SCC including slump flow test, V-funnel test, V-funnel at T_5 min and J-ring test. The hardened properties included compressive strength, split tensile strength and flexural strength. The mix proportions for SCC are designed by using NanSu method of mix design. The major outcome from this phase is maximum dosage of steel fibers in three strengths of SCC 0.5 % by volume of concrete. With the maximum dosage of fibers (0.5 % by volume of concrete) the split and flexural strengths are increased. The details of specimens cast for phase-I is shown in Table. 3.1.

Table 3.1 Details of the specimens cast for Phase-I

Strength of concrete	Dosage of steel fibers (%)	Cubes				Cylinders				Prisms			
		Aspect Ratio				Aspect Ratio				Aspect Ratio			
		Plain	50	70	100	Plain	50	70	100	Plain	50	70	100
A-20 MPa	0	3				3				3			
	0.25	3	3	3	3	3	3	3	3	3	3	3	3
	0.5	3	3	3	3	3	3	3	3	3	3	3	3
	0.75	3	3	3	3	3	3	3	3	3	3	3	3
	1	3	3	3	3	3	3	3	3	3	3	3	3

The above mixes (180 no’s) were cast for 20 MPa strength concrete. Similarly, specimens were cast and tested for B-50 MPa and C-80 MPa strengths respectively.

3.3.2 Phase - II:

Detailed studies were carried out on torsional behaviour of natural aggregate based self compacting concrete and vibrated concrete for three aspect ratios (l/d= 50, 70 and 100) of hooked end steel fibers. The maximum dosage of steel fibers obtained from Phase-I was used to study the effect on the torsional behaviour of 20 MPa, 50 MPa and 80 MPa strength SCC and VC along with plain beams. The beams of width 100 mm, depth 200 mm and length 2300 mm were cast along with three companion standard cubes (150 x 150 x 150 mm) and cylinders (150 mm diameter and 300 mm height) as shown in Table-3.3. Companion cubes and cylinders were cast and tested to obtain the compressive and split tensile strength respectively. To correlate the experimental results obtained from tests on beams, existing theories on torsion available in literature were considered to predict the torsional strength of SCC. The nomenclature of the specimens cast is shown in Table-3.2.

Table 3.2 Nomenclature of Specimens Cast and Tested for Mix A

A-VC Plain	Mix A – Vibrated Concrete without steel fibers
A-SFVC 50	Mix A – Vibrated Concrete with steel fibers of aspect ratio 50
A-SFVC 70	Mix A – Vibrated Concrete with steel fibers of aspect ratio 70
A-SFVC 100	Mix A – Vibrated Concrete with steel fibers of aspect ratio 100
A-SCC Plain	Mix A – SCC without steel fibers
A-SFSCC 50	Mix A – SCC with steel fibers of aspect ratio 50
A-SFSCC 70	Mix A – SCC with steel fibers of aspect ratio 70
A-SFSCC 100	Mix A – SCC with steel fibers of aspect ratio100

Similar nomenclature was followed for mixes B (50 MPa) and C (80 MPa) of Natural and Recycled coarse Aggregate based SCC and VC with 0.5 % dosage (volume of concrete) of steel fibers.

Table 3.3 Details of the specimens cast for Phase-II

S.No.	Beam Designation	Strength of concrete (MPa)	Aspect ratio of steel fiber	Type of Concrete
1	**A-VC Plain**	20	-	Vibrated Concrete
2	**A-SFVC 50**	20	50	Vibrated Concrete
3	**A-SFVC 70**	20	70	Vibrated Concrete
4	**A-SFVC 100**	20	100	Vibrated Concrete
5	**A-SCC Plain**	20	-	SCC
6	**A-SFSCC 50**	20	50	SCC
7	**A-SFSCC 70**	20	70	SCC
8	**A-SFSCC 100**	20	100	SCC

The above beams (8 no's) were cast for 20 MPa strength concrete. Similarly 16 more beams were cast and tested for 50 MPa and 80 MPa strengths respectively.

3.3.3 Phase - III

In third phase of work, studies were carried out on torsional behaviour of recycled concrete coarse aggregate based steel fiber reinforced SCC and vibrated concrete for three aspect ratios (l/d= 50, 70 and 100) of hooked end steel fibers. The experimental programme is similar to that of the phase-II. The Recycled Concrete Aggregates (RCA) used in this investigation was obtained by crushing old specimens of concrete cubes, beams and slabs available in concrete laboratory of the National Institute of Technology Warangal. Before using the aggregates, they were crushed in a jaw crusher and later washed to remove any unwanted substances. The aggregates were presoaked for 30 minutes and brought to Saturated Surface Dry (SSD) condition before using into concrete. 25% RCA was used as replacement for natural coarse aggregates. The detail of specimens cast in this phase was shown in Table-3.4. The experimental results are predicted by using the existing theories available in literature.

3.3.4 Phase - IV

In this phase of work, analytical modelling was performed using finite element software ATENA-GID to study the torsional behaviour of steel fiber reinforced SCC and VC for both natural and recycled coarse aggregates. The effect of three aspect ratios (l/d= 50, 70 and 100) of hooked end steel fibers on 20 MPa, 50 MPa and 80 MPa concretes (both SCC and VC) was evaluated. The analytical results obtained by performing non-linear analysis using ATENA GID software were compared with the experimental results obtained from earlier studies.

Table 3.4 Details of the specimens cast for Phase-III

S.No.	Beam Designation	Strength of concrete (MPa)	Aspect ratio of steel fiber	Type of Concrete
1	**A-RVC Plain**	20	**-**	Vibrated Concrete
2	**A-RSFVC 50**	20	50	Vibrated Concrete
3	**A-RSFVC 70**	20	70	Vibrated Concrete
4	**A-RSFVC 100**	20	100	Vibrated Concrete
5	**A-RSCC Plain**	20	-	SCC
6	**A-RSFSCC 50**	20	50	SCC
7	**A-RSFSCC 70**	20	70	SCC
8	**A-RSFSCC 100**	20	100	SCC

The above beams (8 no's) were cast for 20 MPa strength concrete. Similarly 16 more beams were cast and tested for 50 MPa and 80 MPa strengths respectively.

Chapter 4 Mechanical Properties of Steel fiber reinforced SCC

4.0 General:

Based on objectives defined in previous chapter, entire research investigation is divided into four phases. In the first phase, the work is intended to maximizing the dosage of steel fibers ranging from 0 % to 1 % by volume of concrete for three different strengths of concrete (20 MPa, 50 MPa and 80 MPa). In this chapter, fresh and hardened properties of steel fiber reinforced SCC are presented.

4.1 Mechanical Properties of Steel fiber reinforced SCC:

4.1.1 Development of SCC

In the first stage, fresh and hardened properties were evaluated with the mix proportions of self compacting concrete developed by using Nan-Su method. SCC was developed by various trails with the super plasticizer and admixtures content till fresh and hardened properties were achieved. Fresh properties are evaluated by using slump flow, V-funnel, J-ring tests to check the passing ability, filling ability and segregation resistance respectively as per EFNARC specifications. Three mixes of concrete 20 MPa, 50 MPa and 80 MPa were considered in the present study. To study the mechanical properties such as compressive, split tensile and flexural strength, standard cube mould of size 150 x 150 x 150 mm, 150 mm diameter and 300 mm height cylinders and prisms of size 100 x 100 x 500 mm specimens respectively were cast as per IS 516: 2013 (Re affirmed).

4.1.2 Development of Steel fiber reinforced SCC

In the second stage, steel fiber reinforced SCC with hook end fibers was developed for different dosages and aspect ratios. Dosage of steel fibers is varied from 0 % to 1 % by volume of concrete with a constant increment of 0.25 %. Three different aspect ratios are used such as 50 (0.5 mm diameter, 25 mm length), 70 (0.5 mm diameter, 35 mm length) and 100 (0.5 mm diameter, 50 mm length) for three different mixes of concrete i.e. 20 MPa, 50 MPa and 80 MPa. Table 4.1 shows the details of specimens of cast and tested. Fresh properties were evaluated for each aspect ratio and dosage of steel fiber. It was noted that with the increase of dosage and aspect ratio of hookend steel fibers, there is a decrease in fresh properties. The hardened properties such as compressive, split tensile and flexural strength were evaluated after 28 days of curing.

Table 4.1 Details of SFRSCC Specimens cast in Phase-I

Strength of concrete	Dosage of steel fibers (%)	Cubes				Cylinders				Prisms			
		Aspect Ratio				Aspect Ratio				Aspect Ratio			
		Plain	50	70	100	Plain	50	70	100	Plain	50	70	100
A-20 MPa	0	3				3				3			
	0.25	3	3	3	3	3	3	3	3	3	3	3	3
	0.5	3	3	3	3	3	3	3	3	3	3	3	3
	0.75	3	3	3	3	3	3	3	3	3	3	3	3
	1	3	3	3	3	3	3	3	3	3	3	3	3

The above mixes (180 no's) were cast for 20 MPa strength concrete. Similarly, specimens were cast and tested for B-50 MPa and C-80 MPa strengths respectively.

4.2 Materials Used:

4.2.1 Cement:

Ordinary Portland cement of 53 grade conforming to IS: 12269-2013 with particle size of 90 µ has been used in the present investigation. The specific gravity, standard consistency are 3.12 and 32 % respectively.

4.2.2 Fine Aggregate:

Locally available river sand conforming to Zone-II as per IS: 383-2016 has been used. The bulk density, specific gravity, and fineness modulus of the sand were 1.41 g/cc, 2.68, and 2.9 respectively.

4.2.3 Coarse Aggregate:

Crushed granite aggregate of maximum 16 mm size conforming to IS: 383-2016 has been used. The bulk density, specific gravity and fineness modulus of the coarse aggregate were 1.46 g/cc, 2.7 and 7.1 respectively.

4.2.4 Recycled Coarse Aggregate (RCA):

The RCA used in this study was obtained by crushing the tested specimens of concrete cubes and beams available in concrete laboratory of National Institute of Technology, Warangal. Before using, the aggregates were washed with water to remove any unwanted substances and pre-soaked for 30 minutes and then air-dried. The bulk density, specific gravity and fineness modulus of the coarse aggregate used were 1.308 g/cc, 2.53 and 7.15 respectively.

4.2.5 Fly ash:

Fly ash of Class F conforming to IS: 3812: (Part-II)-2003 obtained from Ramagundam thermal power plant (India) with a specific gravity of 2.18 and fineness of 6422 cm^2/gm was used.

4.2.6 Micro silica:

Micro silica conforming to IS: 15388, (Part-II)-2003 obtained from Elkem company with size of 150nm and specific gravity of 2.22 has been used. The dosage of Micro silica was 8 % and 5 % for by weight of cement in 80 MPa for SCC and VC respectively.

4.2.7 Chemical Admixture:

Modified polycarboxylate ether based superplasticizer confirming to IS 9103-2004 was used. The product name is Chryso Fluid optima S-815. Optimum dosage is confirmed by various trail mixes.

4.2.8 Steel Fibers:

Plain galvanized steel fibers of hook end type confirming to ASTM A820 from Stewols India Private Limited, (India) with aspect ratio 50 (0.5 mm diameter, 25 mm length), 70 (0.5 mm diameter, 35 mm length) and 100 (0.5 mm diameter, 50 mm length) as shown in figure 4.4 were used. Fibers of all aspect ratios had yield strength of 275 MPa.

4.2.9 Water:

Potable water is used for mixing and curing of concrete as per IS 456-2005.

4.3 Mix Proportioning:

The mix proportions for Self Compacting Concrete (SCC) are obtained by using Nan Su design method. The details of mix proportions are presented in Table 4.2. Trial mixes are carried out by varying the super plasticizer dosage and binder content. The fresh properties are evaluated according to EFNARC specifications.

Table 4.2 Quantities (kg/m^3) of 20 MPa, 50 MPa & 80 MPa grade SCC

Mix	Cement	Fly ash	Silica fume	CA	FA	Water	W/b	SP
20MPa	320	200	0	800	908	200	0.38	4.73
50MPa	430	180	0	783	853	194	0.31	5.16
80MPa	500	110	40	775	800	190	0.29	6.03

4.4 Experimental Work:

4.4.1 Test methods for evaluation of fresh properties of SCC:

Fresh SCC must possess the key properties like filling ability, passing ability and resistance to segregation at required levels. The filling ability is the ability of SCC to flow into all spaces within the formwork under its own weight. Without vibrating the concrete, SCC has to fill any space within the formwork and it has to flow in horizontal and vertical directions without keeping air entrapped inside the concrete or at the surface. Passing ability is the ability of SCC to flow through tight openings such as gap between steel reinforcing bars, under its own weight. Passing ability is required to guarantee a homogenous distribution of the components of SCC in the vicinity of obstacles. The resistance to segregation is the resistance of the components of SCC to migration or separation and remains uniform throughout the process of transport and placing. To satisfy these conditions EFNARC (2005) has formulated certain test procedures and details are presented below.

4.4.2 Slump flow test and $T_{500\ mm}$ Slump flow fest (Reference method for filling ability):

The slump flow test measures the flow spread and flow time T_{500mm}. The flow indicates the free, unrestricted deformability and the flow time indicates the rate of deformation within a defined flow distance. This test is used to measure the free horizontal flow of SCC on a plain surface without any obstruction. The time required for concrete to cover 50 cm diameter spread circle (T_{500mm} time) from the time the cone is lifted is noted (Figure 4.1).

4.4.3 V-Funnel Test (Alternative method to T_{500mm} for filling ability):

The V-funnel flow time is the period in which a defined volume of SCC needs to pass through a narrow opening and gives an indication of the filling ability of SCC provided that blocking or segregation do not take place. The flow time of V-funnel test is to some degree related to plastic viscosity. This test is conducted to assess the fluidity and segregation resistance of SCC. Inverted cone shaped equipment with 75 mm square opening at the bottom is used to assess the properties of mix such as unacceptable viscosity, undesirable volume of coarse aggregate, stability etc. This test is an important tool to assess the consistency of the mix. Figure 4.2 shows the equipment and the flow of concrete with uniform distribution of coarse aggregates across the spread.

4.4.4 J-ring (Reference method for filling and/or passing ability):

The J-ring test aims at investigating both the filling ability and the passing ability of SCC as shown in Figure 4.3. It can also be used to investigate the resistance of SCC to segregation by comparing test results from two different portions of sample. The J-ring test measures flow spread, flow time T_{50J} (optional) and blocking step. The J-ring flow spread indicates the restricted deformability of SCC due to blocking effect of reinforcement bars.

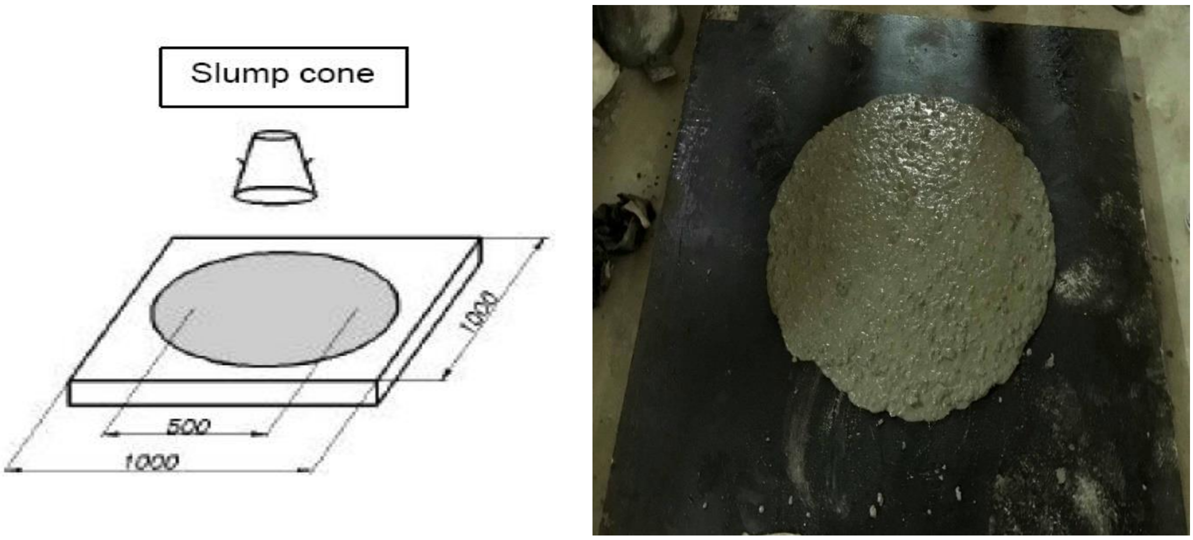
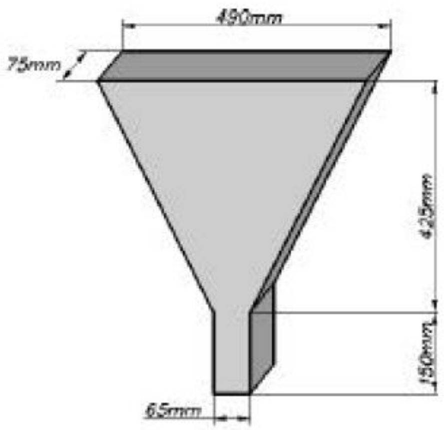


Figure 4.1 Base plate and Abrams cone (dimensions in mm) and flow of SCC



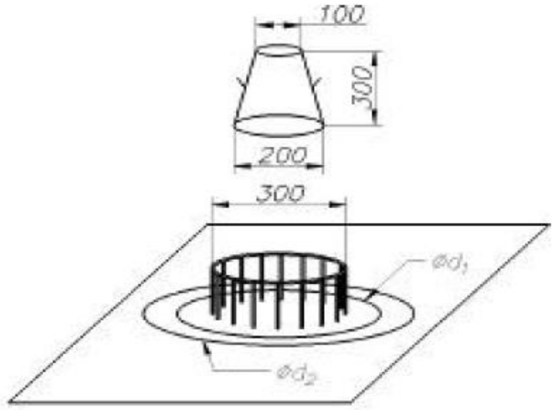


Figure 4.2 V funnel test **Figure 4.3 J-Ring Test (dimensions in mm)**

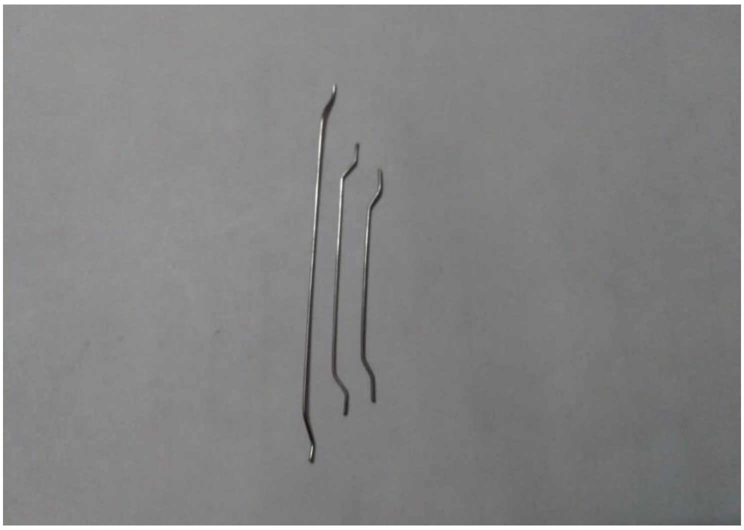


Figure 4.4 Aspect ratios of hooked end steel fibers 100, 70 and 50 respectively

Tables 4.3, 4.4 and 4.5 shows the fresh properties of 20 MPa, 50 MPa and 80 MPa SCC with aspect ratios 50, 70, and 100.

Table 4.3 Fresh properties of SCC with steel fibers of aspect ratio 50

Grade of concrete	Dosage of Steel fibers (%)	Slump Test (550-800 mm)	T_{50} Slump flow, (2-5) sec	V funnel, (6-12) sec	V funnel @ T_5 min, (6-15) sec	J-ring, (0-10) mm
20 MPa	0	760	2.3	6	9	5
	0.25	745	2.85	8	11	6
	0.5	**710**	**3.16**	**10**	**12**	**8**
	0.75	680	3.68	12	16	10
	1	640	4.71	14	18	12
50 MPa	0	780	2.54	6	8	4
	0.25	745	2.92	8	10	6
	0.5	**690**	**3.25**	**9**	**11**	**8**
	0.75	650	4.78	12	16	11
	1	580	5.37	15	19	14
80 MPa	0	755	2.59	6	9	4
	0.25	710	3.21	8	11	5
	0.5	**675**	**3.74**	**9**	**12**	**7**
	0.75	635	4.81	11	15	10
	1	560	5.60	14	18	13

Table 4.4 Fresh properties of SCC with steel fibers of aspect ratio 70

Grade of concrete	Dosage of Steel fibers (%)	Slump Test (550-800 mm)	T_{50} Slump flow, (2-5) sec	V funnel, (6-12) sec	V funnel @ T_5 min, (6-15) sec	J-ring, (0-10) mm
20 MPa	0	760	2.32	6	9	5
	0.25	725	3.12	8	11	7
	0.5	**680**	**3.69**	**10**	**12**	**8**
	0.75	620	4.21	13	16	10
	1	590	4.80	14	10	13
50 MPa	0	780	2.54	6	8	4
	0.25	730	3.12	8	10	6
	0.5	**685**	**3.64**	**9**	**11**	**8**
	0.75	625	4.80	13	17	11
	1	560	6.12	15	19	14
80 MPa	0	755	2.59	6	9	4
	0.25	695	3.31	8	11	5
	0.5	**660**	**3.94**	**9**	**12**	**8**
	0.75	610	4.95	14	16	12
	1	550	6.40	15	18	14

Table 4.5 Fresh properties of SCC with steel fibers of aspect ratio 100

Grade of concrete	Dosage of Steel fibers (%)	Slump Test (550-800 mm)	T_{50} Slump flow, (2-5) sec	V funnel, (6-12) sec	V funnel @ T_5 min, (6-15) sec	J-ring, (0-10) mm
20 MPa	0	760	2.32	6	9	5
	0.25	710	3.41	8	12	7
	0.5	**670**	**4.14**	**11**	**14**	**9**
	0.75	610	4.68	14	17	12
	1	560	5.54	15	19	14
50 MPa	0	780	2.54	6	8	4
	0.25	720	3.16	9	10	6
	0.5	**665**	**3.68**	**10**	**13**	**8**
	0.75	580	5.24	15	18	13
	1	540	6.41	17	14	14
80 MPa	0	755	2.59	6	9	4
	0.25	680	3.32	9	11	5
	0.5	**645**	**3.94**	**10**	**12**	**8**
	0.75	570	5.32	15	19	13
	1	525	6.71	18	21	15

4.4.5 Effect of steel fibers on the fresh properties of SCC:

The addition of steel fibers affects fresh state performance of concrete due to large surface area of fibers, which requires a higher volume of fluid paste or mortar to be properly surround and lubricate. Inter-particle friction and interlocking among fibers play a significant role in affecting the movement between the fibers and aggregates. It was observed that, addition of fibers had affected the flow of self compacting concrete. As the dosage of fibers increased from 0 % to 1 % by volume of concrete, flow properties decreased drastically, but they are satisfied as per EFNARC guidelines up to a dosage of 0.5 % and then decreased. It was noted that for a particular dosage of steel fiber, fresh properties were also affected due to increase in aspect ratio of steel fiber. Higher dosage with aspect ratio 100 has adversely affected flow properties of SCC. Figures 4.5 - 4.10 shows the plot among dosage of steel fibers vs slump flow and V-funnel. As the dosage increased, slump flow was reduced, similarly for V- funnel time increased.

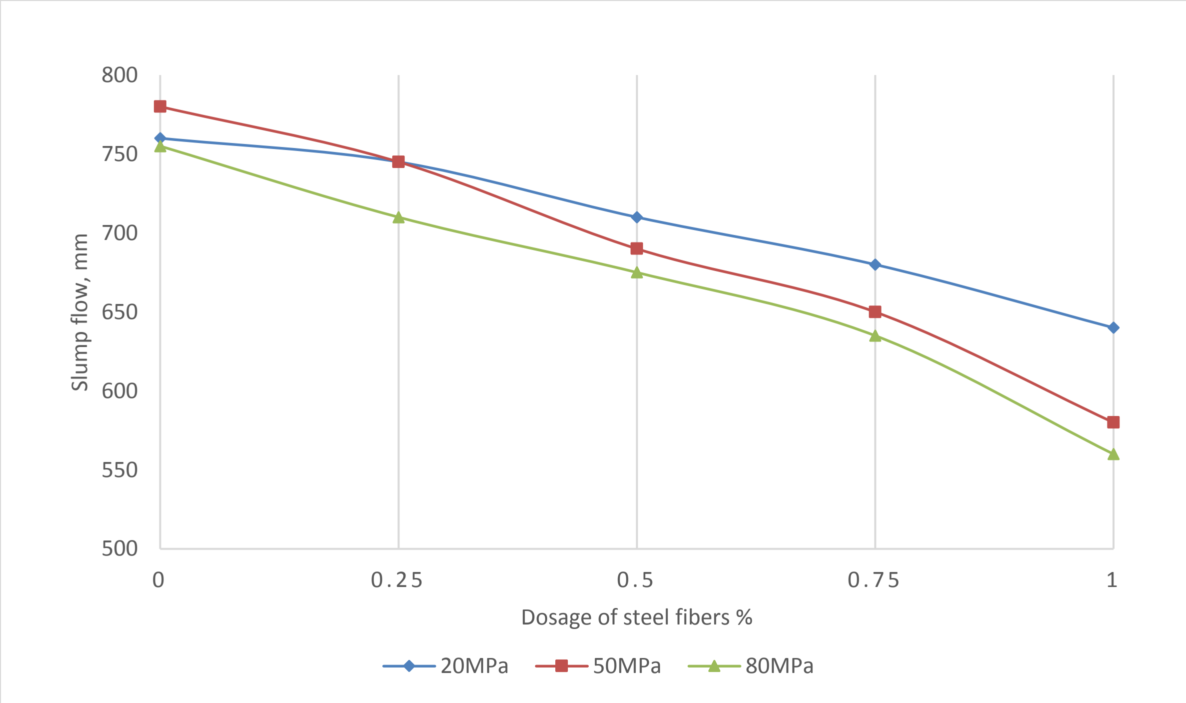


Figure 4.5 Slump Flow vs dosage of steel fiber of aspect ratio 50

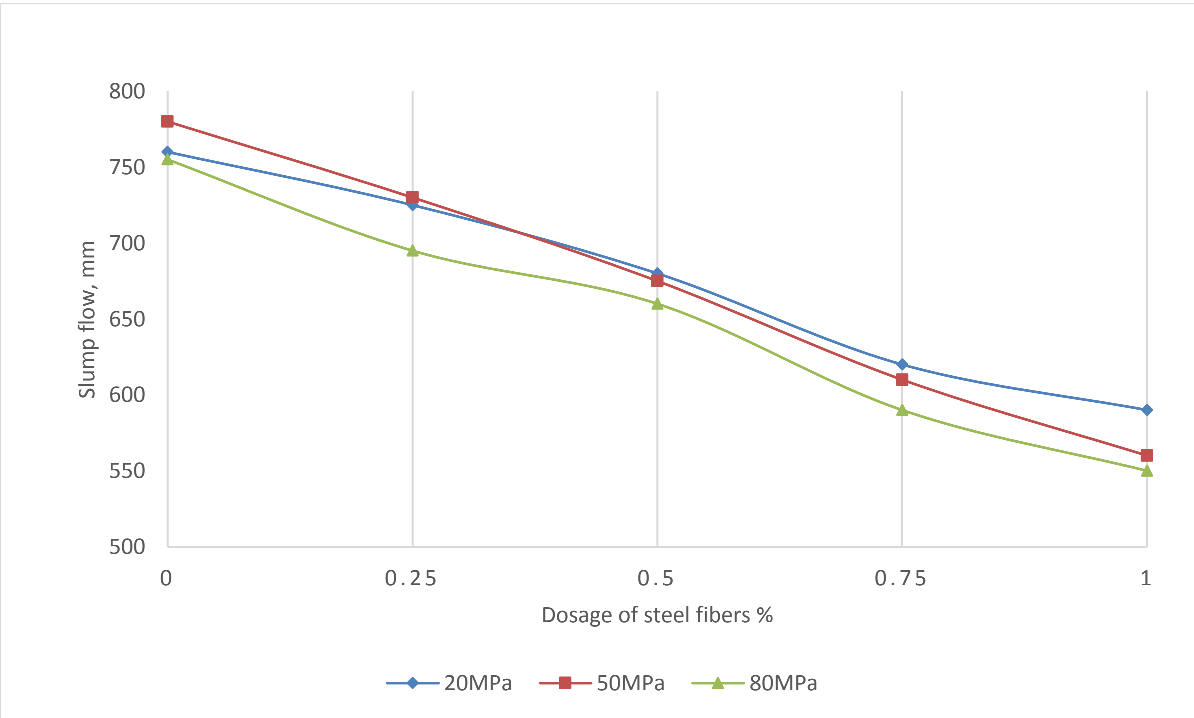


Figure 4.6 Slump Flow vs dosage of steel fiber of aspect ratio 70

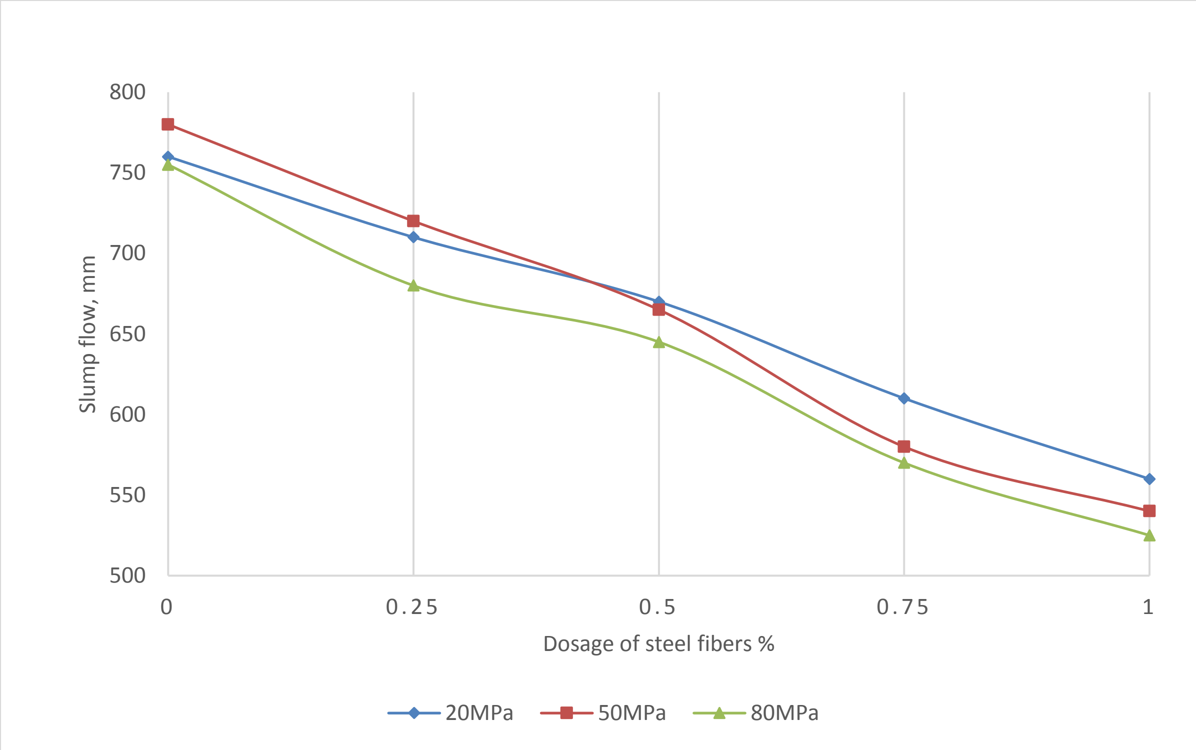


Figure 4.7 Slump Flow vs dosage of steel fiber of aspect ratio 100

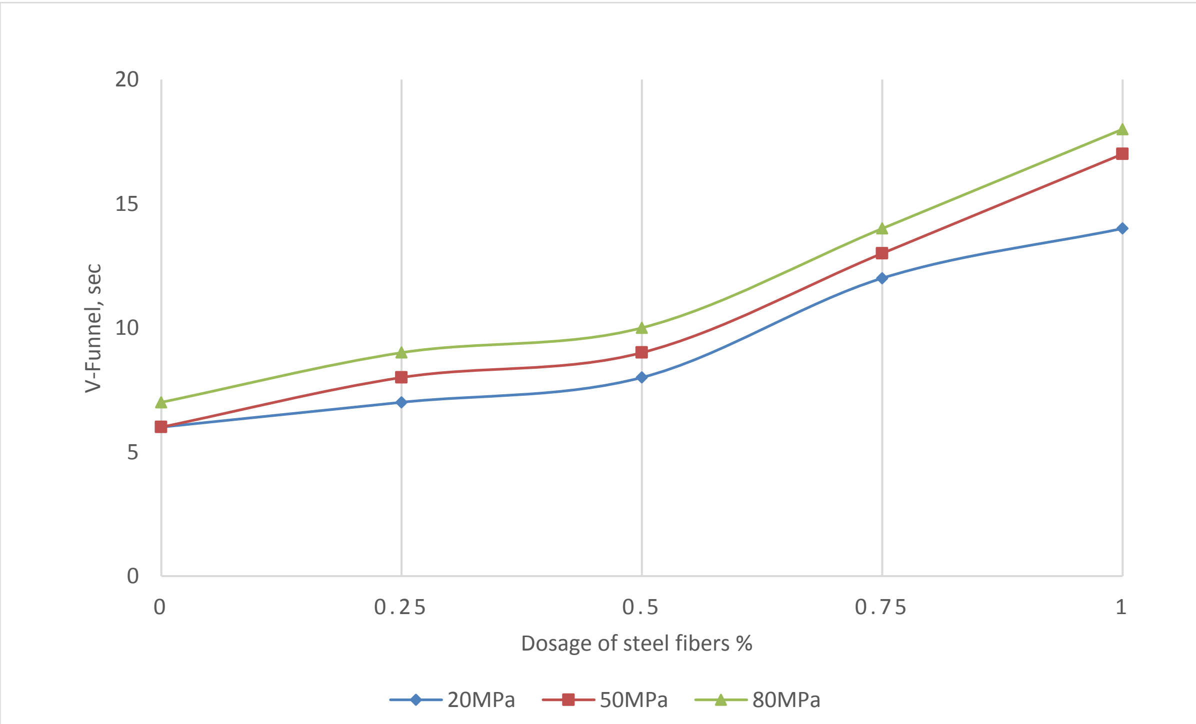


Figure 4.8 V- Funnel (time) vs dosage of steel fiber for aspect ratio 50

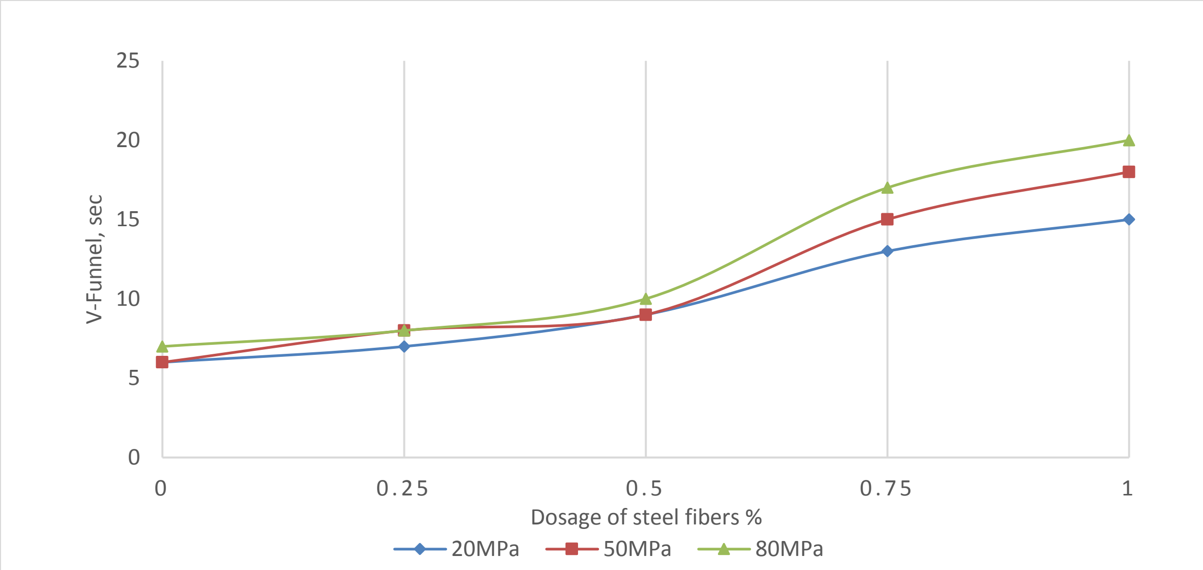


Figure 4.9 V- Funnel (time) vs dosage of steel fiber for aspect ratio 70

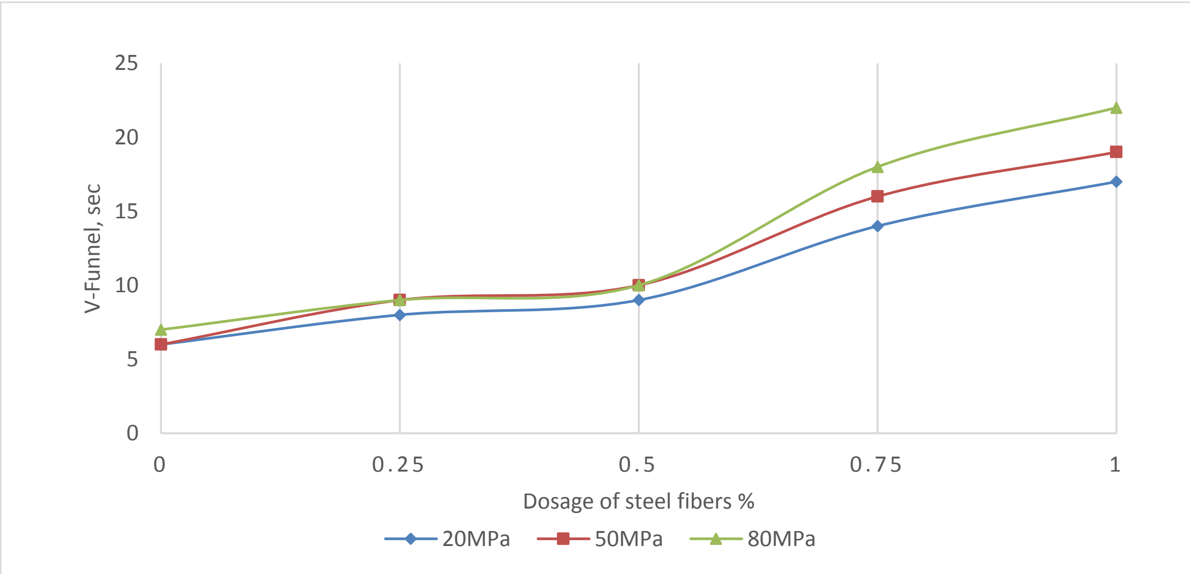


Figure 4.10 V- Funnel (time) vs dosage of steel fiber for aspect ratio 100

4.4.6 Hardened properties of SCC:

After satisfying the fresh properties of SCC, the hardened properties of three grades of concrete (20 MPa, 50 MPa and 80 MPa) were determined after 28 days of curing.

a) *Compressive strength:*

The testing was done on Universal testing machine of capacity 2000 kN in accordance with IS: 516-1956 (1999). The machine has facility to control the rate of loading with a control valve. After 28 days of curing the specimens are taken from curing pond and kept open-air till moisture content on surface of cube was evaporated. The cube specimens are placed on machine such that the load is applied centrally and to opposite sides of the cube specimens as casted. Extreme care was taken such that there is no eccentricity involved in axis of the specimen to loading frame. The smooth surfaces of specimen were placed as the bearing surfaces. The top plate is brought in contact with the specimen by rotating the handle. A uniform rate of loading is maintained without shock until resistance of specimen to the increasing load breaks down. The maximum load applied on the specimen was recorded. The appearance of concrete and any unusual features in the type of failure shall be noted.

b) *Split Tensile Strength:*

The test was carried out by placing cylindrical specimen horizontally between the loading surfaces of the compression testing machine. The axis of the specimen was carefully aligned with center of the loading frames. The load was applied and increased continuously till the specimen breaks. The maximum load was recorded. The test was performed as per IS: 516 (2013).

c) Flexural Tensile Strength:

The flexural strength of the specimen is expressed as modulus of the rupture. Three point loading method is used for testing prisms. The test specimen should be turned its sides with respect to its portion moulded and centered on bearing blades. The load applying blades shall be brought in contact with the upper surface at the third point between the supports. The strength in the bearing is the extreme fiber stress on the tensile side at the point of the failure. The test was performed as per IS: 516 (2013).

4.4.7 Discussion on hardened properties of SCC for without and with steel fibers:

Tables 4.6, 4.7 and 4.8 gives the results of compressive, split tensile and flexural strength of concrete specimens. From the test results it was noticed that as the effect of inclusion of steel fiber varies invariantly with dosage, grade of SCC and aspect ratio. The addition of steel fibers affects the fresh properties, due the large surface area of fibers which requires a higher volume of fluid paste or mortar to be properly surround and lubricate. The inter-particle friction and interlocking among the fibers as well as between the fibers and aggregates play an important role. The effect of steel fibers was significant on split and flexural properties than the compressive strength. It was observed that, addition of fibers had affected the flow of self compacting concrete.

The increase in hardened properties with respect to plain specimens was with 0.5 % dosage of steel fibers of aspect ratio 70 compared to aspect ratio 50 and 100. The increase in mechanical properties was observed from 0 to 1 % dosage of steel fiber, significant increase of 6.5 %, 16.72 %, and 27.53 % was observed in compressive, split and flexural strength respectively for 0.5 % dosage of steel fiber for 80 MPa concrete with aspect ratio 70 compared to plain specimens. In case of Standard grade SCC (50 MPa) due to addition of steel fibers with aspect ratio 70 (0.5 % volume of concrete), the compressive strength was increased by 8.37 %, split tensile strength increased by 18.09 % and flexural strength is increased by 27.53 % respectively compared to plain specimens. The compressive strength was increased by 13.39 % with maximum dosage of steel fiber 0.5 %. The split tensile strength increased by 21.37 % and the flexural strength is increased by 29.32 % for low strength concrete (20 MPa) with aspect ratio 70 compared to plain specimens.

Based on Fresh and hardened properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is the maximum dosage for self compacting concrete of three strengths. There is a good increase in the split and flexural strengths due to the fibers bridging the crack propagation and resulted in increased ultimate load carrying capacity of the specimens.

The decrease in hardened properties after 0.5 % dosage (i.e. 0.75 % and 1 %) is may be to formation of local voids due to large volume of steel fibers. The mixes with dosages of 0.75 % and 1 % could not completely satisfy EFNARC limitations despite the fact there is an increase in mechanical properties with respect to plain specimens. The effect of steel fibers is more pronounced in case of high strength SCC due to its high brittle nature. Therefore, all the fresh and hardened properties are achieved with 0.5 % dosage of steel fibers by volume in all grades of SCC.

