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

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

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Dedicated to

My Beloved Parents
&
My Beloved Brother (Late SRI KANNAM PRANEETH)

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ABSTRACT

Of all the different kinds of failures in concrete, shear failure is a sudden and brittle and occurs abruptly without any prior warning. To avoid these types of failures in concrete beams are traditionally reinforced with stirrups at closer spacing based on design. Congested arrangements of rebars and stirrups in Reinforced Concrete (RC) members such as, columns, beams and slabs makes it difficult to compact concrete into every corner of form work by means of any mechanical vibrators. 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 (SCC) as the name itself indicates, no external effort in compacting the concrete, it compacts itself under its own weight.

Shear failure of conventional reinforced concrete beams usually occurs by tensile failure of concrete in the shear span. For this reason, shear failure in general is sudden and brittle, and in practice shear reinforcement in the form of stirrups are incorporated to prevent this type of failure, and to increase the shear strength of the beams. Addition of steel fibers in concrete improves the post cracking behaviour and enhances the flexural-tensile strength. In recent years, application of use of short steel fibers in concrete increased tremendously. 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.

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 and fine

aggregates. The use of mineral admixtures as partial replacement to cement is a well-established fact that it 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) in flexure and shear. ATENA Gid is one such software developed exclusively to perform non-linear 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.

- ❖ Use of steel fibers in self-compacting concrete not only improves the load carrying capacity but also changes the failure pattern from a brittle behaviour to ductile mode.
- ❖ Effect of steel fibers on shear behaviour of Self compacting concrete needs to be established.
- ❖ Recycled aggregates can be used as replacement for natural aggregates and can be used in self-compacting concrete. The shear behaviour of recycled aggregate based SCC is to be investigated.
- ❖ Effect of stirrup diameter and spacing of stirrups on shear behaviour of SFRSCC needs to be investigated.
- ❖ Analytical modelling using a Finite element based software can be used in studying the shear behaviour of SFRSCC beams for both natural and recycled aggregates.

The scope of the present investigation includes:

- ❖ Evaluation of strength properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers (0%, 0.25%, 0.5%, 0.75% and 1% by volume of concrete) for three grades of SCC i.e. M30, M50 and M70 and maximize the dosage of steel fibers.

- ❖ To study the shear behaviour of NASCC and RASCC beams for three span to depth ratios (a/d =2, 2.5 and 3) for both without and with steel fibers and compare the experimental results with various models available in the literature for vibrated concrete for 30 MPa and 70MPa strengths.
- ❖ To study the effect of stirrup diameter (6mm and 8mm Ø) and spacing of stirrups on shear behaviour of NASFRSCC and RASFRSCC beams of strength 30 MPa and 70MPa .
- ❖ Analytical modelling of steel fiber reinforced self-compacting concrete using a finite element software ATENA for both NASCC and RASCC for 30 MPa and 70 MPa concrete strength.
- ❖ To validate the experimental results with results obtained through analytical modelling using finite element software ATENA.

The following broad objectives have been formulated to study and validate the use of steel fibers in self-compacting concrete to evaluate the shear behaviour.

1. Evaluate the Fresh and hardened properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers (0%, 0.25%, 0.5%, 0.75 % and 1% by volume of concrete) for three grades i.e. M30, M50 and M70 and determine the optimal dosage of steel fibers based on fresh and hardened properties.
2. To investigate the shear behaviour of steel fiber reinforced self-compacting concrete for three shear span to depth ratios (a/d= 2, 2.5 and 3) for 30 MPa and 70 MPa strength concrete for both NASCC and RASCC.
3. To study the effect of stirrup diameter (6mm and 8mm) and spacing of stirrups on shear behaviour of NASFRSCC and RASFRSCC beams of strengths 30 MPa and 70 MPa.
4. To correlate the experimental results with various models available in literature on vibrated concrete for both without and with steel fibers.
5. To validate the experimental results with results obtained through finite element software ATENA for both NASFRSCC and RASFRSCC.