Table 4.6 Mechanical properties of SCC with steel fibers of Mix-A

Grade of Concrete - 20 MPa						
Hardened properties	**Aspect ratio**	**Dosage of Fibers (%)**				
		0	**0.25**	**0.5**	**0.75**	**1**
Compressive strength (MPa)	**50**	22.4	23.2	**24.8**	21.4	20.2
	70		24.1	**25.4**	22.8	21.2
	100		22.9	**23.5**	20.6	19.5
Split tensile strength (MPa)	**50**	2.34	2.52	**2.71**	2.44	2.32
	70		2.68	**2.84**	2.56	2.41
	100		2.46	**2.64**	2.38	2.28
Flexural strength (MPa)	**50**	3.24	3.74	**4.08**	3.54	3.43
	70		3.92	**4.19**	3.69	3.56
	100		3.58	**3.92**	3.45	3.29

Table 4.7 Mechanical properties of SCC with steel fibers of Mix-B

Grade of Concrete - 50 MPa						
Hardened properties	**Aspect ratio**	**Dosage of Fibers (%)**				
		0	**0.25**	**0.5**	**0.75**	**1**
Compressive strength (MPa)	**50**	50.2	51.1	**52.5**	51.5	48.6
	70		52.2	**54.4**	53.7	50.4
	100		49.4	**51.6**	50.4	49.2
Split tensile strength (MPa)	**50**	3.41	3.52	**3.88**	3.6	3.42
	70		3.61	**3.98**	3.72	3.51
	100		3.6	**3.76**	3.68	3.48
Flexural strength (MPa)	**50**	4.54	5.14	**5.64**	5.28	5.04
	70		5.21	**5.79**	5.31	5.11
	100		5.12	**5.51**	5.18	4.94

Table 4.8 Mechanical properties of SCC with steel fibers of Mix-C

Grade of Concrete - 80 MPa						
Hardened properties	**Aspect ratio**	**Dosage of Fibers (%)**				
		0	**0.25**	**0.5**	**0.75**	**1**
Compressive strength (MPa)	**50**	81	81.6	**84.9**	83.2	80.8
	70		83.2	**86.2**	85.2	81.2
	100		80.1	**83.2**	81.9	79.8
Split tensile strength (MPa)	**50**	4.81	5.12	**5.52**	5.32	5.08
	70		5.24	**5.68**	5.44	5.14
	100		4.96	**5.34**	5.27	4.88
Flexural strength (MPa)	**50**	5.76	6.86	**7.16**	6.98	6.82
	70		6.92	**7.22**	7.04	6.94
	100		6.82	**7.11**	6.94	6.88

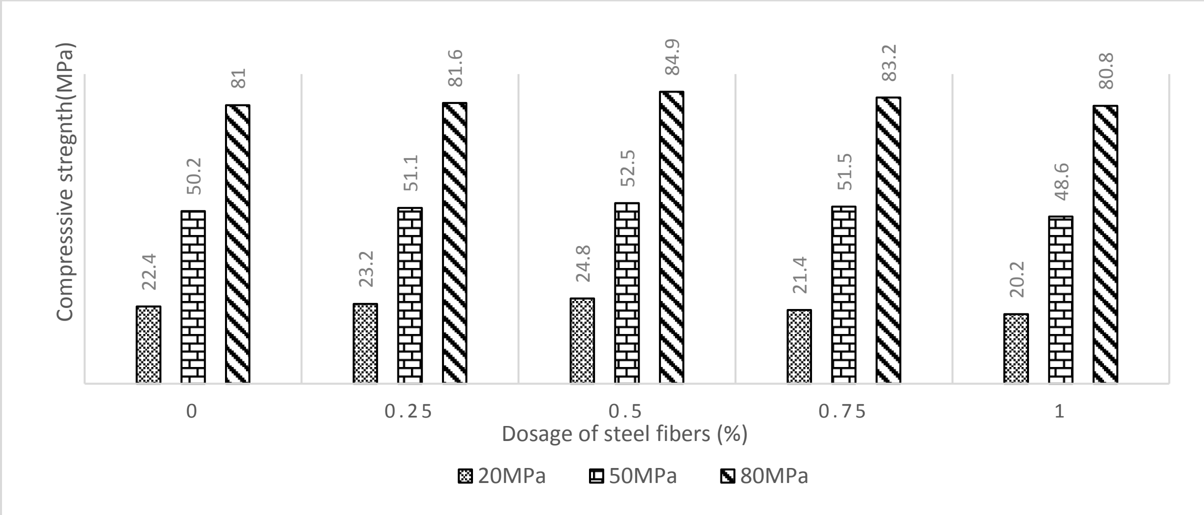


Figure 4.11 Compressive strength vs dosage of steel fiber for aspect ratio 50

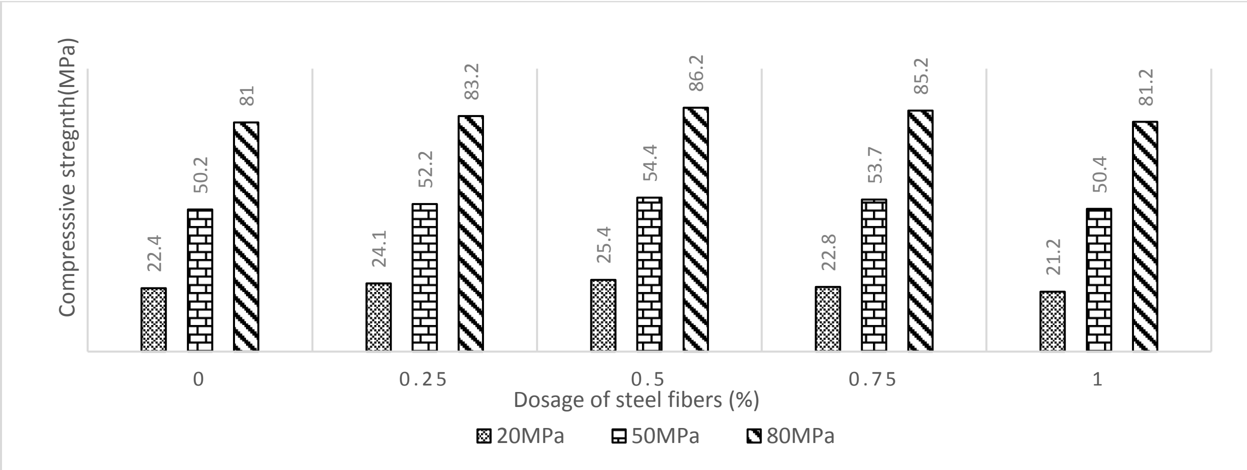


Figure 4.12 Compressive strength vs dosage of steel fiber for aspect ratio 70

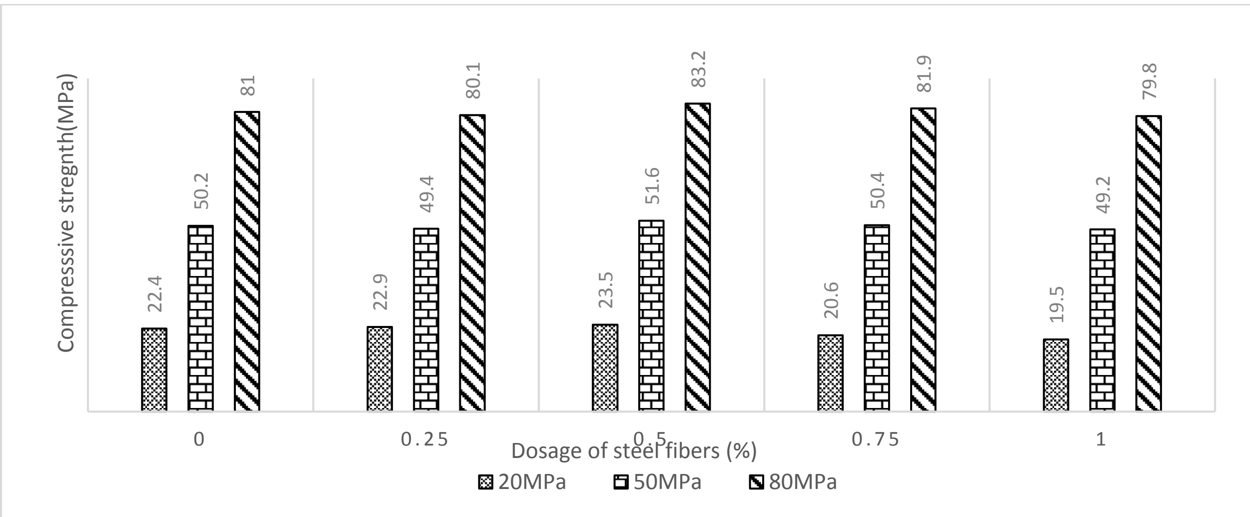


Figure 4.13 Compressive strength vs dosage of steel fiber for aspect ratio 100

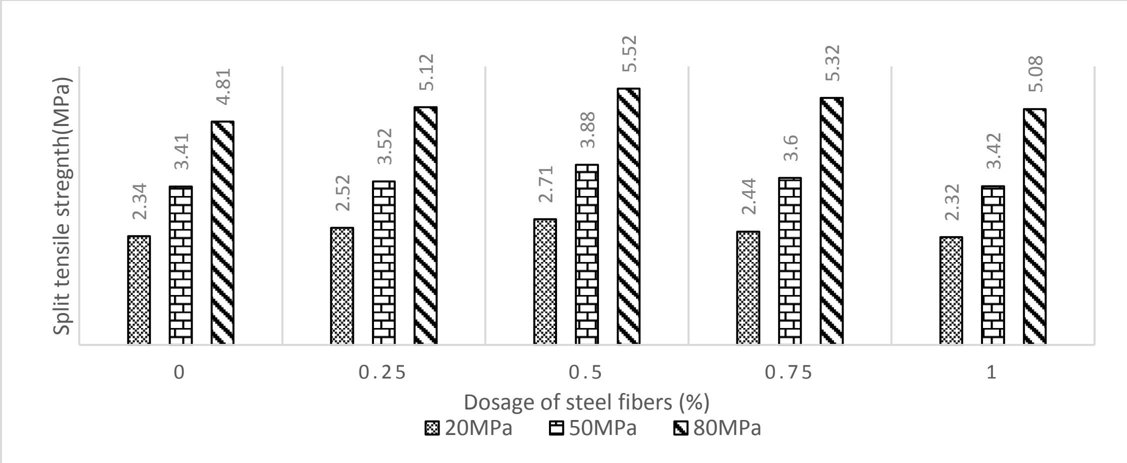


Figure 4.14 Split tensile strength vs dosage of steel fiber for aspect ratio 50

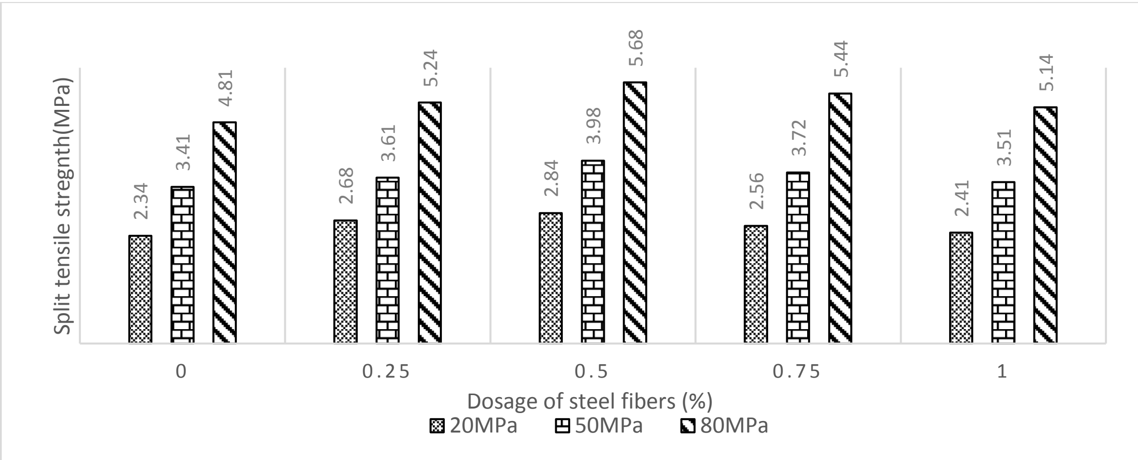


Figure 4.15 Split tensile strength vs dosage of steel fiber for aspect ratio 70

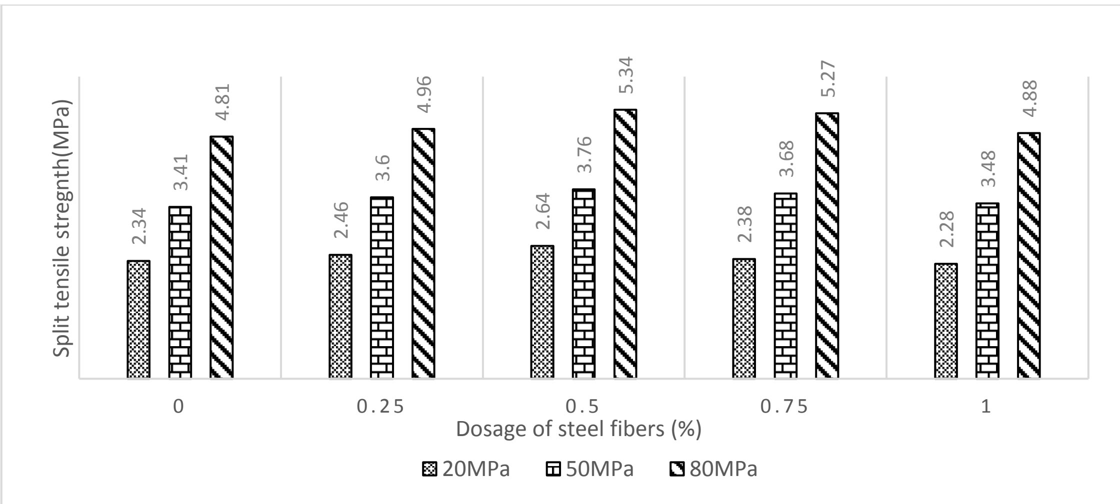


Figure 4.16 Split tensile strength vs dosage of steel fiber for aspect ratio 100

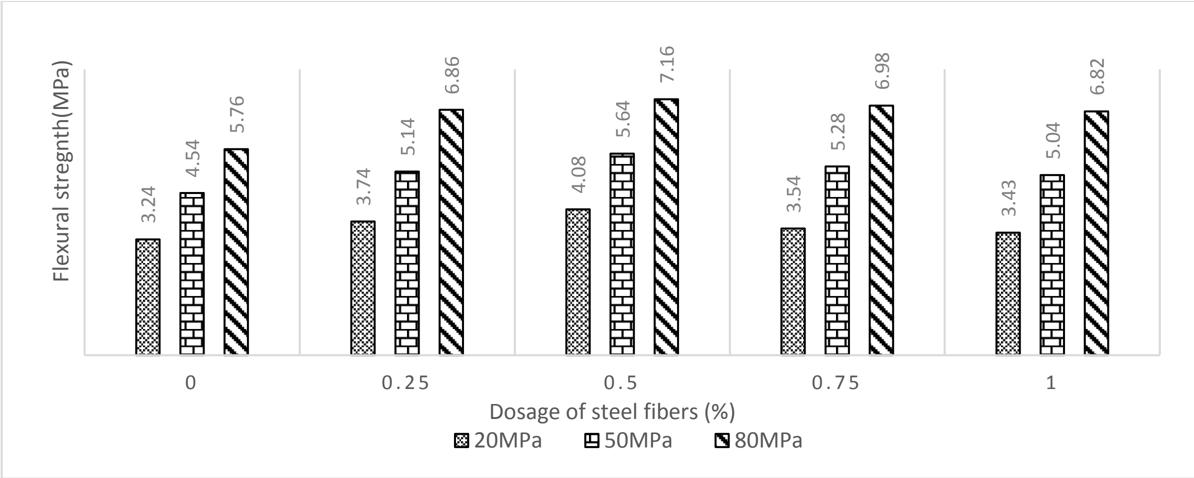


Figure 4.17 Flexural strength vs dosage of steel fiber for aspect ratio 50

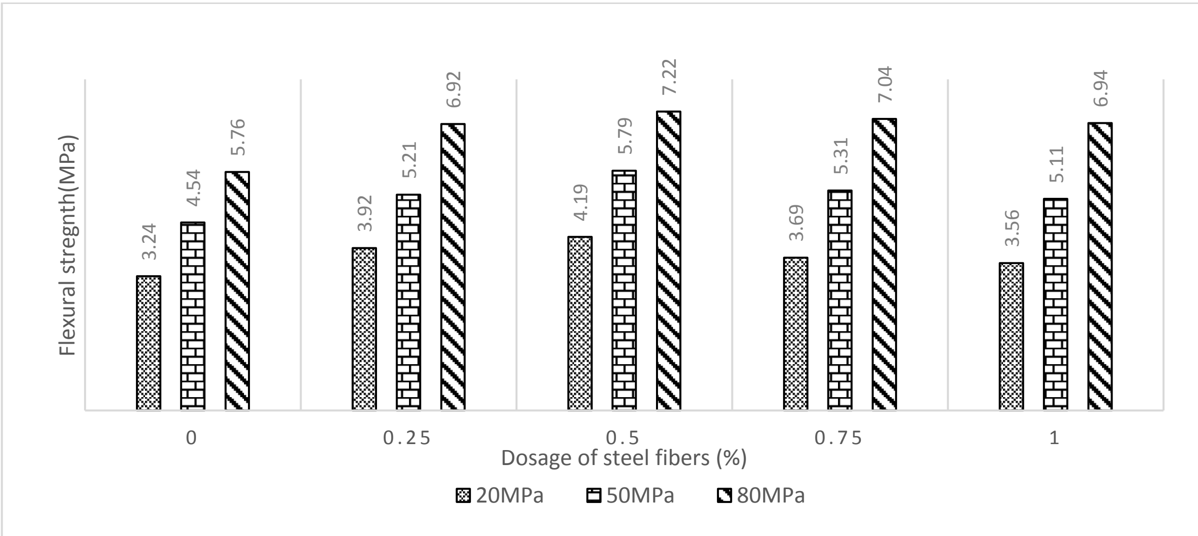


Figure 4.18 Flexural strength vs dosage of steel fiber for aspect ratio 70

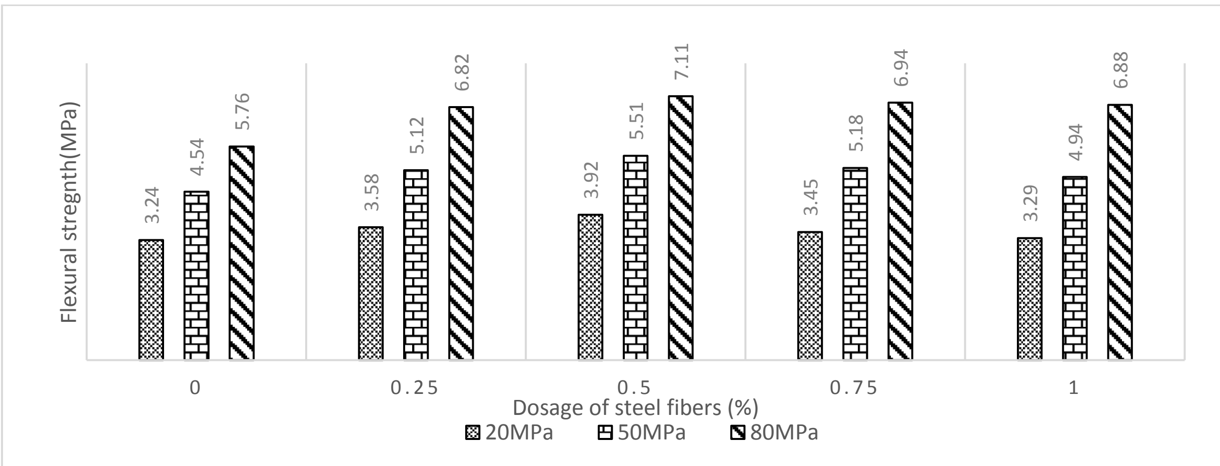


Figure 4.19 Flexural strength vs dosage of steel fiber for aspect ratio 100

4.5 Conclusions from Phase-I:

Based on the preliminary studies on the fresh and hardened properties of Self compacting concrete following conclusions were made:

1. Due to inclusion of steel fiber, fresh properties of SCC i.e. 20 MPa, 50 MPa and 80 MPa has decreased with increase in dosage.
2. There is a marginal increase in compressive strength whereas split tensile and flexural strengths increased as dosage of fibers increased.
3. Based on fresh and hardened properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is the maximum dosage for self compacting concrete.
4. As the dosage of steel fibers increased beyond 0.5 % by volume of concrete, SCC mixes were unable to satisfy EFNARC specifications. Passing and flow ability were significantly affected though required hardened properties were achieved in all three grades of SCC.
5. Due to use of steel fibers, split and flexural strengths increased gradually with the dosage of fibers. This increase can be due to the fibers bridging the crack propagation and resulted in increased ultimate load carrying capacity of the specimens and also delaying the failure of the specimens.

Chapter 5 Torsional Behaviour of Natural aggregate Steel Fiber Reinforced SCC and VC

5.0 General:

Chapter 4 dealt with the mechanical properties of steel fiber reinforced SCC for various dosages and aspect ratios of steel fibers. The studies concluded that due to use of steel fibers, sudden failure of the specimens can be avoided and also increases the tensile strength of concrete. It was also proved from the previous chapter that as the dosage of steel fibers increases, it effects the fresh properties of self compacting concrete. Further, the optimal dosage of steel fibers was also decided based on fresh and hardened properties of SCC as 0.5 % by volume of concrete.

This chapter focuses on the torsional behaviour of self compacting concrete for without and with steel fibers in comparison with vibrated concrete.

5.1 Torsional Behaviour of Steel fiber reinforced SCC and VC:

Torsional failure of conventional reinforced concrete beams usually occurs by tensile failure of concrete. Research works on torsional behavior of Steel Fiber Reinforced Concrete (SFRC) were done by **(Mansur et al., 1982, Narayan et al., 1983-1986, Hsu et al., 1985-1988, T.D.G. et al., 2003-2005, Behra 2006)**. Steel fibers are used to increase the tensile strength and torsional capacity of concrete **(T.D.G. et al., 2003)**. Steel Fiber Reinforced Concrete (SFRC) is a composite material that is characterized by enhanced post-cracking behavior due to the capacity of fibers to bridge the crack faces if they are present in sufficient amount. Researchers attempted to improve tensile strength of plain concrete by adding discrete fibers, thoroughly dispersed across the matrix. Fibers of steel, polymer, carbon etc. are used for this purpose. However, steel fibers are most commonly used because of its low cost and easy availability. Steel fibers in reinforced concrete helps in bridging crack faces, delaying the failure of specimen and increase the ultimate load carrying capacity. If added in sufficient amount the brittle failure can be modified to a ductile behavior and also reduces the crack width **(Yining et al., 2011, Narayanan et al., 1987; Hanai et al., 1997; Yang et al., 2014; Arslan et al., 2017)**.

Self Compacting Concrete (SCC) is a highly flow able and viscous concrete which does not require any external compaction during casting and placing. The Self-Compacting Concrete (SCC) may not be strong enough in shear because of some uncertainties in shear resisting, notably the aggregate interlock mechanism. Due to the presence of comparatively lesser amount and smaller size of coarse aggregate in SCC, the fracture planes are relatively smooth as compared with Normal Concrete (NC), which may reduce the shear resistance of concrete by reducing the aggregate interlock between the fracture surfaces. To overcome this defect, steel fibers can be added which can improve the crack resistance of the SCC **(Kim et al., 2012).** The difference between Steel Fiber Reinforced Self Compacting Concrete (SFRSCC) and traditional Fiber Reinforced Concrete (FRC) is that the fiber content of FRC is mainly determined by the post-cracking behaviour, and the fiber content of SFRSCC is mainly restricted by the workability of fresh SCC. SFRSCC combines the advantages of both SCC and FRC **(Cuenca et al., 2015).** However, research work on the study of SFRSCC beams, especially on the torsional behaviour of SFSCC, is still limited. The present study focuses on the torsional behaviour of steel fiber reinforced self compacting concrete.

Limited studies were reported in literature regarding the torsional behaviour of SCC and SFRSCC. The major factors considered in their studies are: 1) concrete compressive strength (f_c) 2) width/depth ratio of cross section of beam. When fibers are also included, parameters like fiber volume fraction (V_f), fiber type (material, aspect ratio, shape, etc.), also affect the torsional performance of SCC.

5.2 Experimental Programme:

Detailed studies were carried out on torsional behaviour of natural aggregate based self compacting concrete and vibrated concrete for three aspect ratios (l/d= 50, 70 and 100) of hooked end steel fibers. The optimal dosage obtained from Phase-I was used to study the effect on the torsional behaviour of 20 MPa, 50 MPa and 80 MPa strength SCC and VC along with plain beams. The beams of width 100 mm, depth 200 mm and length 2300 mm were cast along with three companion standard cubes (150 x 150 x 150 mm) and cylinders (150 mm diameter and 300 mm height). The variables in the study are aspect ratio of steel fibers (l/d), grade of concrete, type of concrete (SCC and VC). To correlate the experimental results obtained from tests on beams, various models of torsion available in literature were considered to predict the torsional strength of vibrated concrete. Nomenclature of specimens used in the phase is shown in Table 5.1.

Table 5.1 Nomenclature of Specimens Cast and Tested for Mix A (20 MPa):

A-VC Plain	Mix A – Vibrated Concrete without steel fibers
A-SFVC 50	Mix A – Vibrated Concrete with steel fibers of aspect ratio 50
A-SFVC 70	Mix A – Vibrated Concrete with steel fibers of aspect ratio 70
A-SFVC 100	Mix A – Vibrated Concrete with steel fibers of aspect ratio 100
A-SCC Plain	Mix A – SCC without steel fibers
A-SFSCC 50	Mix A – SCC with steel fibers of aspect ratio 50
A-SFSCC 70	Mix A – SCC with steel fibers of aspect ratio 70
A-SFSCC 100	Mix A – SCC with steel fibers of aspect ratio100

Similar nomenclature was followed for mixes B (50 MPa) and C (80 MPa) of SCC and VC with 0.5 % dosage (volume of concrete) of steel fibers.

A total of 24 beams of size width 100 mm, depth 200 mm and length 2300 mm were cast and tested by varying above parameters. In the present study, three grades were considered i.e. 20 MPa, 50 MPa and 80 MPa. Three aspect ratios of steel fibers were considered (l/d= 50, 70 and 100). From the preliminary study presented in chapter 4, based on the fresh and hardened properties of SCC it was found that 0.5 % dosage of steel fibers by volume of concrete is maximum, beyond which fresh properties were not satisfying the EFNARC criteria in all aspect ratios of steel fibers. Hence in casting of beams only maximum dosage of steel fibers was used i.e. 0.5 % by volume of concrete. Three companion standard cubes and cylinders of sizes 150 x 150 x 150 mm and 150 mm diameter x 300 mm height were cast and tested for obtaining the compressive and split tensile strengths respectively. All the specimens were cured for 28 days. The details of the beams cast for three grades of SCC and VC are presented in Table 5.2.

Table 5.2 Details of the specimens cast for Phase-II

S. No.	Beam Designation	Strength of Concrete (MPa)	Aspect ratio of steel fiber	Type of concrete
1	**A-VC Plain**	20	-	Vibrated Concrete
2	**A-SFVC 50**	20	50	Vibrated Concrete
3	**A-SFVC 70**	20	70	Vibrated Concrete
4	**A-SFVC 100**	20	100	Vibrated Concrete
5	**A-SCC Plain**	20	-	SCC
6	**A-SFSCC 50**	20	50	SCC
7	**A-SFSCC 70**	20	70	SCC
8	**A-SFSCC 100**	20	100	SCC

The above mixes (8 no's) were cast and tested for 20 MPa strength concrete. Similarly 16 more beams were cast and tested for Mix B (50 MPa) and Mix C (80 MPa) strengths respectively.

5.2.1 Mix Proportions:

Mix proportions for 20 MPa, 50 MPa and 80 MPa vibrated concrete are developed based on IS: 10262-2009 while SCC mix proportions were developed based on Nan Su method. The details of quantities of ingredients are presented in Table 5.3.

Table 5.3 Quantities of ingredients (kg/m^3)

Strength of concrete	Type of Concrete	Cement	Fly ash	Micro silica	Fine Aggregate	Coarse Aggregate	Water	SP	w/b
20 MPa	SCC	320	200	-	908	800	200	4.2	0.38
	VC	383	-	-	632	1174	183.6	-	0.48
50 MPa	SCC	430	180	-	847	783	194	5.16	0.32
	VC	450	150	-	732	844	200	0.6	0.33
80 MPa	SCC	500	110	40	800	775	190	6	0.29
	VC	435	100	22	521	1130	162	1.7	0.29

5.2.2 Experimental setup:

After 28 days of curing, the beams described earlier were white washed and two sections were selected at distances of L/3 and 2L/3 from east side of the beam where 'L' is the unsupported length. The two sections were marked on all faces of the beams to enable measure the inclination of crack. Simply supported end conditions were created by mounting the beams on two rigid supports. To enable twisting of beam, a roller was positioned on the supports in the longitudinal direction.

The support on East face of beam about the longitudinal axis was partly restrained to rotate. The twist arms at each support of the beam were specially made and positioned with an arm length of 1.6 m. Mechanical screw jack was used to apply the load on the twist arm. The beam was subjected to pure torsion and any probability of bending was avoided, so that the twisting arm and plane of loading were at right angles to the longitudinal axis of the beam. To avoid local crushing, neoprene pads of 5 mm thickness were placed between the steel plates of twisting arms and sides of the beam. The complete testing arrangement is shown in Figure 5.1.

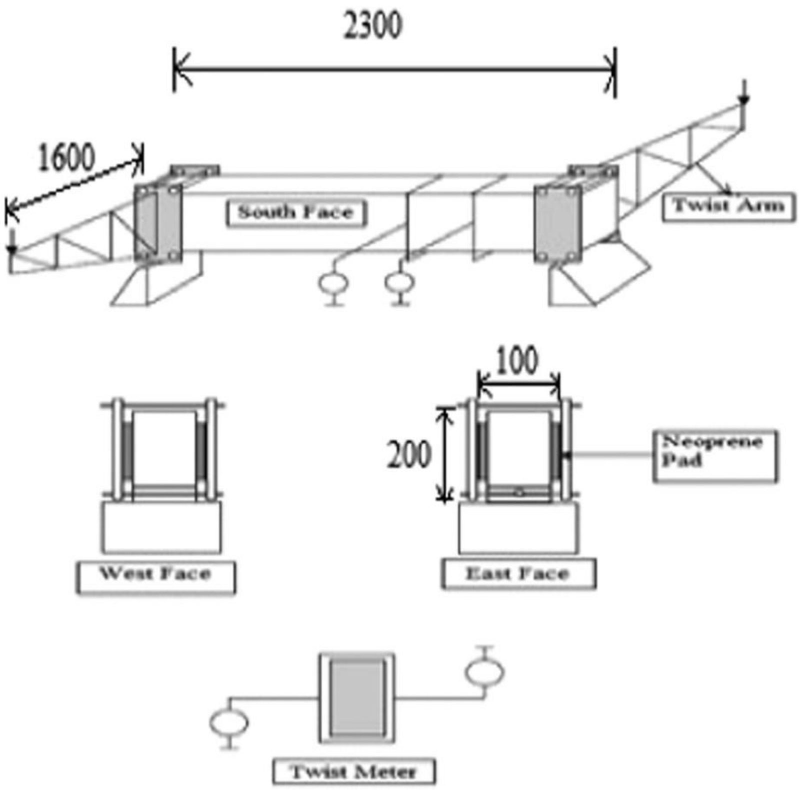


Figure 5.1 Different views of test setup

Eccentricity of the load was 1.51 m from centre of the beam. The load was measured by using a proving ring. Twist meters were used to measure the twist of the beam. By means of transverse screws, twist meters consisting of steel frame attached to the beam as shown in Figure 5.2. To facilitate the measurement of rotation, rigid steel frames with an arm length of 230 mm on vertical faces of the frame were used. Four dial gauges were positioned underneath the steel arms as shown in Figure 5.2. The spacing between the dial gauges was 250 mm which enabled calculation of twist per unit length.

5.2.3 Testing Procedure:

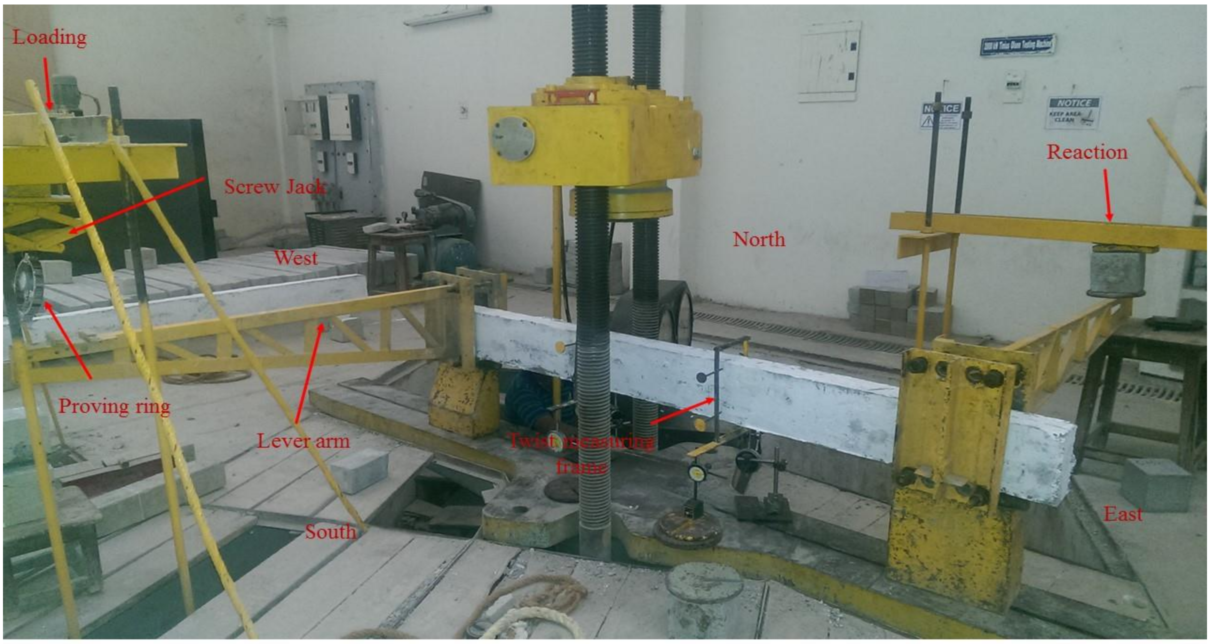


Figure 5.2 Torsional setup

Transverse load was applied gradually through mechanical jack on rigid supports of the beam placed in East-West direction on table of Tinius-Olsen testing machine. While applying the load, extreme care was taken such that the plane of loading does not fall out of the plane of twist arms. Consequently, bending of beam has been restrained. Until the failure of the specimen, the respective twist per unit length was calculated for every increment of the load. Inclination of potential crack was measured after the completion of the test. Testing procedure was adopted based on the experimentation done by **T.D.G Rao. et al (2003).**

5.3 Results and Discussion:

5.3.1 Discussion on fresh properties of SCC and VC:

Various Tests were conducted to verify the characteristics of fresh SCC. All the test results like slump flow, V-funnel and J-ring were confirming to EFNARC (European Federation of National Trade Associations) guidelines for SCC. Slump test and compaction factor test were conducted for VC as per IS 1199-2004. The fresh properties of SCC and VC are shown in Tables: 5.4 and 5.5.

Table 5.4 Fresh Properties of SCC with 0.5 % Steel Fiber dosage

Mix Designation	Slump Flow (mm)	$T_{500\ mm}$ (sec)	J- ring (mm)	V- funnel (sec)	V- funnel $T_{5\ min}$ (sec)
EFNARC Limits	**550-850**	**2-5**	**0-10**	**6-12**	**6-15**
A-SCC Plain	760	2.31	5	6	9
A-SFSCC 50	710	3.16	8	8	12
A-SFSCC 70	680	3.69	8	9	13
A-SFSCC 100	670	4.14	9	9	14
B-SCC Plain	780	2.46	4	6	8
B-SFSCC 50	690	3.25	8	9	11
B-SFSCC 70	675	3.62	8	9	11
B-SFSCC 100	665	3.68	8	10	13
C-SCC Plain	755	2.59	4	7	10
C-SFSCC 50	675	3.74	7	10	12
C-SFSCC 70	660	3.94	8	10	12
C-SFSCC 100	645	4.12	8	10	12

Table 5.5 Fresh Properties of Vibrated concrete with 0.5 % Steel Fiber dosage

Mix designation	Slump (mm)			Compaction Factor (CF)		
	20 MPa	**50 MPa**	**80 MPa**	**20 MPa**	**50 MPa**	**80 MPa**
VC Plain	126	120	95	0.96	0.95	0.93
SFVC 50	104	98	78	0.92	0.91	0.88
SFVC 70	97	93	72	0.9	0.89	0.84
SFVC 100	90	87	68	0.88	0.87	0.8

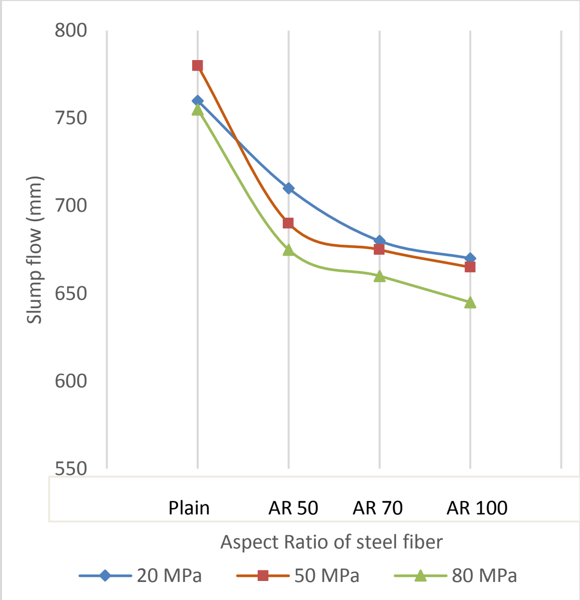


Figure 5.3 Variation of slump flow of SCC due to addition of steel fibers

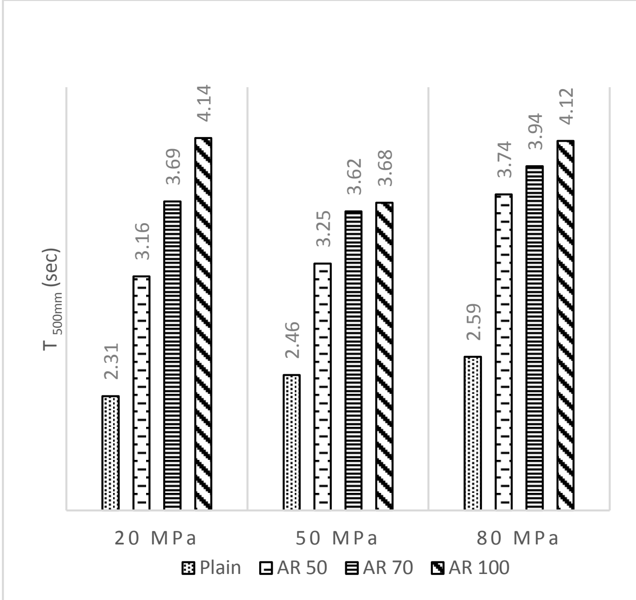


Figure 5.4 Variation of $T_{500\ mm}$ (sec) in SCC due to addition of steel fibers

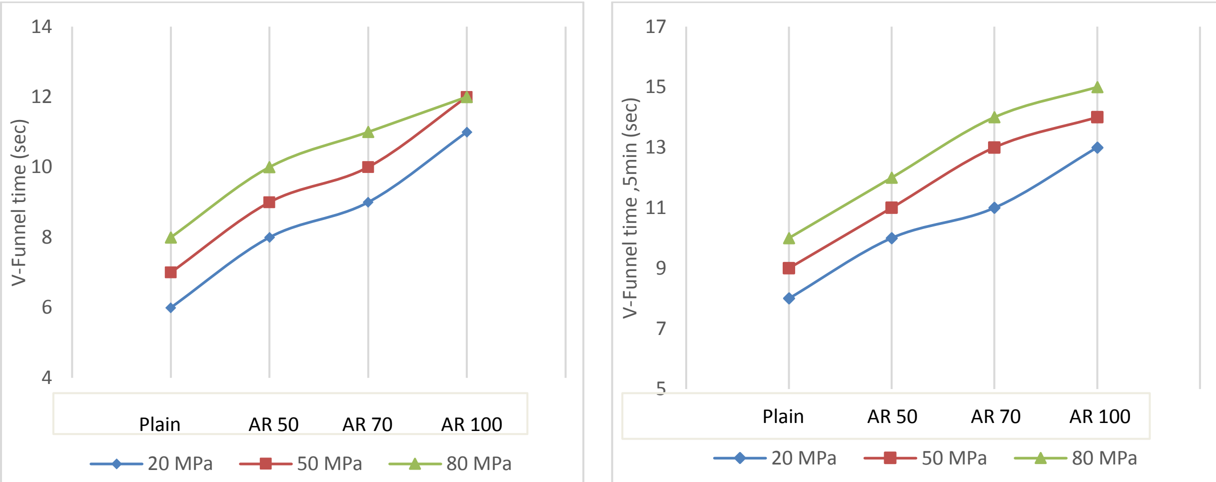


Figure 5.5 Variation of V-Funnel time of SCC due to addition of steel fibers

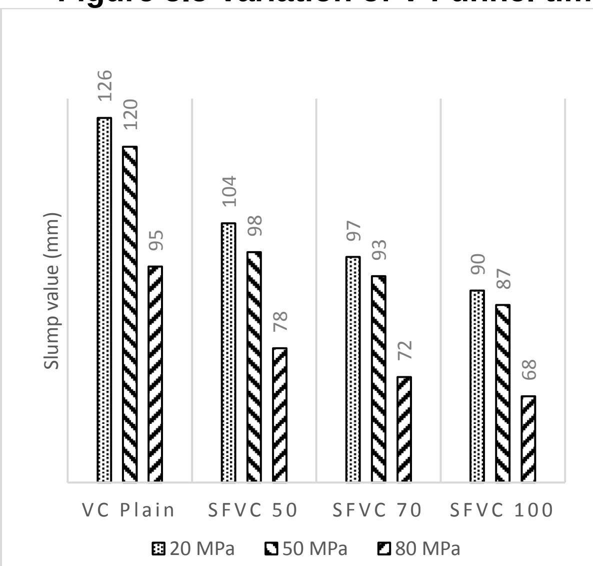


Figure 5.6 Variation of slump value of VC due to addition of steel fibers

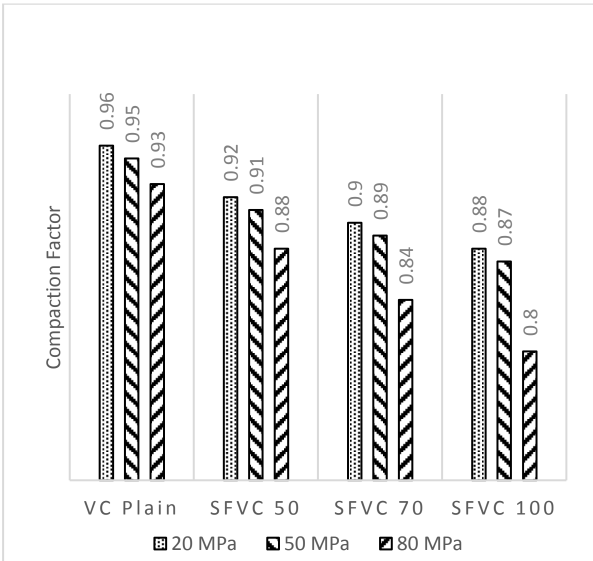


Figure 5.7 Variation of CF of VC due to addition of steel fibers

The addition of steel fibers in SCC reduces the workability as steel fibers act as barrier to the movement of aggregates in concrete. Reduction of workability was observed but these are within the limits of **EFNARC (2005)**. Adequate workability is achieved along with attainment of desired strength in hardened state. In SCC, addition of supplementary materials increase viscosity and workability. They provide ball bearing effects and reduce internal friction in concrete. This increases the flowability of concrete leading to uniform distribution of fibers.

5.3.2 Mechanical properties of SCC and VC:

Table 5.6 Details of mechanical properties in VC and SCC (NA)

Mix designation	Cube Compressive strength (MPa)			Split Tensile strength (MPa)		
	20 MPa	50 MPa	80 MPa	20 MPa	50 MPa	80 MPa
VC Plain	21.2	50.1	80.6	2.31	3.37	4.67
SFVC 50	23.4	53.7	84.2	2.68	3.75	5.22
SFVC 70	24.4	55.1	85.6	2.75	3.89	5.36
SFVC 100	22.6	52.8	83.4	2.62	3.68	5.16
SCC Plain	22.4	50.22	81	2.34	3.41	4.81
SFSCC 50	24.8	52.51	84.9	2.71	3.88	5.52
SFSCC 70	25.4	54.36	86.2	2.84	3.98	5.68
SFSCC 100	23.5	51.6	83.2	2.64	3.76	5.34

It is observed that inclusion of steel fibers has increased the mechanical properties of concrete. The enhancement in mechanical properties is due to the localized reinforcing capability of fibers around mortar mix around coarse aggregate. Volume fraction and aspect ratio were selected as per workability requirement. Improper selection of these parameters leads to poor residual-tensile strength of concrete.

5.3.3 Discussion on torsional behaviour of SCC and VC with natural aggregates:

In this section, the behaviour of 24 beams with steel fibers of aspect ratios 50, 70, 100 tested is discussed. The results of these beams are presented in Tables 5.7, 5.8 and 5.9.

Table 5.7 Torsional behaviour of SCC and VC using steel fibers of aspect ratios of 50, 70 and 100 of Mix A-20 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
A-VC Plain	1.63	5.45	432.41	5.73
A-SFVC 50	1.88	6.43	463.82	8.04
A-SFVC 70	**1.93**	**6.8**	**480.54**	**9.04**
A-SFVC 100	1.84	6.27	457.75	7.66
A-SCC Plain	1.69	5.67	465.69	6.27
A-SFSCC 50	1.93	7.1	493.51	9.61
A-SFSCC 70	**2.04**	**7.45**	**504.33**	**10.67**
A-SFSCC 100	1.87	6.86	485.16	8.95

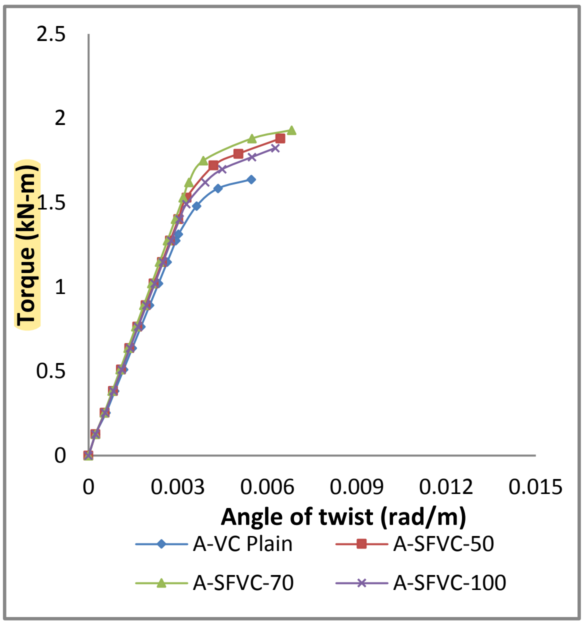


Figure 5.8 Torque-Twist response of A-VC

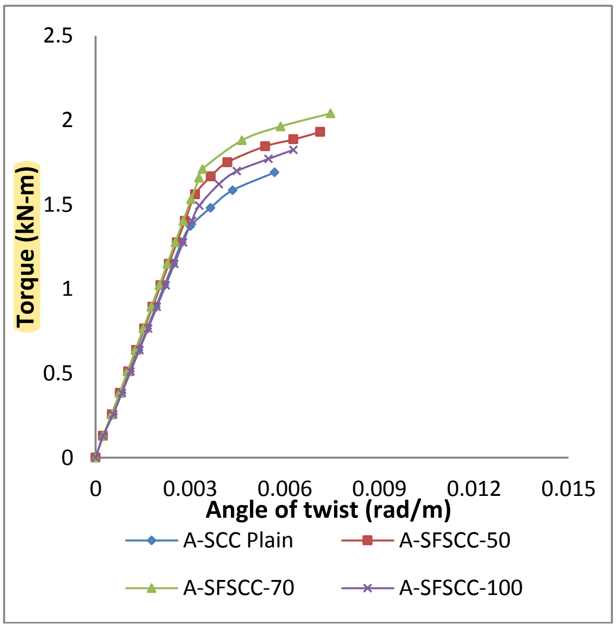


Figure 5.9 Torque-Twist response of A-SCC

Table 5.8 Torsional behaviour of SCC and VC using steel fibers of aspect ratios of 50, 70 and 100 of Mix B-50 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
B-VC Plain	2.52	6.5	541.87	10.59
B-SFVC 50	2.82	7.9	585.41	15.09
B-SFVC 70	**2.95**	**8.5**	**602.23**	**17.23**
B-SFVC 100	2.74	7.3	572.34	12.68
B-SCC Plain	2.65	6.7	600.55	10.87
B-SFSCC 50	2.95	8.9	642.14	19.02
B-SFSCC 70	**3.08**	**9.2**	**662.57**	**19.92**
B-SFSCC 100	2.86	7.9	632.56	14.81

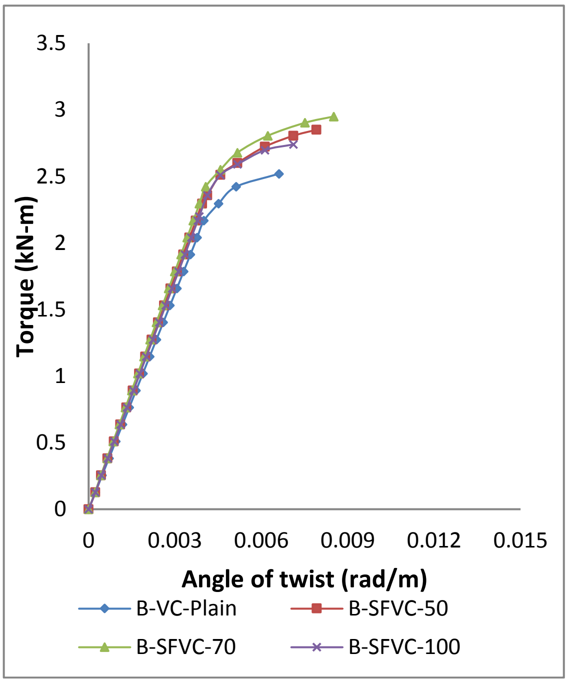


Figure 5.10 Torque-Twist response of B-VC

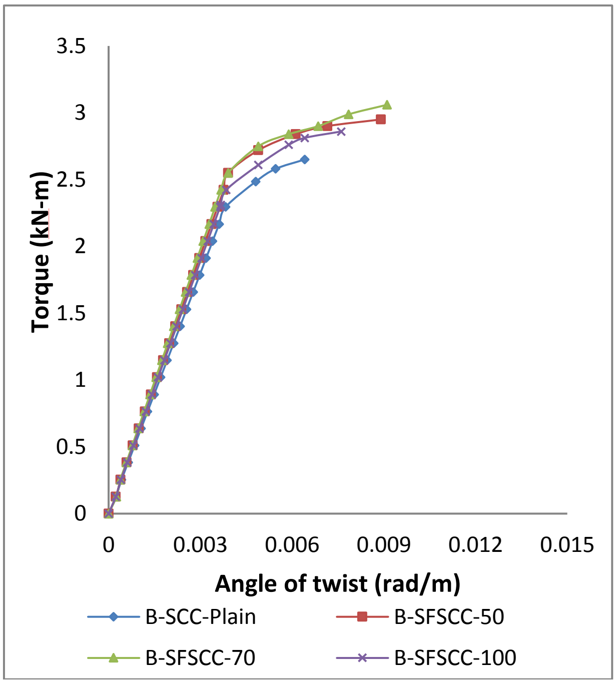


Figure 5.11 Torque-Twist response of B-SCC

Table 5.9 Torsional behaviour of SCC and VC using steel fibers of aspect ratios of 50, 70 and 100 of Mix C-80 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
C-VC Plain	3.57	7.1	741.74	16.49
C-SFVC 50	3.95	9.5	776.46	28.32
C-SFVC 70	**4.08**	**11.2**	**796.84**	**34.13**
C-SFVC 100	3.82	9.1	767.54	24.58
C-SCC Plain	3.7	7.54	757.48	18.46
C-SFSCC 50	4.24	11.92	804.76	37.78
C-SFSCC 70	**4.38**	**13.8**	**817.65**	**46.97**
C-SFSCC 100	4.12	11.32	794.93	34.89

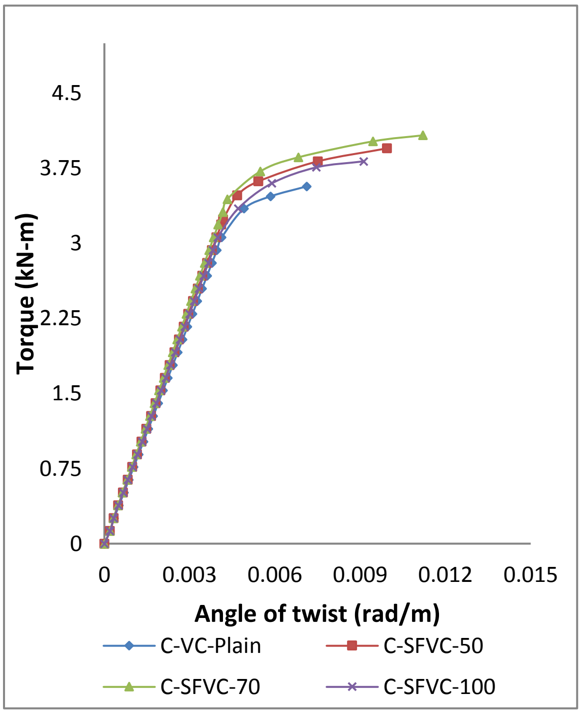


Figure 5.12 Torque-Twist response of C-VC

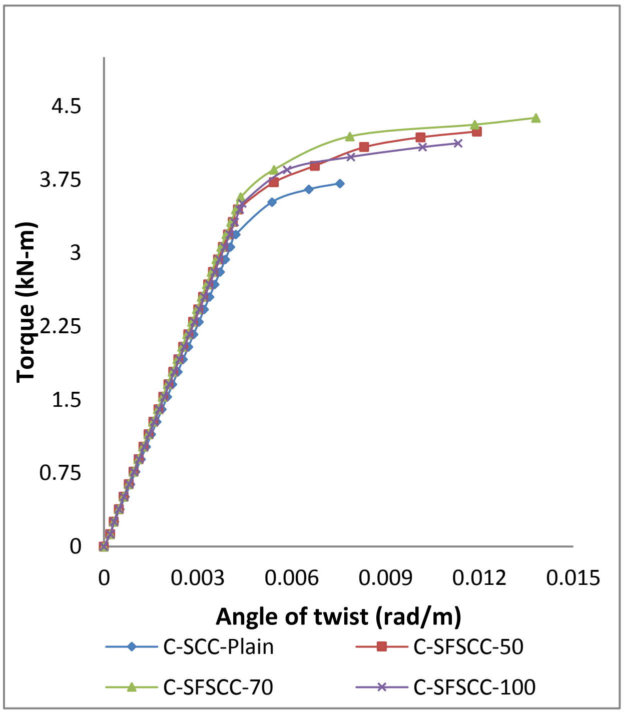


Figure 5.13 Torque-Twist response of C-SCC

The torsional response of concrete in precracking is practically linear. In post cracking range, the response depends primarily on proportion, distribution and physical properties of steel fibers provided.

a) Influence of Aspect ratio of Steel fibers on Torsional strength of SCC and VC:

Figures 5.8-5.13 show the comparison of torque-twist curves of 20 MPa, 50MPa and 80 MPa strengths of concrete of SCC and VC with and without steel fibers of aspect ratios (l/d) 50, 70 and 100. It can be observed that,

1. The plain beams of SCC and VC failed suddenly and separated into two pieces under pure torsion, due to addition of steel fibers load carrying capacity increased in all grades of concrete. Beams with fibers has shown higher torsional strength and the failure mode has changed from brittle to ductile mode by arresting of opening, widening and extension of cracks in concrete mass due to steel fibers.
2. It can be observed the increase in the torsional strength has increased with the increase of aspect ratio (l/d) from 50 to 70 for all grades of SCC and VC. Highest increase in torsional strength was observed for beams with fibers of aspect ratio 70 in all strengths of concrete.
3. In Mix A (20 MPa) concrete beams with fibers of aspect ratio 70, torsional strength has increased by 18.40% and 20.77% in VC and SCC respectively in comparison with respective plain beams.
4. Similarly, the Mix B (50 MPa) concrete beams with fibers of aspect ratio 70, torsional strength has increased by 16.22% and 17.02% in VC and SCC respectively in comparison with respective plain beams.
5. In High strength concrete (Mix C-80 MPa), torsional strength has increased by 14.28% and 18.38% in VC and SCC respectively in beams with fibers of aspect ratio 70.