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 on fresh and hardened properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers (0%, 0.25%, 0.5%, 0.75 % and 1% by volume of concrete) for three grades i.e. M30, M50 and M70 and determine the optimal dosage of steel fibers based on fresh and hardened properties. The fresh properties include Slump flow test, V-funnel test, V-funnel at T_5 minutes and J-ring test .The mechanical properties include compressive strength, split tensile strength and flexural strength. Also a preliminary study was carried out to know the difference on shear behaviour of SCC and NC.

Phase - II:

Studies on shear behaviour of natural aggregate based self-compacting concrete for three shear span depth ratios (a/d= 2, 2.5 and 3) and also to evaluate the effect of stirrup diameter (6mm and 8mm) and spacing of stirrups for 30 MPa and 70 MPa strengths for both without and with steel fibers. To correlate the experimental results with various models available in literature for vibrated concrete.

Phase - III:

Studies on shear behaviour of recycled aggregate based self-compacting concrete for three shear span depth ratios (a/d= 2, 2.5 and 3) and also to evaluate the effect of stirrup diameter (6mm and 8mm) and spacing of stirrups for 30 MPa and 70 MPa strengths for both without and with steel fibers. Correlate the experimental results with various model 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 stirrup diameter (6mm and 8mm) and spacing of stirrups using a finite element software ATENA. Compare the experimental results with results obtained through analytical modelling for 30 MPa and 70 MPa strength SCC.

The parameters of investigation include

- ❖ Grade of concrete - SCC of grade M30, M50 and M70 for (preliminary study to determine the optimal dosage of steel fibers.)
- ❖ Dosage of steel fibers - 0%, 0.25%,0.5%,0.75% and 1 % by volume of concrete
- ❖ Strength of concrete - 30 MPa and 70 MPa (adopted for casting of beams)
- ❖ Type of aggregate - Natural aggregate and Recycled concrete aggregate
- ❖ Shear Span to depth ratio (a/d) - 2, 2.5 and 3
- ❖ Diameter of Stirrup (Ø) - 6mm and 8 mm
- ❖ Spacing of stirrups (s_v) - $\mathbf{a}$, $\frac{\mathbf{a}}{\mathbf{2}}$ (where a is shear span)
- ❖ Dosage of steel fiber - 0% and optimal dosage of fiber (adopted for casting of beams)

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

1. Based on Fresh and hardened properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is maximum for self-compacting concrete in all the three grades (30MPa, 50MPa and 70 MPa). There is a good increase in the split and flexural strengths due to the fibres bridging the crack propagation resulting in increased ultimate load carrying capacity of the specimens.
2. The compressive strength increased by 4.9% whereas, split tensile by 15.44% and flexural strength by 22.3% for normal strength concrete (30 MPa) with the use of maximum dosage of steel fibers (i.e. 0.5% by volume of concrete).
3. In case of standard grade SCC (50 MPa) due to addition of maximum dosage of steel fibers(0.5% volume of concrete), the compressive strength increased by 2.63%, split tensile strength by 20.8% and flexural strength by 14.5%.
4. Similarly, in case of high strength SCC (70 MPa) due to addition of steel fibers, the compressive strength increased by 6.51%,split tensile strength increased by 12% and flexural strength by 21.67% with 0.5% dosage of steel fibers.