Fiber embedment length into the mortar matrix depends on the aspect ratio, orientation with respect to loading direction and matrix strength greatly influence pullout resistance. Short and discrete fibers (Aspect Ratio 50, 70) are more effective in behaviour of torsion than long fibers (Aspect Ratio 100) in both concretes. Fiber strengthening in concrete is due to Adhesion, Friction and Mechanical Anchorage. Random orientation of steel fiber create an efficient web-like structural system around coarse aggregate, which mainly controls the residual tensile strength.

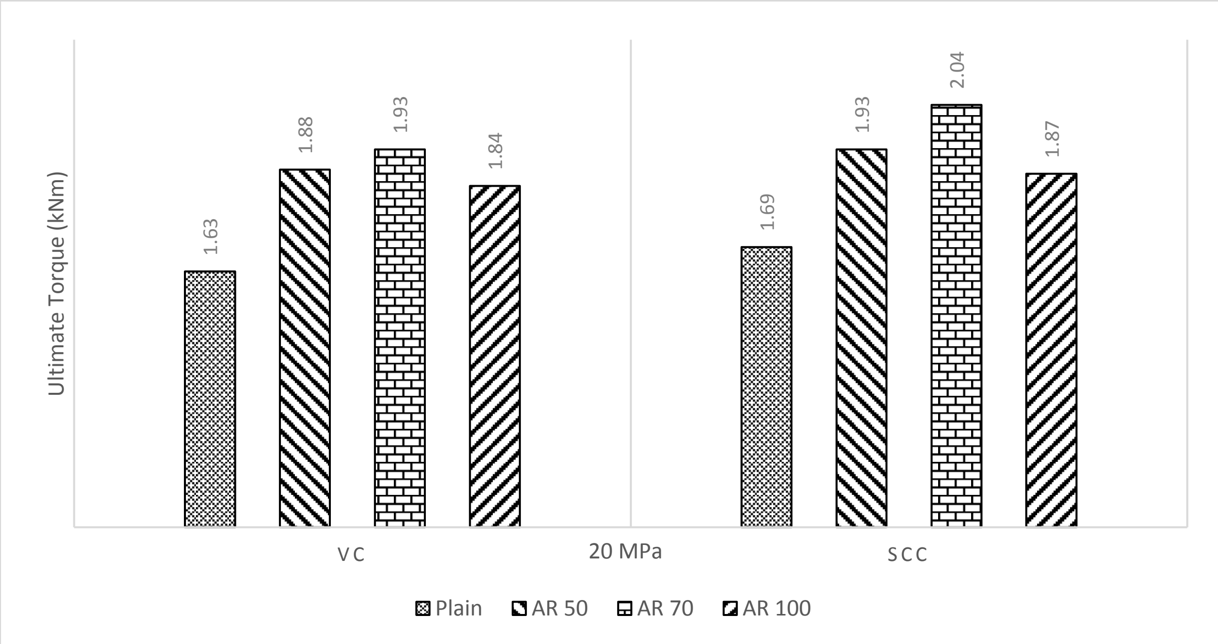


Figure 5.14 Torsional Strength Vs Aspect ratio of steel fiber (Mix A-20 MPa)

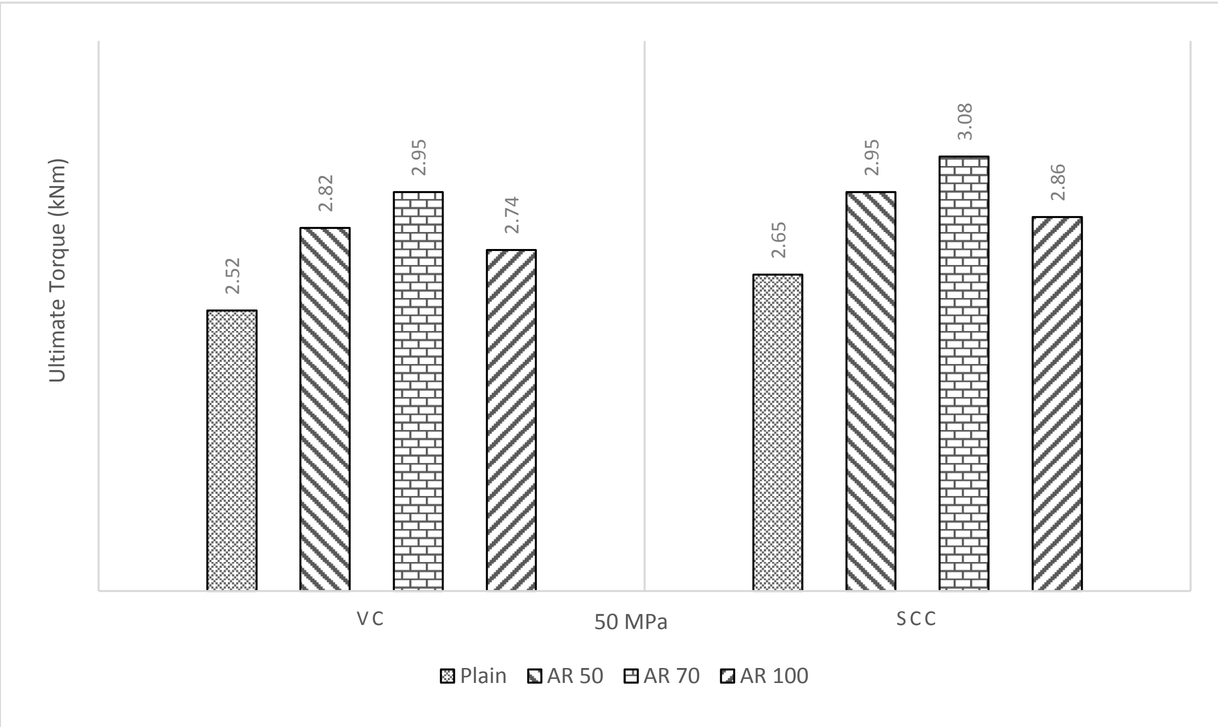


Figure 5.15 Torsional Strength Vs Aspect ratio of steel fiber (Mix B-50 MPa)

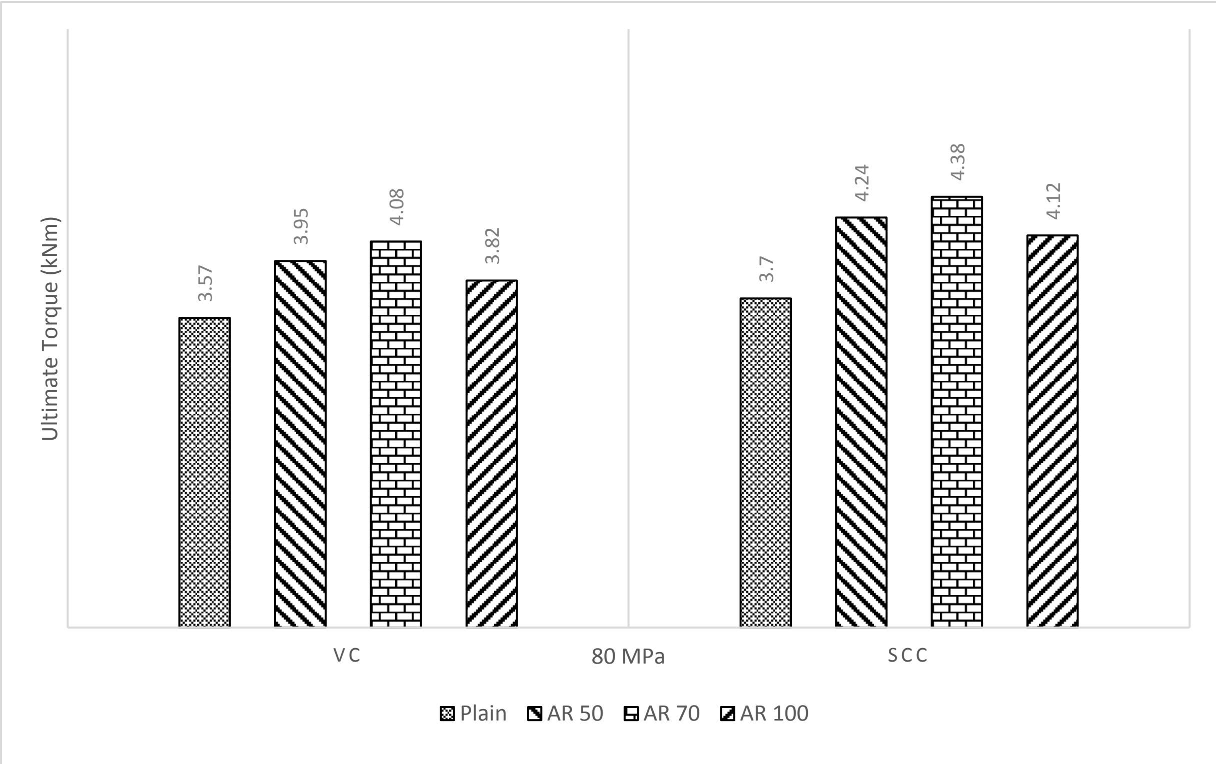


Figure 5.16 Torsional Strength Vs Aspect ratio of steel fiber (Mix C-80 MPa)

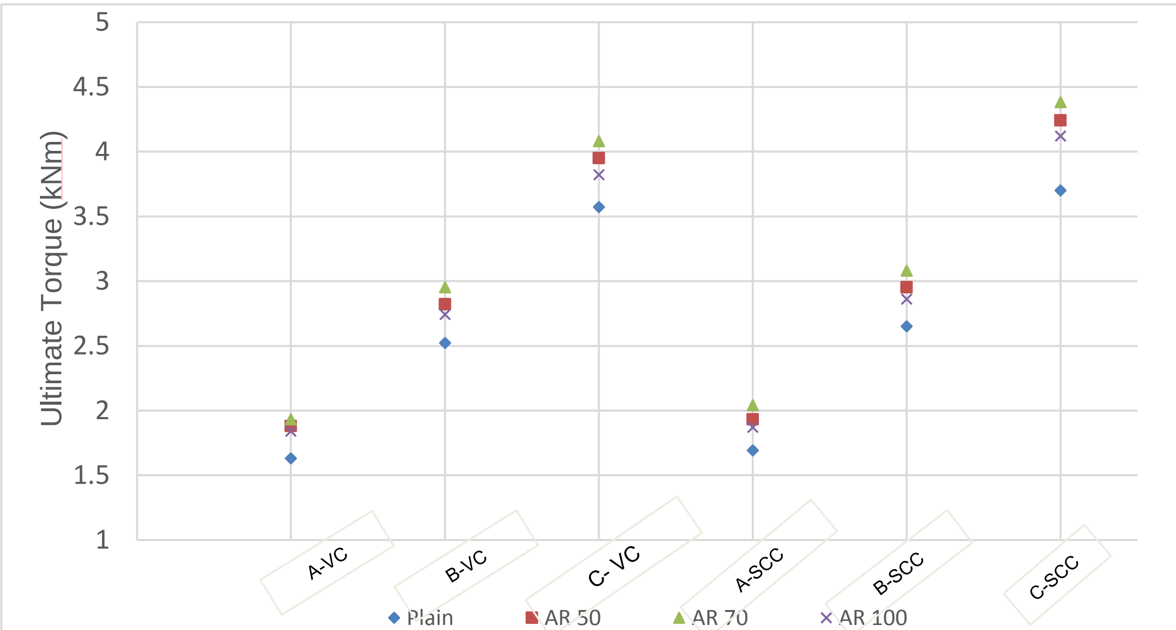


Figure 5.17 Variation of Ultimate torque in SCC and VC with aspect ratio of steel fiber

b) Influence of aspect ratio of Steel fibers on Twist at ultimate torque of SCC and VC:

It can be observed from the Tables 5.7, 5.8 & 5.9 with the increase in strength and aspect ratio, twist at ultimate torque increased. Angle of twist at any point is the rotation of the of the member at the point about the longitudinal centroidal axis of the members

1. It can be observed the increase in the twist at ultimate torque has increased with the increase of aspect ratio (l/d) from 50 to 100 for all grades of SCC and VC. Highest increase in twist at ultimate torque was observed for beams with fibers of aspect ratio 70 in all strengths of concrete.
2. In Mix A (20 MPa) concrete beams with fibers of aspect ratio 70, twist at ultimate torque has increased by 24.77 % and 31.39 % in VC and SCC respectively compared to respective plain beams.
3. Similarly, Mix B (50 MPa) concrete beams with fibers of aspect ratio 70, twist at ultimate torque has increased by 30.77 % and 37.3 1% in VC and SCC respectively in comparison with respective plain beams.
4. In High strength concrete (Mix C-80 MPa), twist at ultimate torque has increased by 57.75 % and 83.02 % in VC and SCC respectively in beams with fibers of aspect ratio 70.

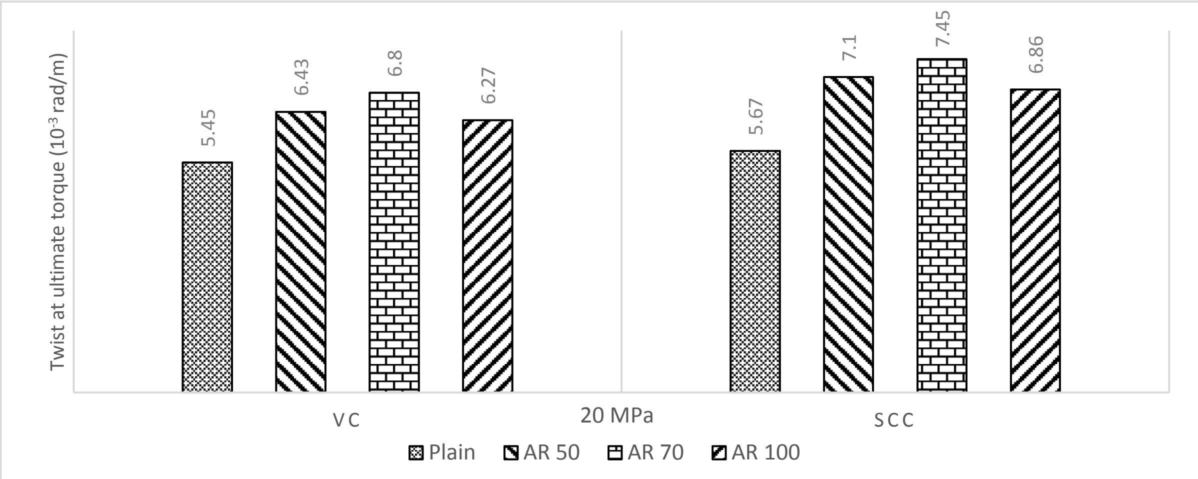


Figure 5.18 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix A 20 MPa)

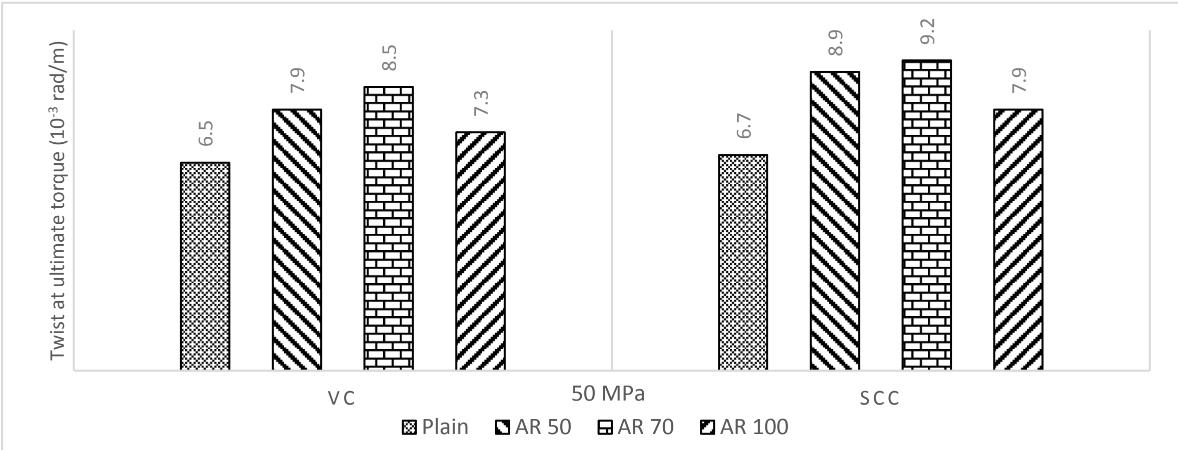


Figure 5.19 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix B 50 MPa)

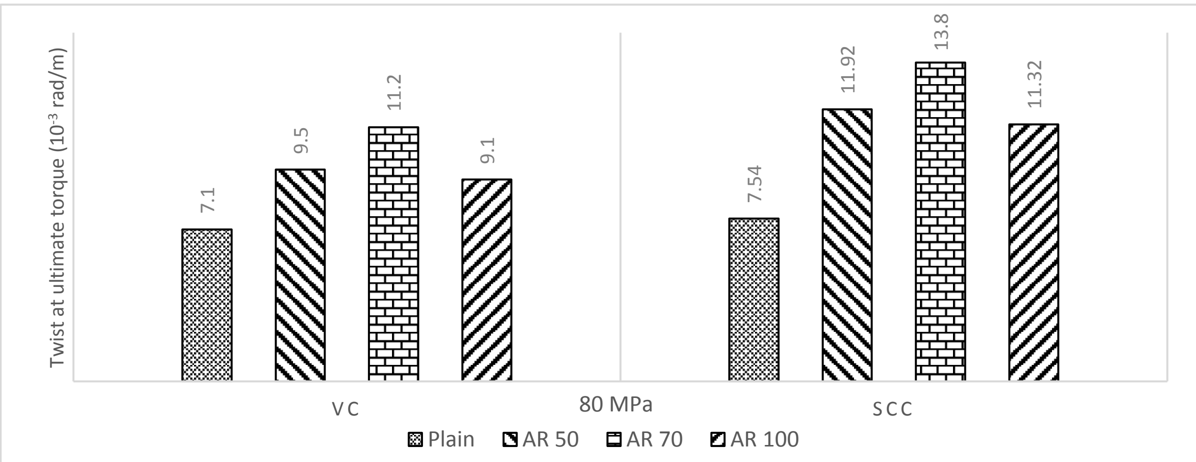


Figure 5.20 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix C 80 MPa)

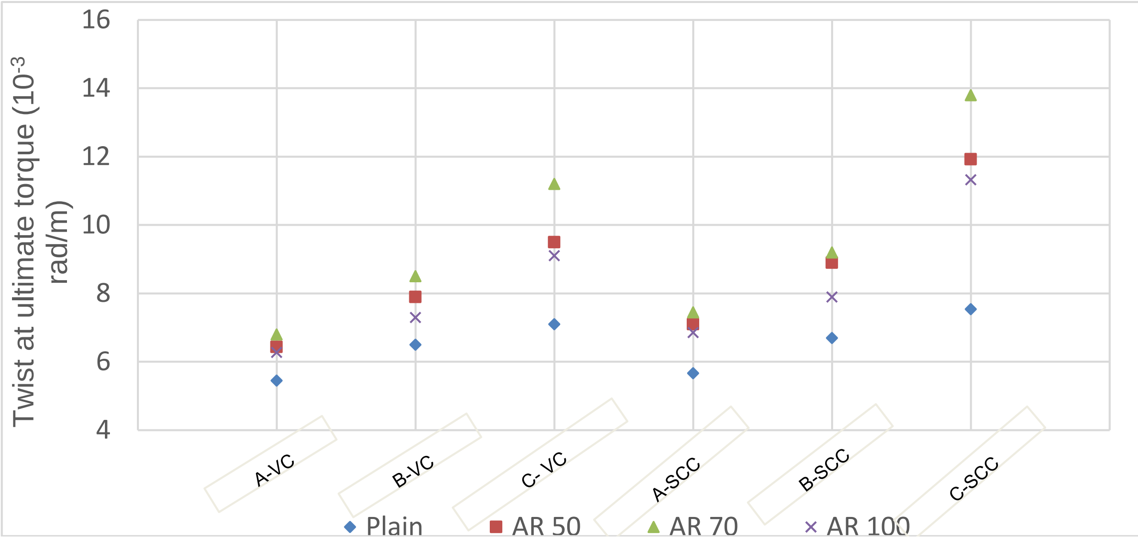


Figure 5.21 Variation of Ultimate torque in SCC and VC with aspect ratio of steel fiber

c) Effect of aspect ratio of Steel fibers on Torsional Toughness of beams of SCC and VC:

Torsional Toughness is defined as the amount of energy per unit volume that a material can absorb before rupturing. In can also be defined as area under torque-twist curve. In the present study, torsional toughness of the beams is measured by calculating the area under torque-twist curve. Addition of steel fibers not only improved the torsional performance of SCC and VC beams but there is also enhancement in the energy absorption capacity. This is due to crack delaying property and energy absorption capacity of fibrous matrix.

Due to inclusion of steel fibers of aspect ratio 70 for plain beams, there is an increment of 57.88 % and 70.11 % in toughness of the 20 MPa beam of VC and SCC respectively, compared to identical beam without steel fiber. Similarly, in case of 50 MPa concrete beams, due to addition of fibers (aspect ratio 70) the toughness of the plain beams increased by 62.70 % and 83.26 % in VC and SCC beams respectively compared to plain beams.

Fiber embedment length into the mortar matrix depends on the fiber aspect ratio, orientation with respect to loading direction and matrix strength greatly influence pullout resistance. In high strength concrete, the effect of steel fiber is more significant, due to high matrix strength due to silica fume and also high embedment length into matrix. Steel fibers are effective in strain hardening by allowing the additional transfer of interfacial shear through enhanced aggregate interlock caused by the reduced crack-opening of the diagonal cracks. In high strength concrete (80 MPa), there was an increase of 106.97 % and 154.44 % in toughness of VC and SCC beams respectively with steel fibers of aspect ratio 70 compared to plain beams of 80 MPa strength concrete.

Figures 5.22-5.24 shows the variation of torsional toughness with respect to aspect ratios for three grades of concrete and for SCC and VC beams.

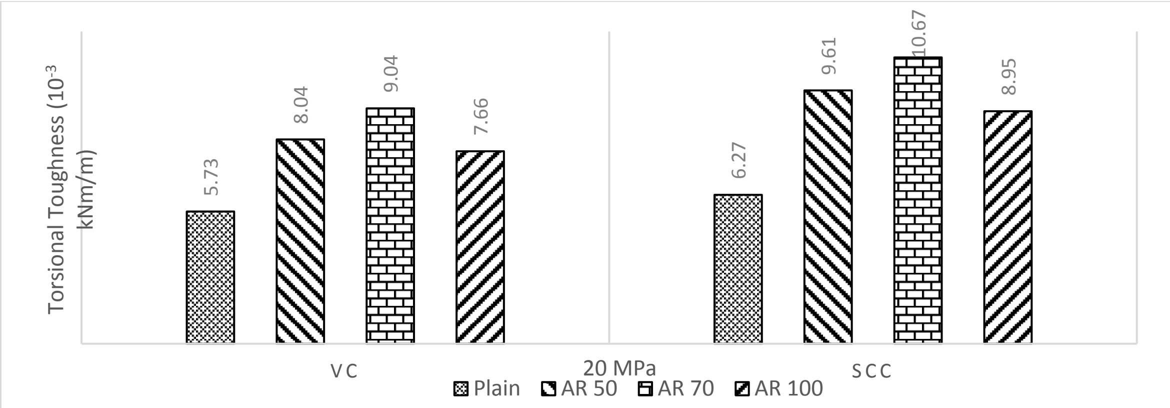


Figure 5.22 Variation of Torsional toughness of Mix A-20 MPa

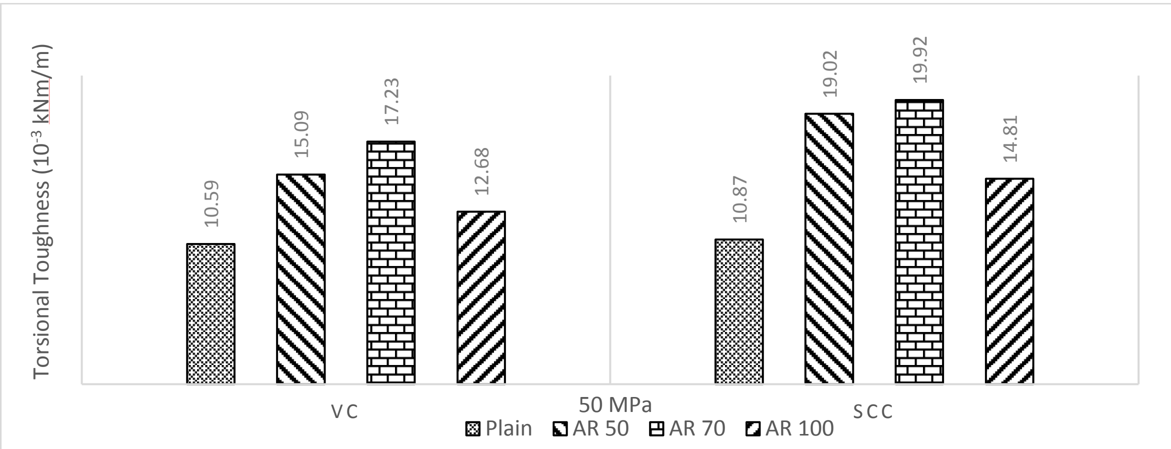


Figure 5.23 Variation of Torsional toughness of Mix B-50 MPa

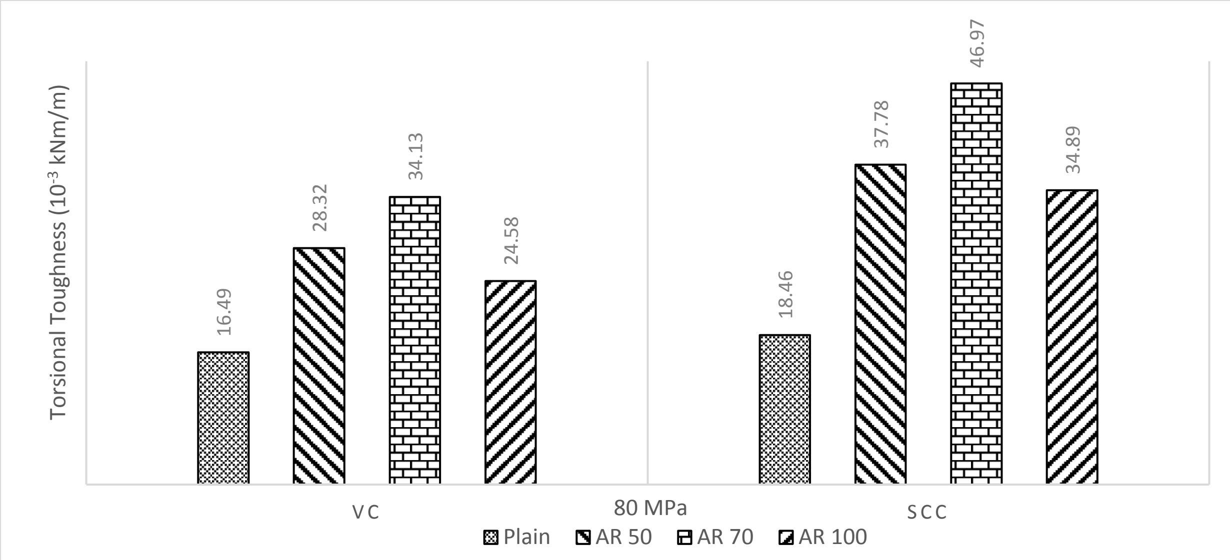


Figure 5.24 Variation of Torsional toughness of Mix C-80 MPa

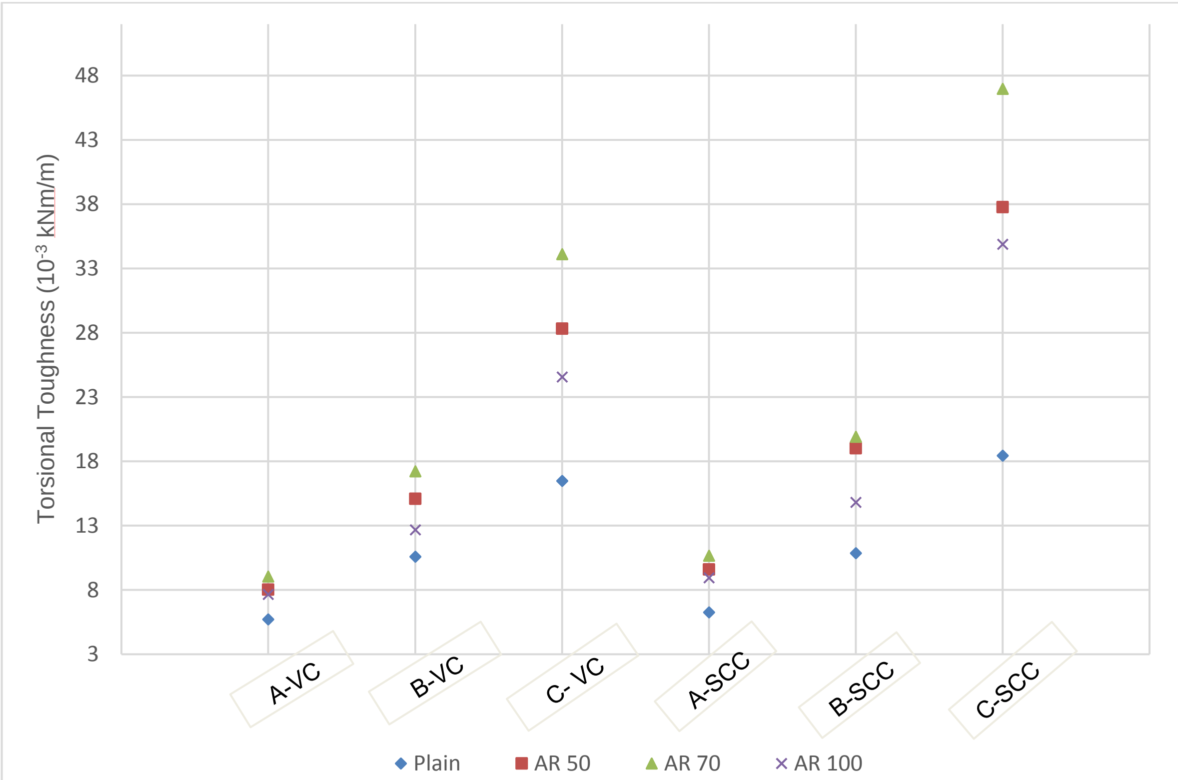


Figure 5.25 Variation of torsional toughness in SCC and VC beams

The linear portion of torque-twist curve (slope of initial tangent) indicate torsional stiffness of beams and was found to increase with addition of steel fibers as shown in Table 5.7-5.9. This increase is essentially with increase in modulus of matrix due to steel fibers. Similar trend is observed even incase of torsional stiffness in both concretes with fibers.

d) Failure Pattern:

A torsional moment induces pure shear condition in a structural member, known as torsional shear. A pure shear condition results in a biaxial compression-tension condition along diagonal directions. Torsion, has no direct relation with either shear or flexure. Torsion produce shear stress which inturn give rise to diagonal tension. Diagonal tension leads to diagonal cracks in the structural member. Skew bending type of failure was observed in plain and fibrous beams of both the concretes. Steel fibers subsequently carry the redistributed tensile stress along (across) the crack and prevent premature concrete splitting. SFRC possess residual tensile strength that is good enough to keep the crack-width in the section sufficiently small to ensure effective and efficient transfer of shear stresses produced due to torsion. It is observed that the torsion cracks don’t start at the midpoint of the wider face of a rectangular section but that they actually form simultaneously along the perimeter of the specimen.

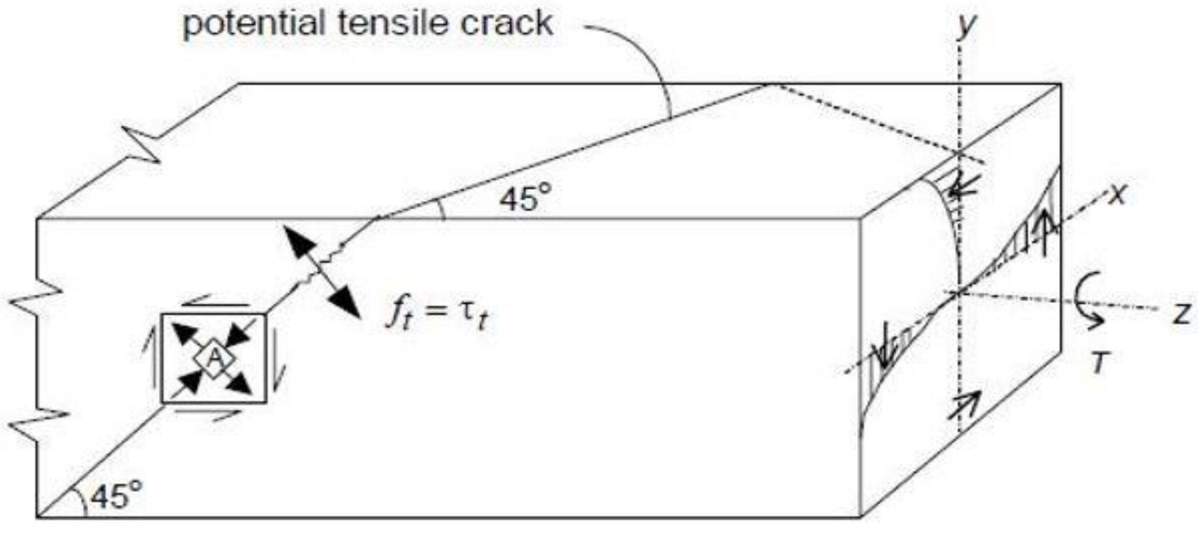


Figure 5.26 Crack proportion along the section due to torsion

For all beams, inclination of crack varied from 42° to 48° with respect to longitudinal axis. The failure of all plain beams were sudden, violent and got separated. While steel fibrous beams of both SCC and VC have shown better ductile nature without separating into two pieces though failed with a solitary potential crack. Crack angle is not much varied with the addition of steel fibers, as failure pattern is dependent on the type action applied on the member than the material of the member. Crack pattern on all four sides of beam for all grades are shown in Figures 5.27-5.29

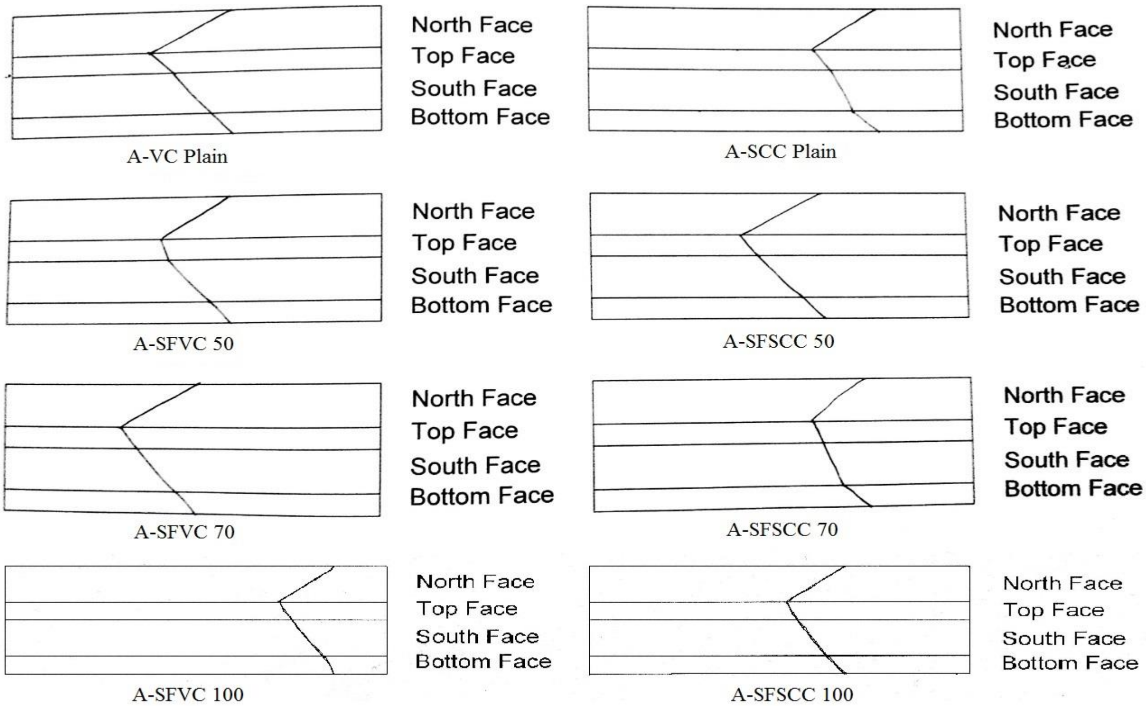


Figure 5.27 Crack pattern on all four sides of beam for Mix-A 20 MPa

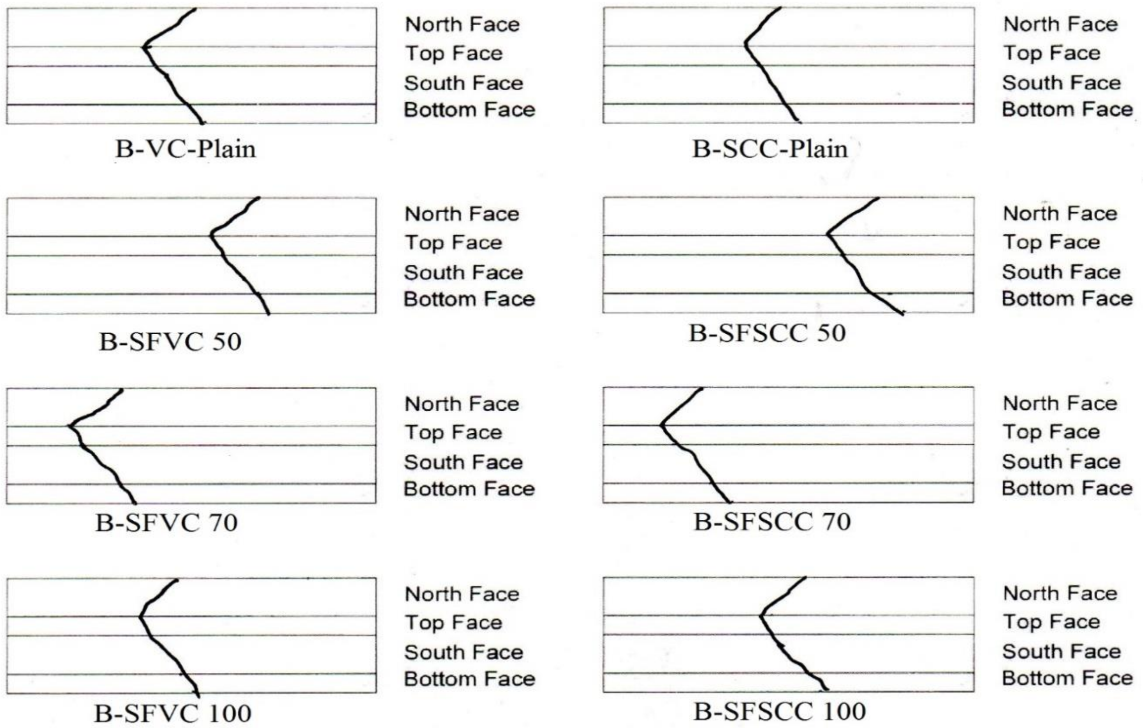


Figure 5.28 Crack pattern on all four sides of beam for Mix-B 50 MPa

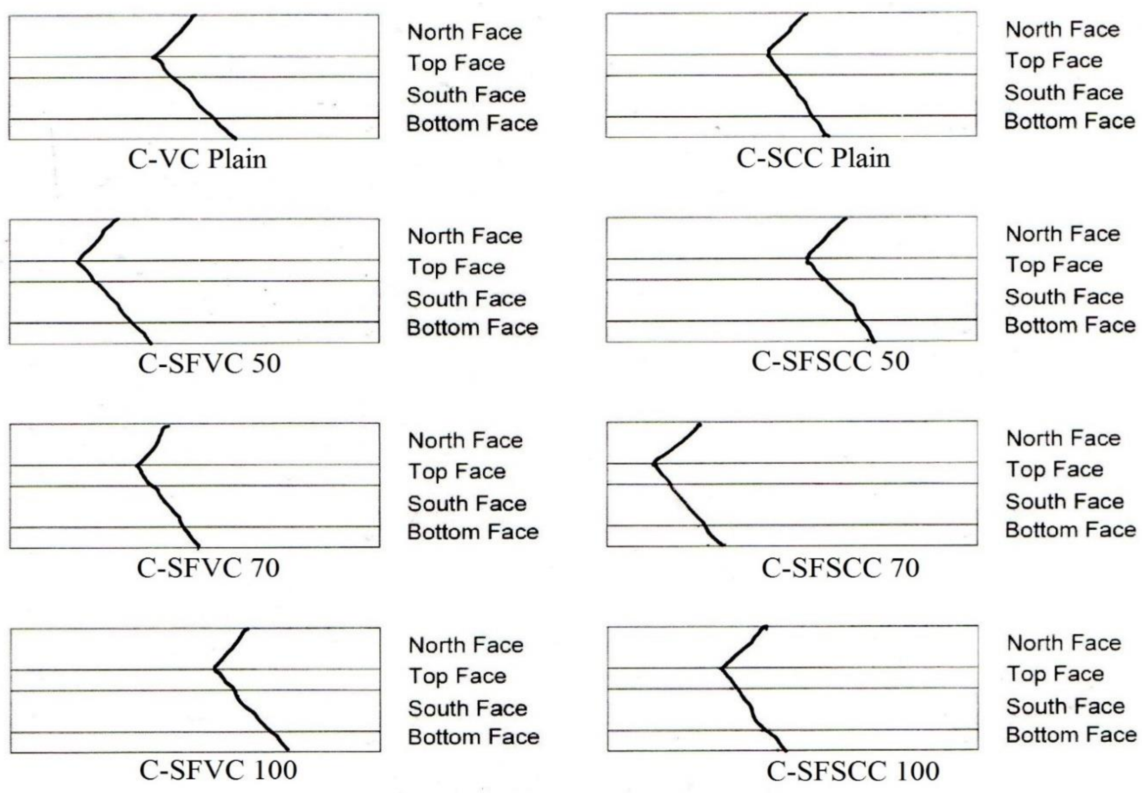


Figure 5.29 Crack pattern on all four sides of beam for Mix-C 80 MPa

5.4 Comparison of test results with various models from Literature:

In this section, the experimental results obtained for ultimate torsional strength of VC and SCC are compared with torsional strength models available in the literature for vibrated concrete.

1. **Elastic Theory:**

Saint Venant for rectangular sections proposed an equation for computing the torsional strength (T_e) of the beam based on elastic analysis which is given by

$$T_e = \alpha b^2 d f_t \qquad \textbf{(5.1)}$$

Where, α = Constant depends on b/d ratio = 0.246 for the b/d ratio 0.5, b = breadth of the beam (smaller dimension), d = depth of the beam (larger dimension), f_t = Tensile strength of the concrete.

The solution for the torsion of a fully plastic elastic rectangular section is obtained by membrane analogy. In this theory, the marginal increase in ultimate torque of plain concrete member due to plasticity may be ignored for the sake of conservatism. It would, therefore, appear that the ultimate torque should be predicted with reasonable accuracy by Saint-Venant's elastic theory of torsion. Tests on plain concrete members, however, show that the ultimate torque is underestimated significantly by elastic theory.

2. Plastic Theory:

The solution for the torsion of a fully plastic rectangular section is obtained by sand heap analogy. The expression for torsional strength is expressed as,

$$T_p = \alpha b^2 d f_t \quad \textbf{(5.2)}$$

For plastic analysis, the value of 'α' is given as $(0.5 - (\frac{b}{6d}))$.

3. **Hsu [1968]** reported extensive pure torsion tests on plain concrete rectangular and flanged sections. The most striking observation was that plain concrete rectangular members subjected to pure torsion actually failed by skew bending. The ultimate torque of plain concrete rectangular section was expressed by the equation,

$$T_{ue} = \frac{1}{3}(b^2 d\ (0.85 f_r)) \quad \textbf{(5.3)}$$

   In which 0.85 represent the reduction factor applied to the flexural tensile strength f_r determined from the modulus of rupture test.

4. **Souza and Wilhem [1973]** conducted tests on plain rectangular concrete beams and proposed an equation for predicting the torsional strength of the member. The torsional strength was expressed as

$$T_{cr} = 0.412\ (1-0.233\frac{b}{d})\ b^2 d f_t' \quad \textbf{(5.4)}$$

   In which the direct tensile strength of concrete f_t' may be taken equal to $0.75(0.42\sqrt{cube\ compressive\ strength})$ or $\frac{5}{6.7}$ times the split tensile strength.

5. **T.D.G Rao et al. [2004]** conducted pure torsional tests on rectangular plain steel fibrous concrete members. A semi empirical formula was proposed to estimate the ultimate torsional strength of the member (T_g).

$$T_g = (0.5-0.233(\frac{b}{d}))\ (b^2 d f_t) \quad \textbf{(5.5)}$$

Table 5.10 Torsional strength of VC and SCC beams of Mix A (20 MPa) in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
A-VC Plain	1.025	1.733	1.482	1.256	1.595	1.630
A-SFVC 50	1.183	2.001	1.711	1.457	1.841	1.880
A-SFVC 70	1.216	2.056	1.758	1.495	1.894	1.930
A-SFVC 100	1.155	1.953	1.670	1.425	1.802	1.840
A-SCC Plain	1.042	1.763	2.019	1.273	1.626	1.690
A-SFSCC 50	1.202	2.033	2.339	1.474	1.871	1.930
A-SFSCC 70	1.257	2.125	2.451	1.544	1.956	2.041
A-SFSCC100	1.168	1.975	2.278	1.436	1.818	1.870

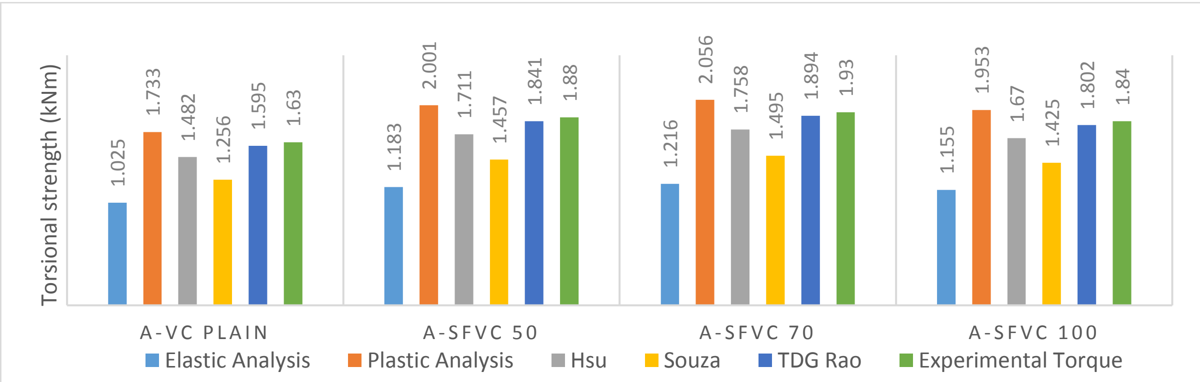


Figure 5.30 Comparison of torsional strength values with various models and Experimental results of Mix-A VC

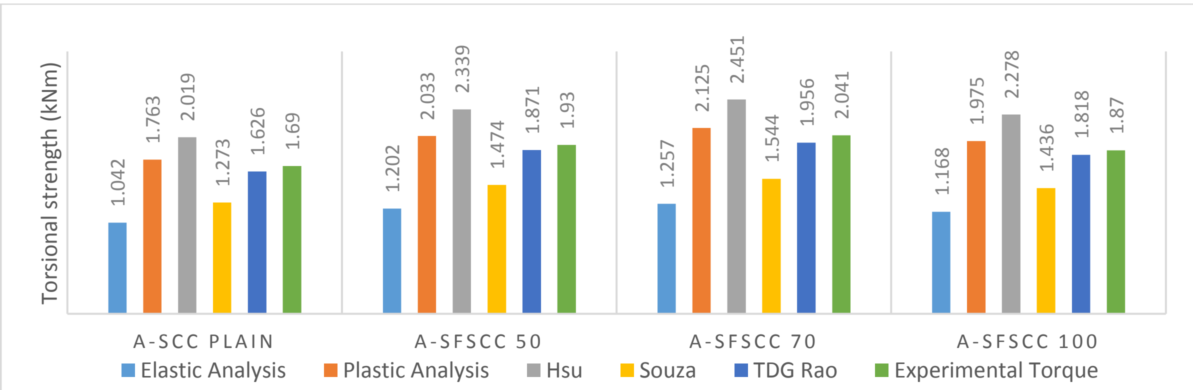


Figure 5.31 Comparison of torsional strength values with various models and Experimental results of Mix-A SCC

Table 5.11 Torsional strength of VC and SCC beams of Mix B (50 MPa) in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
B-VC Plain	1.553	2.627	2.247	1.833	2.424	2.52
B-SFVC 50	1.725	2.916	2.494	2.039	2.692	2.82
B-SFVC 70	1.788	3.023	2.585	2.115	2.784	2.95
B-SFVC 100	1.693	2.862	2.448	2.001	2.638	2.74
B-SCC Plain	1.571	2.657	2.943	1.854	2.447	2.65
B-SFSCC 50	1.778	3.006	3.349	2.110	2.769	2.95
B-SFSCC 70	1.825	3.085	3.435	2.164	2.846	3.08
B-SFSCC100	1.724	2.916	3.245	2.045	2.685	2.86

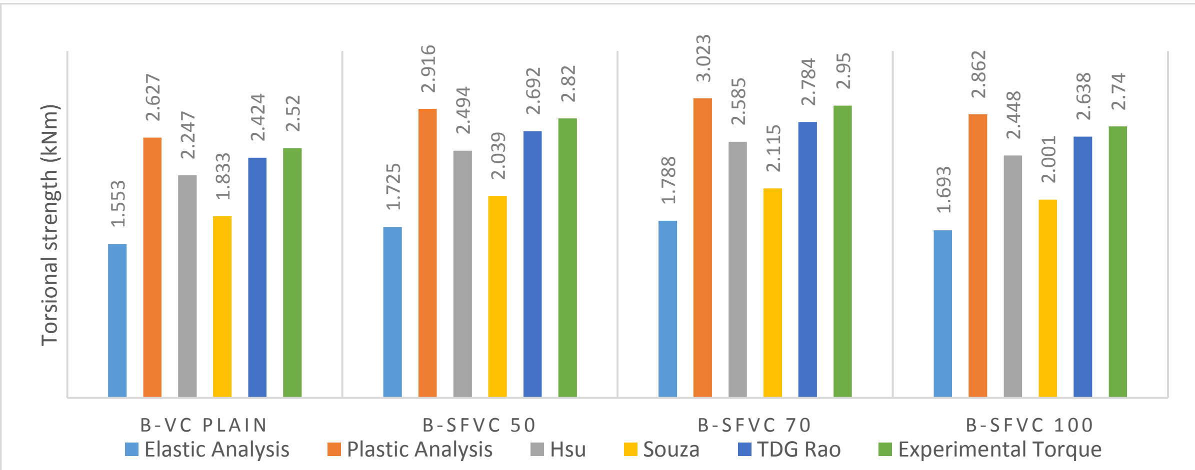


Figure 5.32 Comparison of torsional strength values with various models and Experimental results of Mix-B VC

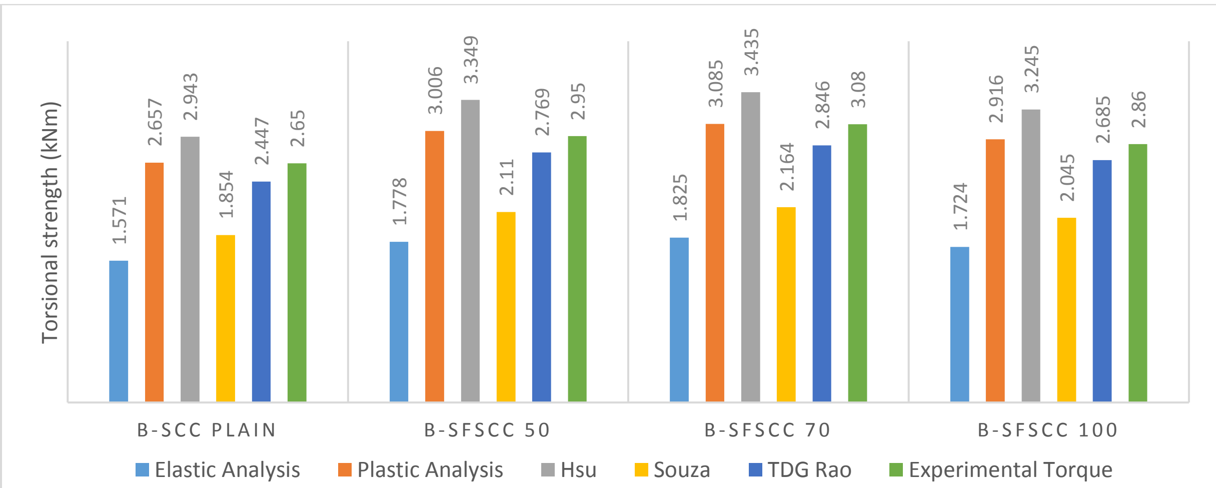


Figure 5.33 Comparison of torsional strength values with various models and Experimental results of Mix-B SCC

Table 5.12 Torsional strength of VC and SCC beams of Mix C (80 MPa) in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
C-VC Plain	2.172	3.673	3.141	2.540	3.382	3.57
C-SFVC 50	2.418	4.090	3.498	2.839	3.774	3.95
C-SFVC 70	2.482	4.197	3.589	2.915	3.866	4.08
C-SFVC 100	2.391	4.043	3.458	2.806	3.728	3.82
C-SCC Plain	2.234	3.777	4.151	2.616	3.482	3.70
C-SFSCC 50	2.550	4.312	4.764	3.002	3.973	4.24
C-SFSCC 70	2.622	4.434	4.902	3.089	4.088	4.38
C-SFSCC100	2.469	4.175	4.609	2.904	3.850	4.12

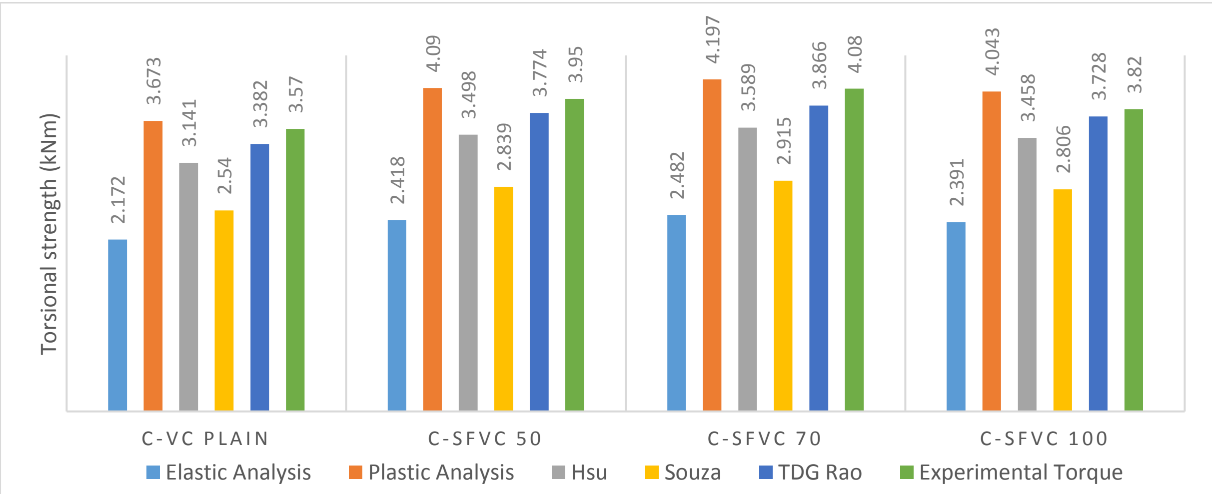


Figure 5.34 Comparison of torsional strength values with various models and Experimental results of Mix-C VC

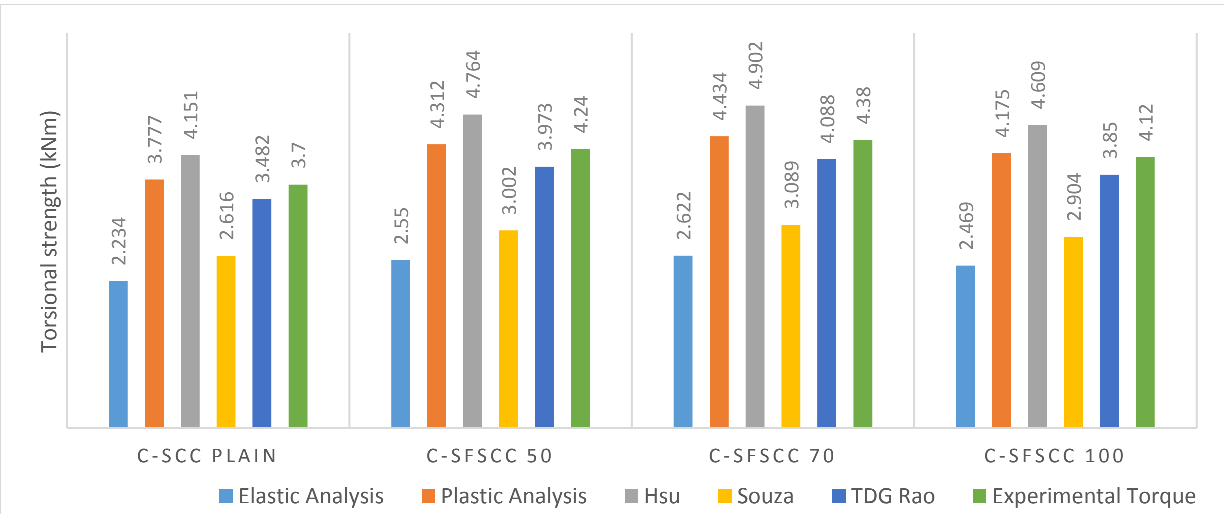


Figure 5.35 Comparison of torsional strength values with various models and Experimental results of Mix-C SCC

The torsional strength of the beam is underestimated by elastic analysis and overestimated by plastic analysis. From the above results it can be concluded that the torsional strength predicted by **TDG Rao et al.,** is relatively close to that of the experimental values. Figures 5.30-5.35 shows the variation of torsional strength for various models and experiential results for Mix A, B and C.

5.5 Conclusions from Phase-II:

Based on the detailed studies on Torsional behaviour of plain and fibrous beams of SCC and VC using three aspect ratios of steel fibers the following conclusions were made.

1. Due to addition of steel fibers, the ultimate torsional strength increased and also the failure mode changed from sudden brittle failure to ductile behaviour. This is true for both SCC and VC in 20 MPa, 50 MPa and 80 MPa concrete.
2. With increase in the aspect ratio of steel fibers increased from 50 to 100, the ultimate torsional strength and twist increased, similar behaviour was observed in case of both SCC and VC with respect to plain beams. The significant improvement was seen for beams with aspect ratio 70 in all strengths of concretes.
3. Addition of steel fibers has improved initial torsional stiffness, angle of twist and torsional toughness of beams in case of all strengths of concrete.
4. A comparison was made between experimental and existing theories of torsion on vibrated concrete. It was noticed that the ultimate torsional strength was under estimated by elastic analysis and was over estimated by plastic analysis.
5. Due to brittle nature of high strength concrete the effect of addition of steel fibers were more significant in all torsional properties of both SCC and VC.

Chapter 6 Torsional Behaviour of Recycled aggregate Steel Fiber Reinforced SCC and VC

6.0 General:

Chapter 5 dealt with the torsional properties of steel fiber reinforced SCC and VC for various strengths of concrete and aspect ratios of steel fibers. The studies concluded that steel fiber plays a very important role in crack arresting mechanism and also improves the torsional performance of concrete by increasing its tensile strength. The studies concluded that due to use of steel fibers, sudden failure of the specimens can be avoided and also increases the tensile strength of concrete. As the aspect ratio increased from 50 to 100 torsional strength increased irrespective of strength and type of concrete. From the experimental results it was found that as the strength of concrete increased, the significance of steel fibers has been increased. Further it was noticed that, torsional performance of fiber reinforced SCC is more pronounced than VC and also comparison of experimental results with various models available in the literature on VC was done and the correlation was found satisfactory.

This chapter focuses on the torsional behaviour of SCC, VC for both without and with steel fibers by replacing natural coarse aggregates (25 % replacement by weight) with recycled concrete aggregates.

6.1 Introduction:

Globally every year, more than 26.8 billion tonnes of normal concrete is used, which creates a very huge amount of construction and demolition waste. The use of natural aggregate has increased drastically over the past few years in the construction industry which leads to scarcity of natural resources in near future. The nature of the construction industry is not environmentally friendly and the need for sustainable methods in construction is very crucial to ensure that natural materials are not depleted for future need. In past few years due to increasing concern for the environment as well as scarcity of natural resources such as natural coarse and fine aggregates has prompted the use of recycled aggregates produced from construction and building demolished wastes in concrete as a replacement of natural aggregates in many parts of the world. Although the use of recycled concrete aggregate is well recognized as a sustainable material that offers solutions to this problem, but still it is considered as inferior to natural aggregate in terms of its structural properties.

As discussed in the earlier chapter about the importance and benefits of using self-compacting concrete and also some of the uncertainties in self-compacting concrete which can be overcomed by using steel fibers and use of steel fibers in self-compacting concrete can change the brittle failure nature to a ductile behaviour especially in torsion. The present chapter focuses on study of the torsional behaviour of recycled aggregate based self-compacting concrete without and with fibers.

As we know Self compacting concrete is a highly flow able concrete which can fill into every corner of form work without any external vibration effort. From the literature it is found that due to the use of recycled aggregate as a replacement of natural aggregates can result in reduction of mechanical properties due to the presence of second Interfacial Transition Zone (ITZ) which is the weakest link in the concrete where failure occurs. Addition of steel fiber can overcome this defect and also improve the post cracking behaviour of SCC with recycled aggregate concrete (RCA). Steel fiber reinforced recycled aggregate self-compacting concrete (SFRRASCC) combines the benefits of SCC in the fresh state and addition of steel fibers can shows an improved performance in the hardened state by avoiding cracking compared to conventional concrete.

Recycled aggregates are obtained by crushing waste concrete and then, the coarse fraction of crushed aggregates can be used to replace natural coarse aggregates. The complete use of recycled aggregates over natural aggregates is not appreciated due high water absorption capacity and high depletion of mechanical and durability properties. From the various research investigations it’s been found that the use of recycled aggregates to be limited 30 – 40 % by weight to achieve similar properties of concrete with natural aggregates. In the present study 25 % (by weight of concrete) natural coarse aggregates are replaced with recycled coarse aggregates and mechanical, torsional behaviour of SCC and VC are studied by incorporating steel fibers. The recycled aggregates are presoaked in water for 30 minutes before concreting was done, so that the recycled aggregates may not absorb excess water during mixing process of concrete.

In the present chapter, a detailed discussion on the torsional behaviour recycled aggregate based SCC for both with out and with steel fibers are presented in the following sections. The parameters varied are a) Strength of concrete 20 MPa, 50 MPa and 80 MPa b) aspect ratio (l/d) 50, 70 and 100 c) Type of concrete SCC and VC d) volume of steel fiber 0% and 0.5% by volume of concrete.

6.2 Experimental Programme:

The experimental programme is similar to that presented in the chapter 5. Detailed studies were carried out on torsional behaviour of recycled aggregate based self-compacting concrete and vibrated concrete for three aspect ratios (l/d= 50, 70 and 100) of hooked end steel fibers. The optimal dosage obtained from Phase-I was used to study the effect on the torsional behaviour of 20 MPa, 50 MPa and 80 MPa strength SCC and VC along with plain beams. The beams of width 100 mm, depth 200 mm and length 2300 mm were cast along with three companion standard cubes (150 x 150 x 150 mm) and cylinders (150 mm diameter and 300 mm height). The variables in the study are aspect ratio of steel fibers (l/d), grade of concrete, type of concrete (SCC and VC). To correlate the experimental results obtained from tests on beams, various models of torsion available in literature were considered to predict the torsional strength of vibrated concrete. Nomenclature of specimens used in the phase is shown in Table 6.1.

Table 6.1 Nomenclature of Specimens Cast and Tested for Mix A (20 MPa):

A-RVC Plain	Mix A – Recycled aggregate based Vibrated Concrete without steel fibers
A-RSFVC 50	Mix A – Recycled aggregate based Vibrated Concrete with steel fibers of aspect ratio 50
A-RSFVC 70	Mix A – Recycled aggregate based Vibrated Concrete with steel fibers of aspect ratio 70
A-RSFVC 100	Mix A – Recycled aggregate based Vibrated Concrete with steel fibers of aspect ratio 100
A-RSCC Plain	Mix A – Recycled aggregate based SCC without steel fibers
A-RSFSCC 50	Mix A – Recycled aggregate based SCC with steel fibers of aspect ratio 50
A-RSFSCC 70	Mix A – Recycled aggregate based SCC with steel fibers of aspect ratio 70
A-RSFSCC 100	Mix A – Recycled aggregate based SCC with steel fibers of aspect ratio100

Similar nomenclature was followed for mixes B (50 MPa) and C (80 MPa) of Natural and Recycled coarse Aggregate based SCC and VC with 0.5 % dosage (volume of concrete) of steel fibers.

A total of 24 beams of width 100 mm, depth 200 mm and length 2300 mm were cast and tested by varying above parameters. In the present study three grades were considered i.e. 20 MPa, 50 MPa and 80 MPa. Three aspect ratios of steel fibers were considered (l/d= 50, 70 and 100). From the preliminary study presented in chapter 4, based on the fresh and hardened properties of SCC it was found that 0.5 % dosage of steel fibers by volume of concrete is maximum, beyond which fresh properties were not satisfying the EFNARC criteria in all aspect ratios of steel fibers. Hence in casting of beams only maximum dosage of steel fibers was used i.e. 0.5 % by volume of concrete. Three companion standard cubes and cylinders of sizes 150 x 150 x 150 mm and 150 mm diameter x 300 mm height were cast and tested for obtaining the compressive and split tensile strengths respectively. All the specimens were cured for 28 days. The details of the beams cast for three grades of SCC and VC are presented in Table 6.2.

Table 6.2 Details of the specimens cast for Phase-III

S. No.	Beam Designation	Strength of Concrete (MPa)	Aspect ratio of steel fiber	Type of concrete
1	**A-RVC Plain**	20	-	Vibrated Concrete
2	**A-RSFVC 50**	20	50	Vibrated Concrete
3	**A-RSFVC 70**	20	70	Vibrated Concrete
4	**A-RSFVC 100**	20	100	Vibrated Concrete
5	**A-RSCC Plain**	20	-	SCC
6	**A-RSFSCC 50**	20	50	SCC
7	**A-RSFSCC 70**	20	70	SCC
8	**A-RSFSCC100**	20	100	SCC

The above mixes (8 no’s) were cast for 20 MPa strength concrete. Similarly, 16 more beams were cast and tested for 50 MPa and 80 MPa strengths respectively.

6.2.1 Materials used

6.2.1.1 Recycled Coarse Aggregate (RCA):

The RCA used in this study was obtained by crushing old specimens of concrete cubes and beams and slabs available in concrete laboratory of the National Institute of Technology Warangal. Before using the aggregates, they were washed with water to remove any unwanted substances, and presoaked for 30 minutes and then they were air-dried. The source of the RCA is 100% concrete. The Properties are given in table 6.3. The other materials used were same as per previous chapters.

Table 6.3 Physical Properties of Recycled coarse aggregates

Properties	
Bulk density(kg/m^3)	1257
Percentage voids	48.35
Void ratio	0.92
Specific gravity	2.53
Fineness Modulus	7.15
Water absorption (%)	6.8

6.2.2 Mix Proportions:

Mix proportions for 20 MPa, 50 MPa and 80 MPa vibrated concrete are developed based on IS: 10262-2009 while SCC mix proportions were developed based on Nan Su method. The details of quantities of ingredients are presented in Table 6.4.

Table 6.4 Quantities of ingredients (kg/m^3)

Strength of concrete	Type of Concrete	Cement	Fly ash	Micro silica	Fine Aggregate	Coarse Aggregate	Water	SP	w/b
20 MPa	SCC	320	200	-	908	800	200	4.2	0.38
	VC	383	-	-	632	1174	184	-	0.48
50 MPa	SCC	430	180	-	847	783	194	5.16	0.32
	VC	450	150	-	732	844	200	0.6	0.33
80 MPa	SCC	500	110	40	800	775	190	6.0	0.29
	VC	435	100	22	521	1130	162	1.7	0.29

6.2.3 Beams:

For casting of beams two channel sections are placed back to back such that the space between the channels is equal to the width of the beam to be cast. Wooden pieces of required width of were kept in between the two channels to maintain the spacing (equal to the width of beam). The whole casting was done on a level platform. The ends of the channels were provided with holes of 8 mm diameter for providing bolts and nuts to keep the channels in position. In addition, two C – clamps were used to avoid any bulging of the sides. For casting the control cubes, standard cast iron cube moulds are used. Steel fibers were added during the dry mix of concrete before adding water.

6.2.4 Curing of beams:

After demolding the channel, beam specimens were kept in curing pond for curing. The curing was done for a period of 28 days. After the completion of curing the specimens were kept under shade.

6.2.5 Experimental Investigation:

The study includes testing of fiber reinforced SCC and VC beams with hooked end steel fibers of aspect ratios 50, 70 and 100. The dosage of fiber was kept constant in the entire work i.e. 0.5 % by volume of concrete. 24 beams were cast each with a cross-sectional width of 100 mm and depth of 200 mm having an overall span of 2300 mm. Three companion cubes of size 150 x 150 x 150 mm and cylinders of size 300 mm height and 150 mm diameter were cast to determine compressive strength and split tensile strength of concrete respectively as per IS: 516-1999. All the specimens were cured under same conditions upto 28 days.

6.2.6 Experimental setup:

The torsional experimental setup is done as explained in chapter - 5.

6.3 Results and Discussion:

6.3.1 Discussion on fresh properties of SCC and VC:

Various Tests were conducted to verify the characteristics of fresh SCC. All the test results like slump flow, V-funnel and J-ring were confirming to EFNARC (European Federation of National Trade Associations) guidelines for SCC. Slump test and compaction factor test were conducted for VC as per IS 1199-2004. The fresh properties of SCC and VC are shown in Tables 6.5 and 6.6.

Table 6.5 Fresh Properties of SCC with 0.5 % Steel Fiber dosage

Mix Designation	Slump Flow (mm)	$T_{500\ mm}$ (sec)	J- ring (mm)	V- funnel (sec)	V- funnel $T_{5\ min}$ (sec)
EFNARC Limits	**550-850**	**2-5**	**0-10**	**6-12**	**6-15**
A-RSCC Plain	740	2.46	6	6	7
A-RSFSCC 50	670	3.28	8	8	9
A-RSFSCC 70	630	3.92	9	9	12
A-RSFSCC 100	600	4.42	9	10	13
B-RRSCC Plain	750	2.62	5	7	9
B-RSFSCC 50	690	3.42	7	9	11
B-RSFSCC 70	675	3.80	9	10	13
B-RSFSCC 100	660	4.12	10	11	14
C-RSCC Plain	775	2.84	6	8	10
C-RSFSCC 50	730	3.54	8	10	12
C-RSFSCC 70	720	3.98	9	11	14
C-RSFSCC 100	690	4.05	10	12	15

Table 6.6 Fresh Properties of Vibrated concrete with 0.5 % Steel Fiber dosage

Mix designation	Slump (mm)			Compaction Factor		
	20 MPa	50 MPa	80 MPa	20 MPa	50 MPa	80 MPa
RVC Plain	114	110	90	0.94	0.91	0.88
RSFVC 50	92	93	82	0.90	0.87	0.83
RSFVC 70	88	87	76	0.89	0.82	0.79
RSFVC 100	82	80	68	0.87	0.78	0.75

The addition of steel fibers and recycled coarse aggregates in SCC and VC reduced the workability as steel fibers act as barrier to the movement of aggregates in concrete. Addition of fibers increase the cohesiveness, leading to reduction in slump value and workability. Reduction of workability was observed but these are within the limits of **EFNARC (2005)**. The effect of fibers and recycled aggregates is shown in Figures 6.1-6.5.

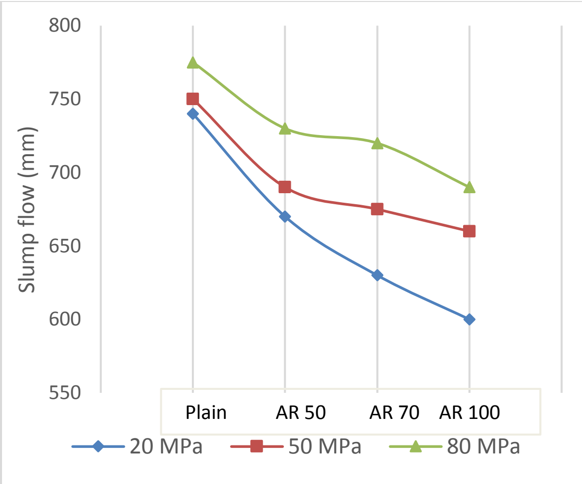


Figure 6.1 Variation of slump flow of RSCC due to addition of steel fibers

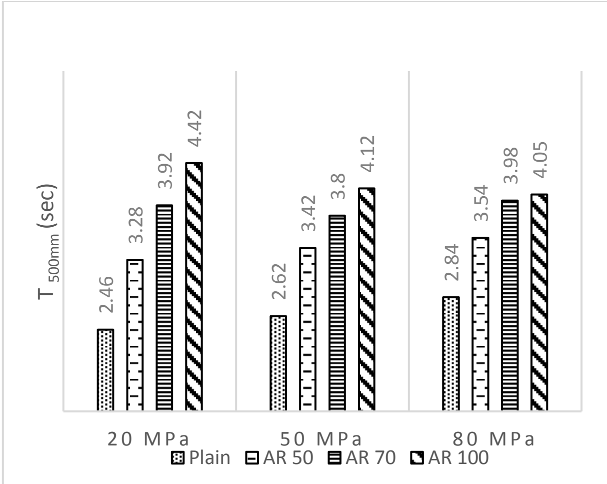


Figure 6.2 Variation of RSCC T_{500} (sec) due to addition of steel fibers

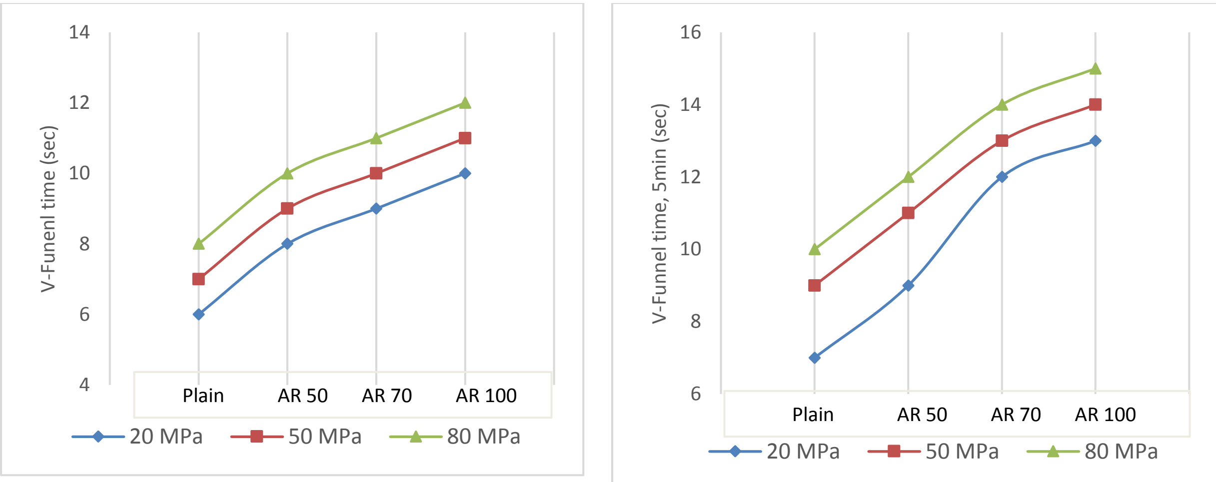


Figure 6.3 Variation of V-Funnel time of RSCC due to addition of steel fibers

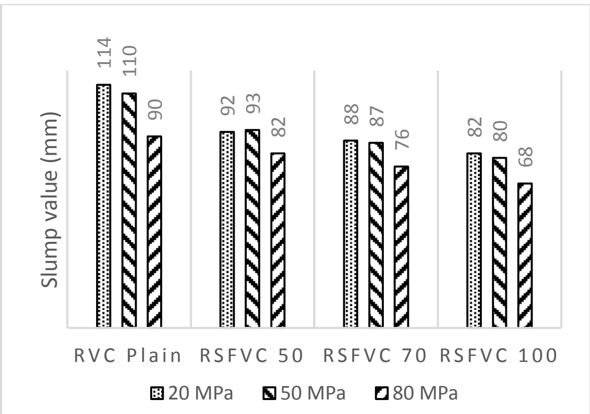


Figure 6.4 Variation of slump value of RVC due to addition of steel fibers

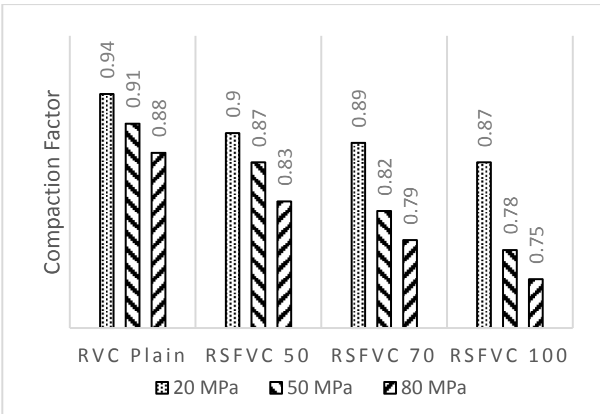


Figure 6.5 Variation of Compaction Factor of RVC due to addition of steel fibers

6.3.2 Mechanical properties of RSCC and RVC:

The details of hardened properties of 20 MPa, 50 MPa and 80 MPa with recycled aggregate and steel fiber at the age of 28 days were shown in Table 6.7. All the tests were done as per IS: 516-2013 specifications. Due to use of recycled aggregate, there is slight decrease in the mechanical properties compared with that of natural aggregate in both SCC and VC. Due to use of recycled aggregates, compressive strength of is reduced by 13.21 %, 6.59 % and 8.81 % for plain VC of strength 20, 50 and 80 MPa respectively compared with natural aggregate concrete. Similarly, in case of SCC compressive is reduced by 9.37 %, 5.81 % and 7.53 % in 20, 50 and 80 MPa concrete. Figures 6.6-6.11 and Table 6.7 show the variation of compressive strength, split tensile strength of 20, 50 and 80 MPa for both without and with steel fiber.

Table 6.7 Details of mechanical properties in RVC and RSCC in MPa

Mix designation	Cube Compressive strength			Split Tensile strength		
	20 MPa	50 MPa	80 MPa	20 MPa	50 MPa	80 MPa
RVC Plain	18.4	46.8	73.5	2.11	3.18	4.24
RSFVC 50	20.8	50.9	76.8	2.46	3.56	4.92
RSFVC 70	22.3	52.4	79.8	2.52	3.68	5.06
RSFVC 100	19.8	49.7	76.1	2.37	3.45	4.88
RSCC Plain	20.3	47.3	74.9	2.15	3.25	4.56
RSFSCC 50	22.4	49.9	79.6	2.53	3.73	5.25
RSFSCC 70	23.3	52.5	80.5	2.62	3.84	5.38
RSFSCC 100	20.7	49.1	77.2	2.41	3.62	4.96

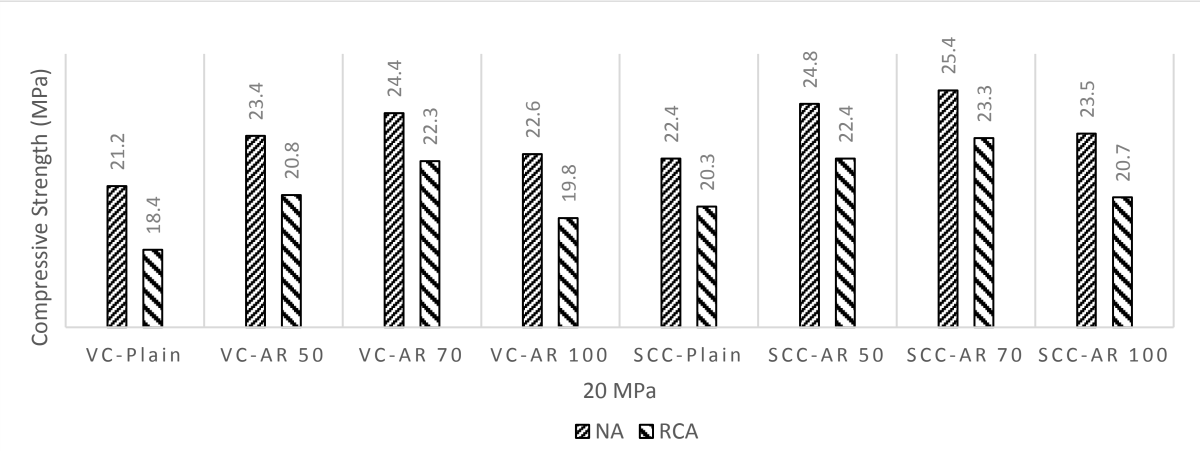


Figure 6.6 Comparison of compressive strength of natural aggregates concrete with recycled aggregate concrete of Mix A – 20 MPa

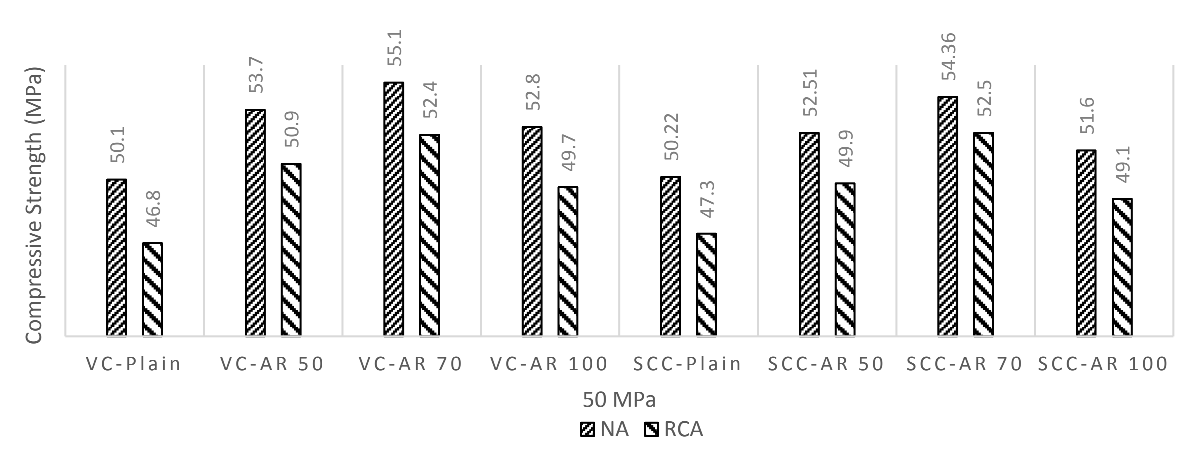


Figure 6.7 Comparison of compressive strength of natural aggregates concrete with recycled aggregate concrete of Mix B – 50 MPa

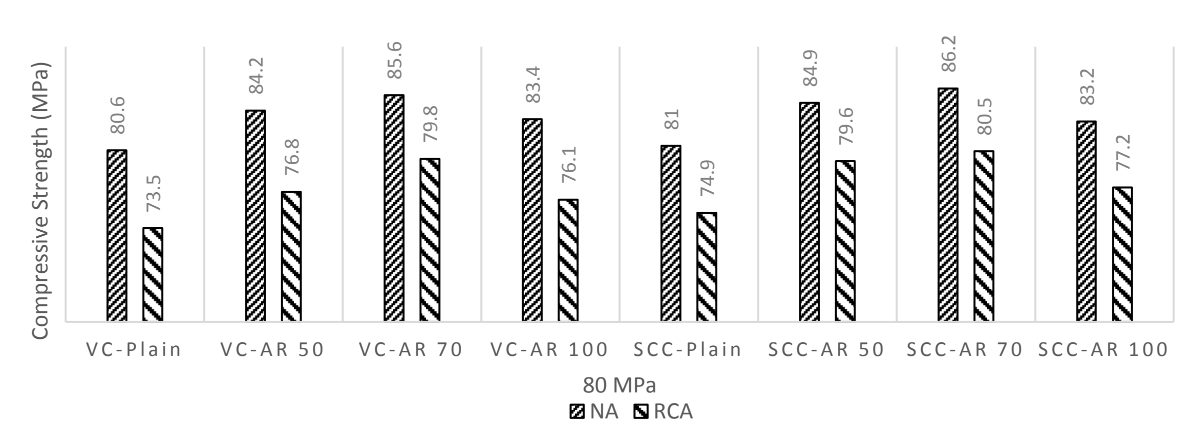


Figure 6.8 Comparison of compressive strength of natural aggregates concrete with recycled aggregate concrete of Mix C – 80 MPa

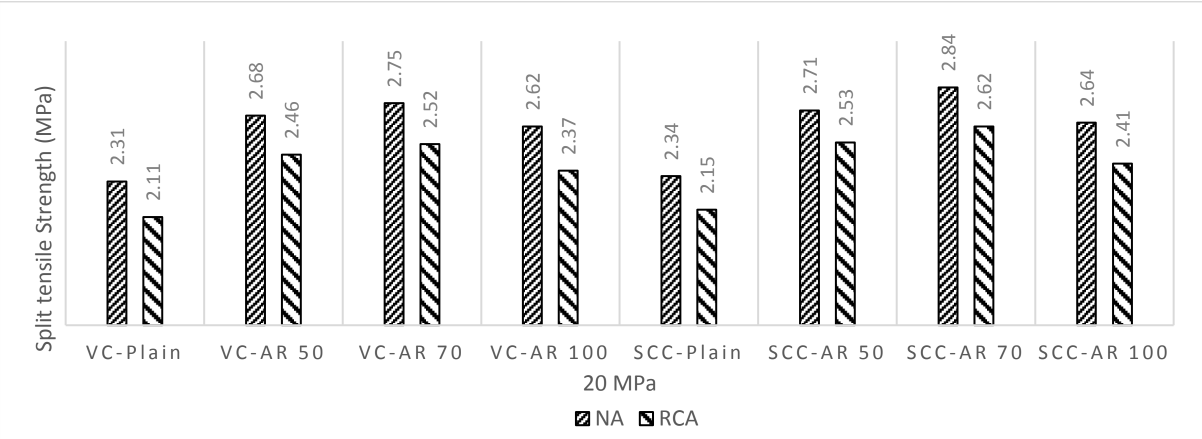


Figure 6.9 Comparison of split tensile strength of natural aggregates concrete with recycled aggregate concrete of Mix A – 20 MPa

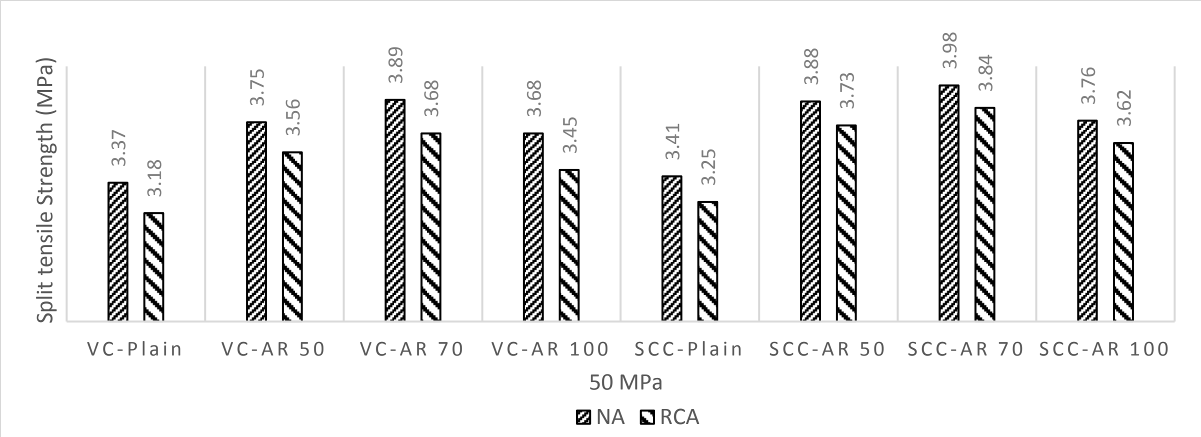


Figure 6.10 Comparison of split tensile strength of natural aggregates concrete with recycled aggregate concrete of Mix B – 50 MPa

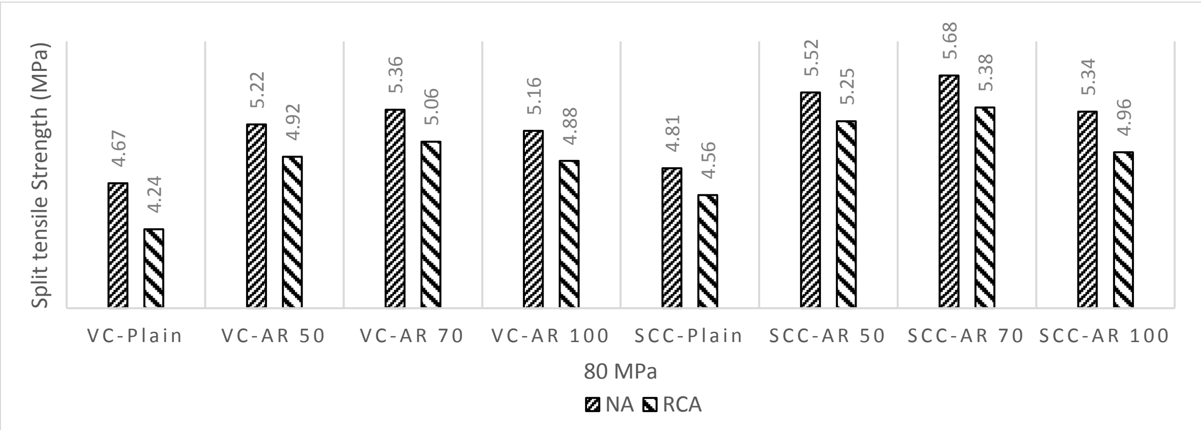


Figure 6.11 Comparison of split tensile strength of natural aggregates concrete with recycled aggregate concrete of Mix C – 80 MPa

6.3.3 Discussion on torsional behaviour of RSCC and RVC with recycled aggregates:

In this section, the behaviour of 24 beams with steel fibers with aspect ratios 50, 70, 100 are discussed. The results of these beams are presented in Tables 6.8-6.10.