5. Due to addition of steel fibers, the ultimate shear strength increased by 36.8% and 15% in SCC30 and SCC70 respectively compared to plain beams. The failure mode changed from a sudden brittle failure to a ductile flexural type failure. This is true for both the stirrup diameters (6mm and 8mm).
6. Due to the combined effect of stirrups and steel fibers, the ultimate shear strength increased by 89.34% and 80.65% in SCC30 and SCC70 respectively compared to plain beams for beam with a/d=2 at 180 mm spacing.
7. With increase in the shear span to depth (a/d) ratio, the ultimate shear strength reduced by 5.2% and 22.54% for SCC30 for a/d =2.5 and 3 when compared with a/d=2. Similarly, in case of SCC70, it is reduced by 19.59% and 22.44% respectively. This behaviour was true in case of both fibrous and non-fibrous concrete beams with 8mm stirrup.
8. With increase in the area of shear reinforcement, the ultimate shear strength increased by 18.7% and 51.09% for SCC30-180 and SCC70-180. Similarly, the shear strength decreased with increase in the spacing of stirrups. It was also noticed that with the use of steel fiber reduction in area of stirrup was possible. Similar behaviour was observed in case of beams tested for shear span to depth ratio 2.5 and 3 also.
9. As the shear span to depth (a/d) ratio increased, crack angle (θ) has reduced and this is true for both grades SCC30 and SCC70. The Theoretical Shear Strength for NASCC is given by:
   - $\mathbf{V_u = V_{uc} + V_{us}}$
   - $\mathbf{V_u = \left\{\frac{d}{Sin\theta} * b * F_t * Cos\theta\right\} + \left\{\frac{0.87 * f_y * A_{sv}}{Cos\theta}\right\} * k_1}$; Where F_t = Split tensile strength of NASCC or NASFRSCC and θ = 50.459 - 3.2802(a/d).

   $k_1 = 0$, when crack does not cross the stirrup and $k_1 = 1$ **,** when crack crosses the stirrup
10. The Analytical shear strength predicted based on Non-linear Regression analysis for NASCC is given by:
   - **Vu = (0.3*f_{ck})+(0.016*A_{sv})-(0.001*S_v)-(0.038*A_{st})-(0.712*a/d) + (0.8*V_f)**

Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5)

11. With the use of recycled aggregates, the compressive strength decreased by 7.8% and 8% respectively for 30MPa and 70 MPa concrete.
12. The ultimate shear strength decreased by 12% and 10.2% in case of plain SCC beams with use of recycled aggregates. Similarly, in case of fibrous SCC beams the ultimate shear strength reduced by 2.36% and 6.98% respectively for standard (30 MPa) and high strength (70 MPa) SCC with respect to plain NA beams.
13. Due to addition of steel fibers in RASCC beams, the shear strength increased by 2.3% for 30 MPa and 1.2% for 70 MPa concrete, compared to plain NASCC beams.
14. The predicted theoretical shear strength for RASCC is given by:
    - ❖ $\mathbf{V_u = V_{uc} + V_{us}}$;
    - ❖ $\mathbf{V_u} = \left\{\frac{\mathbf{d}}{\mathbf{Sin\theta}} * \mathbf{b} * \mathbf{F_t} * \mathbf{Cos\theta}\right\} + \left\{\frac{\mathbf{0.87 * f_y * A_{sv}}}{\mathbf{Cos\theta}}\right\} * \mathbf{k_2}$; Where F_t = Split tensile strength of RASCC or RASFRSCC and θ = 50.459 - 3.2838(a/d).

    $k_2 = 0$, when crack does not cross the stirrup and $k_2 = 1$ **,** when crack crosses the stirrup
15. The analytical shear strength predicted based on Non-linear Regression analysis for RASCC is given by
    - ❖ **V_u = (0.35*f_{ck}) + (0.014*A_{sv})-(0.001*S_v)-(0.04*A_{st})-(0.73*a/d) + (0.24*V_f)**

    Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of Shear reinforcement, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5).
16. The Numerical results obtained compared well with those of the experimental results and the values are within 85-90% limits.
17. A correlation among experimental deflections and the deflections obtained though ATENA modelling are close to each other, with a percentage variation less than 15%.
18. A comparison of Numerical shear strength obtained based on ATENA modelling with the predicted theoretical shear strength was found to be satisfactory.