Table 6.8 Torsional behaviour of RSCC and RVC Mix A-20 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
A-RVC Plain	1.49	4.98	404.64	4.64
A-RSFVC 50	1.74	5.46	431.71	5.93
A-RSFVC 70	**1.82**	**6.14**	**444.79**	**7.30**
A-RSFVC 100	1.69	5.73	418.97	6.16

A-RSCC Plain	1.56	5.11	421.02	4.96
A-RSFSCC 50	1.82	6.42	450.69	7.87
A-RSFSCC 70	**1.89**	**6.75**	**472.69**	**8.70**
A-RSFSCC 100	1.72	6.22	441.57	7.23

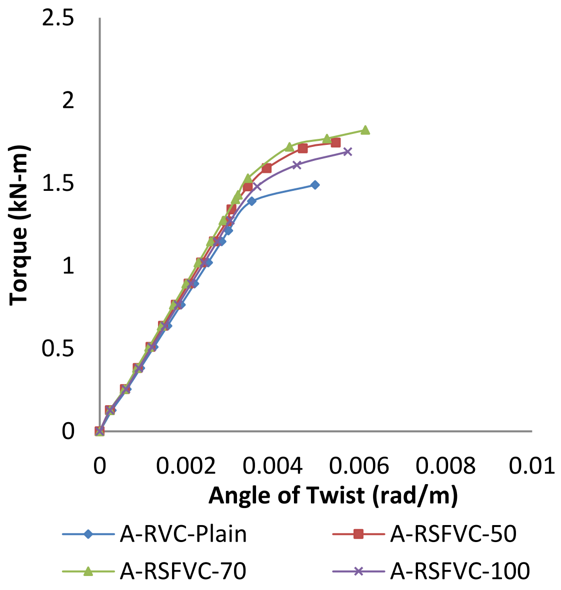


Figure 6.12 Torque-Twist response of A-RVC

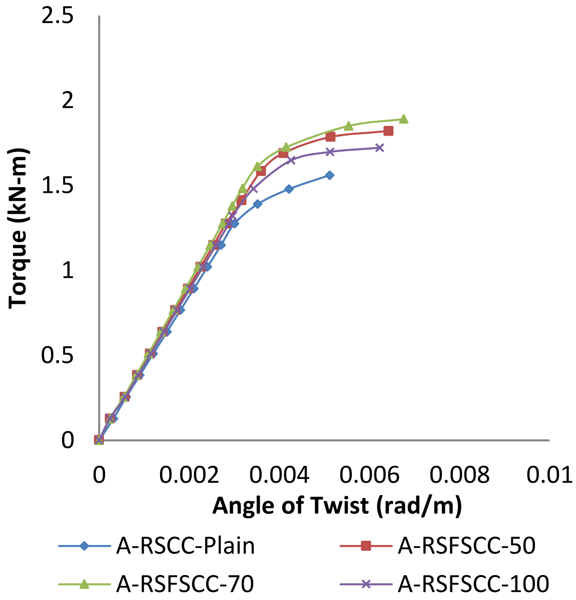
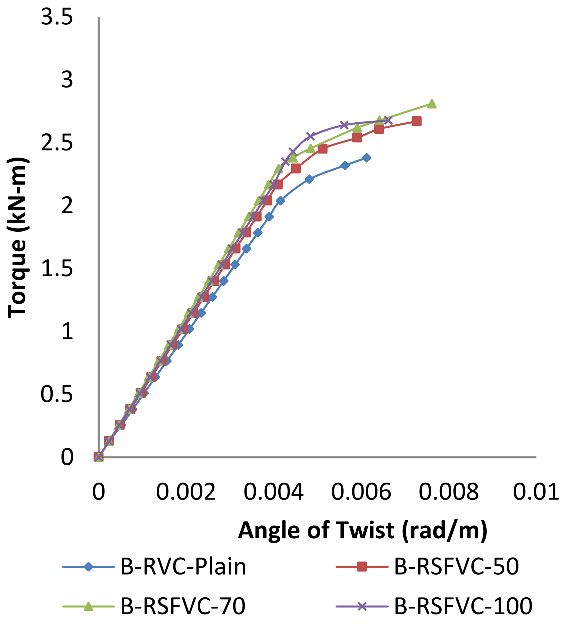


Figure 6.13 Torque-Twist response of A-RSCC

Table 6.9 Torsional behaviour of RSCC and RVC Mix B-50 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
B-RVC Plain	2.38	6.1	490.12	8.64
B-RSFVC 50	2.67	7.27	542.97	12.23
B-RSFVC 70	**2.81**	**7.85**	**558.32**	**13.78**
B-RSFVC 100	2.62	6.6	529.52	11.03
B-RSCC Plain	2.51	6.2	538.54	9.73
B-RSFSCC 50	2.83	8.2	592.82	16.02
B-RSFSCC 70	**2.97**	**8.7**	**611.54**	**18.01**
B-RSFSCC 100	2.77	7.1	581.37	12.92



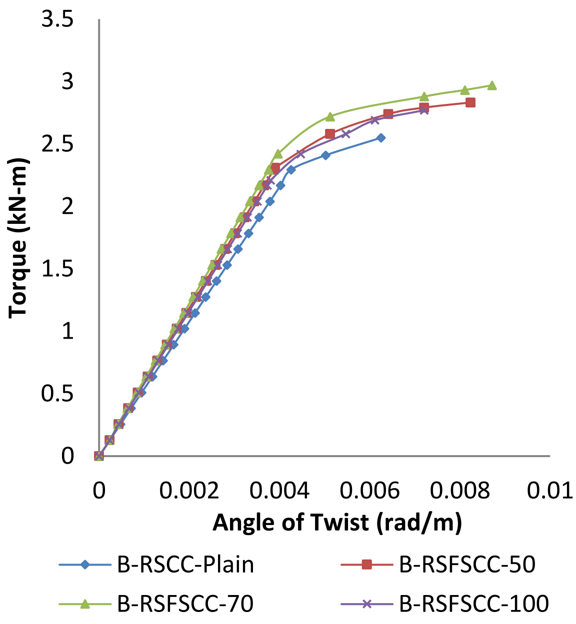


Figure 6.14 Torque-Twist response of B-RVC

Figure 6.15 Torque-Twist response of B-RSCC

Table 6.10 Torsional behaviour of RSCC and RVC Mix C-80 MPa

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)	Initial Torsional Stiffness (kNm^2)	Torsional Toughness (10^{-3} kNm/m)
C-RVC Plain	3.25	6.5	690.64	13.45
C-RSFVC 50	3.72	8.6	736.3	22.00
C-RSFVC 70	**3.84**	**10.2**	**751.2**	**28.29**
C-RSFVC 100	3.64	8.2	724.01	20.14
C-RSCC Plain	3.48	6.9	702.35	15.12
C-RSFSCC 50	4.08	10.9	743.82	32.22
C-RSFSCC 70	**4.16**	**12.2**	**752.21**	**38.60**
C-RSFSCC100	3.78	10.4	730.21	29.59

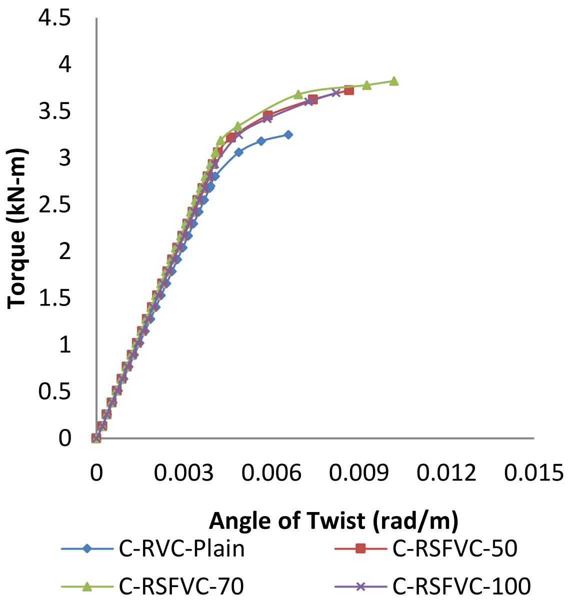


Figure 6.16 Torque-Twist response of C-RVC

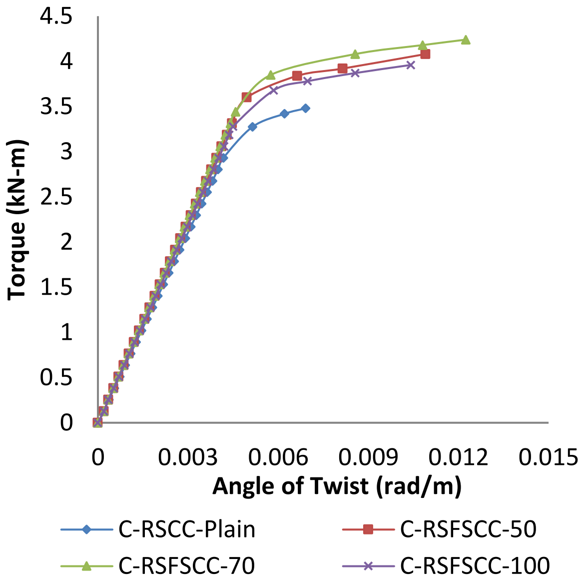


Figure 6.17 Torque-Twist response of C-RSCC

The torsional response of concrete in precracking is practically linear. In post cracking range, the response depends primarily on proportion, distribution and physical properties of steel fibers provided.

a) Influence of Aspect ratio of Steel fibers on Torsional strength of RSCC and RVC:

Figures 6.12-6.17 show the comparison of torque-twist curves of 20 MPa, 50MPa and 80 MPa strengths of concrete of RSCC and RVC with and without steel fibers of aspect ratios (l/d) 50, 70 and 100. It can be observed that,

1. The plain beams of SCC and VC failed suddenly and separated into two pieces under pure torsion, due to addition of steel fibers load carrying capacity has increased in all grades of concrete. Beams with fibers have shown higher torsional strength and the failure mode has changed from brittle to ductile mode by arresting of opening, widening and extension of cracks in concrete mass due to steel fibers.
2. It can be observed the increase in the torsional strength has increased with the increase of aspect ratio (l/d) ratio from 50 to 100 for all grades of SCC and VC. Highest increase in torsional strength was observed for beams with fibers of aspect ratio 70 in all strengths of concrete.

3. In Mix A (20 MPa) concrete beams with fibers of aspect ratio 70, torsional strength has increased by 22.15 % and 21.15 % in RVC and RSCC respectively in comparison with respective recycled aggregate plain beams.
4. Similarly, Mix B (50 MPa) concrete beams with fibers of aspect ratio 70, torsional strength has increased by 18.07 % and 18.33 % in RVC and RSCC respectively in comparison with respective recycled aggregate plain beams.
5. In High strength concrete (Mix C-80 MPa), torsional strength has increased by 18.15 % and 21.84 % in RVC and RSCC respectively in beams with fibers of aspect ratio 70.

Fiber embedment length into the mortar matrix depends on the fiber aspect ratio, orientation with respect to loading direction and matrix strength greatly influence pullout resistance. Short and discrete fibers (Aspect Ratio 50, 70) are more effective in behaviour of torsion than long fibers (Aspect Ratio 100) in both concretes. Fiber strengthening in concrete is due to Adhesion, Friction and Mechanical Anchorage. Random orientation of steel fiber create an efficient web-like structural system around coarse aggregate, which mainly controls the residual tensile strength. The effect of recycled aggregates and steel fiber on torsional strength of SCC and VC is shown in Figures 6.18-6.21.

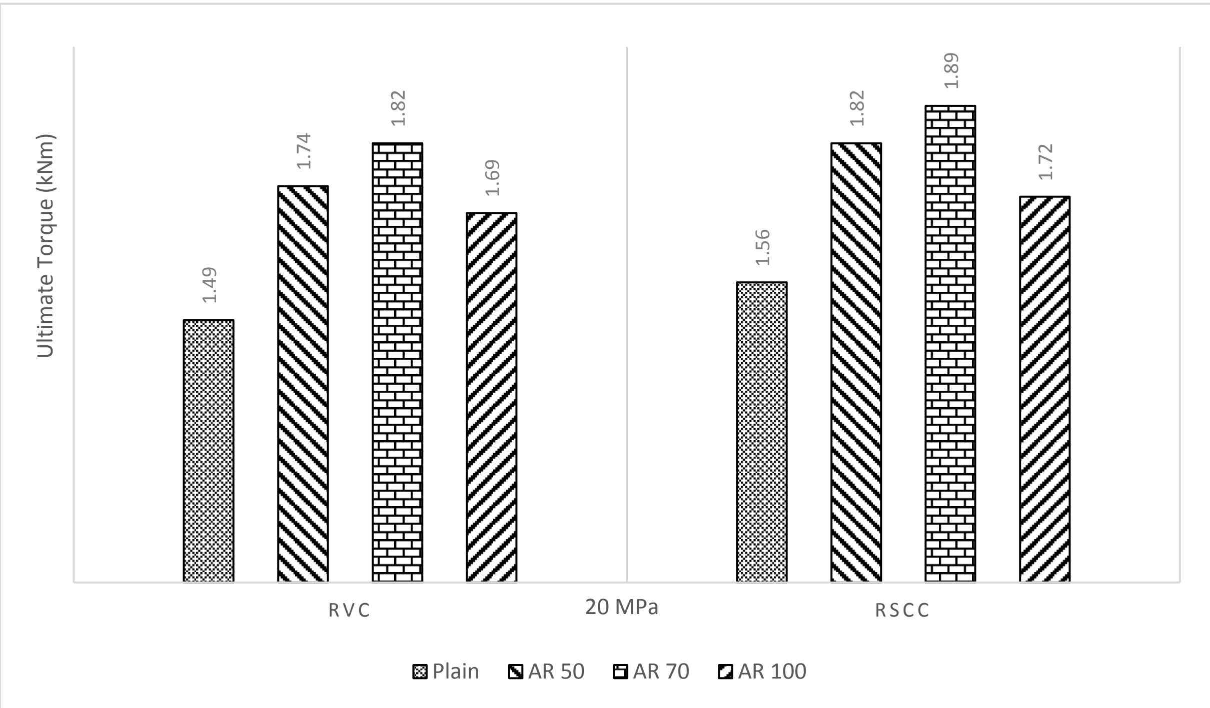


Figure 6.18 Torsional Strength Vs Aspect ratio of steel fiber (Mix A-20 MPa)

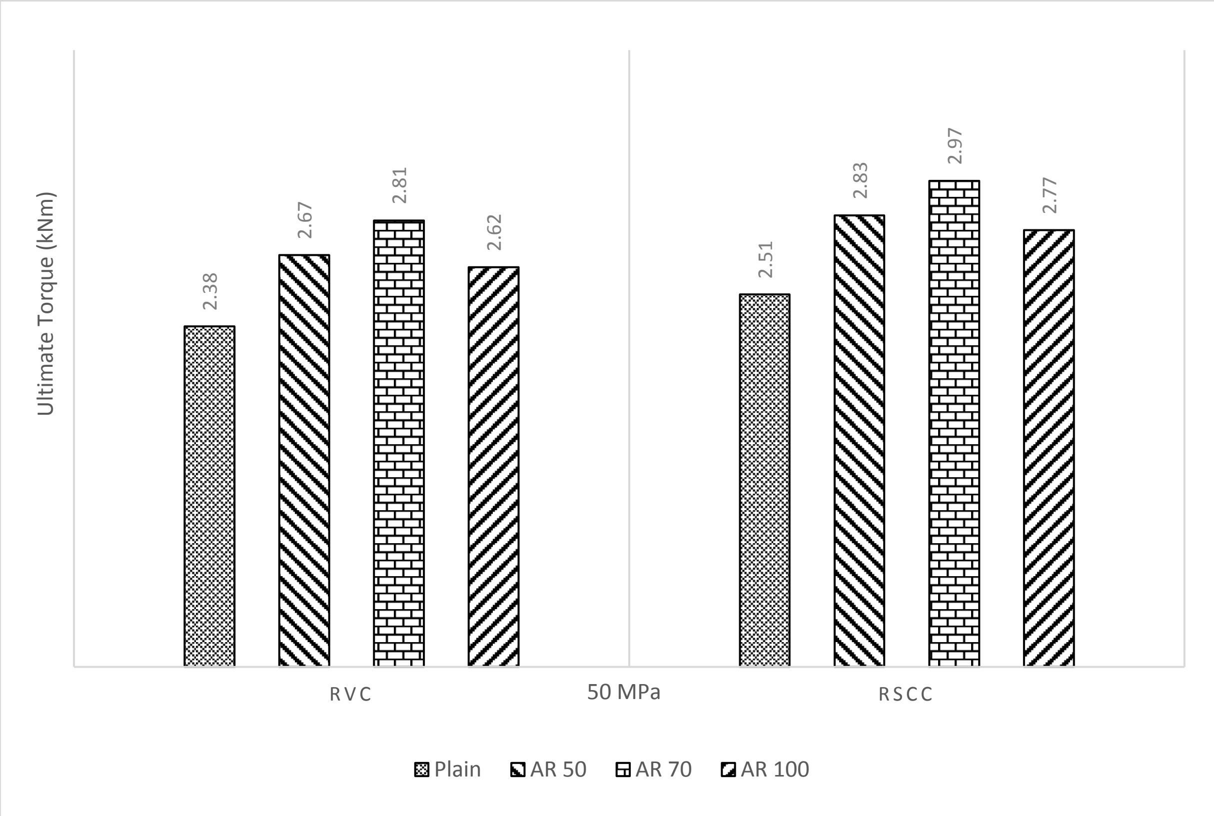


Figure 6.19 Torsional Strength Vs Aspect ratio of steel fiber (Mix B-50 MPa)

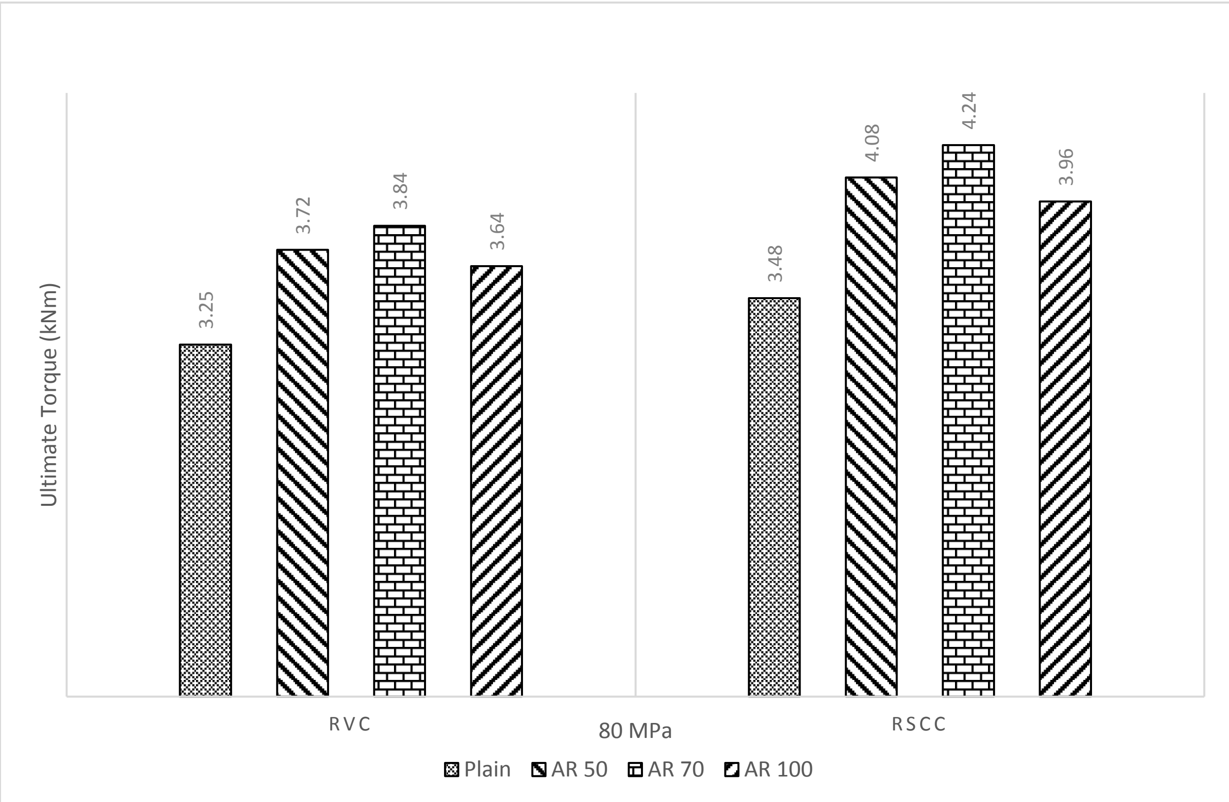


Figure 6.20 Torsional Strength Vs Aspect ratio of steel fiber (Mix C-80 MPa)

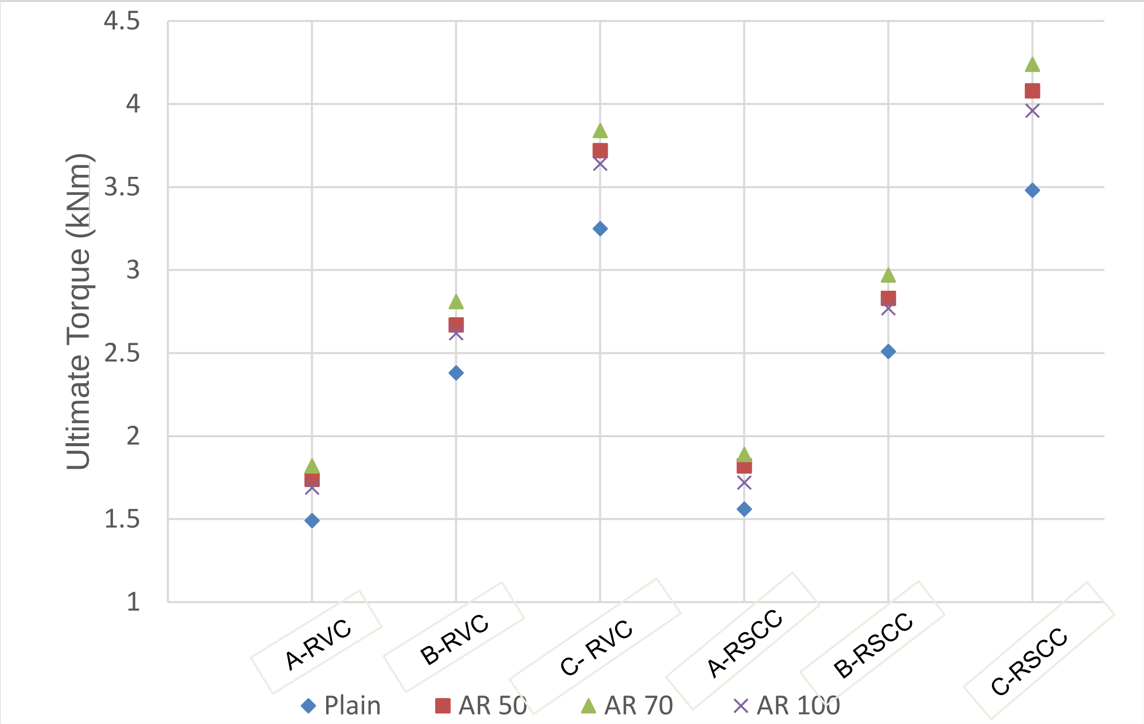


Figure 6.21 Variation of Ultimate torque in RSCC and RVC with aspect ratio of steel fiber

b) Influence of Aspect ratio of Steel fibers on Twist at ultimate torque of RSCC and RVC:

It can be observed from the Tables 6.8-6.10 that as the strength and aspect ratio increases, twist at ultimate torque has increased. Angle of twist at any point is the rotation of the of the member at the point about the longitudinal centroidal axis of the members

1. It can be observed the increase in the twist at ultimate torque has increased with the increase of aspect ratio (l/d) ratio from 50 to 100 for all grades of SCC and VC. Highest increase in twist at ultimate torque was observed for beams with fibers of aspect ratio 70 in all strengths of concrete.
2. In Mix A (20 MPa) concrete beams with fibers of aspect ratio 70, twist at ultimate torque has increased by 23.29 % and 32.09 % in RVC and RSCC respectively in comparison with plain beams.
3. Similarly, the Mix B (50 MPa) concrete beams with fibers of aspect ratio 70, twist at ultimate torque has increased by 28.69 % and 40.32 % in RVC and RSCC respectively with respect to plain beams.

4. In High strength concrete (Mix C-80 MPa), twist at ultimate torque has increased by 56.92 % and 76.81 % in RVC and RSCC respectively in beams with fibers of aspect ratio 70.

The effect of recycled aggregates and steel fiber on angle of twist of SCC and VC is shown in Figures 6.22-6.24.

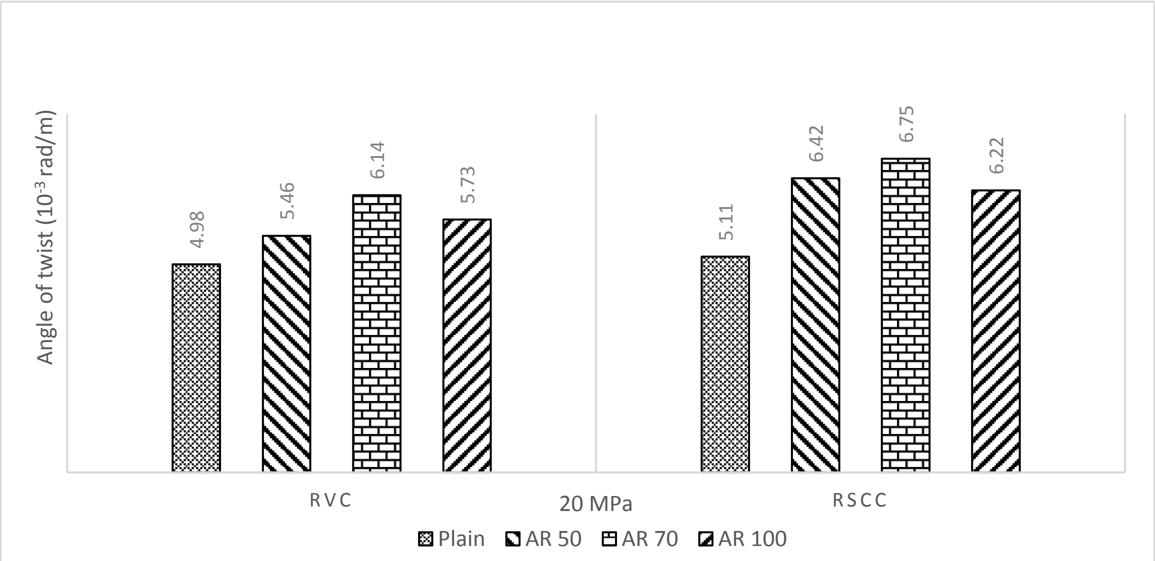


Figure 6.22 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix A 20 MPa)

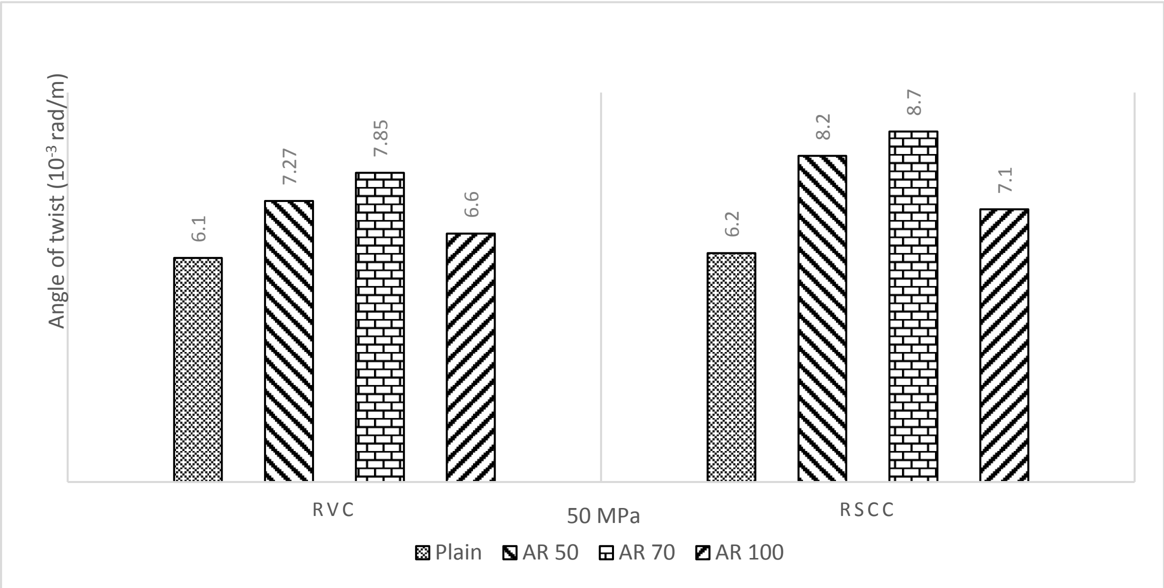


Figure 6.23 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix B 50 MPa)

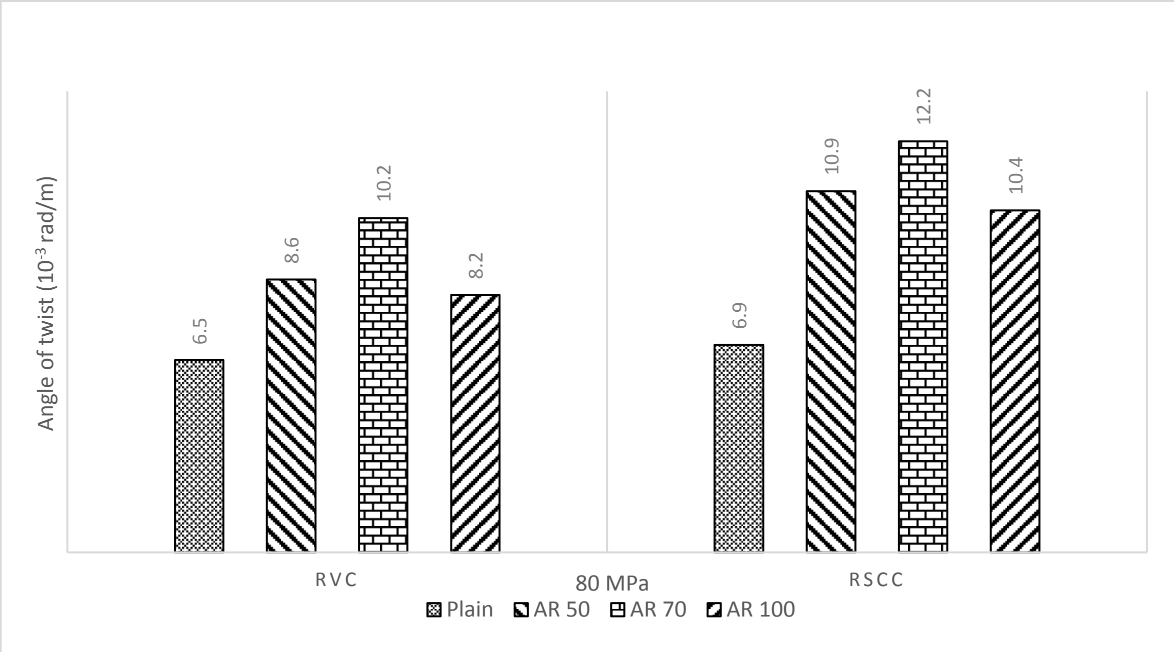


Figure 6.24 Twist at ultimate torque Vs Aspect ratio of steel fiber (Mix C 80 MPa)

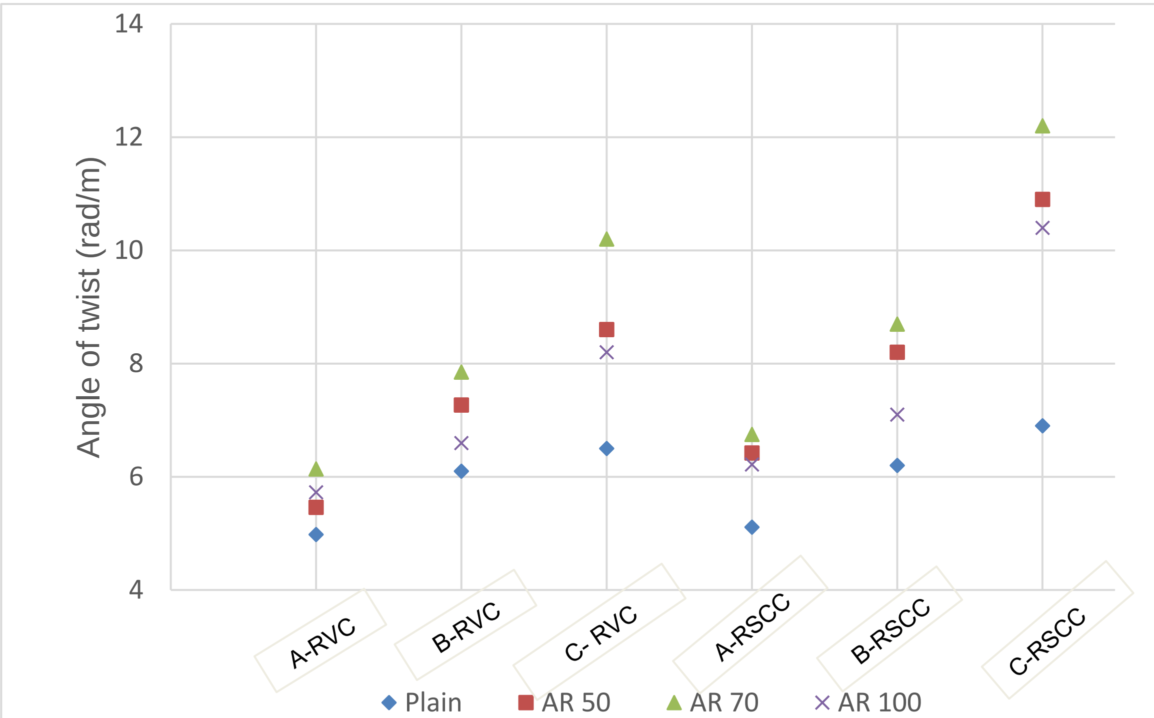


Figure 6.25 Variation of Ultimate torque in RSCC and RVC with aspect ratio of steel fiber

c) Effect of aspect ratio of Steel fibers on Torsional Toughness of beams of RSCC and RVC:

Torsional Toughness is defined as the amount of energy per unit volume that a material can absorb before rupturing. In can also be defined as area under torque-twist curve. In the present study torsional toughness of the beams is measured by calculating the area under torque-twist curve. Addition of steel fibers not only improved the torsional performance of SCC and VC beams but there is also enhancement in the energy absorption capacity. This is due to crack delaying property and energy absorption capacity of fibrous matrix.

Due to inclusion of steel fibers of aspect ratio 70 for plain beams, there an increment of 57.33 % and 75.40 % in toughness of the 20 MPa beam of RVC and RSCC respectively. When compared with the identical beam without steel fiber. Similarly, in case of 50 MPa concrete beams, due to addition of fibers (aspect ratio 70) the toughness of the plain beams increased by 59.49 % and 85.10 % in RVC and RSCC beams respectively in comparison with plain beams.

Fiber embedment length into the mortar matrix depends on the fiber aspect ratio, orientation with respect to loading direction and matrix strength greatly influence pullout resistance. In high strength concrete (80 MPa) there was an increase of 110.33 % and 155.29 % in toughness of VC and SCC beams respectively with steel fibers of aspect ratio 70 in comparison with plain beams of 80 MPa strength concrete.

Figures 6.26-6.29 shows the variation of torsional toughness with respect to aspect ratios for three grades of concrete and for RSCC and RVC beams.

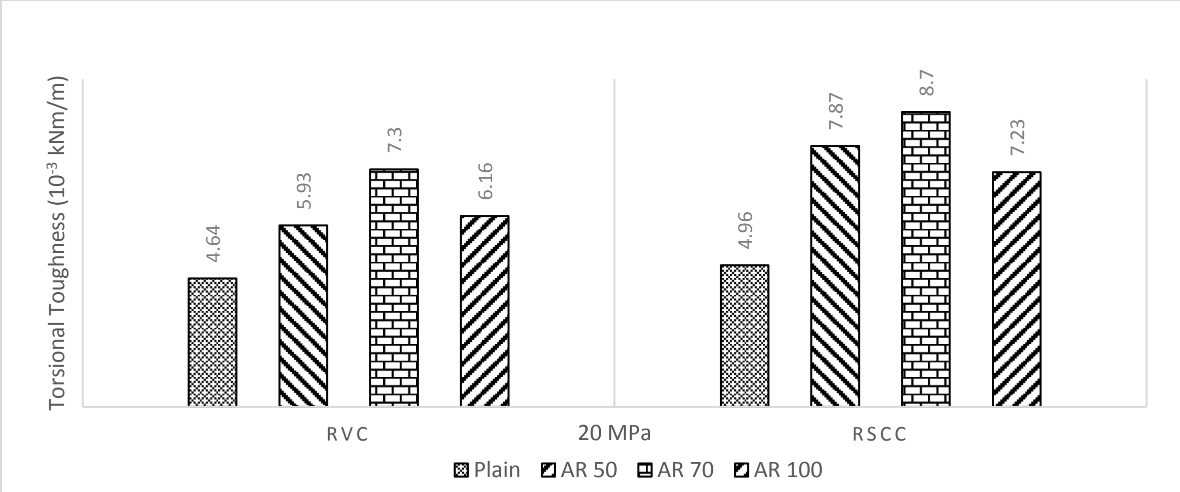


Figure 6.26 Variation of Torsional toughness of Mix A-20 MPa

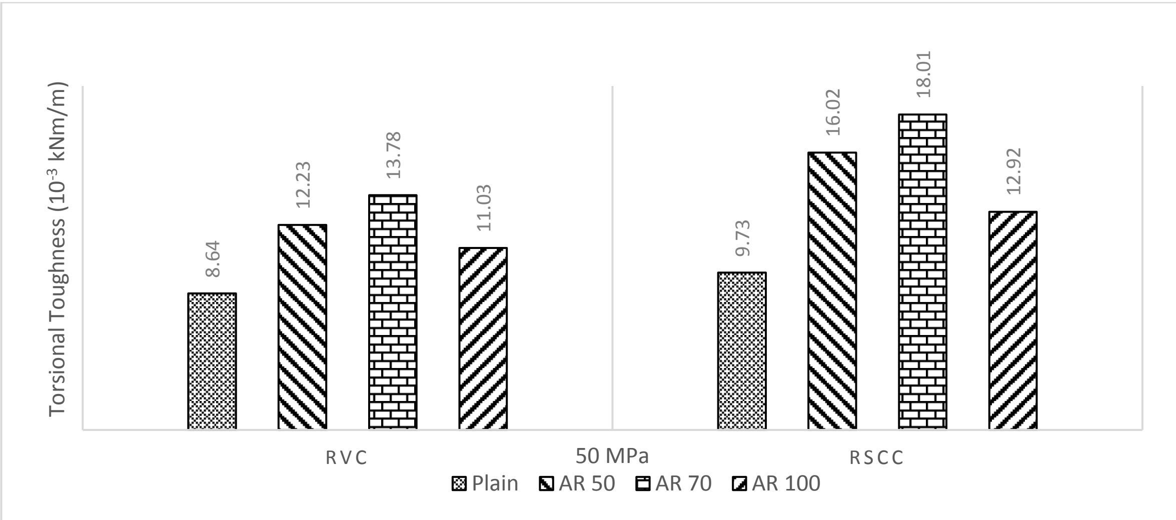


Figure 6.27 Variation of Torsional toughness of Mix B-50 MPa

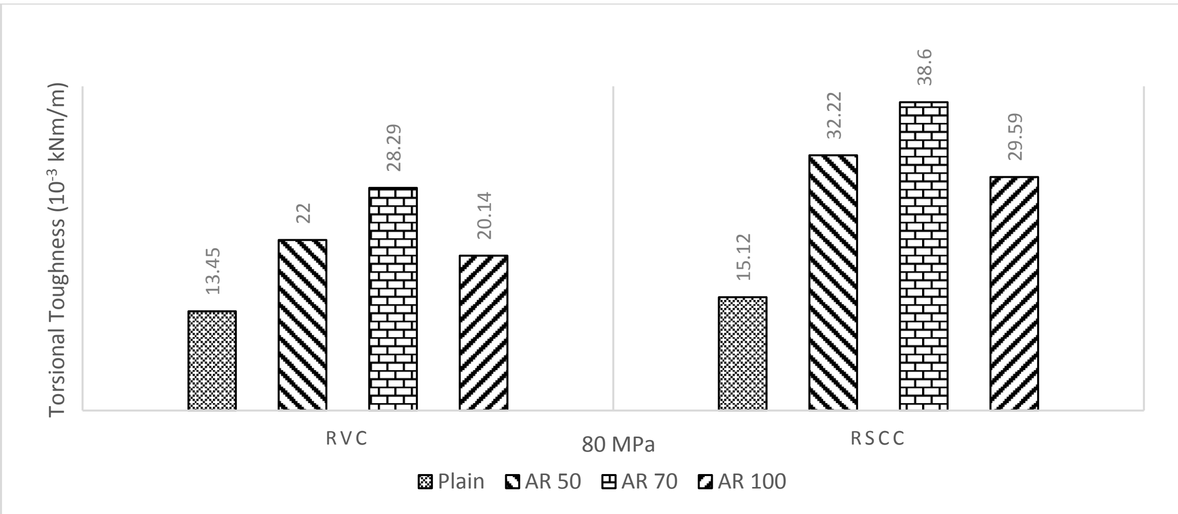


Figure 6.28 Variation of Torsional toughness of Mix C-80 MPa

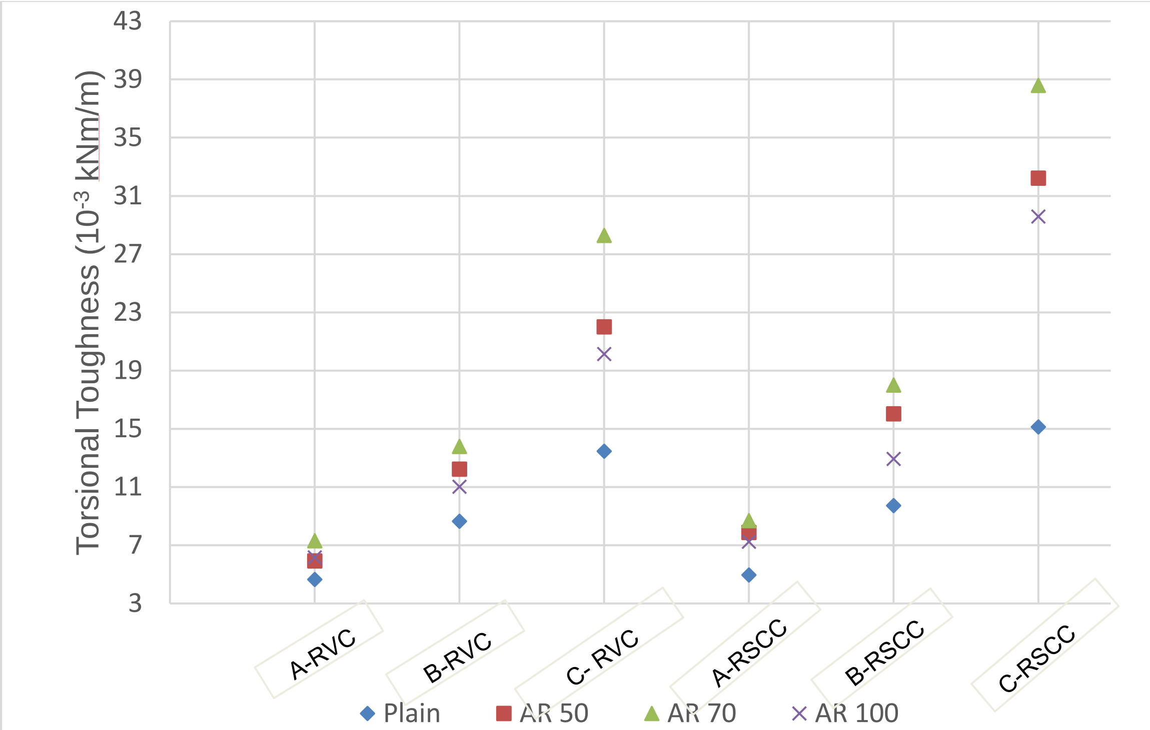


Figure 6.29 Variation of torsional toughness in SCC and VC beams

The linear portion of torque-twist curve (slope of initial tangent) indicate torsional stiffness of beams and was found to increase with addition of steel fibers. This increase is essentially with increase in modulus of matrix due to steel fibers. Similar trend was observed even in case of torsional stiffness in both concretes with fibers.

d) Failure Pattern:

Torsion produces shear stress which inturn give rise to diagonal tension. Diagonal tension leads to diagonal cracks in the structural member. Skew bending type of failure was observed in plain and fibrous beams of both the concretes. Steel fibers subsequently carry the redistributed tensile stress along (across) the crack and prevent premature concrete splitting. SFRC possess residual tensile strength that is good enough to keep the crack-width in the section sufficiently small to ensure effective and efficient transfer of shear stresses produced due to torsion. It is observed that the torsion cracks don't start at the midpoint of the wider face of a rectangular section but that they actually form simultaneously along the perimeter of the specimen.

For all beams, inclination of crack varies from 42° to 48° with respect to longitudinal axis. The failure of all plain beams were sudden, violent and got separated. While steel fibrous beams of both RSCC and RVC have shown better ductile nature without separating into two pieces though failed with a solitary potential crack. Crack angle is not much varied with the addition of recycled aggregates and steel fibers, as failure pattern is dependent on the type action applied on the member than the material of the member. Crack pattern on all four sides of beam for all grades are shown in figure 6.30-6.32

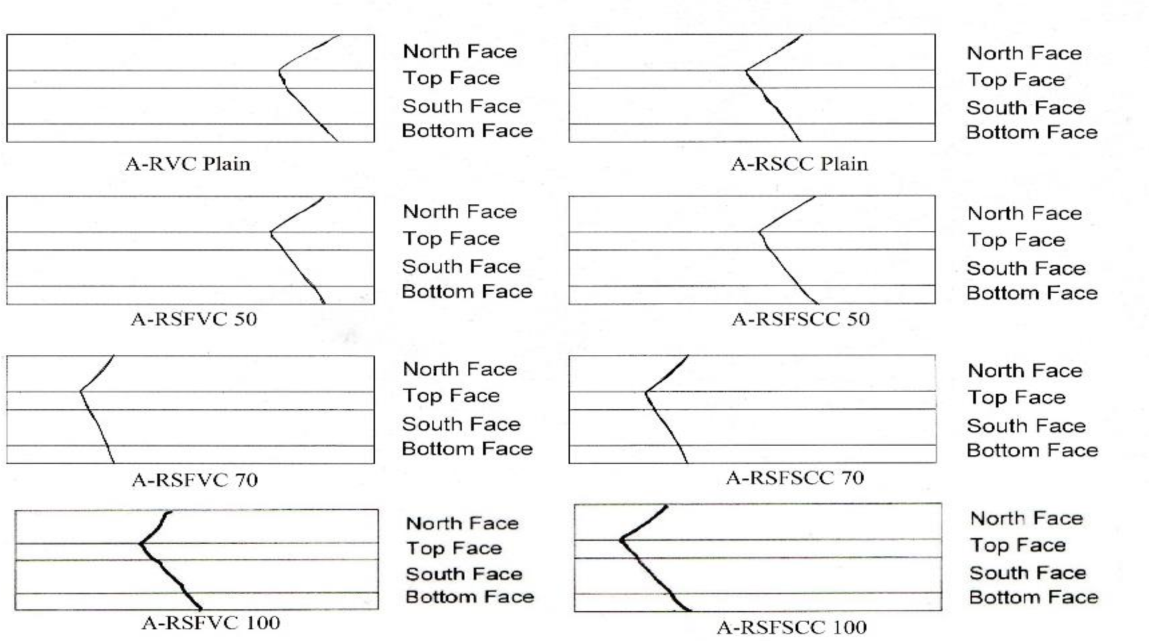


Figure 6.30 Crack pattern on all four sides of beam for Mix-A 20 MPa

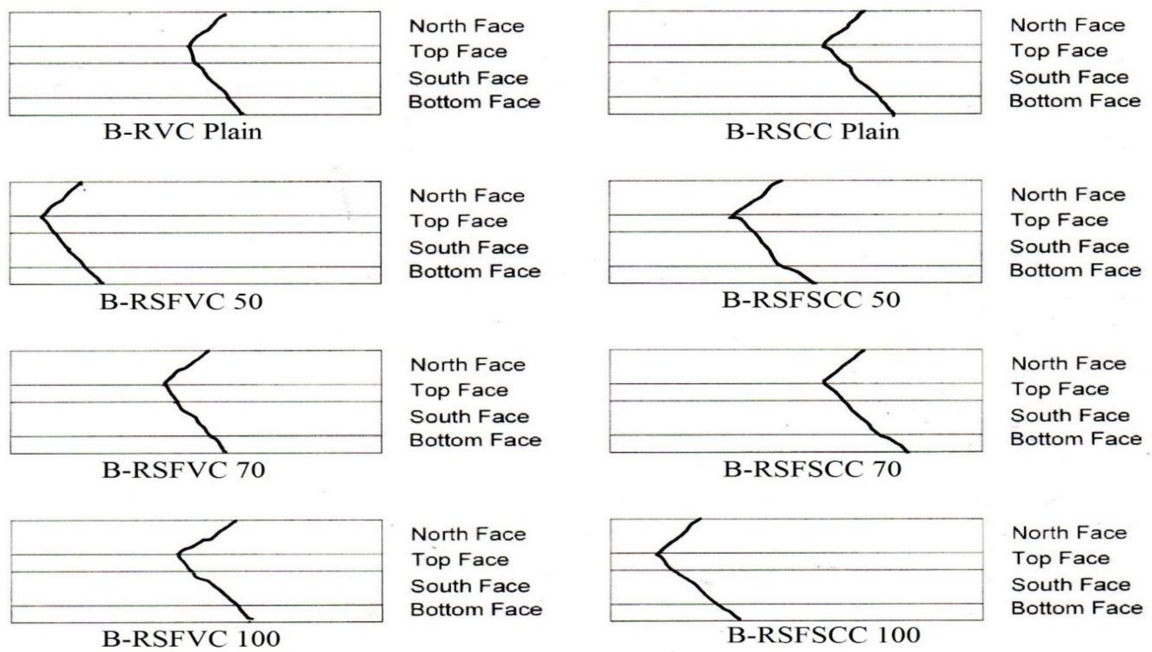


Figure 6.31 Crack pattern on all four sides of beam for Mix-B 50 MPa

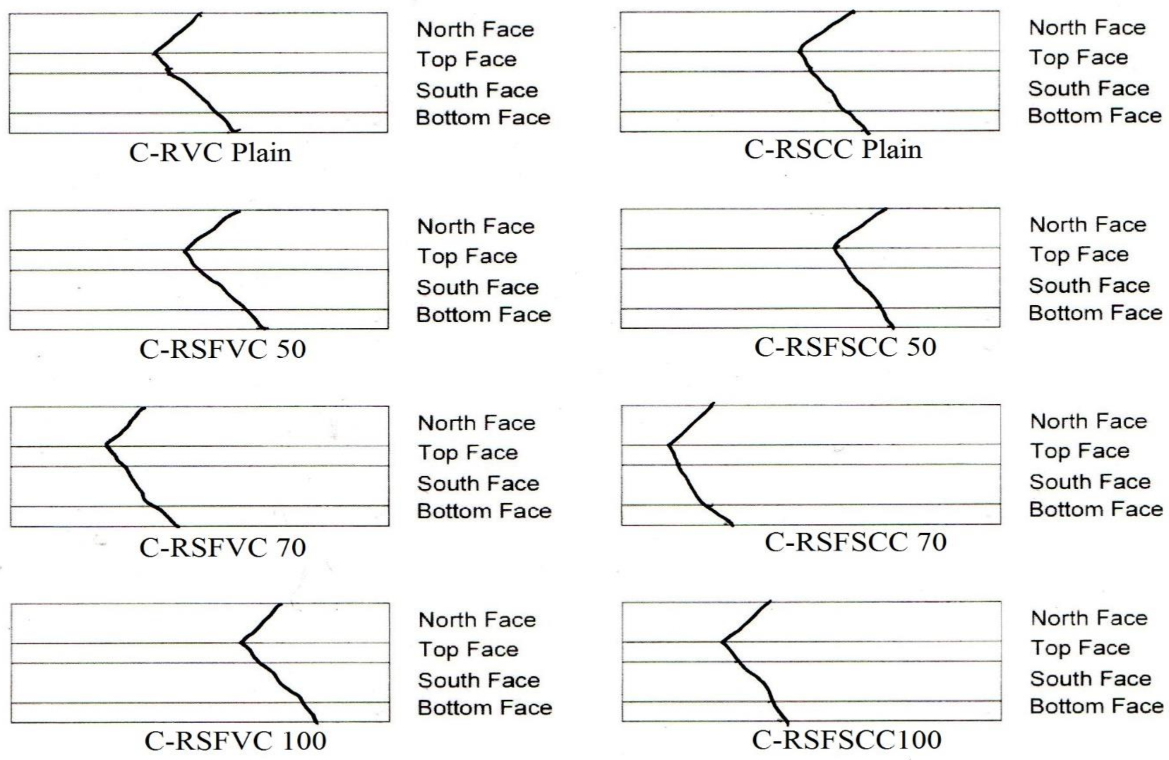


Figure 6.32 Crack pattern on all four sides of beam for Mix-C 80 MPa

6.4 Comparison of test results with natural and recycled aggregates:

6.4.1 Effect of recycled aggregate on Ultimate Torque of SCC and VC:

To study the torsional performance of SCC and VC, a comparison is made with beams cast with natural and recycled aggregates. Due to use of recycled aggregates, torsional strength decreased by 5-8 % in all strengths of concrete. The least decrease was found by 5.70 % and 7.35 % in beams with aspect ratio 70 in A-VC and A-SCC respectively. Whereas, in B-VC and B-SCC the decrease was observed to be 4.75 % and 3.57 % in beams with aspect ratio 70. Similarly, in 80 MPa strength concrete with aspect ratio 70 the decrement was observed to be 5.88 % and 4.57 %.

The comparison of ultimate torque of natural and recycled aggregate concrete is shown in Figures 6.33-6.35. Whereas, comparison of twist at ultimate torque of natural and recycled aggregate concrete is shown in Figures 6.36-6.38. Similarly, the comparison of Torsional toughness of natural and recycled aggregate concrete is shown in Figures 6.39- 6.41

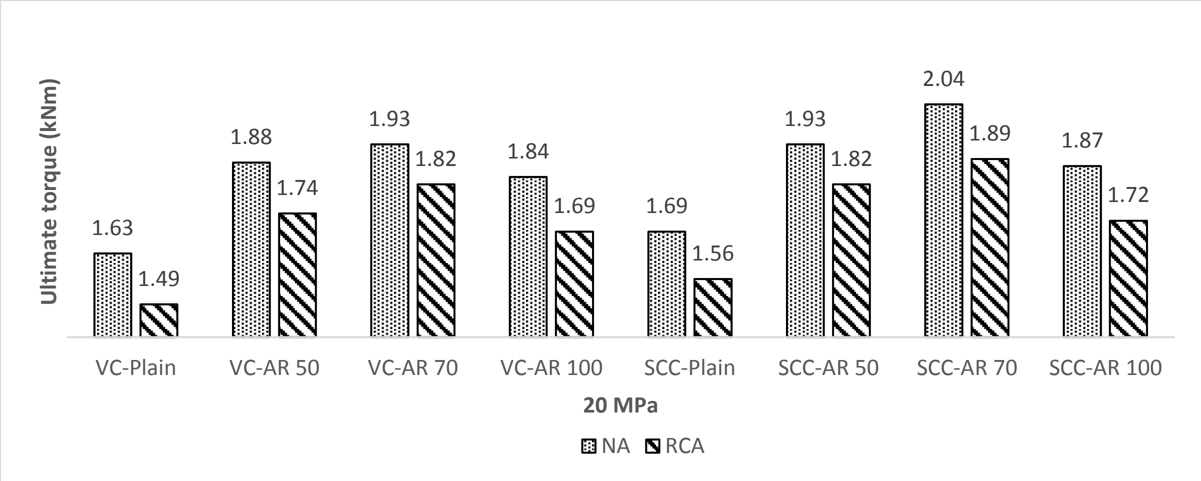


Figure 6.33 Comparison of ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix A – 20 MPa

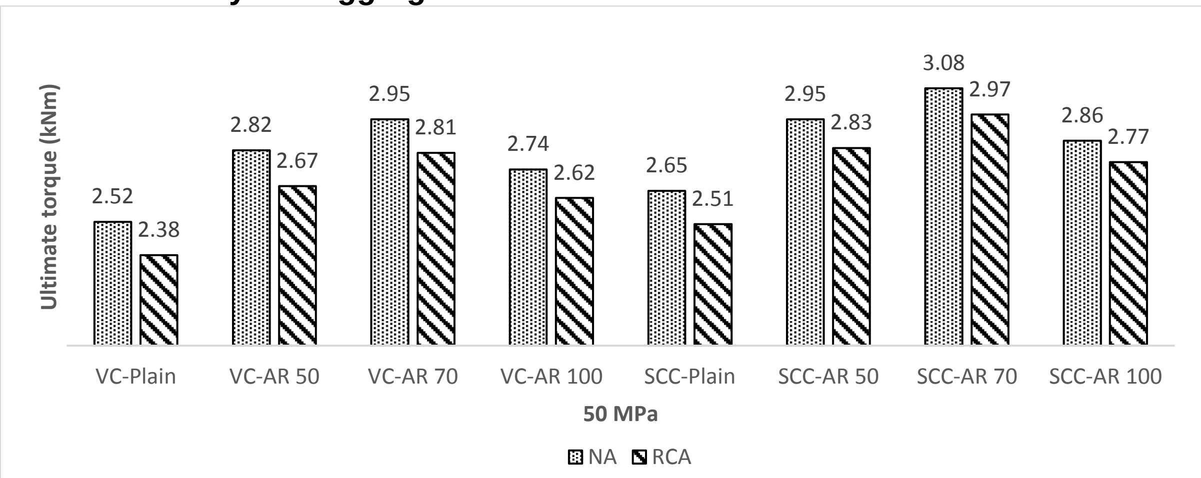


Figure 6.34 Comparison of ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix B – 50 MPa

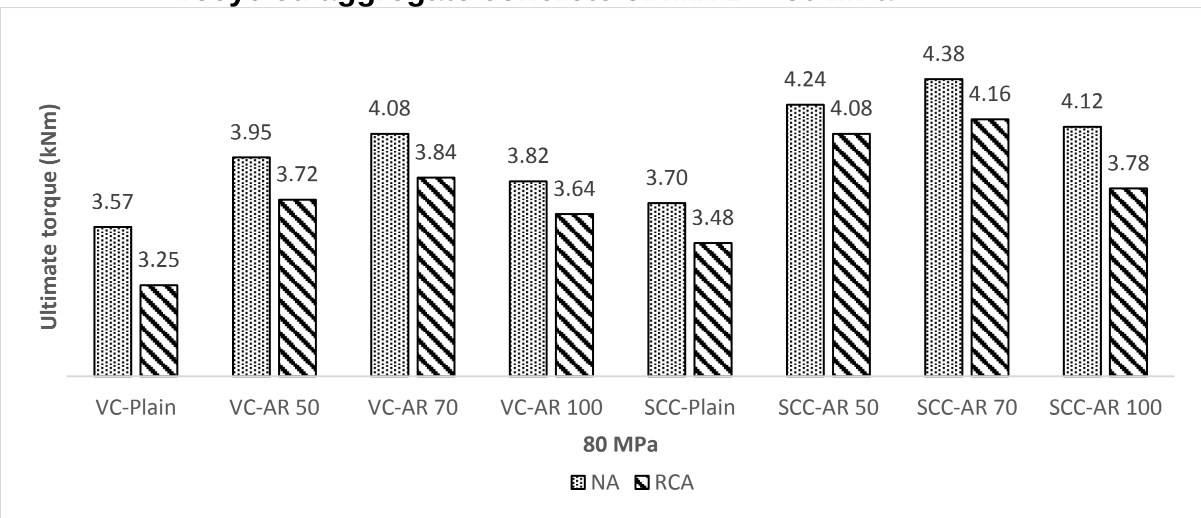


Figure 6.35 Comparison of ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix C – 80 MPa

6.4.2 Effect of recycled aggregate on Twist at ultimate torque of SCC and VC:

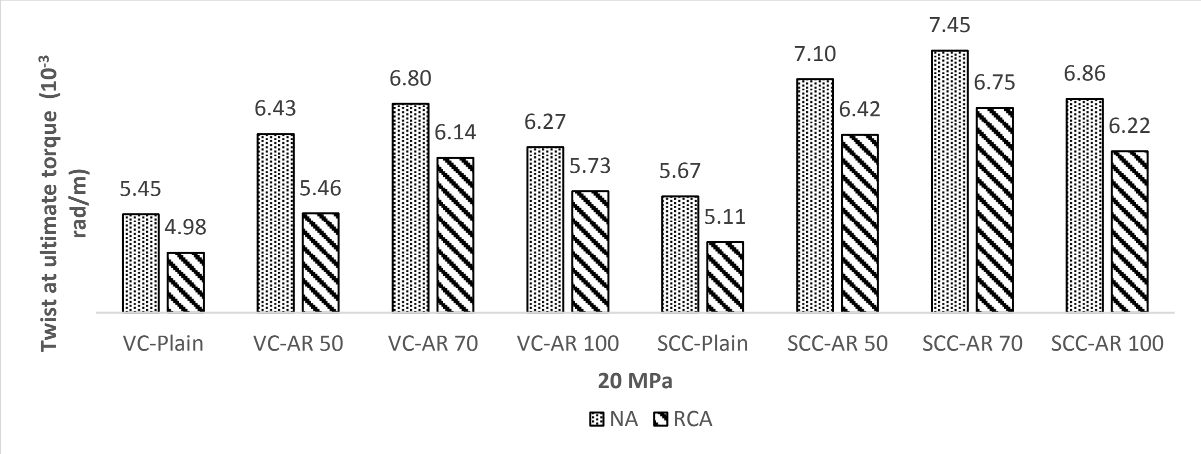


Figure 6.36 Comparison of twist at ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix A – 20 MPa

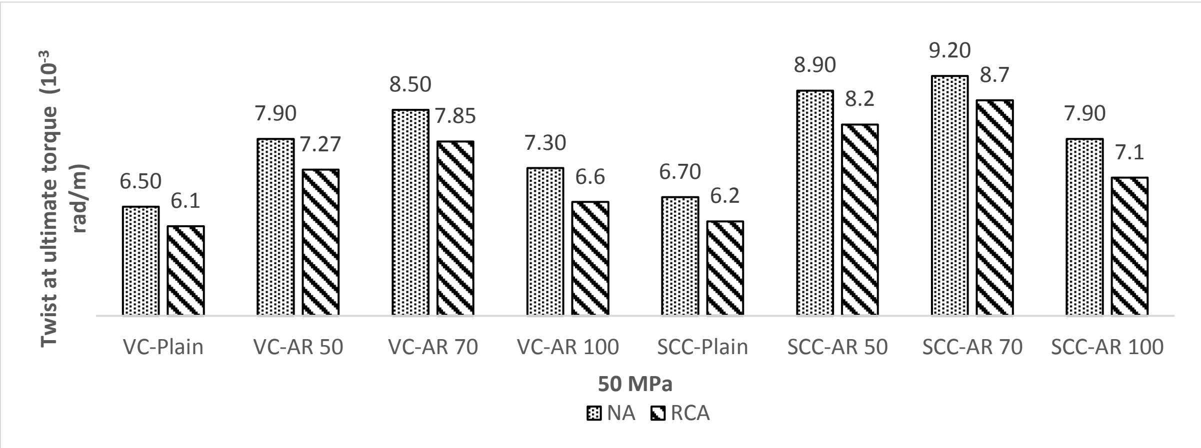


Figure 6.37 Comparison of twist at ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix B – 50 MPa

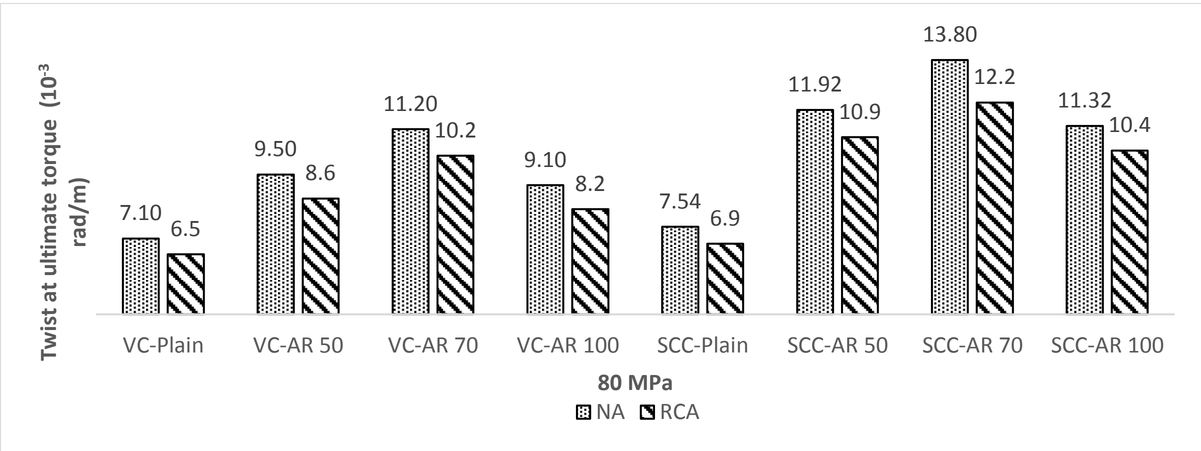


Figure 6.38 Comparison of twist at ultimate torque of natural aggregates concrete with recycled aggregate concrete of Mix C – 80 MPa

6.4.3 Effect of recycled aggregate on Torsional toughness torque of SCC and VC:

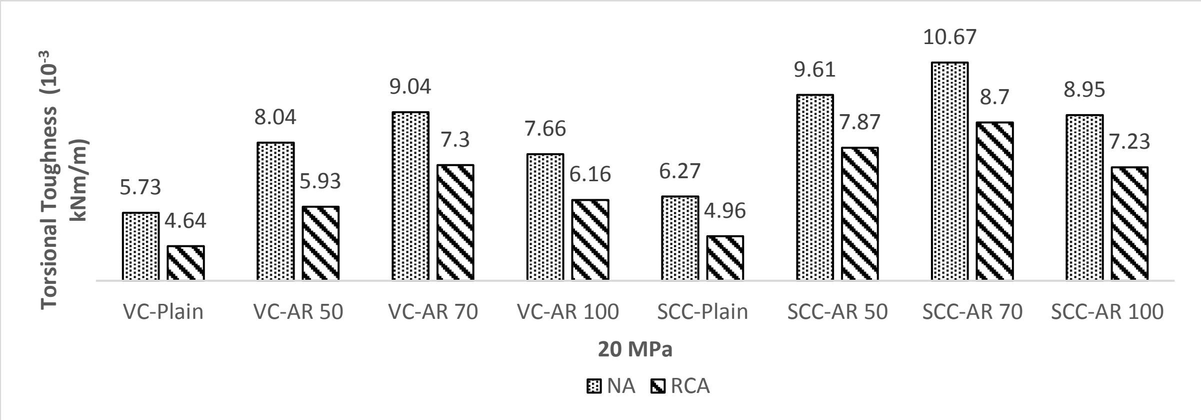


Figure 6.39 Comparison of torsional toughness of natural aggregates concrete with recycled aggregate concrete of Mix A – 20 MPa

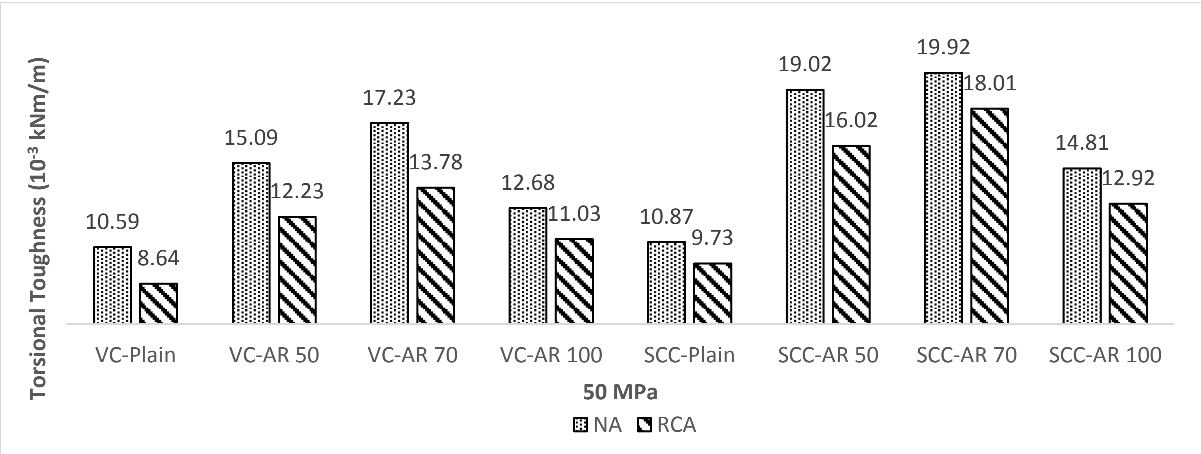


Figure 6.40 Comparison of torsional toughness of natural aggregates concrete with recycled aggregate concrete of Mix B – 50 MPa

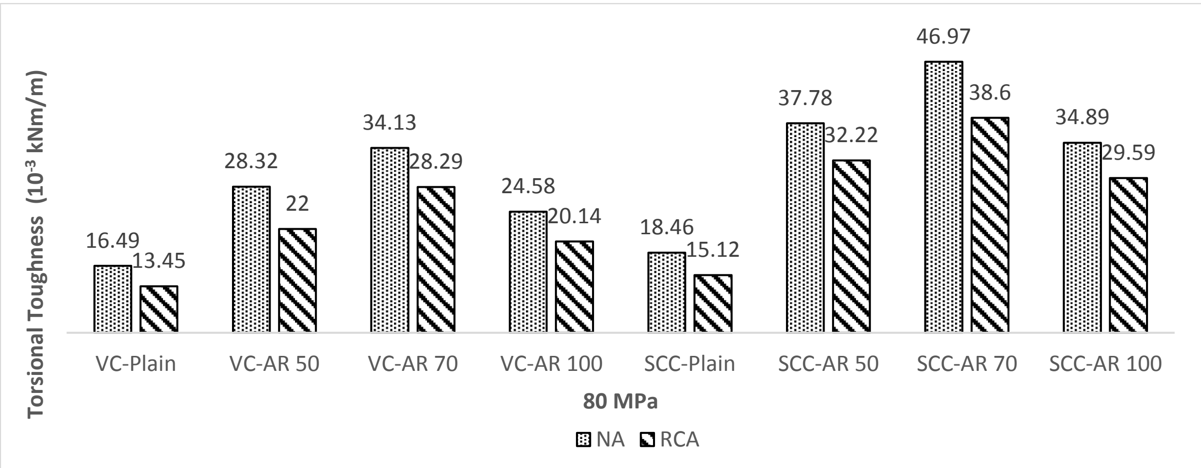


Figure 6.41 Comparison of torsional toughness of natural aggregates concrete with recycled aggregate concrete of Mix C – 80 MPa

6.5 Comparison of test results with various models from Literature:

In this section, the experimental results obtained for ultimate torsional strength of RVC and RSCC are compared with torsional strength models available in the literature for vibrated concrete.

1. **Elastic Theory:**

Saint Venant for rectangular sections proposed an equation for computing the torsional strength (T_e) of the beam based on elastic analysis which is given by

$$T_e = \alpha b^2 d f_t \quad \textbf{(6.1)}$$

Where, α = Constant depends on b/d ratio = 0.246 for the b/d ratio 0.5, b = breadth of the beam (smaller dimension), d = depth of the beam (larger dimension), f_t = Tensile strength of the concrete.

The solution for the torsion of a fully plastic elastic rectangular section is obtained by membrane analogy. In this theory, the marginal increase in ultimate torque of plain concrete member due to plasticity may be ignored for the sake of conservatism. It would, therefore, appear that the ultimate torque should be predicted with reasonable accuracy by Saint-Venant's elastic theory of torsion. Tests on plain concrete members, however, show that the ultimate torque is underestimated significantly by elastic theory.

2. **Plastic Theory:**

The solution for the torsion of a fully plastic rectangular section is obtained by sand heap analogy. The expression for torsional strength is expressed as,

$$T_p = \alpha b^2 d f_t \quad \textbf{(6.2)}$$

For plastic analysis, the value of 'α' is given as $(0.5 - (\frac{b}{6d}))$.

3. **Hsu [1968]** reported extensive pure torsion tests on plain concrete rectangular and flanged sections. The most striking observation was that plain concrete rectangular members subjected to pure torsion actually failed by skew bending. The ultimate torque of plain concrete rectangular section was expressed by the equation,

$$T_{ue} = (b^2 d\ (0.85 f_r)) \quad \textbf{(6.3)}$$

In which 0.85 represent the reduction factor applied to the flexural tensile strength f_r determined from the modulus of rupture test.

4. **Souza and Wilhem [1973]** conducted tests on plain rectangular concrete beams and proposed an equation for predicting the torsional strength of the member. The torsional strength was expressed as

$$T_{cr}=0.412\ (1-0.233)\ b^2 d f_t' \qquad \textbf{(6.4)}$$

In which the direct tensile strength of concrete f_t' may be taken equal to $0.75(0.42\sqrt{cube\ compressive\ strength})$ or $\frac{5}{6.7}$ times the split tensile strength.

5. **T.D.G Rao et al. [2004]** conducted pure torsional tests on rectangular plain steel fibrous concrete members. A semi empirical formula was proposed to estimate the ultimate torsional strength of the member (T_g).

$$T_g = (0.5-0.233(\tfrac{b}{d}))\ (b^2 d f_t) \qquad \textbf{(6.5)}$$

The torsional strength of the beam is underestimated by elastic analysis and overestimated by plastic analysis. From the above results it can be concluded that the torsional strength predicted by TDG Rao is relatively close to that of the experimental values. Figures 6.42-6.47 and Table 6.11 show the variation of torsional strength for various models and experiential results for Mix A, B and C.

Table 6.11 Torsional strength of RVC and RSCC beams of Mix A in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
A-RVC Plain	0.931	1.575	1.347	1.147	1.450	1.49
A-RSFVC 50	1.082	1.83	1.565	1.338	1.687	1.74
A-RSFVC 70	1.114	1.884	1.611	1.370	1.733	1.82
A-RSFVC 100	1.041	1.761	1.506	1.289	1.626	1.69
A-RSCC Plain	0.956	1.617	1.855	1.169	1.488	1.56
A-RSFSCC 50	1.118	1.891	2.183	1.376	1.741	1.82
A-RSFSCC 70	1.159	1.96	2.261	1.425	1.810	1.89
A-RSFSCC 100	1.062	1.796	2.080	1.311	1.657	1.72

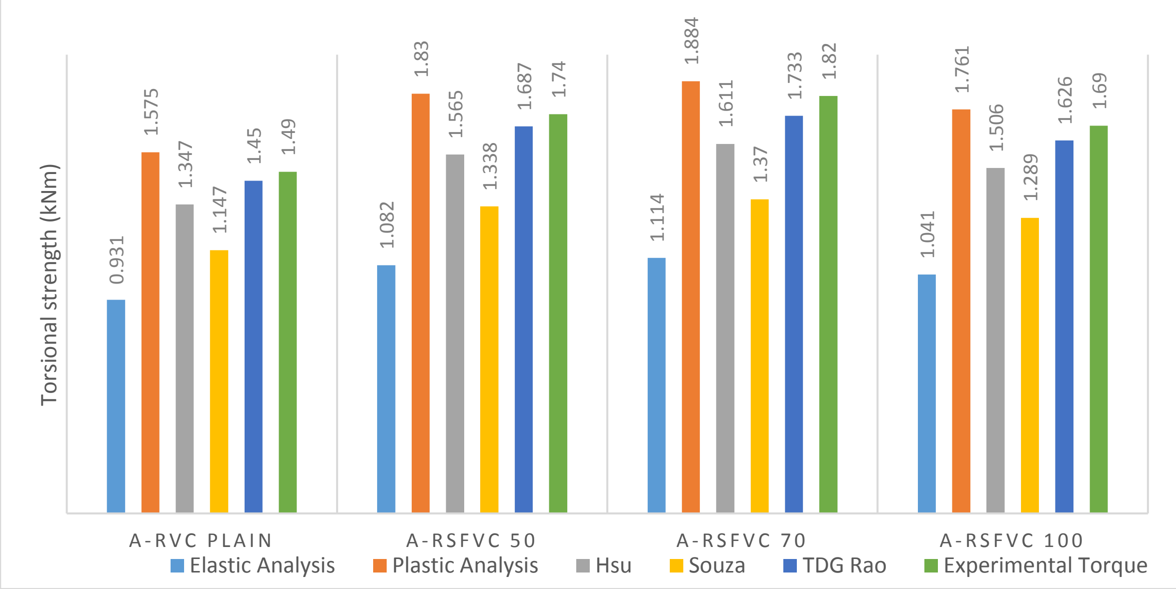


Figure 6.42 Comparison of torsional strength values with various models and Experimental results of Mix-A RVC

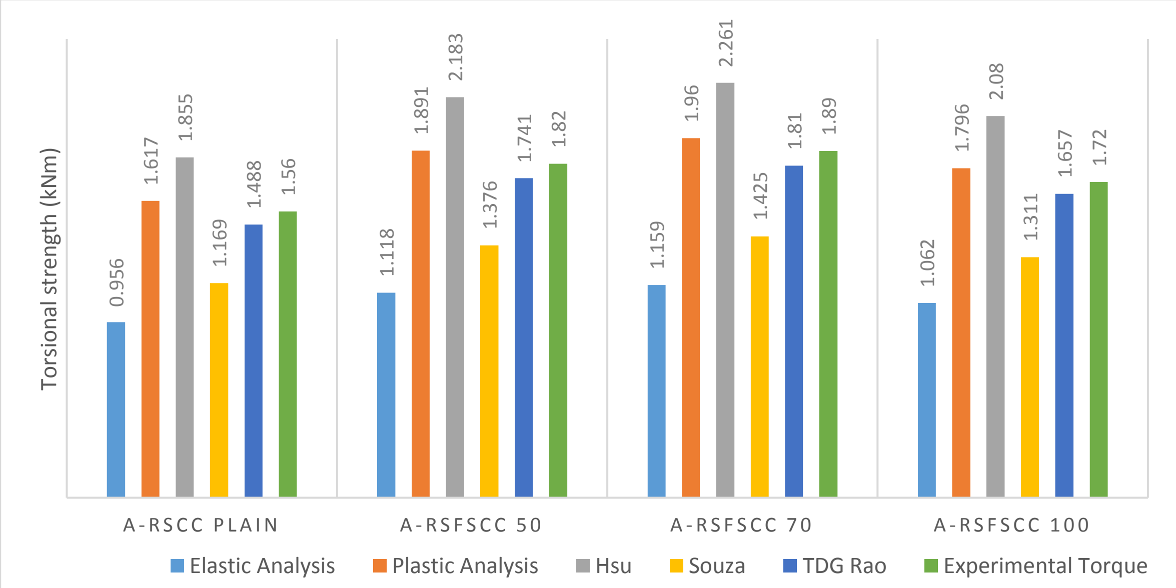


Figure 6.43 Comparison of torsional strength values with various models and Experimental results of Mix-A RSCC

Table 6.12 Torsional strength of RVC and RSCC beams of Mix B in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
B-RVC Plain	1.465	2.477	2.118	1.729	2.286	2.38
B-RSFVC 50	1.637	2.768	2.367	1.936	2.554	2.67
B-RSFVC 70	1.692	2.861	2.447	2.001	2.638	2.81
B-RSFVC 100	1.587	2.684	2.295	1.876	2.477	2.62
B-RSCC Plain	1.496	2.53	2.805	1.767	2.332	2.51
B-RSFSCC 50	1.708	2.888	3.219	2.028	2.661	2.83
B-RSFSCC 70	1.761	2.977	3.314	2.088	2.746	2.97
B-RSFSCC 100	1.659	2.805	3.124	1.969	2.585	2.77

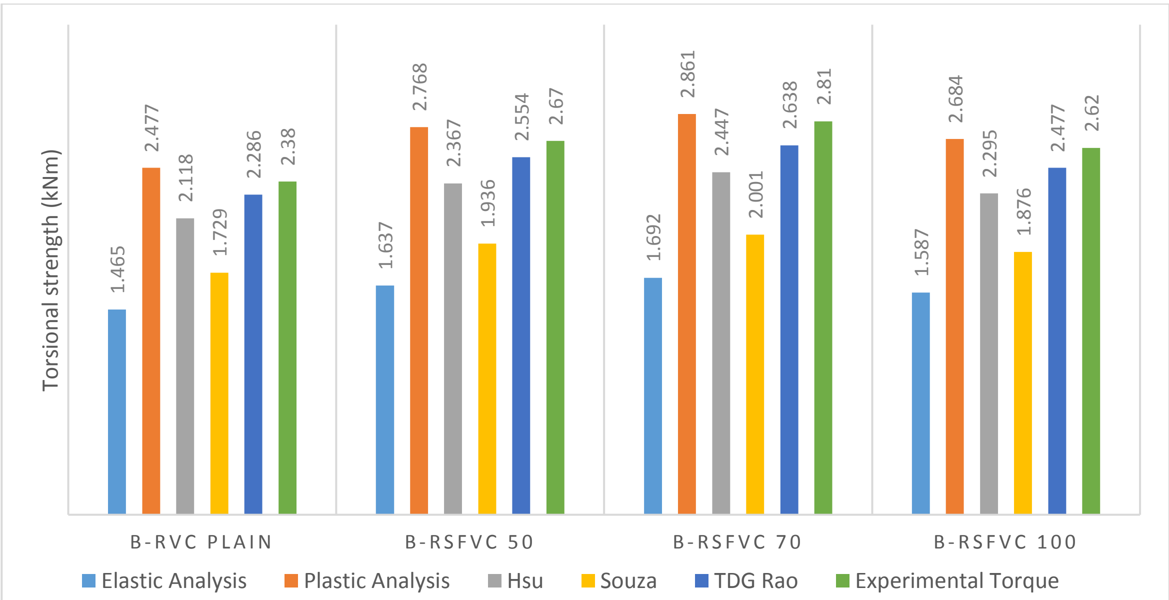


Figure 6.44 Comparison of torsional strength values with various models and Experimental results of Mix-B RVC

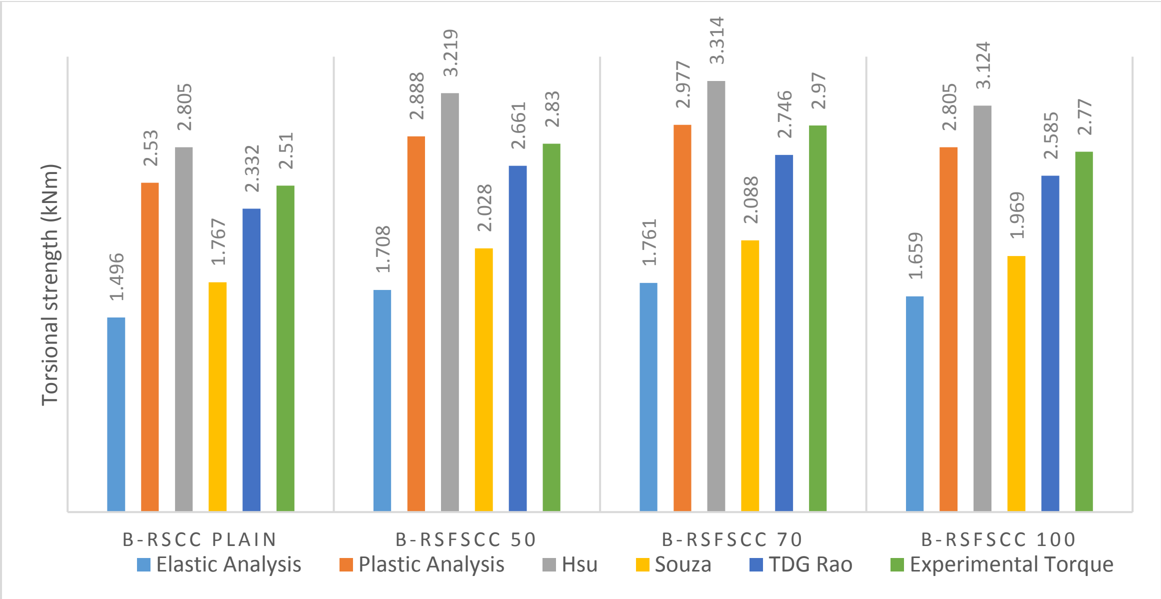


Figure 6.45 Comparison of torsional strength values with various models and Experimental results of Mix-B RSCC

Table 6.13 Torsional strength of RVC and RSCC beams of Mix C in kNm.

Beam Designation	Elastic Analysis (T_e)	Plastic Analysis (T_p)	Hsu (1968) (T_{ue})	Souza (1973) (T_{cr})	Rao (2004) (T_g)	Experimental Torque (T_{exp})
C-RVC Plain	1.972	3.335	2.852	2.306	3.076	3.25
C-RSFVC 50	2.275	3.847	3.290	2.676	3.544	3.72
C-RSFVC 70	2.341	3.959	3.386	2.752	3.651	3.84
C-RSFVC 100	2.256	3.815	3.263	2.654	3.521	3.64
C-RSCC Plain	2.115	3.576	3.935	2.480	3.298	3.48
C-RSFSCC 50	2.423	4.098	4.531	2.855	3.781	4.08
C-RSFSCC 70	2.481	4.196	4.643	2.926	3.866	4.18
C-RSFSCC 100	2.293	3.878	4.281	2.697	3.574	3.82

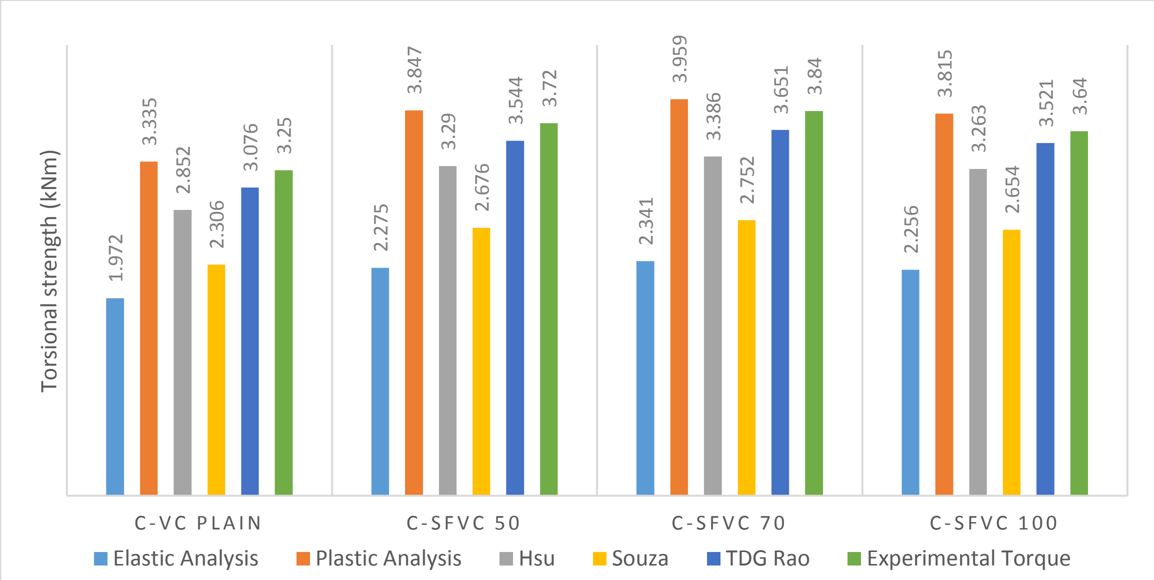


Figure 6.46 Comparison of torsional strength values with various models and Experimental results of Mix-C RVC

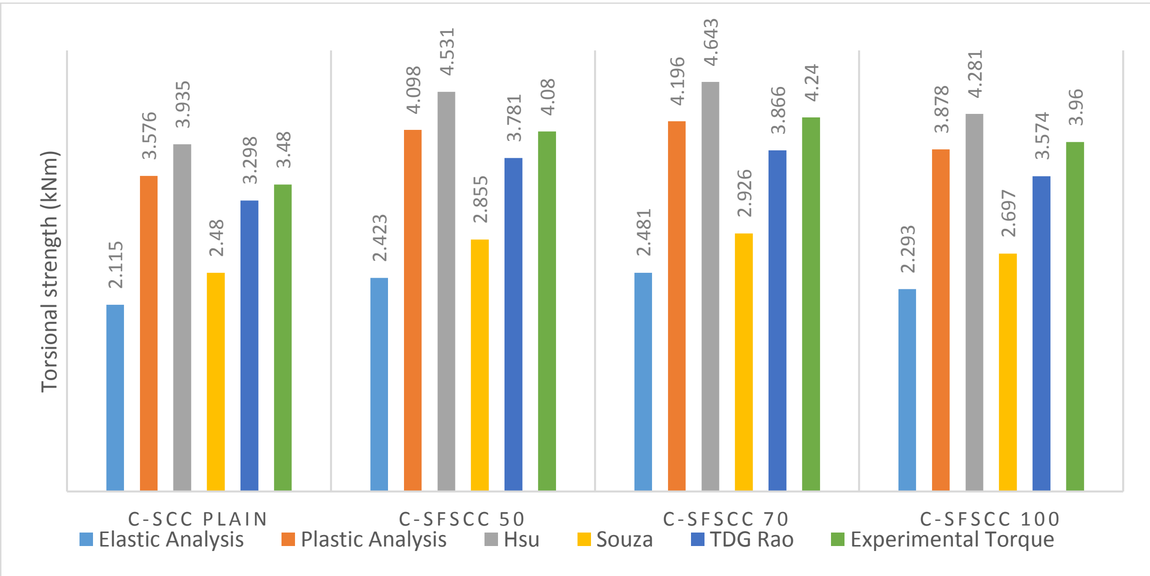


Figure 6.47 Comparison of torsional strength values with various models and Experimental results of Mix-C RSCC

6.6 Predicted Analytical Torsional Strength based on Non-linear regression analysis:

An equation to predict ultimate torsional strength is proposed by performing non-linear regression analysis, the predicted equation is given by:

1. Semi empirical formula proposed to estimate the ultimate torsional strength of the member (T_{emp}) for SCC.

$$T_{SCC} = (0.5-0.092(b/d))\ (b^2 d f_t) + \left(\frac{l}{dia}\right) * f_t \qquad \textbf{Eq (6.6)}$$

2. Semi empirical formula proposed to estimate the ultimate torsional strength of the member (T_{emp}) for VC.

$$T_{VC} = (0.5-0.118(b/d))\,(b^2 d f_t) + \left(\frac{l}{dia}\right)*f_t \qquad \textbf{Eq (6.7)}$$

$$1/f_t = (1/f_c) + (1/f_{spt})$$

Where, f_t = Tensile strength of concrete; f_c = Compressive strength of concrete; f_{spt} = Split tensile strength; b = width of beam; d = depth of beam; l = length of steel fiber; dia= diameter of steel fiber

Table 6.14 Experimental vs Analytical Torsional strength for VC

Designation	Experimental (kNm)	Predicted (kNm)	Pre/Exp
Mix A – 20 MPa			
A-VC Plain	1.63	1.835	1.125
A-SFVC 50	1.88	2.117	1.126
A-SFVC 70	1.93	2.179	1.129
A-SFVC 100	1.84	2.073	1.127
A-RVC Plain	1.49	1.667	1.119
A-RSFVC 50	1.74	1.941	1.115
A-RSFVC 70	1.82	1.993	1.095
A-RSFVC 100	1.69	1.870	1.107
Mix B – 50 MPa			
B-VC Plain	2.52	2.787	1.106
B-SFVC 50	2.82	3.096	1.098
B-SFVC 70	2.95	3.202	1.085
B-SFVC 100	2.74	3.034	1.107
B-RVC Plain	2.38	2.628	1.104
B-RSFVC 50	2.67	2.937	1.100
B-RSFVC 70	2.81	3.034	1.080
B-RSFVC 100	2.62	2.849	1.087
Mix C – 80 MPa			
C-VC Plain	3.57	3.890	1.090
C-SFVC 50	3.95	4.340	1.099
C-SFVC 70	4.08	4.446	1.090
C-SFVC 100	3.82	4.287	1.122
C-RVC Plain	3.25	3.537	1.088
C-RSFVC 50	3.72	4.075	1.095
C-RSFVC 70	3.84	4.199	1.093
C-RSFVC 100	3.64	4.049	1.112
Average			**1.104**

Table 6.15 Experimental vs Analytical Torsional strength for SCC

Designation	Experimental	Predicted	Pre/Exp
Mix A – 20 MPa			
A-SCC Plain	1.69	1.925	1.139
A-SFSCC 50	1.93	2.216	1.148
A-SFSCC 70	2.041	2.316	1.135
A-SFSCC 100	1.87	2.152	1.151
A-RSCC Plain	1.56	1.762	1.129
A-RSFSCC 50	1.82	2.061	1.133
A-RSFSCC 70	1.89	2.143	1.134
A-RSFSCC 100	1.72	1.961	1.140
Mix B – 50 MPa			
B-SCC Plain	2.65	2.897	1.093
B-SFSCC 50	2.95	3.278	1.111
B-SFSCC 70	3.08	3.369	1.094
B-SFSCC 100	2.86	3.178	1.111
B-RSCC Plain	2.51	2.760	1.100
B-RSFSCC 50	2.83	3.151	1.113
B-RSFSCC 70	2.97	3.251	1.095
B-RSFSCC 100	2.77	3.060	1.105
Mix C – 80 MPa			
C-SCC Plain	3.7	4.122	1.114
C-SFSCC 50	4.24	4.704	1.109
C-SFSCC 70	4.38	4.840	1.105
C-SFSCC 100	4.12	4.559	1.106
C-RSCC Plain	3.48	3.904	1.122
C-RSFSCC 50	4.08	4.477	1.097
C-RSFSCC 70	4.18	4.577	1.095
C-RSFSCC 100	3.82	4.232	1.108
Average			**1.116**

6.7 Conclusions from Phase-III:

Based on the detailed studies on Torsional behaviour of plain and fibrous beams of SCC and VC using three aspect ratios of steel fibers the following conclusions were made.

1. As the aspect ratio of steel fibers increased from 50 to 100, ultimate torsional strength and twist increased, similar behaviour was observed in case of both SCC and VC. Significant improvement was seen for beams with aspect ratio 70 in all strengths of concretes.

2. The torsional strength of the beams using recycled aggregates reduced by 8.59 %, 5.56 % and 8.96 % for plain VC beams of strength 20, 50 and 80 MPa respectively compared to natural aggregate concrete.
3. The torsional strength of the beams using recycled aggregates reduced by 7.69 %, 5.28 % and 5.95 % for plain SCC beams of strength 20, 50 and 80 MPa respectively compared to natural aggregate concrete.
4. The torsional strength of the beams using recycled aggregates reduced by 5.70 %, 4.75 % and 5.88 % for VC beams with aspect ratio 70 of strength 20, 50 and 80 MPa respectively compared to natural aggregate concrete.
5. The torsional strength of the beams using recycled aggregates reduced by 7.35 %, 3.57 % and 3.20 % for SCC beams of strength 20, 50 and 80 MPa respectively compared to natural aggregate concrete.
6. The depletion of torsional properties due to use of recycled aggregate could be restored by addition of steel fibers in both concretes.
7. A comparison was made between experimental and various models of torsion on vibrated concrete. It was noticed that the ultimate torsional strength was under estimated by elastic analysis and was over estimated by plastic analysis.

Chapter 7 Analysis of Torsional Behaviour of Steel fiber Reinforced SCC and VC by using ATENA-GID

7.0 General

Chapters 5 and 6 dealt with the studies on torsional behaviour of SCC and VC using natural and recycled concrete aggregate for both without and with steel fibers and different aspect ratios for 20 MPa, 50 MPa and 80 MPa concrete. From the experimental results it is found that using steel fibers can greatly enhance the torsional properties and increase the load carrying capacity of SCC and VC. It was also found that with the use of steel fibers, tensile strength of concrete was increased and the failure mode changed from brittle to ductile. The increase in initial torsional stiffness is due to the increase in modulus of matrix. The toughness of the steel fiber reinforced SCC beams increased tremendously when compared with plain SCC beams. It was also noticed that with use of recycled aggregate as the partial replacement of natural aggregate, has decreased the compressive strength of concrete marginally for 20 MPa, 50 MPa and 80 MPa SCC and VC. This defect in RASCC can be overcome by using steel fibers. It was also observed that with the use of recycled aggregate, the torsional strength of both SCC and VC is reduced when compared with natural aggregate based SCC and VC for all three grades.

The present chapter is aimed at studying the torsional behaviour of steel fiber reinforced SCC and VC using finite element software ATENA GID for both natural and recycled aggregate beams for 20 MPa, 50 MPa and 80 MPa compressive strengths. The experimental results were compared with the values obtained from finite element model developed using Atena software.

7.1 Introduction on ATENA GID Software:

ATENA is finite element based software used for nonlinear analysis of fiber reinforced concrete members. By using Atena software actual behaviour of reinforced concrete structures, such has concrete crushing, cracking and yielding of reinforcement can be analyzed and it is a user friendly tool for modelling reinforced concrete elements. It also helps in visualization of crack propagation and real-time display of results even during the nonlinear analysis.

GID is an interactive graphical user interface program used for the preparation of input data for ATENA analysis. GID is a universal, adaptive and user-friendly program used for geometrical modeling. GID is mainly used for the definition, preparation, and visualization of all the data related to a numerical simulation.

In the present study, finite element model of the beam with same cross sectional dimensions was created in Atena software and nonlinear analysis is performed for both fibrous and non-fibrous beams (20 MPa, 50 MPa and 80 MPa) of SCC and VC for both using natural aggregates and recycled aggregates.

7.1.1 FEM Modelling using ATENA-GID:

The purpose of the geometrical model is to describe the geometry of the structure, its material properties and boundary conditions. The analytical model for the finite element analysis will be created during the pre-processing with the help of the fully automated mesh generator. The definition of the geometry starts with the creation of geometrical points. These points are later connected into boundary lines. The surfaces are defined by selecting appropriate boundary lines. Volumes can be formed either by extrusion of surfaces or manually by selecting all bounding surfaces. Three-dimensional regions are modelled by volumes in GID. All the steel fiber properties such as aspect ratio (diameter and length), dosage in volume and its material properties are updated in a special section.

After creation of the geometry, material properties should be defined and assigned to individual volumes. Boundary conditions are used to define the supports and loads. The boundary conditions and loads are defined in GID with the help of “Intervals”. Interval represents a set of boundary conditions and loads that are applied in a specified number of steps. An appropriate definition of intervals can be used to specify a complete loading history. In ATENA analysis it is always useful to define monitoring points. The monitoring points are used to see the evolution of certain quantities during the analysis. For instance they can be used to follow the development of deflection or forces at given locations. Monitoring points are selected at points where the dial gauges were placed under the beams for recording deflections during the experiment.

7.1.2 Selection of Materials

a) Plain beam

Material used is Reinforced concrete (GID Name) and also called as CC Combined Material (Atena name). This material can be used to create a composite material consisting of various components, such as for instance concrete with smeared reinforcement in various directions. The basic material parameters are defined in the Basic dialog – the Young's modulus of elasticity E, the Poisson's coefficient of lateral expansion, the strength in direct tension F_t, and the cube compressive strength F_c as shown in Figure 7.1.

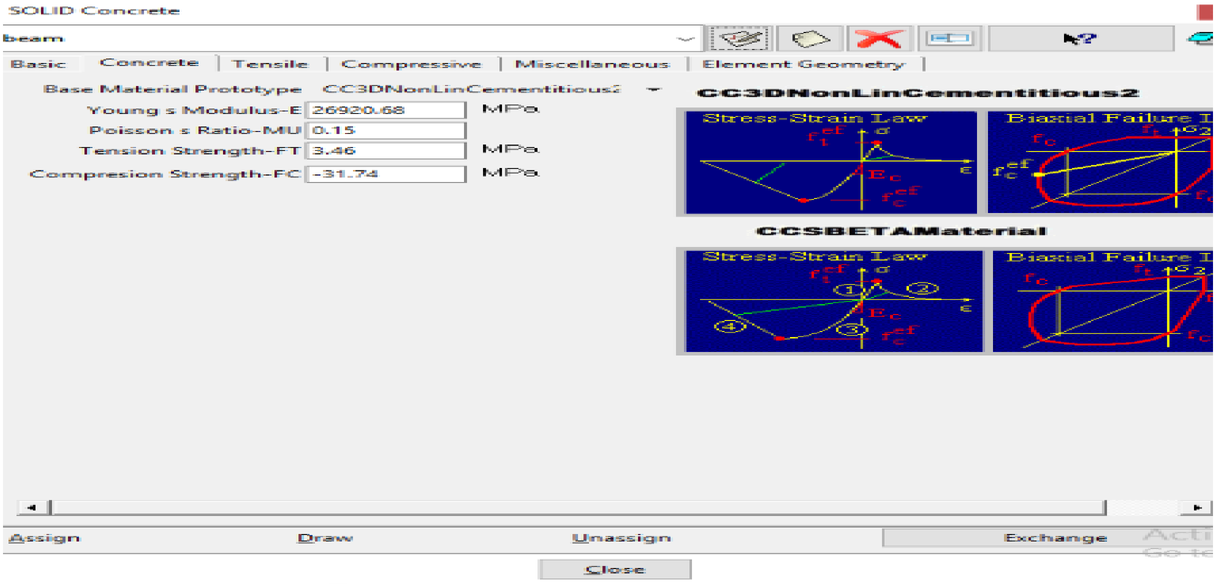


Figure 7.1 Section showing the material properties of Plain beam

(b) Fiber Reinforced Concrete Beam:

Material used is Cementitious SHCC. SHCC is a special material for strain hardening cementitious composites (e.g., special mixtures with addition of plastic fibres) as shown in Figure 7.2 and 7.3. The only difference from Reinforced Concrete is the Fibre Reinforcement tab.