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ABBEREVATIONS

SCC	:	Self - compacting concrete
NC	:	Normal concrete
FA	:	Fine aggregate
CA	:	Coarse aggregate
SP	:	Super plasticizer
SF	:	Steel fibers
RC	:	Reinforced concrete
RAC	:	Recycled aggregate concrete
ITZ	:	Interfacial transition zone
RFA	:	Recycled fine aggregate
RCA	:	Recycled coarse aggregate
FRC	:	Fiber reinforced concrete
NASCC	:	Natural aggregate based Self-compacting concrete
RASCC	:	Recycled aggregate based self-compacting concrete
SFRSCC	:	Steel fiber reinforced Self-compacting concrete
RASFRSCC	:	Recycled aggregate based steel fiber reinforced self-compacting concrete

NOTATIONS

F_{ck}	:	Compressive strength
F_t	:	Split- Tensile strength
Ø	:	Diameter of the bar
S_v	:	Stirrup spacing
a/d	:	Shear span to depth ratio
V_f	:	Volume of fibers
A_{st}	:	Area of tensile reinforcement
A_{sv}	:	Area of shear reinforcement
F_y	:	Yield strength
V_u	:	Shear force
V_{uc}	:	Shear force of uncracked concrete
V_{us}	:	Shear force taken by vertical stirrup
ϴ	:	Crack angle

CHAPTER 1
INTRODUCTION

1.0 General:

Overcrowded arrangement of rebars in reinforcement concrete (RC) members, such as beams, column and slabs, is 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 **[Broomfield 2003].**

Conventional concretes used in construction and civil engineering applications requires compaction to attain required compressive strength there by increase the life of the structure. The traditional method of vibration and compaction creates costs and also generates lots of sound pollution and in turn serious health hazard in and around construction sites. To overcome these difficulties **Hajime 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).

Self-Compacting Concrete (SCC) as the name itself indicates, 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 a Reinforced Concrete (RC) beams arise when the principal tensile stress of concrete exceeds the tensile strength of concrete within the shear span causing a shear failure **[Narayanan et al, 1987]**. As we know that shear failure is sudden and brittle arise without any prior waring. To overcome these type of failures beams are reinforced with stirrups at appropriate spacing based on design.

Shear is the one of the important criteria in limit state of collapse. The exact analysis of shear in reinforced beams is quite complex. For instance the shear of reinforced concrete beam without stirrups is resisted by uncracked concrete in compression region, aggregate interlocking force and shear acting steel bars. The shear behaviour of reinforced concrete beams not only depend on shear reinforcement but also on grade of concrete, percentage of longitudinal reinforcement and shear span to depth ratio(a/d). 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.

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].** Addition of steel fibers increases the shear capacity of concrete and moreover it can partially replace the lateral ties (stirrups) in RC structural members. This relieves reinforcement congestion at critical sections such as beam–column junctions **[Kwak et al, 2002]** and **[Ding et al, 2011]** and if sufficient amount of steel fibers are added a brittle shear failure can be modified to a ductile behavior, also with reduced crack widths **[Kim et al, 2012].**

The property of self-compactability in SCC can be achieved by using higher powder content and by reducing the coarse aggregate content. By limiting the size of the aggregate content, the inter particle friction between aggregates is minimized which helps in increasing the flow ability of SCC **[Okamura, H. and Ozawa, K., 1995]**. In self-compacting concrete, 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 shear behaviour of SFRSCC, is still limited.

1.1 Self Compacting Concrete:

Self-Compacting Concrete is a new generation high performance concrete was first developed in Japan to address the issue related to durability of concrete structures. As the name itself suggest that the concrete flows into every corner of formwork and compacts under its own weight without use of any external vibration by maintaining required consistency. The basic materials required for preparing SCC are similar to that of normal vibrated concrete. Only difference being the using of mineral admixtures such as Flyash, GGBS, and Silica fumes and also high range water reducing admixtures (Super Plasticizers). The binder content in SCC is relatively higher comparative to that of normal vibrated concrete, moreover to achieve self-compatibility the ratio of coarse aggregates to total volume of concrete is kept constant at 50% whereas fine aggregates to total mortar volume is 40% . SCC can be used due to numerous advantages, they are:

- ✓ Faster construction process with improved quality,
- ✓ Reduction in manpower,
- ✓ Ability to flow in dense reinforcement,
- ✓ Improvement in structural integrity,
- ✓ Reduction in noise levels,
- ✓ Enhancement in strength and durability performance,
- ✓ Adequate bond between concrete and reinforcing steel,
- ✓ Thinner concrete members can be cast easily.