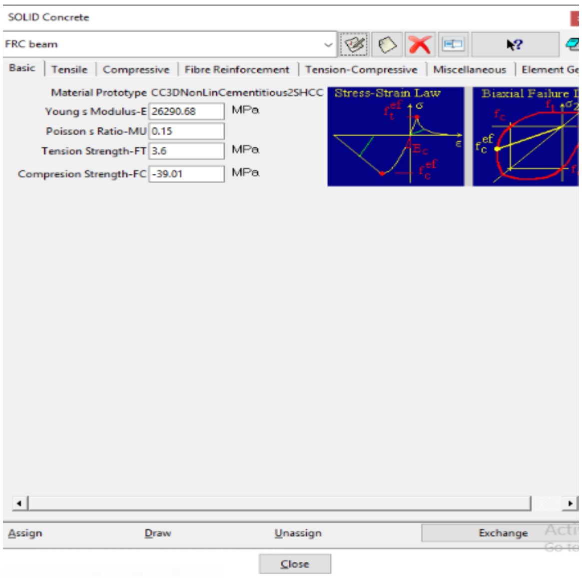


Figure 7.2 Section showing the concrete properties of FRC beam

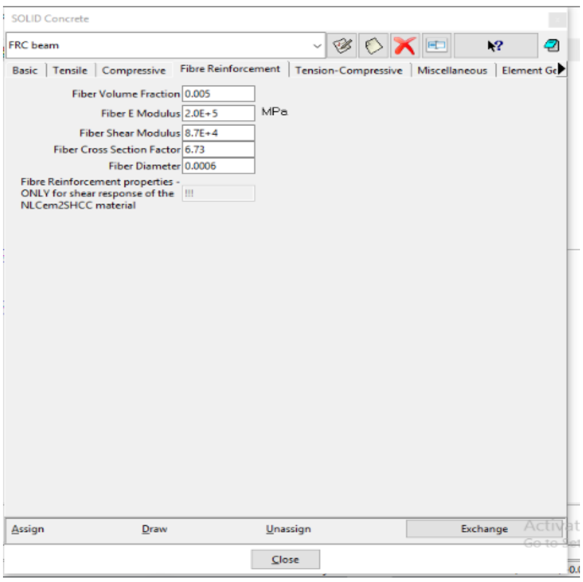


Figure 7.3 Section showing the steel fibre properties of FRC beam

7.1.3 Analysis of a typical beam with the following steps:

1. Create a geometrical model in GID as shown in Figure 7.4.

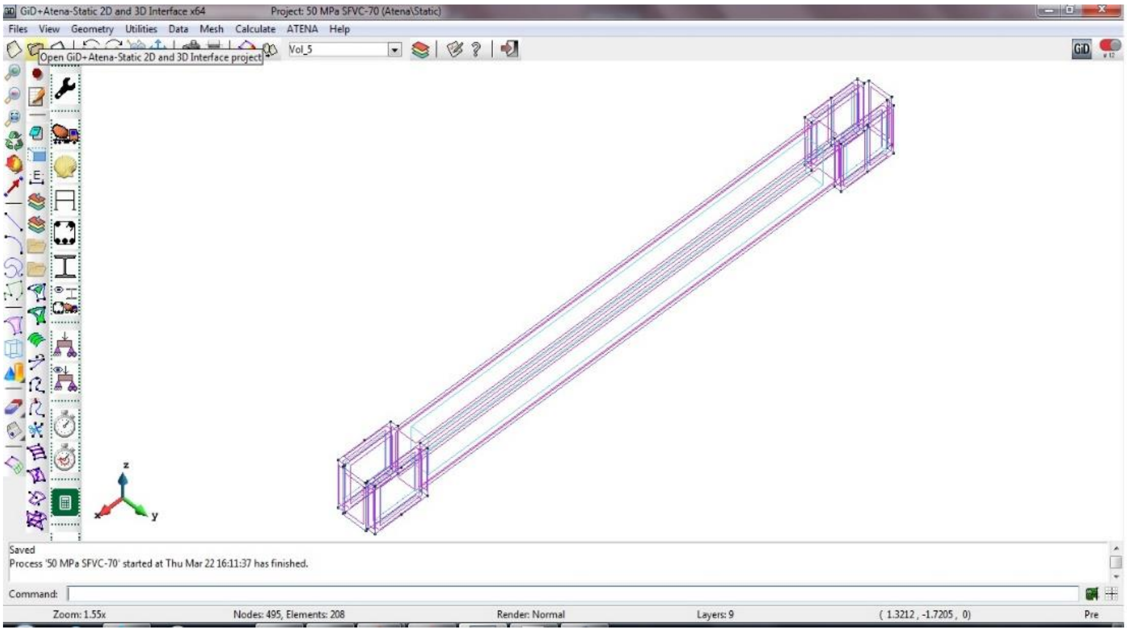


Figure 7.4 Geometrical model of beam showing plates

2. Impose conditions such as boundary conditions and loading on the geometrical model as shown in Figure 7.5.

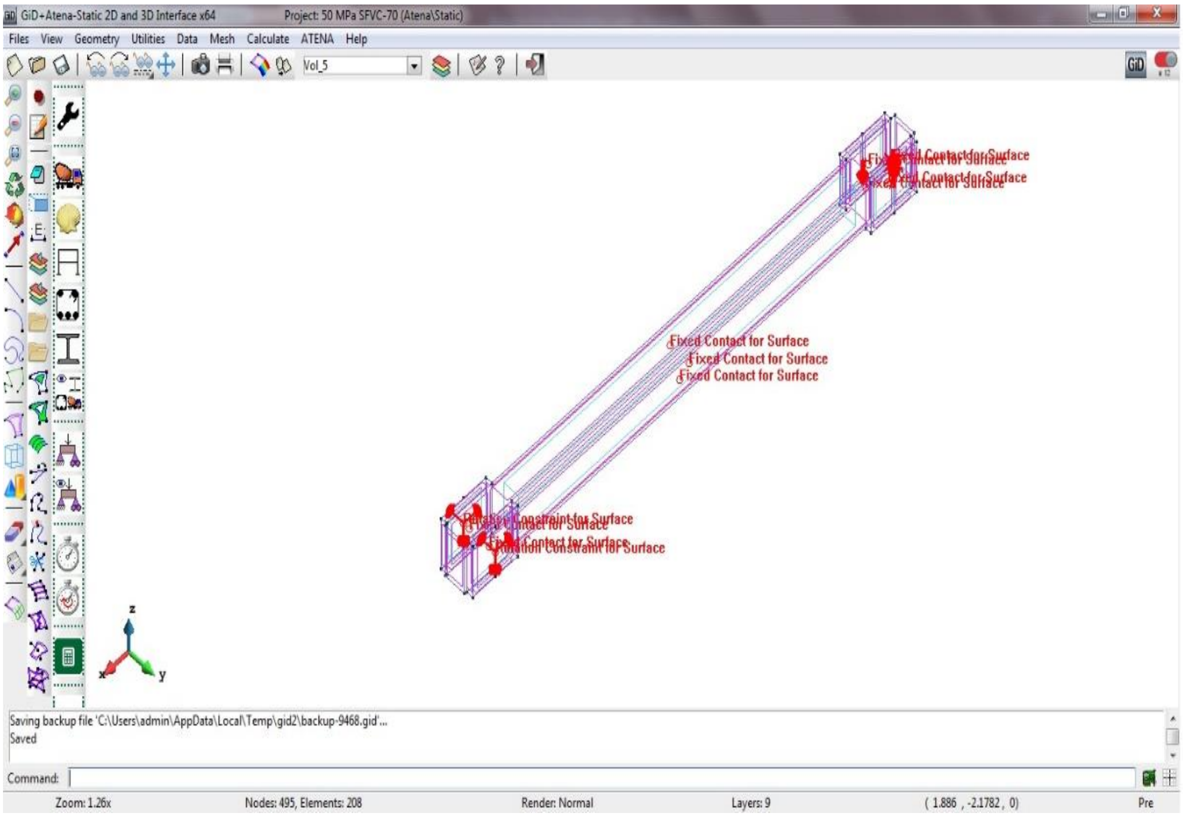


Figure 7.5 Beam showing boundary and loading conditions

3. Select material models, define parameters and assign them to the geometry as shown in Figure 7.6.

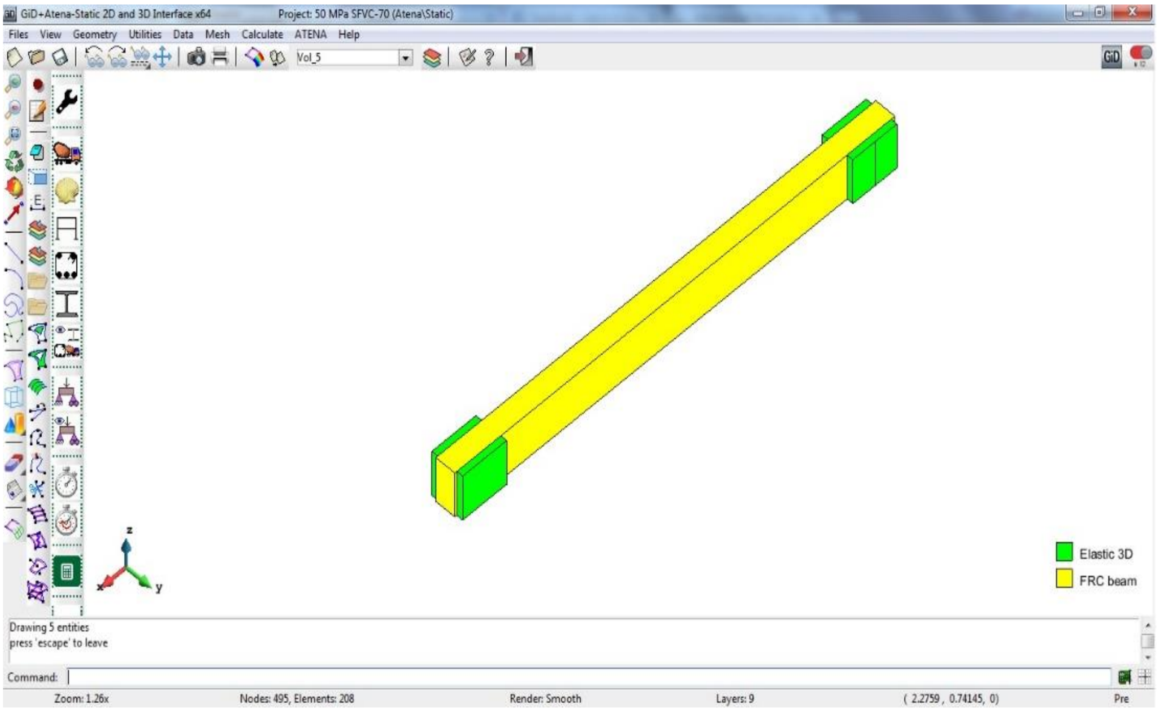


Figure 7.6 Beam showing the type of materials for beam and plates

4. Generate finite element mesh as shown in Figure 7.7.

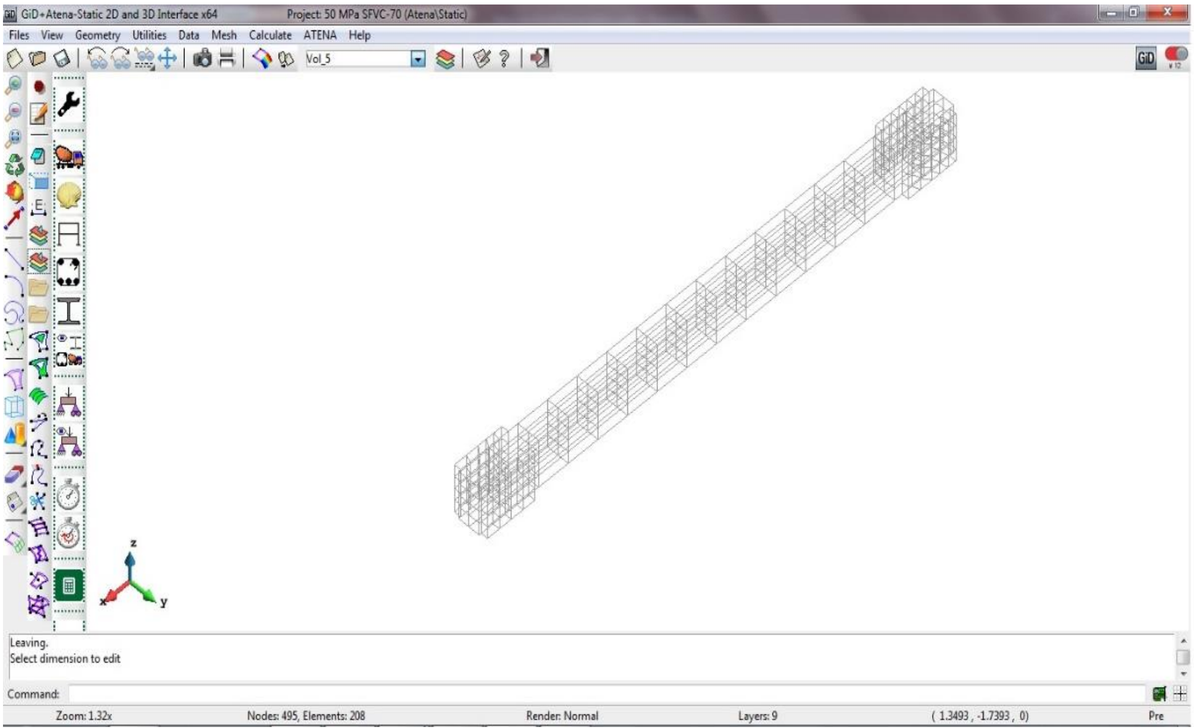


Figure 7.7 Beam showing the finite element mesh

5. Create loading history by defining interval data as shown in Figure 7.8.

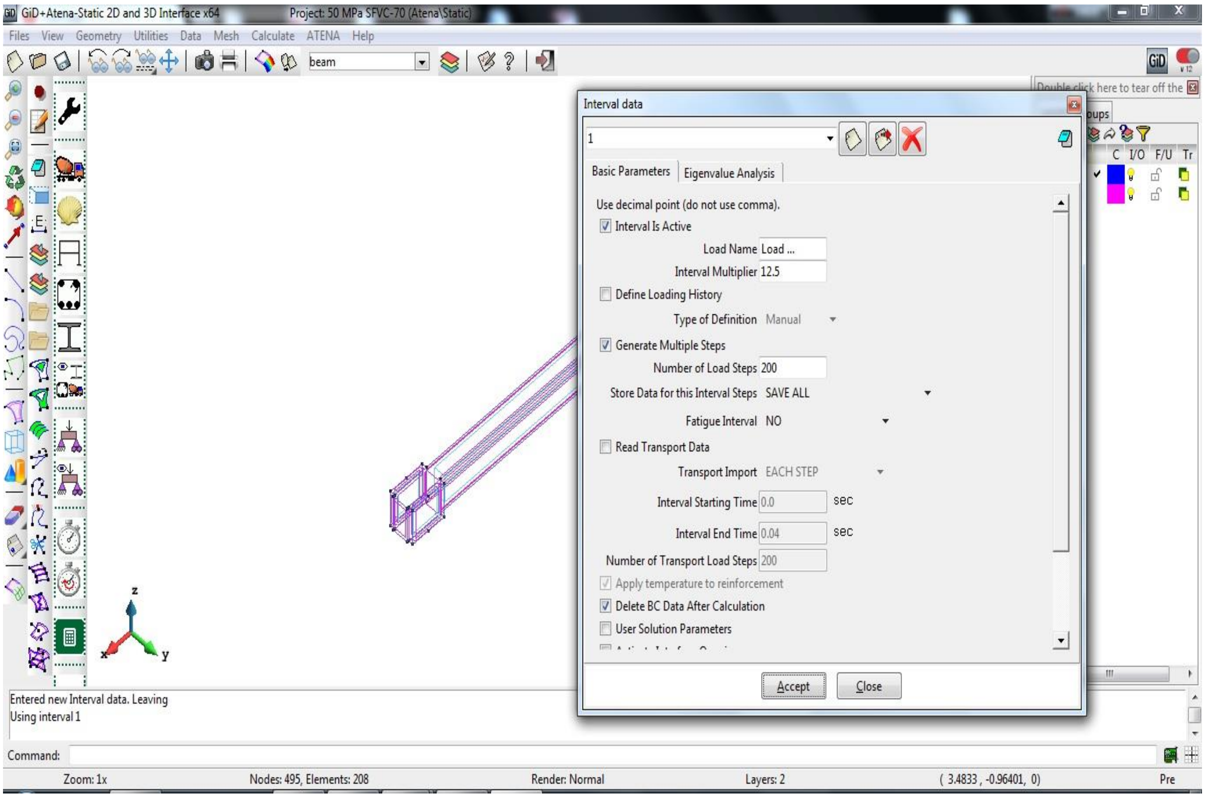


Figure 7.8 Section showing loading history and interval data

6. Execute finite element analysis with ATENA Studio as shown in Figure 7.9.

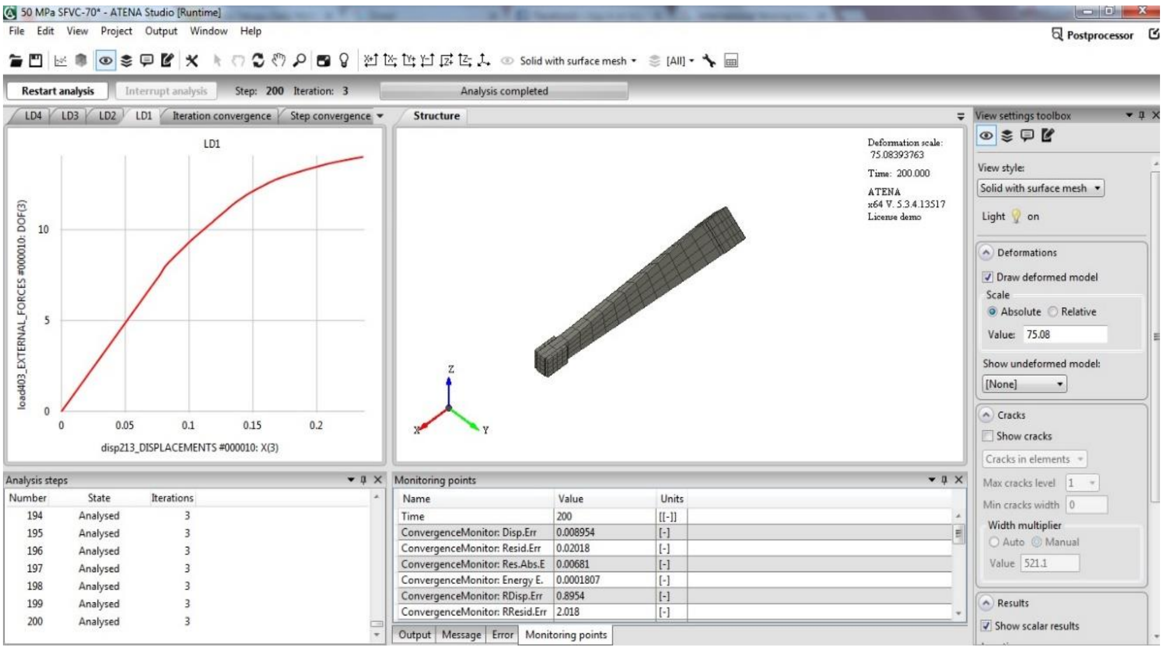


Figure 7.9 Showing the deformation and failure pattern along with Load-Deflection diagram during analysis

7.2 Torsional Behaviour of Steel Fiber Reinforced SCC and VC Beams using FEM (Natural Aggregate):

To validate the experimental results of natural aggregate based steel fibrous SCC and VC, a finite element software (ATENA) is used and a nonlinear analysis is performed by creating an identical beam model of same cross sectional dimensions and providing the details of steel fibers similar to the experimental study for all three strengths of concrete (20 MPa, 50 MPa and 80 MPa) and for three aspect ratios (l/d) 50, 70 and 100. All the loading and supporting conditions are provided similar to the experimental setup. Angle of twist is calculated with the deflections obtained from the results of monitoring points as done in chapters 5 and 6. The detailed discussion is presented in the following sections.

7.2.1 Effect of Steel fibers on Torsional Performance of VC:

In this section results obtained from the finite element modelling on the Steel Fiber Reinforced VC beams are presented. The nomenclature used for representation of Torque-Twist curves obtained from ATENA results is shown in Table 7.1. Table 7.2 shows the ultimate torque and angle of twist values of fibrous and non-fibrous beams of VC for all the three aspect ratios (50, 70 and 100) of Mix-A 20 MPa, Mix-B 50 MPa and Mix-C 80 MPa.

Table 7.1 Nomenclature of ATENA results for Mix A (20 MPa) with natural aggregates

A 20 VC Plain	ATENA results of Mix A (20 MPa) – VC without steel fibers
A 20 SFVC 50	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 50
A 20 SFVC 70	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 70
A 20 SFVC 100	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 100
A 20 SCC Plain	ATENA results of Mix A (20 MPa) – SCC without steel fibers
A 20 SFSCC 50	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio 50
A 20 SFSCC 70	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio 70
A 20 SFSCC 100	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio100

Similar Nomenclature is used for Torque-Twist curve obtained from ATENA results Mix B (50 MPa) and Mix C (80 MPa).

Table 7.2 Torsional behaviour of VC using steel fibers of aspect ratios of 50, 70 and 100 using ATENA

Beam Designation	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)
Mix-A VC 20 MPa		
A-VC Plain	1.63	5.96
A-SFVC 50	1.88	7.2
A-SFVC 70	1.93	7.7
A-SFVC 100	1.84	6.97
Mix-B VC 50 MPa		
B-VC Plain	2.52	5.72
B-SFVC 50	2.82	7.29
B-SFVC 70	2.95	7.67
B-SFVC 100	2.74	6.59
Mix-C VC 80 MPa		
C-VC Plain	3.57	6.29
C-SFVC 50	3.95	8.57
C-SFVC 70	4.08	10.59
C-SFVC 100	3.82	8.46

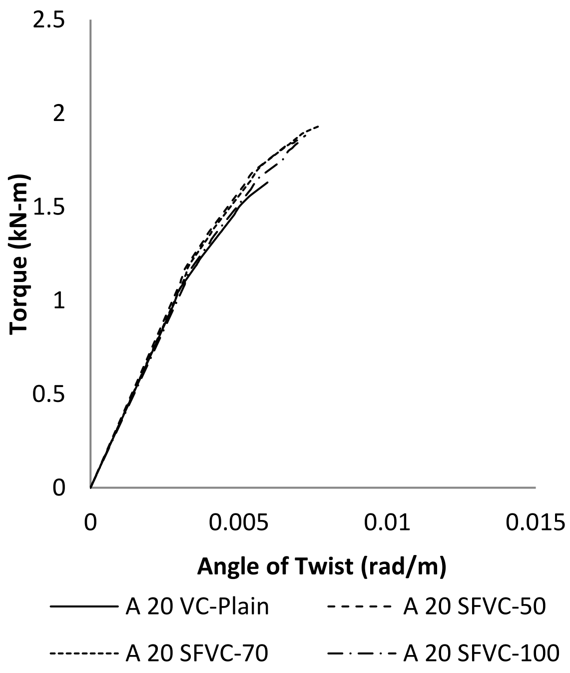


Figure 7.10 Torque-Twist response A-VC using ATENA

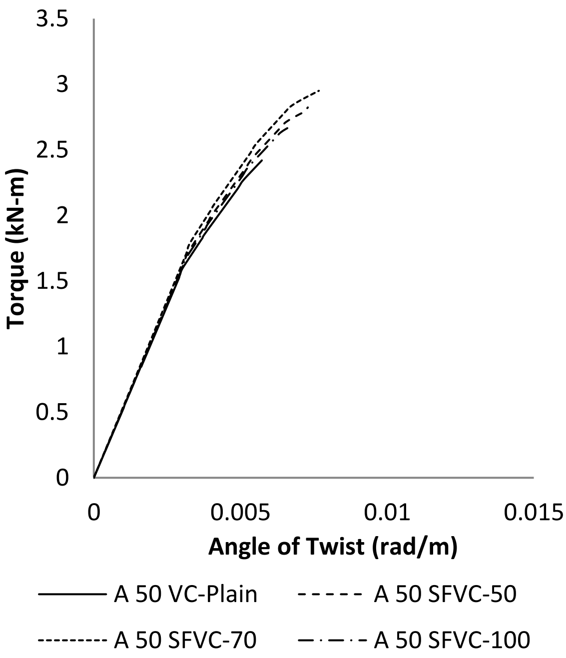


Figure 7.11 Torque-Twist response B-VC using ATENA

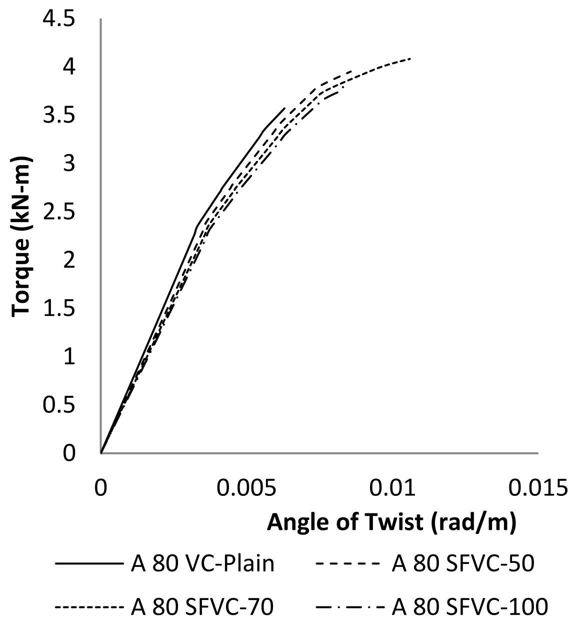


Figure 7.12 Torque-Twist response C-VC using ATENA

Aspect ratio is one of the important parameters that effects the torsional performance of beams. To study the effect on aspect ratio of steel fiber on torsional performance of VC and SCC beams, three aspect ratios (50, 70 and 100) were considered for three strengths of concrete and plain beam with no steel fibers is used as companion specimen. From the table 7.2 it was observed that due to the addition of steel fibers the twist at ultimate torque has improved and also failure of VC beams was delayed as steel fibers helps in bridging the cracks faces and delaying the crack propagation. Figures 7.10-7.12 shows the torque-twist response curves of A-VC, B-VC and C-VC beams for aspect ratios of steel fibers (l/d) 50, 70 and 100. The maximum increase in twist at ultimate torque is observed in beams with aspect ratio 70 in all three strengths of concrete. For the beams with steel fibers of aspect ratio (l/d) 70, the twist at ultimate torque of the beams has increased by 29.19%, 34.09% and 68.36% for A-VC, B-VC and C-VC beams respectively in comparison with their respective plain beams. The increase in twist at ultimate torque has increased with the increase strength of concrete. Similar behaviour was observed for beams modelled for in steel fibers with aspect ratios 50 and 100.

7.2.2 Effect of Steel fibers on Torsional Performance of SCC:

In this section results obtained from the finite element modelling on the Steel Fiber Reinforced SCC beams are presented. Table 7.3 shows the ultimate torque and angle of twist values of fibrous and non-fibrous beams of SCC for all the three aspect ratios (50, 70 and 100) of Mix-A 20 MPa, Mix-B 50 MPa and Mix-C 80 MPa.

Table 7.3 Torsional behaviour of SCC using steel fibers of aspect ratios of 50, 70 and 100 using ATENA

Beam Designation	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)
Mix-A SCC 20 MPa		
A-SCC Plain	1.69	6.23
A-SFSCC 50	1.93	7.54
A-SFSCC 70	2.04	8.4
A-SFSCC 100	1.87	7.45
Mix-B SCC 50 MPa		
B-SCC Plain	2.65	5.97
B-SFSCC 50	2.95	8.01
B-SFSCC 70	3.08	8.29
B-SFSCC 100	2.86	7.43
Mix-C SCC 80 MPa		
C-SCC Plain	3.70	6.69
C-SFSCC 50	4.24	10.66
C-SFSCC 70	4.38	12.99
C-SFSCC 100	4.12	10.38

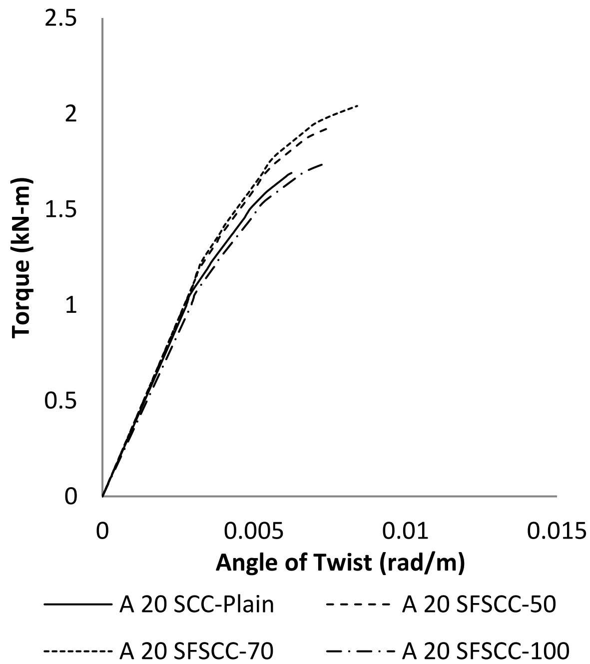


Figure 7.13 Torque-Twist response A-SCC using ATENA

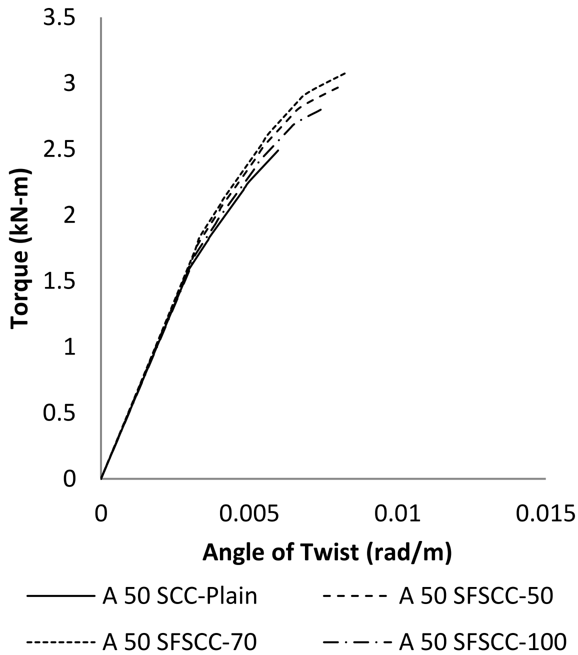


Figure 7.14 Torque-Twist response B-SCC using ATENA

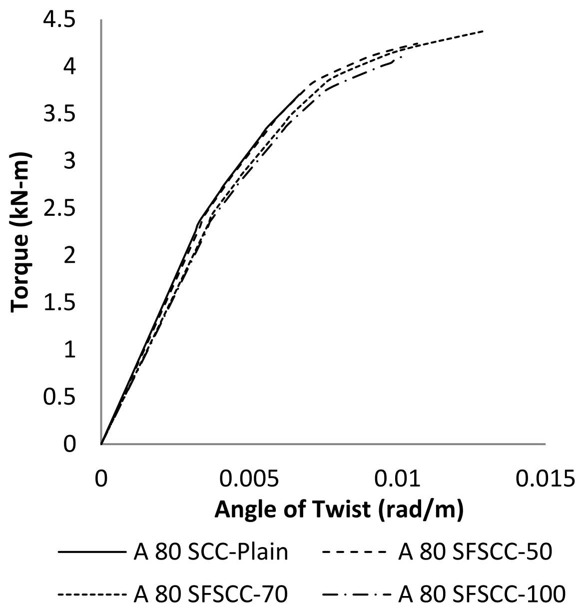


Figure 7.15 Torque-Twist response C-SCC using ATENA

From the Table 7.3, it was observed that due to the addition of steel fibers the twist at ultimate torque has improved and also failure of SCC beams was delayed as steel fibers helps in bridging the crack faces and delaying the crack propagation. Figures 7.13-7.15 shows the torque-twist response curves of A-SCC, B-SCC and C-SCC beams for aspect ratios of steel fibers (l/d) 50, 70 and 100. The maximum increase in twist at ultimate torque was observed in beams with aspect ratio 70 in all three strengths of concrete. For the beams with steel fibers of aspect ratio (l/d) 70, the twist at ultimate torque of the beams has increased by 34.83 %, 38.86 % and 94.17 % for A-SCC, B-SCC and C-SCC beams respectively in comparison with their respective plain beams. The increase in twist at ultimate torque has increased with the increase strength of concrete. Similar type of behaviour is observed for beams modelled for aspect ratios 50 and 100. It is observed that the increase is more in case of SCC than VC in all aspect ratios and strengths of concrete.

7.2.3 Effect of aspect ratio on torsional performance of SCC and VC beams:

As the analysis of torsional performance of SCC is scant it needs to be compared with conventional vibrated concrete. It was found that torsional performance of SCC from experimental results was superior to VC from chapter 5 and chapter 6. Similar behaviour was found in analytical modelling using FEM, it was true for all strengths and aspect ratios. In 20 MPa concrete, it was observed that there is an increase of 29.19 % and 34.83 % in twist at ultimate torque of VC and SCC beams with aspect ratio 70 respectively in comparison with plain beams. An increase of 34.09 % and 38.86 % in twist at ultimate torque was observed in VC and SCC beams with aspect ratio 70 for 50 MPa concrete. In 80 MPa concrete, it was observed that there is an increase of 68.36 % and 94.17 % in twist at ultimate torque of VC and SCC beams with aspect ratio 70 respectively in comparison with plain beams. Similar behaviour was observed for beams with aspect ratio 50 and 100. Figures 7.16-7.18 shows the variation of twist at ultimate torque for VC and SCC with different aspect ratios of steel fibers.

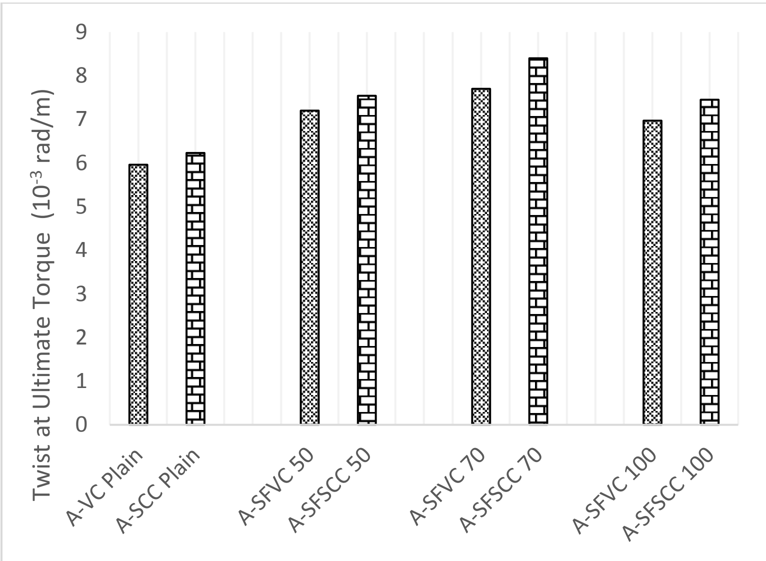


Figure 7.16 Comparison of VC and SCC on Twist at Ultimate Torque of 20 MPa

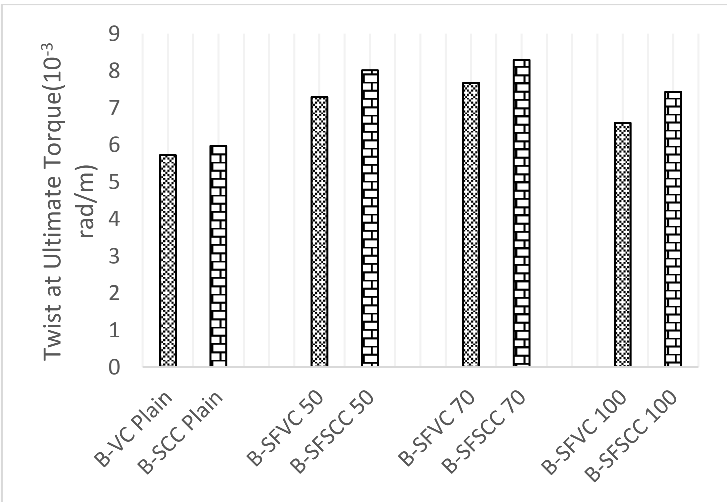


Figure 7.17 Comparison of VC and SCC on Twist at Ultimate Torque of 50 MPa

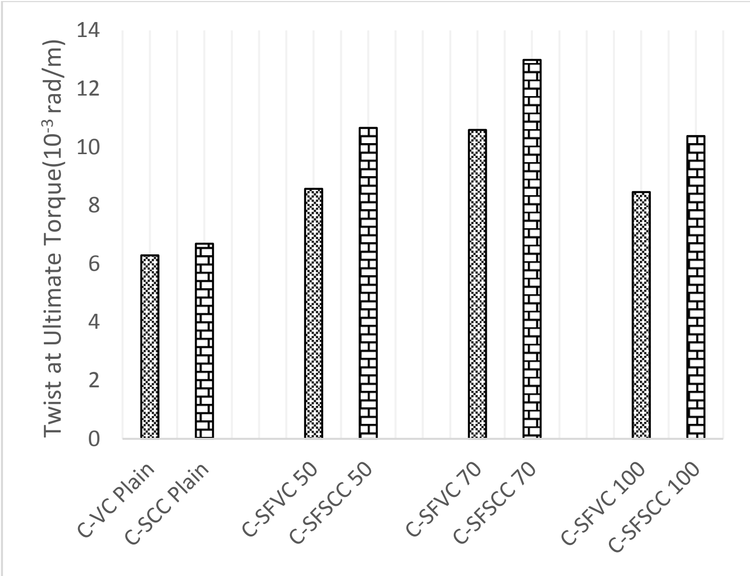


Figure 7.18 Comparison of VC and SCC on Twist at Ultimate Torque of 80 MPa

7.3 Torsional Behaviour of Steel Fiber Reinforced SCC and VC Beams using FEM (with Recycled concrete Aggregate):

To validate the experimental results of recycled concrete aggregate as partial replacement to natural aggregates based steel fibrous SCC and VC, a finite element software (ATENA) is used and a nonlinear analysis is performed by creating an identical beam model of same cross sectional dimensions and providing the details of steel fibers as that of a similar beams used in experimental study for all three strengths of concrete and for three aspect ratios (l/d) 50, 70 and 100. All the loading and supporting conditions are provided similar to experimental setup. Angle of twist is calculated with the deflections obtained from the results of monitoring points as done in chapters 5 and 6. The detailed discussion is presented in the following sections.

7.3.1 Effect of Steel fibers on Torsional Performance of RVC:

In this section results obtained from the finite element modelling on the Recycled aggregate based Steel Fiber Reinforced VC beams are presented. Table 7.5 shows the ultimate torque and angle of twist values of fibrous and non-fibrous beams of RVC for all the three aspect ratios (50, 70 and 100) of Mix-A 20 MPa, Mix-B 50 MPa and Mix-C 80 MPa. The nomenclature used for representation of Torque-Twist curves obtained from ATENA results is shown in Table 7.4.

Table 7.4 Nomenclature of ATENA results for Mix A (20 MPa) with recycled aggregates

A 20 RVC Plain	ATENA results of Mix A (20 MPa) – VC without steel fibers with Recycled aggregates
A 20 RSFVC 50	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 50 with Recycled aggregates
A 20 RSFVC 70	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 70 with Recycled aggregates
A 20 RSFVC 100	ATENA results of Mix A (20 MPa) – VC with steel fibers of aspect ratio 100 with Recycled aggregates
A 20 RSCC Plain	ATENA results of Mix A (20 MPa) – SCC without steel fibers with Recycled aggregates
A 20 RSFSCC 50	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio 50 with Recycled aggregates
A 20 RSFSCC 70	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio 70 with Recycled aggregates
A 20 RSFSCC 100	ATENA results of Mix A (20 MPa) – SCC with steel fibers of aspect ratio100 with Recycled aggregates

Table 7.5 Torsional behaviour of RVC using steel fibers of aspect ratios of 50, 70 and 100 using ATENA

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)
Mix-A RVC 20 MPa		
A-RVC Plain	1.49	5.61
A-RSFVC 50	1.74	6.04
A-RSFVC 70	1.82	6.67
A-RSFVC 100	1.69	6.36
Mix-B RVC 50 MPa		
B-RVC Plain	2.38	5.38
B-RSFVC 50	2.67	6.79
B-RSFVC 70	2.81	6.75
B-RSFVC 100	2.62	6.12
Mix-C RVC 80 MPa		
C-RVC Plain	3.25	5.87
C-RSFVC 50	3.72	8.06
C-RSFVC 70	3.84	9.44
C-RSFVC 100	3.64	7.59

Similar Nomenclature is used for Torque-Twist curve obtained from ATENA results Mix B (50 MPa) and Mix C (80 MPa).

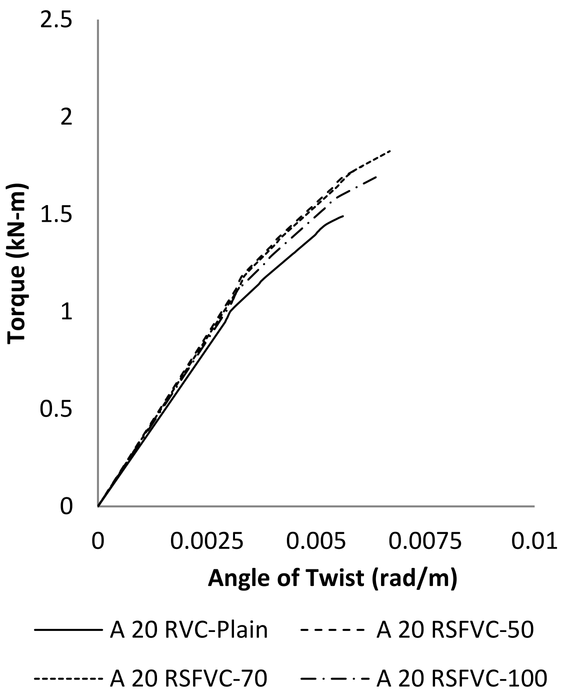


Figure 7.19 Torque-Twist response A-RVC using ATENA

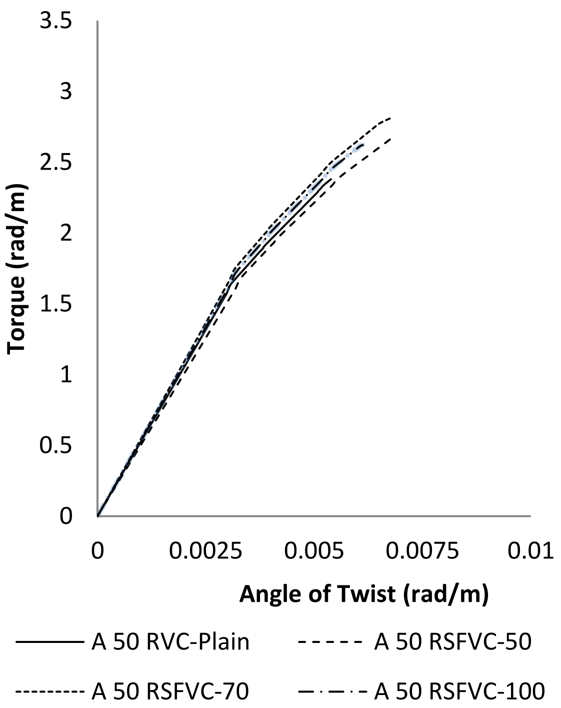


Figure 7.20 Torque-Twist response B-RVC using ATENA

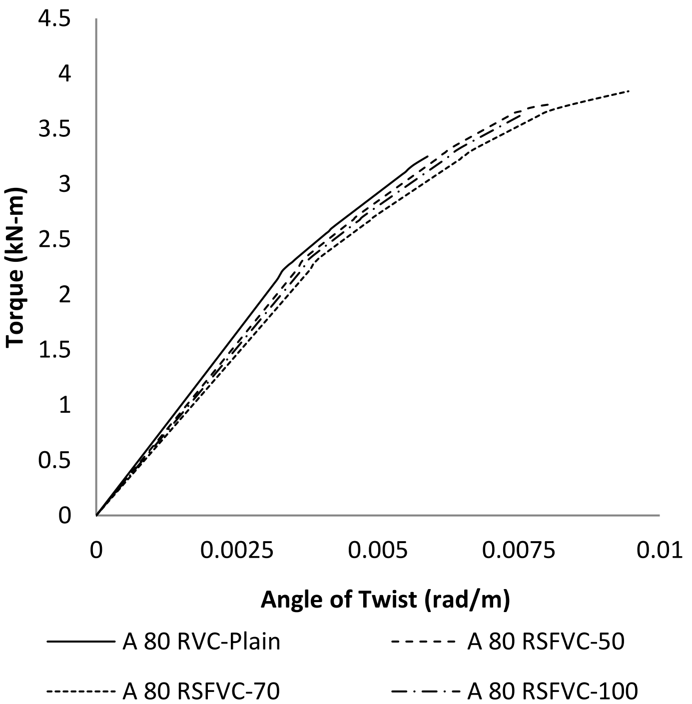


Figure 7.21 Torque-Twist response C-RVC using ATENA

As observed in case of beams made with normal aggregate and with the addition of steel fibers, the twist at ultimate torque of beams is increased and also steel fibres has bridged the crack faces and delayed the failure of VC beams. Similarly in case of beams made with recycled coarse aggregates (25 % replacement by weight) has shown similar type of behaviour. This is true for the beams analyzed for all the aspect ratios of steel fibers. From the table 7.4 it is observed that due to the addition of steel fibers the twist at ultimate torque has improved and also failure of RVC beams. Figures 7.19-7.21 shows the torque-twist response curves of A-RVC, B-RVC and C-RVC beams for aspect ratios of steel fibers (l/d) 50, 70 and 100. The maximum increase in twist at ultimate torque is observed in beams with aspect ratio 70 in all three strengths of concrete. For the beams with steel fibers of aspect ratio (l/d) 70, the twist at ultimate torque of the beams has increased by 18.89 %, 25.46 % and 60.82 % for A-RVC, B-RVC and C-RVC beams respectively in comparison with their respective plain beams. The increase in twist at ultimate torque has observed in recycled aggregate based concrete was less than the beams with natural aggregates. The increase in twist at ultimate torque has increased with the increase strength of concrete. Similar type of behaviour is observed for beams modelled for in steel fibers with aspect ratios 50 and 100.

7.3.2 Effect of Steel fibers on Torsional Performance of RSCC:

In this section results obtained from the finite element modelling on the Recycled aggregate based Steel Fiber Reinforced SCC beams are presented. Table 7.6 shows the ultimate torque and angle of twist values of fibrous and non-fibrous beams of RSCC for all the three aspect ratios (50, 70 and 100) of Mix-A 20 MPa, Mix-B 50 MPa and Mix-C 80 MPa.

Table 7.6 Torsional behaviour of RSCC using steel fibers of aspect ratios of 50, 70 and 100 using ATENA

Designation of Beam	Ultimate Torque (kNm)	Twist at Ultimate Torque (10^{-3} rad/m)
Mix-A RSCC 20 MPa		
A-RSCC Plain	1.56	5.78
A-RSFSCC 50	1.82	7.16
A-RSFSCC 70	1.89	7.45
A-RSFSCC 100	1.72	6.75
Mix-B RSCC 50 MPa		
B-RSCC Plain	2.51	5.53
B-RSFSCC 50	2.83	7.54
B-RSFSCC 70	2.97	8.02
B-RSFSCC 100	2.77	6.60
Mix-C RSCC 80 MPa		
C-RSCC Plain	3.48	6.12
C-RSFSCC 50	4.08	9.97
C-RSFSCC 70	4.24	11.23
C-RSFSCC 100	3.96	9.30

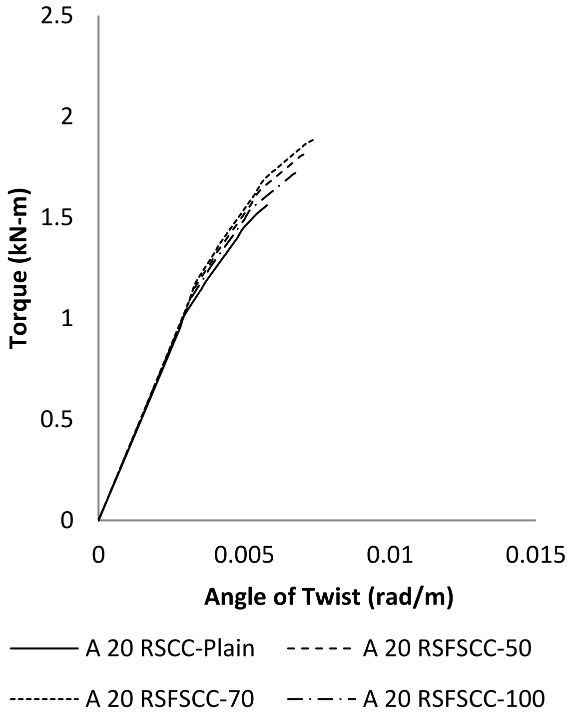


Figure 7.22 Torque-Twist response A-RSCC using ATENA

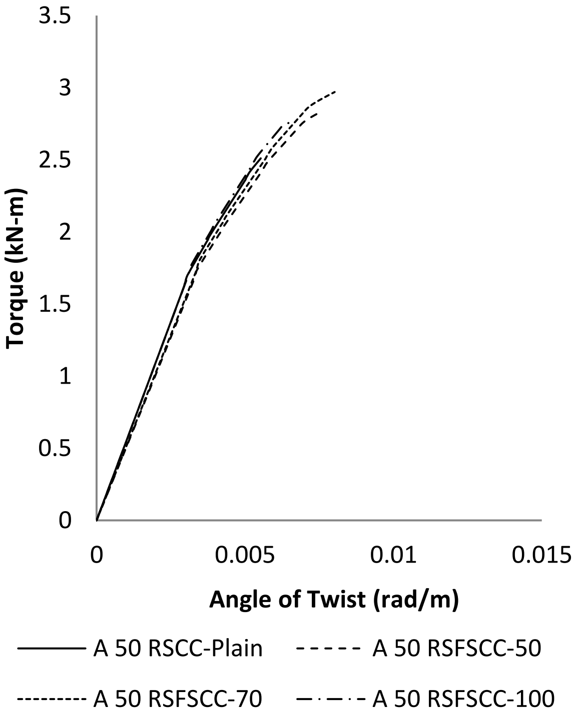


Figure 7.23 Torque-Twist response B-RSCC using ATENA

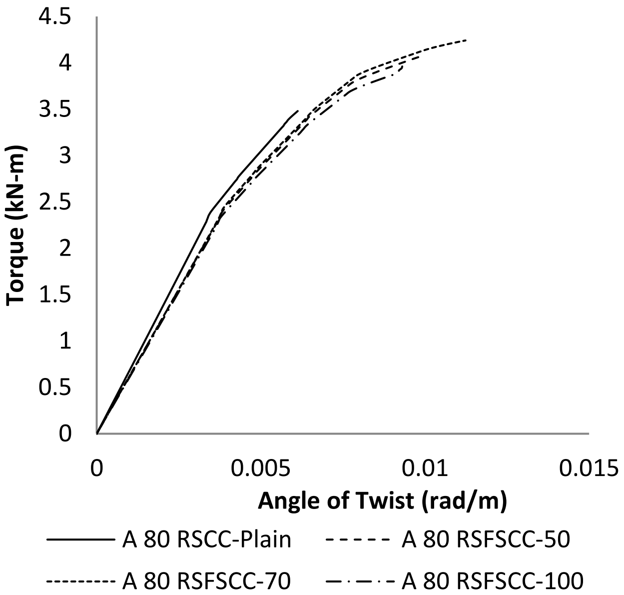


Figure 7.24 Torque-Twist response C-RSCC using ATENA

To study the effect of aspect ratio of steel fibers on torsional behaviour of recycled aggregate based SCC beams, nonlinear analysis is performed for all the beams with recycled aggregates (25 % replacement by weight). As it is observed as in the case of normal aggregates beams with aspect ratio 70 have the higher twist at ultimate torque, a similar type of behaviour was observed in the case of beams with recycled coarse aggregate. From the table 7.6 it is observed that due to the addition of steel fibers the twist at ultimate torque has improved and also failure of RSCC beams was delayed as steel fibers helps in bridging the cracks faces and delaying the crack propagation. Figures 7.22-7.24 shows the torque-twist response curves of A-RSCC, B-RSCC and C-RSCC beams for aspect ratios of steel fibers (l/d) 50, 70 and 100. The maximum increase in twist at ultimate torque is observed in beams with aspect ratio 70 in all three strengths of concrete. For beams with steel fibers of aspect ratio (l/d) 70, the twist at ultimate torque of the beams has increased by 28.89 %, 45.03 % and 83.50 % for A-RSCC, B-RSCC and C-RSCC beams respectively in comparison with their respective plain beams. The increase in twist at ultimate torque has increased with the increase strength of concrete. Similar type of behaviour is observed for beams modelled for in steel fibers with aspect ratios 50 and 100. It is observed that the increase is more in case of SCC than VC in all aspect ratios and strengths of concrete.

7.3.3 Effect of aspect ratio on torsional performance of Recycled aggregate based SCC and VC beams:

As the analysis of torsional performance of recycled aggregate based SCC is scant it needs to be compared with conventional vibrated concrete. It was found that the torsional performance of RSCC was superior to RVC from chapters 5 and 6. Similar behaviour was found in analytical model by using FEM, it was true for all strengths and aspect ratios. In 20 MPa concrete, it was observed that there is an increase of 18.89 % and 28.89 % in twist at ultimate torque of RVC and RSCC beams with aspect ratio 70 respectively in comparison with plain beams. An increase of 25.46 % and 45.03 % in twist at ultimate torque was observed in RVC and RSCC beams with aspect ratio 70 for 50 MPa concrete compared with plain beams. In 80 MPa concrete, it was observed that there is an increase of 60.82 % and 83.50 % in twist at ultimate torque of RVC and RSCC beams with aspect ratio 70 respectively in comparison with plain beams. Similar behaviour was observed for beams with aspect ratio 50 and 100. Figures 7.25-7.27 shows the variation of twist at ultimate torque for VC and SCC with different aspect ratios of steel fibers.

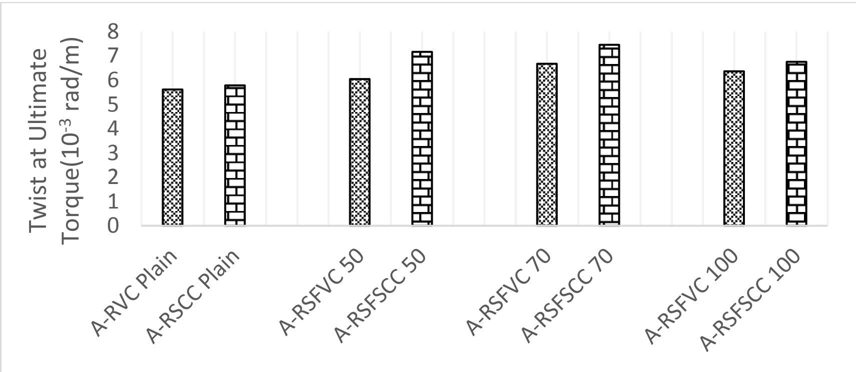


Figure 7.25 Comparison of RVC and RSCC on Twist at Ultimate Torque of 20 MPa

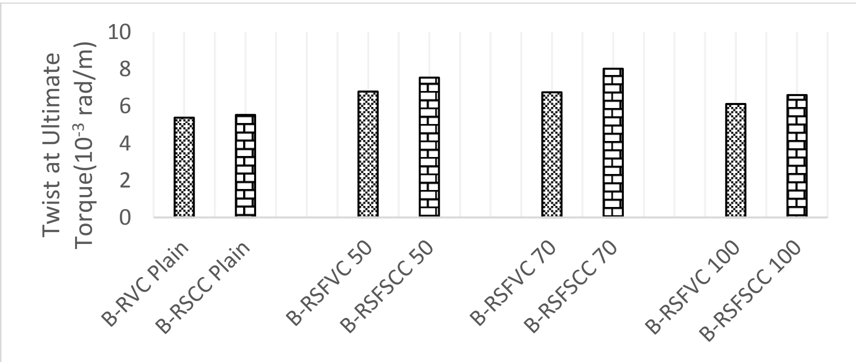


Figure 7.26 Comparison of RVC and RSCC on Twist at Ultimate Torque of 50 MPa

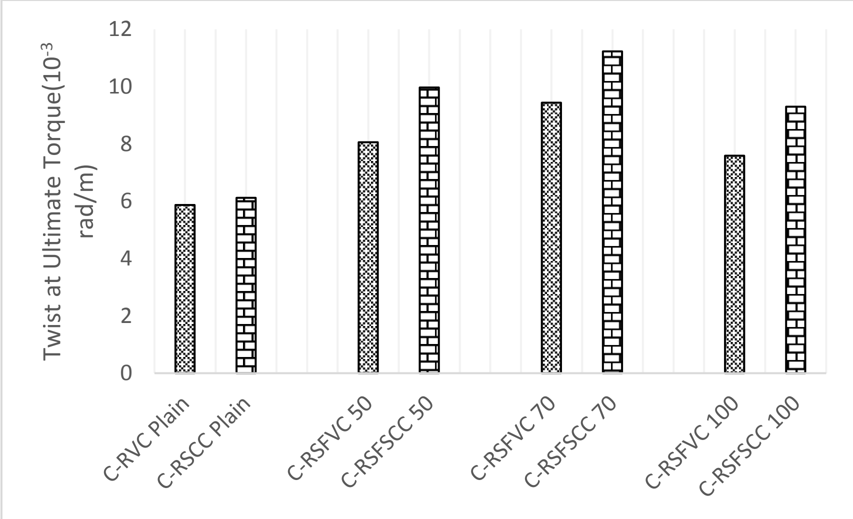


Figure 7.27 Comparison of RVC and RSCC on Twist at Ultimate Torque of 80 MPa

7.4 Comparison of Torsional Strength among Experimental and ATENA results:

A comparison of experimental results with the results obtained through analytical model is done and the results are presented in Tables 7.7-7.10 and Figures 7.28-7.29 for both VC and SCC. The comparison of experimental results with that of analytical results are compared well with most the values are near to each other with percentage error in the all cases is less than 15% with a confidence level of 85-90 %.

Table 7.7 Comparison of Experimental results with ATENA Software for VC Beams with natural aggregates

Designation of Beam	Twist at Ultimate Torque (10^{-3} rad/m)		% error
	Experiment	ATENA	
Mix-A VC 20 MPa			
A-VC Plain	5.45	5.96	9.36
A-SFVC 50	6.43	7.2	11.98
A-SFVC 70	6.8	7.7	13.24
A-SFVC 100	6.27	6.97	11.16
Mix-B VC 50 MPa			
B-VC Plain	6.5	5.72	12.00
B-SFVC 50	7.9	7.29	7.72
B-SFVC 70	8.5	7.67	9.76
B-SFVC 100	7.3	6.59	9.73
Mix-C VC 80 MPa			
C-VC Plain	7.1	6.29	11.41
C-SFVC 50	9.5	8.57	9.79
C-SFVC 70	11.2	10.59	5.45
C-SFVC 100	9.1	8.46	7.03

Table 7.8 Comparison of Experimental results with ATENA Software for SCC Beams with natural aggregates

Designation of Beam	Twist at Ultimate Torque (10^{-3} rad/m)		% error
	Experiment	ATENA	
Mix-A SCC 20 MPa			
A-SCC Plain	5.67	6.23	9.88
A-SFSCC 50	7.1	7.54	6.20
A-SFSCC 70	7.45	8.4	12.75
A-SFSCC 100	6.86	7.45	8.60
Mix-B SCC 50 MPa			
B-SCC Plain	6.7	5.97	10.90
B-SFSCC 50	8.9	8.01	10.00
B-SFSCC 70	9.2	8.29	9.89
B-SFSCC 100	7.9	7.43	5.95
Mix-C SCC 80 MPa			
C-SCC Plain	7.54	6.69	11.27
C-SFSCC 50	11.92	10.66	10.57
C-SFSCC 70	13.8	12.99	5.87
C-SFSCC 100	11.32	10.38	8.30

Table 7.9 Comparison of Experimental results with ATENA Software for RVC Beams with recycled aggregates

Designation of Beam	Twist at Ultimate Torque (10^{-3} rad/m)		% error
	Experiment	ATENA	
Mix-A RVC 20 MPa			
A-RVC Plain	4.98	5.61	12.65
A-RSFVC 50	5.46	6.04	10.62
A-RSFVC 70	6.14	6.67	8.63
A-RSFVC 100	5.73	6.36	10.99
Mix-B RVC 50 MPa			
B-RVC Plain	6.1	5.38	11.80
B-RSFVC 50	7.27	6.79	6.60
B-RSFVC 70	7.85	6.75	14.01
B-RSFVC 100	6.6	6.12	7.27
Mix-C RVC 80 MPa			
C-RVC Plain	6.5	5.87	9.69
C-RSFVC 50	8.6	8.06	6.28
C-RSFVC 70	10.2	9.44	7.45
C-RSFVC 100	8.2	7.59	7.44

Table 7.10 Comparison of Experimental results with ATENA Software for RSCC Beams with recycled aggregates

Designation of Beam	Twist at Ultimate Torque (10^{-3} rad/m)		% error
	Experiment	ATENA	
Mix-A RSCC 20 MPa			
A-RSCC Plain	5.11	5.78	13.11
A-RSFSCC 50	6.42	7.16	11.53
A-RSFSCC 70	6.75	7.45	10.37
A-RSFSCC 100	6.22	6.75	8.52
Mix-B RSCC 50 MPa			
B-RSCC Plain	6.2	5.53	10.81
B-RSFSCC 50	8.2	7.54	8.05
B-RSFSCC 70	8.7	8.02	7.82
B-RSFSCC 100	7.1	6.6	7.04
Mix-C RSCC 80 MPa			
C-RSCC Plain	6.9	6.12	11.30
C-RSFSCC 50	10.9	9.97	8.53
C-RSFSCC 70	12.2	11.23	7.95
C-RSFSCC 100	10.4	9.3	10.58

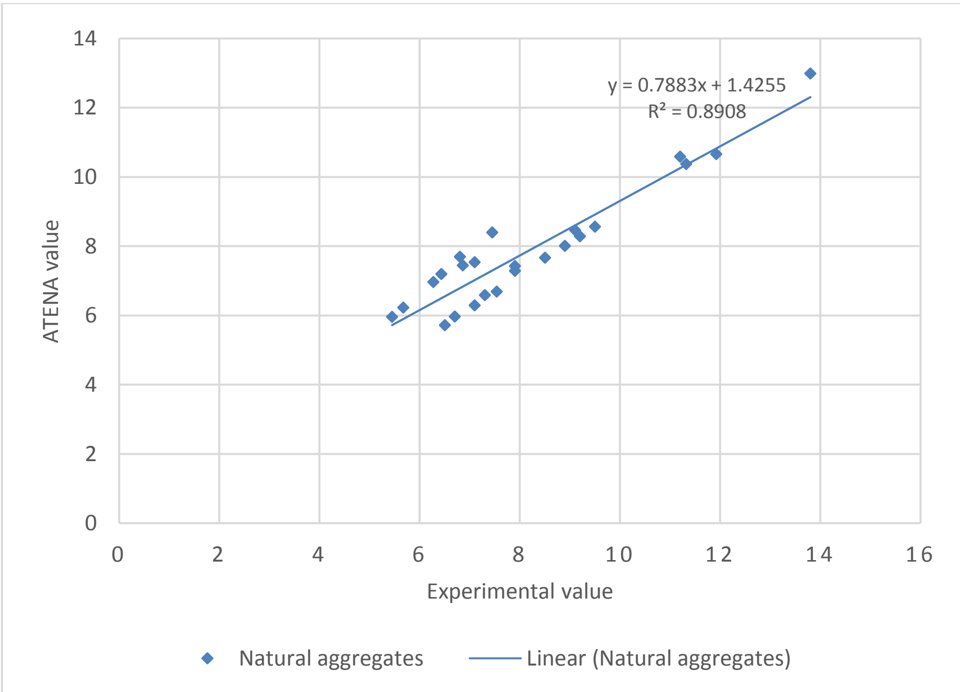


Figure 7.28 Comparison of Experiment twist at ultimate torque vs ATENA twist at ultimate torque for beams with natural aggregates.

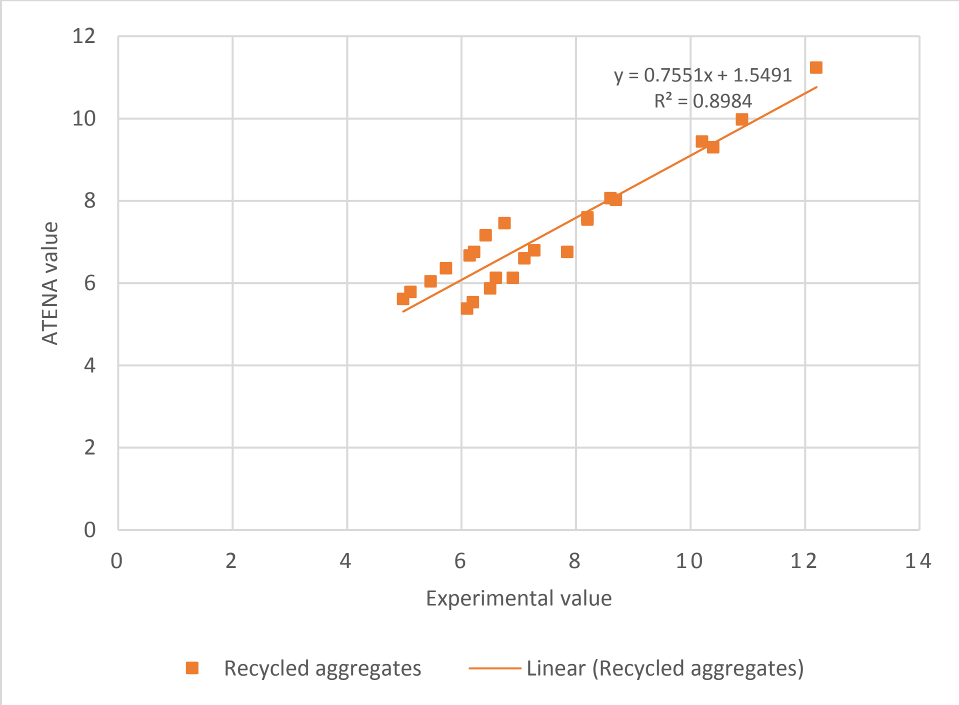


Figure 7.29 Comparison of Experiment twist at ultimate torque vs ATENA twist at ultimate torque for beams with recycled aggregates.

7.5 Comparison of torsional behaviour of Natural aggregate beams and Recycled aggregate beams:

As observed in the case of experimental study due to use of recycled aggregate as 25% replacement (by weight) of coarse aggregates, the ultimate torsional strength and twist at ultimate torque were was reduced. A detailed comparison among twist at ultimate torque obtained through analytical modeling for Natural and recycled aggregate beams for all three strengths of concrete of SCC and VC was given in this section. Figures 7.30-7.35 shows the twist at ultimate torque of Natural and recycled aggregate beams for both concretes of all three strengths of concrete. Due to use of recycled aggregates, the highest reduction in twist at ultimate torque was 19.21 % and 12.75 % for RVC and RSCC beams with aspect ratio 70 respectively for 20 MPa strength concrete when compared with similar types of beams with natural aggregates i.e. A-VC and A-SCC. Similarly in case of 50 MPa of concrete beams due to use of recycled aggregates, the twist at ultimate torque is reduced by 13.63 % and 12.58 % in VC and SCC with aspect ratio 70 respectively, when compared with similar type of beams with natural aggregates i.e. B-VC and B-SCC. In case of 80 MPa strength concrete twist at ultimate torque is due recycled aggregates is reduced by 12.18 % and 15.67 % in VC and SCC with aspect ratio 70 respectively when compared to similar beams with natural aggregates.

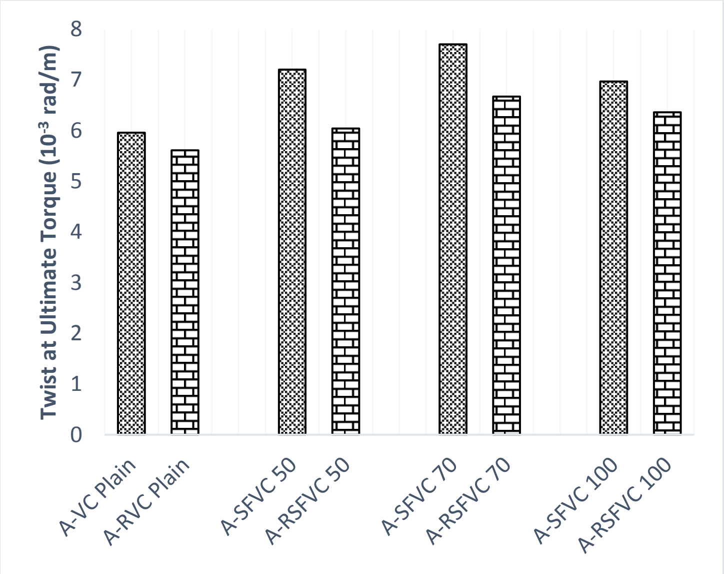


Figure 7.30 Comparison of VC and RVC on Twist at Ultimate Torque of 20 MPa

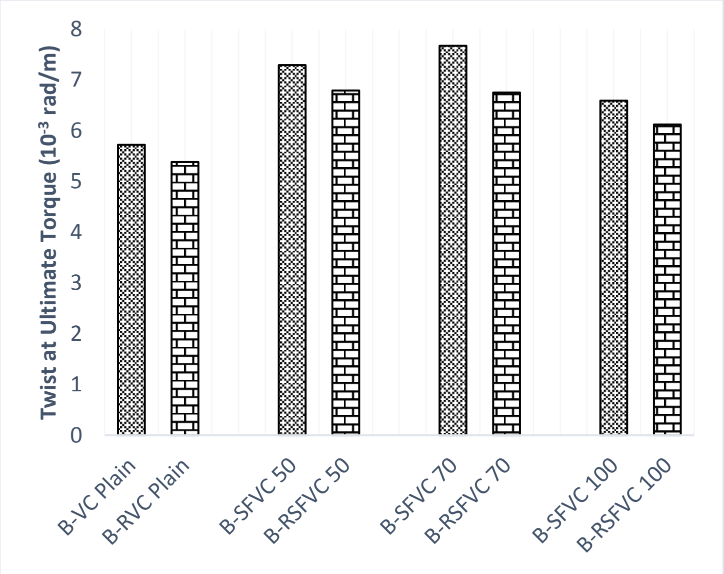


Figure 7.31 Comparison of VC and RVC on Twist at Ultimate Torque of 50 MPa

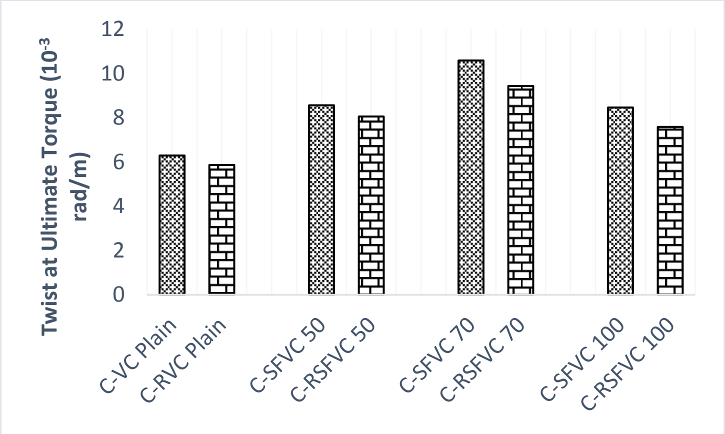


Figure 7.32 Comparison of VC and RVC on Twist at Ultimate Torque of 80 MPa

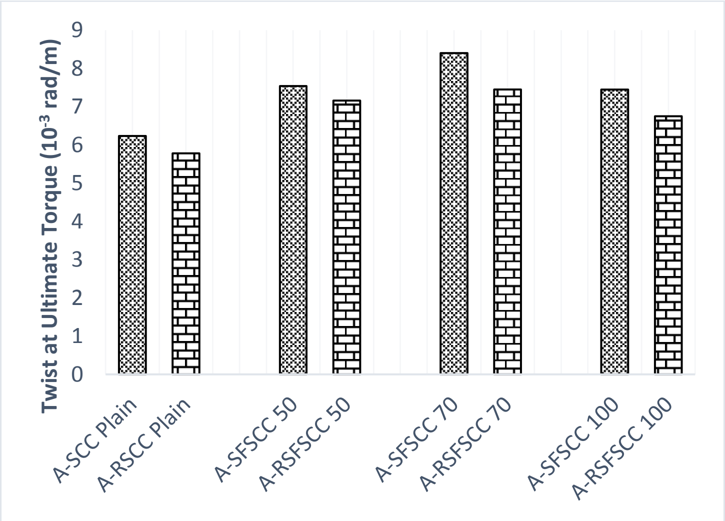


Figure 7.33 Comparison of SCC and RSCC on Twist at Ultimate Torque of 20 MPa

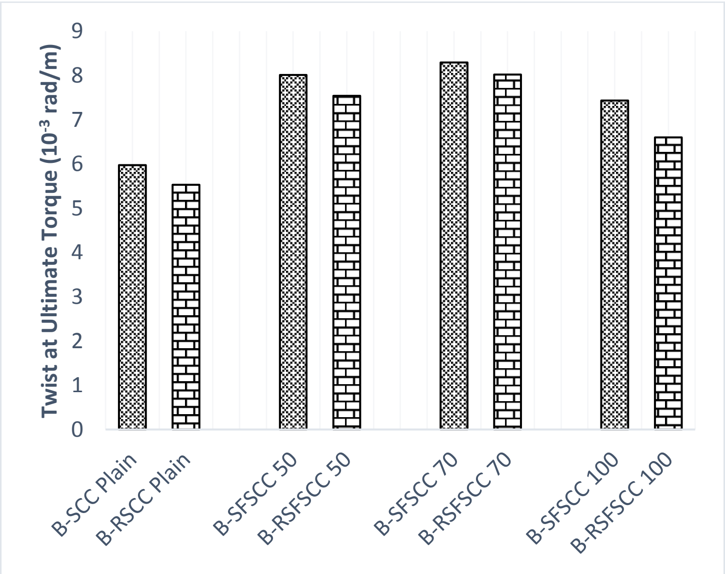


Figure 7.34 Comparison of SCC and RSCC on Twist at Ultimate Torque of 50 MPa

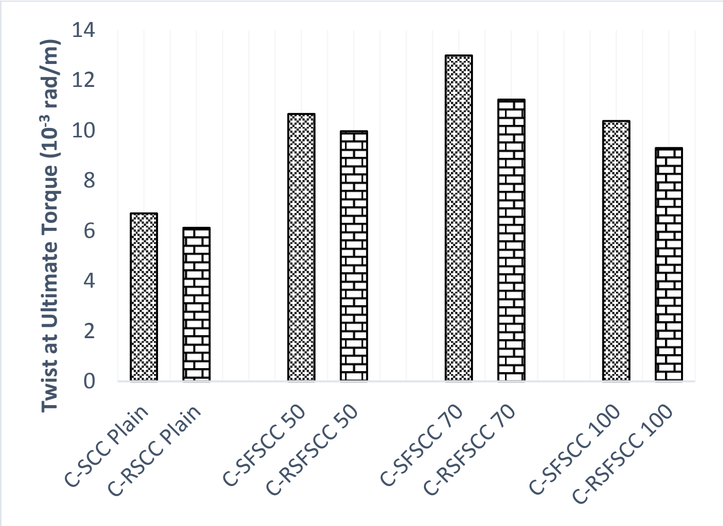


Figure 7.35 Comparison of SCC and RSCC on Twist at Ultimate Torque of 80 MPa

7.6 Conclusions from Phase-IV:

Based on Numerical studies using finite element software ATENA on Torsional behaviour of recycled aggregate based SCC and VC for both fibrous and non-fibrous concretes beams for all three strengths of concrete, following conclusions were made.

1. Based on Numerical modelling using ATENA, angle of twist increased by 29.19 %, 34.09 % and 68.36 % due to the maximum dosage of steel fiber (0.5 %) with aspect ratio 70 in 20 MPa, 50 MPa and 80 MPa respectively for VC beams. Similarly, in case of SCC beams, an increase of 34.83 %, 38.86 % and 94.17 % was observed in 20 MPa, 50 MPa and 80 MPa SCC beams respectively with natural aggregates in case of plain beams.
2. There is an increase in angle of twist by 18.89 %, 25.46 % and 60.82 % due to the maximum dosage of steel fiber (0.5 %) of aspect ratio 70 in 20 MPa, 50 MPa and 80 MPa of VC beams. Similarly, an increase of 28.89 %, 45.03 % and 83.05 % is observed in 20 MPa, 50 MPa and 80 MPa of SCC beams respectively with recycled aggregates with plain beams.
3. The decrease in angle of twist due to addition of recycled aggregates was observed to be 13.38 %, 11.92 % and 10.86 % in beam VC beams with aspect ratio 70 in concretes 20 MPa, 50 MPa and 80 MPa respectively compared to natural aggregate beams.

4. The decrease in angle of twist due to addition of recycled aggregates was observed to be 11.31 %, 3.26 % and 13.55 % in SCC beams with aspect ratio 70 in concretes 20 MPa, 50 MPa and 80 MPa respectively compared to natural aggregate beams.
5. The Numerical results obtained compared well with those of the experimental results and maximum values are within 85 - 90 % level of confidence and with an average error of 9.54 %.

Chapter 8 Conclusions

8.0 Conclusions:

From a detailed experimental study on Torsional Behaviour of Recycled Aggregate based Steel Fiber Reinforced Self Compacting Concrete and Vibrated Concrete, the following conclusions have been drawn. The same are detailed under different sub-headings.

<u>Phase-I Mechanical properties of steel fiber reinforced SCC</u>

1. Based on Fresh properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is maximum for all three grades. All the aspect ratios of fibers could not achieve the fresh properties of EFNARC specifications for dosages 0.75 % and 1 %.
2. Based on hardened properties also it can be inferred that 0.5 % dosage of steel fibers by volume of concrete is the maximum dosage for self compacting concrete of three strengths. There is a good increase in the split and flexural strengths due to the fibers bridging the crack propagation and resulted in increased ultimate load carrying capacity of the specimens.
3. It can be concluded that steel fibers with aspect ratio 70 has significant contribution towards increase in mechanical properties of SCC compared to low (50) and high (100) aspect ratios with 0.5 % dosage of steel fibers. It is true for all strengths of SCC.
4. The compressive strength increased by 13.39 % with maximum dosage of steel fiber 0.5 %. The split tensile strength increased by 21.37 % and the flexural strength increased by 29.32 % for low strength concrete (20 MPa) with aspect ratio 70 compared to plain specimens.
5. In case of Standard grade SCC (50 MPa) due to addition of steel fibers with aspect ratio 70 (0.5 % volume of concrete), the compressive strength increased by 8.37 %, split tensile strength increased by 18.09 % and flexural strength increased by 27.53% respectively compared to plain specimens.
6. Similarly, in case of high strength SCC (80 MPa) due to addition of steel fibers with aspect ratio 70, the compressive strength increased by 6.42 % with 0.5 % dosage of steel fibers. The split tensile increased by 16.72 % and flexural strength is increased by 25.35 % respectively compared to plain specimens.

Phase-II Torsional behaviour of steel fiber reinforced SCC and VC using natural aggregates

1. Due to addition of steel fibers, the ultimate torsional strength and angle of twist increased by 18.40 %, 24.77 % in A-VC-70 and 20.77 %, 31.39 % respectively in A-SCC-70 compared to plain beams.
2. In case of B-VC-70 and B-SCC-70, the increase in ultimate torsional strength and angle of twist was 16.22 %, 30.77 % and 17.06 %, 37.31 % respectively.
3. Due to addition of steel fibers, the ultimate torsional strength and angle of twist increased by 14.28 %, 57.75 % in C-VC-70 and 18.38 %, 83.02 % respectively in C-SCC-70 compared to plain beams.
4. The effect of addition of steel fibers in SCC influenced all strengths of concrete compared to VC. This is due to the uniform distribution of fibers throughout the mix leading to increase in bond between fibers and cement matrix.
5. The failure mode changed from a sudden brittle failure to a ductile behaviour with inclusion of steel fibers. This is true for both the concretes with all aspect ratios.
6. Due to brittle nature of high strength concrete the effect of addition of steel fibers was more significant in torsional properties of both SCC and VC.
7. The inclination of crack pattern for beams subjected to pure torsion is not influenced by inclusion of steel fibers and recycled aggregate in both SCC and VC.
8. A comparison was made between experimental and various models of torsion from literature on vibrated concrete. It can be noticed that the ultimate torsional strength was under estimated by elastic analysis and was over estimated when analyzed using plastic analysis.

Phase–III Torsional Behaviour of Steel fiber reinforced SCC and VC using Recycled aggregates

3. The torsional strength of beams using recycled aggregates reduced by 8.59 %, 5.56 % and 8.96 % for plain VC beams of strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
4. The torsional strength of beams using recycled aggregates reduced by 7.69 %, 5.28 % and 5.95 % for plain SCC beams of strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
5. As the aspect ratio of steel fibers increased from 50 to 100, ultimate torsional strength and twist increased. Similar behaviour was observed in case of both

SCC and VC. The significant improvement was seen for beams with aspect ratio 70 in all strengths of concretes.

6. The torsional strength of beams using recycled aggregates reduced by 5.70 %, 4.75 % and 5.88 % for VC beams with aspect ratio 70 and strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
7. The torsional strength of beams using recycled aggregates reduced by 5.35 %, 3.57 % and 3.20 % for SCC beams with strength 20, 50 and 80 MPa respectively compared to beams with natural aggregates.
8. Similarly, a comparison was made between experimental and existing theories of torsion on vibrated concrete. It can be noticed that the ultimate torsional strength was under estimated by elastic analysis and was over estimated by plastic analysis.

Empirical formula is proposed to estimate the ultimate torsional strength of the member (T_{SCC}) for SCC. This is given by

$$T_{SCC} = (0.5-0.092(b/d))\,(b^2 d f_{t1}) + \left(\frac{l}{dia}\right)*f_{t2}$$

Similarly, an empirical formula proposed to estimate the ultimate torsional strength of the member (T_{VC}) for VC.

$$T_{VC} = (0.5-0.118(b/d))\,(b^2 d f_{t1}) + \left(\frac{l}{dia}\right)*f_{t2}$$

$$1/f_t = (1/f_c) + (1/f_{spt})$$

Where, f_{t1} = Tensile strength of plain concrete; f_{t2} = Tensile strength of fiber reinforced concrete; f_c = Compressive strength of concrete; f_{spt} = Split tensile strength; b = width of beam; d = depth of beam; l = length of steel fiber; dia= diameter of steel fiber.

Phase-IV Analytical behaviour of Steel fiber reinforced SCC and VC Using Finite Element Software ATENA-GID under torsion

6. Based on Numerical modelling using ATENA, angle of twist increased by 29.19 %, 34.09 % and 68.36 % due to the maximum dosage of steel fiber (0.5 %) with aspect ratio 70 in 20 MPa, 50 MPa and 80 MPa for VC beams. Similarly, in case of SCC beams, an increase of 34.83 %, 38.86 % and 94.17 % was observed in 20 MPa, 50 MPa and 80 MPa SCC beams respectively with natural aggregates with respect to plain beams.
7. There is an increase in angle of twist by 18.89 %, 25.46 % and 60.82 % due to the maximum dosage of steel fiber (0.5 %) of aspect ratio 70 in 20 MPa, 50 MPa and 80 MPa of VC beams. Similarly, an increase of 28.89 %, 45.03 % and 83.05

% is observed in 20 MPa, 50 MPa and 80 MPa of SCC beams respectively with recycled aggregates with respect to plain beams.

8. The decrease in angle of twist due to addition of recycled aggregates was observed to be 13.38 %, 11.92 % and 10.86 % in beam VC beams with aspect ratio 70 in concretes 20 MPa, 50 MPa and 80 MPa respectively compared to natural aggregate beams.
9. The decrease in angle of twist due to addition of recycled aggregates was observed to be 11.31 %, 3.26 % and 13.55 % in SCC beams with aspect ratio 70 in concretes 20 MPa, 50 MPa and 80 MPa respectively compared to natural aggregate beams.
10. The Numerical results obtained are compared well those with experimental results and maximum values are within 85-90 % level of confidence and with an average error of 9.54 %.

8.1 Significant Contribution from the Research Work:

1. The influence of steel fibers on different strengths (20 MPa, 50 MPa and 80 MPa) of recycled aggregate based self compacting concrete was evaluated and maximum dosage of steel fibers was found based on fresh and mechanical properties.
2. Studies on torsional behaviour of steel fiber reinforced SCC and vibrated concrete were carried out independently for three aspect ratios of hooked end steel fibers (l/d= 50, 70 and 100) and for low (20 MPa), normal (50 MPa) and high strength (80 MPa) concrete.
3. Studies on recycled coarse aggregate (25 % replacement to natural coarse aggregate) based steel fiber reinforced SCC and vibrated concrete under torsion was carried out independently for three aspect ratios with hooked end steel fibers (l/d= 50, 70 and 100) and for low (20 MPa), normal (50 MPa) and high strength (80 MPa) concrete.
4. Numerical behaviour of Steel fiber reinforced SCC and VC under torsion was carried out using Finite element software ATENA and the correlation of experimental and predicted results with numerical results was done and the correlation was satisfactory.

5. An analytical model was proposed to predict the ultimate torsional strength for both SCC and VC involving all the major parameters influencing the torsional strength of a beam.

8.2 Scope for Further work:

1. To study the influence of hybrid fiber effect on torsional behaviour of self compacting concrete for different span to depth ratios (a/d).
2. To study the effect of steel fibers on SCC under combined behaviour of torsion and bending.
3. Detailed studies on the shear behaviour of SCC and VC using hybrid fibers can be under taken.

Publications Related to Present work:

International Journals:

1. **K J N Sai Nitesh** and S Venkateswara Rao. “An Experimental Investigation on effect of Fibers on High Strength Self Compacting Concrete and Vibrated Concrete.” International Journal of Earth Sciences and Engineering 9.3 (2016): 400-403. (SCOPUS Indexed)
2. **K J N Sai Nitesh**, S Venkateswara Rao and Kumar, P. R. (2016). “A Study on the Effect of Aspect Ratio of Steel Fiber on Torsional Properties of High Strength Self Compacting Concrete.” Transylvanian Review. Vol 26(11): 2861-2872. (SCI Journal)
3. **K J N Sai Nitesh**, S Venkateswara Rao and Kumar, P. R. (2018) “Torsional behaviour of Steel Fiber Reinforced Recycled Aggregate based Self Compacting Concrete.” Cement Wapno Beton 4 : 259-276 (SCI Journal)
4. **K J N Sai Nitesh**, S Venkateswara Rao. And Kumar, P.R. (2019) “A Comparative Study on Torsional Behaviour of Steel Fiber Reinforced Self Compacting Concrete and Vibrated Concrete with Recycled Aggregate”. Journal of Building Engineering. Vol 22, March: 242-251 (SCI Journal).

International Conferences:

1. **K J N Sai Nitesh** and S Venkateswara Rao. “A study on effect of aspect ratio of fiber on Torsional behaviour Recycled Aggregate based Self Compacting Concrete.” International Conference on Composite Materials and Structures (2017), IIT-Hyderabad, Dec 27th-29th.

2. **K J N Sai Nitesh**, S Venkateswara Rao and Kumar, “An Experimental Study on Torsional Behaviour of High Strength Self Compacting Concrete.” Proceedings of the 3rd International Conference on Trends and Recent Advances in Civil Engineering (TRACE 2016), Amity University, New Delhi, Aug 11th-12th.

3. **K J N Sai Nitesh** and S Venkateswara Rao. “An Experimental Investigation on effect of Hybrid Fiber on High Strength Self Compacting Concrete and Vibrated Concrete.” International Conference of Earth Sciences and Engineering (2016)-Coimbatore, June 17th-19th.

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APPENDIX-A

A) Nan Su Method of Mix Design (Mix A-20 MPa)

Target Mean Strength		20	MPa
Max. Size of Aggregate		16.00	mm
Specific Gravity of C.A		2.80	
Bulk Density of C.A		1.50	g/cm^3
Specific Gravity of F.A		2.65	
Bulk Density of F.A		1.45	g/cm^3
Specific Gravity of Cement		3.10	
Specific Gravity of Fly Ash		2.11	
Volume of F.A		54.00	%
Volume of C.A		46.00	%
Specific Gravity of SP		1.10	
Packing Factor		1.18	
Water/Fly Ash(W/F)		0.45	
Step 1	**Determination of C.A & F.A content**		
	Weight of sand (W_s)=1450 x 1.16 x 54.00 %	908.28	kg/m^3
	Weight of coarse aggregate (W_a) =1500 x 1.18 x 46.00 %	800.40	kg/m^3
Step 2	**Determination of Cement**		
	Weight of cement (W_c)= 30/0.14= 214.29	320.00	kg/m^3
Step 3	**Determination of Water required**		
	Weight of water (W_w)=0.45 x 320=	144	kg/m^3
Step 4	**Determination of Fly Ash**		
	V_{pf} = 1 – [(800.4 / 1000 x 2.8) + (908.28 / 1000 x 2.65) + (357.14 / 1000 x 3.10) +(144 / 1000 x 1) + 0.02]= 0.092	0.092	m^3
	Fly ash content W_f=[0.092 x 1000 x 2.11] / [(1+0.45) x 1.0]	133.88	kg/m^3
Step 5	**Water Content for Fly Ash**		
	W_{fa}=0.45x133.88	60.25	kg/m^3
Step 6	**Determination of S.P dosage**		
	W_{sp}=0.008x(320.00+133.88)	3.63	kg/m^3
Step 7	**Adjustment of mixing water needed in SCC Amount of Water in S.P**		
	W_{wsp}=(1-0.33)x3.63	2.43	kg/m^3
	Amount of Water (W)=144+60.25-2.43	201.82	kg/m^3

Nan-Su method of mix design for Natural Aggregate Based Self Compacting Concrete (NASCC) was used to arrive at initial trial mixes but then these mixes were modified accordingly as per EFNARC to achieve optimum mix proportions satisfying the fresh and hardened properties at the same time economical. The proportion arrived for 20 MPa grade SCC is as given below.

Mix Design Results- Mix-A			
S. No.	**Material**	**Quantity kg/m³**	**Proportions**
i)	Cement	320.00	1.000
ii)	Fine Aggregate	908.00	2.840
iii)	Coarse Aggregate	800.00	2.500
iv)	Water	200.00	0.620
v)	Fly ash	200.00	0.620
vi)	Super Plasticizer	4.20	0.013

B) Nan Su Method of Mix Design (Mix B- 50 MPa)

Target Mean Strength		50	MPa
Max. Size of Aggregate		16.00	mm
Specific Gravity of C.A		2.80	
Bulk Density of C.A		1.50	g/cm^3
Specific Gravity of F.A		2.65	
Bulk Density of F.A		1.45	g/cm^3
Specific Gravity of Cement		3.10	
Specific Gravity of Fly Ash		2.11	
Volume of F.A		53.00	%
Volume of C.A		47.00	%
Specific Gravity of SP		1.10	
Packing Factor (Nan-Su, 2001)		1.11	
Water Cement Ratio(W/C)		0.36	
Water/Fly Ash(W/F)		0.45	
Step 1	**Determination of C.A & F.A content**		
	Weight of sand (W_s)=1450 x 1.11 x 53.00 %	853.10	kg/m^3
	Weight of coarse aggregate (W_a) =1500 x 1.11 x 47.00 %	782.60	kg/m^3
Step 2	**Determination of Cement**		
	Weight of cement (W_c)= 50/0.14= 357.14	430.00	kg/m^3
Step 3	Determination of Water required		
	Weight of water (W_w)=0.36 x 430.00	154.80	kg/m^3
Step 4	**Determination of Fly Ash**		
	V_{pf} = 1 – [(782.6 / 1000 x 2.8) + (853.1 / 1000 x 2.65) + (430.00 / 1000 x 3.10) +(154.8 / 1000 x 1) + 0.02]	0.086	m^3
	Fly ash content W_f=[0.086 x 1000 x 2.11] / [(1+0.45) x 1.0]	133.19	kg/m^3
Step 5	**Water Content for Fly Ash**		
	W_{fa}=0.45x133.19	59.93	kg/m^3
Step 6	**Determination of S.P dosage**		
	W_{sp}=0.008x(430.00+133.19)	4.50	kg/m^3
Step 7	**Adjustment of mixing water needed in SCC Amount of Water in S.P**		
	W_{wsp}=(1-0.33)x4.5	3.015	kg/m^3
	Amount of Water (W)=154.8+59.93-3.015	211.715	kg/m^3

Mix Design Results- Mix-B			
S.No.	**Material**	**Quantity kg/m^3**	**Proportions**
i)	Cement	430.00	1.000
ii)	Fine Aggregate	853.00	1.980
iii)	Coarse Aggregate	783.00	1.820
iv)	Water	194.00	0.450
v)	Fly ash	180.00	0.420
vi)	Super Plasticizer	5.16	0.012

C) Nan Su Method of Mix Design (Mix C-80 MPa)

Target Mean Strength		80.00	MPa
Max. Size of Aggregate		16.00	mm
Specific Gravity of C.A		2.80	
Bulk Density of C.A		1.52	g/cm^3
Specific Gravity of F.A		2.65	
Bulk Density of F.A		1.45	g/cm^3
Specific Gravity of Cement		3.10	
Specific Gravity of Fly Ash		2.11	
Specific Gravity of Micro silica		2.23	
% Volume of F.A		52.00	
% Volume of C.A		48.00	
Specific Gravity of SP		1.10	
Packing Factor (Nan-Su, 2001)		1.06	
Water Cement Ratio(W/C)		0.35	
Water/Fly Ash(W/F)		0.45	
Step 1	**Determination of C.A & F.A content**		
	Weight of sand (W_s)=1450 x 1.06 x 0.52	800	kg/m^3
	Weight of coarse aggregate (W_a) =1520 x 1.06 x 0.48	775	kg/m^3
Step 2	**Determination of Cement**		
	Weight of cement (W_c)= 70/0.14= 500	500.00	kg/m^3
Step 3	Determination of Water required		
	Weight of water (W_w)=0.35 x 500.00	175	kg/m^3
Step 4	**Determination of Fly Ash**		
	V_{pf} = 1 – [(775 / 1000 x 2.80) + (800 / 1000 x 2.65) + (500.00 / 1000 x 3.10) +(175 / 1000 x 1) + 0.01]	0.075	m^3

	Fly ash content W_f=[0.075 x 1000 x 2.11] / [(1+0.45) x 1.0]	109.14	kg/m^3
Step 5	**Water Content for Fly Ash**		
	W_{fa}=0.45x109.14	49.11	kg/m^3
Step 6	**Determination of S.P dosage**		
	W_{sp}=0.008x(500.00+109.14) =	4.87	kg/m^3
Step 7	**Adjustment of mixing water needed in SCC** **Amount of Water in S.P**		
	W_{wsp}=(1-0.33)x4.87	3.27	kg/m^3
	Amount of Water (W)=175.00+49.11-3.27	220.84	kg/m^3

Quantities of Materials for Mix-C			
S.No.	**Material**	**Quantity kg/m³**	**Proportions**
i)	Cement	500.00	1.000
ii)	Fine Aggregate	800.00	1.600
iii)	Coarse Aggregate	775.00	1.550
iv)	Water	190.00	0.380
v)	Fly ash	110.00	0.220
vi)	Micro Silica (Addition)	40.00	0.080
vii)	Super Plasticizer	6.00	0.012

APPENDIX – II

Theoretical ultimate torsional strength calculation:

Overall depth of the beam (b)	= 200 mm
Overall breadth of the beam (d)	= 100 mm
Length of the beam (l)	= 2300 mm
Compressive strength of concrete (f_c)	= 80.6 MPa
Split tensile strength of concrete (f_s)	= 4.67 MPa
Overall depth of the beam (b)	= 200 mm
Tensile strength of concrete (f_t)	= $(f_c * f_s) / (f_c + f_s)$
	= (80.6*4.67) / (80.6 + 4.67)
	= 4.41 MPa
Ultimate torsional strength using Elastic theory	= $\alpha * b^2 * d * f_t$
	= 0.246 * 0.1* 0.1* 0.2 * 4.41
	= $2.172 * 10^{-3}$ N-m
	= 2.172 kN-m
Ultimate torsional strength using Plastic theory	= $(0.5 - (\frac{b}{6d})) * b^2 * d * f_t$
	= 0.416 * 0.1* 0.1 * 0.2 * 4.41
	= 3.673 kN-m

Sample calculation of torque and angle of twist:

One division in proving ring	= 0.85 kg
No of divisions in between readings	= 5
Reading on the proving ring	= 20
Length of lever arm	= 1.5 m
Least count of dial gauge	= 0.01 mm
Reading on dial gauge 1 at steel frame 1	= 264
Reading on dial gauge 2 at steel frame 1	= 270
Reading on dial gauge 3 at steel frame 2	= 197
Reading on dial gauge 4 at steel frame 2	= 296
Distance between two steel frames	= 550 mm
Angle of twist at steel frame 1	= ((264 + 270) * 0.01) / 325 = 0.01643 rad
Angle of twist at steel frame 2	= ((197 + 296) * 0.01) / 340 = 0.0145 rad
Change in angle of twist between two steel frames	= (0.01643 – 0.0145) / 550 = 0.00351 rad/m
Torque applied to beam	= 20 * 0.85 * 5 * 1.5 * 10 = 1275 N-m = 1.275 kN-m