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.

Self-compacting concrete in its fresh sate has satisfy some of the fresh properties as per EFNARC specification i.e. Flowability, Passing ability, Filling ability and Segregation resistance. Slump flow values describes the flowability of fresh SCC and is the primary test to check the consistency of SCC. Measurement of $T_{50\ cm}$ time and visual observations can give additional information regarding segregation resistance. Viscosity of SCC can be achieved by performing V-funnel test and segregation resistance can be known by allowing the concrete to settle in the V-funnel for 5 mins (V-funnel at T_{5mins}) the time lapse between V-funnel time and V-funnel at T_{5mins} should not be more than 0-3mins. If the time is more than 3 minutes, then concrete is subjected to segregation. Passing ability of SCC is ability of fresh mix to pass to narrow and congested reinforcement. The passing ability of SCC can be performed using J-ring and L-box test. **[EFNARC 2005]**

SCC has wide spread usage in precast industry, building, tunnel constructions, and mass concreting where heat of hydration is very high and also in earth retaining structures.

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 inherit 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 described 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 **Fig.1.1.**

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 less active under compressive loading. [**Arnon Bentur and Sidney Mindess, 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 disturbed 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 discontinues fibers **[Kishor S. Sable et al 2012].**

Addition of steel fibers in self-compacting concrete (SCC) combines of 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 with influence the performance of fiber reinforced concrete (FRC) will affect the fresh properties of SCC **[Abbas almin, 2013].**

1.3 Shear Behaviour of Fiber Reinforced Concrete:

Shear is the one of important criteria in the limit sate of collapse. The exact analysis of shear in reinforced concrete design is extremely difficult. Shear in RC beams without stirrups is resisted by uncracked concrete in compression, the aggregate interlocking force and longitudinal tensile reinforcement. The shear behaviour of RC beam not only depended up on shear reinforcement (stirrups) but also, on compressive strength of concrete (f_{ck}), longitudinal tensile reinforcement (s_t), shear span to depth ratio (a/d) and spacing of shear reinforcement (s_v).

1.3.1 Modes of failure in reinforced concrete (RC) beam:

Reinforced Concrete (RC) beam of normal composition are subjected to relatively higher flexural stresses and low shear stresses. The maximum principle stresses are governed by the flexural stress in the outermost fiber (bottom of the beam) at the peak moment locations, the subsequent cracks are labelled as flexural cracks as shown in **Fig.1.2 (a**). These cracks are controlled by tension reinforcement. Further, in short span beams which are reasonably deep having thin web are subjected to higher shear stresses and fairly lower flexural stresses, with the maximum principle stresses are located near the neutral axis with an inclination $\alpha=45^o$ to the longitudinal axis of the beam. These cracks are termed as web shear cracks or diagonal tensile cracks (which commonly take place near the supports of the beams where shear force is dominant) as shown in **Fig.1.2 (b)**.

The tensile strength of the concrete in a RC beam subjected to flexural stresses will not be as much as that of uniaxial tensile strength of concrete. Usually, diagonal cracks in a RC beam can occur when required amount of shear reinforced is not provided. To avoid these types of cracks, beams are reinforced with stirrups at appropriate spacing based on design. The corresponding cracks formed due to combination of flexural and shear are termed as flexural-shear cracks as shown in **Fig. 1.2(c)**. When this type of situation arise, the flexural crack form first and due to enlargement of shear stresses at the tip of the crack, these flexural cracks spread in to diagonal tensile cracks. Such cracks are termed as secondary cracks or splitting cracks as shown in **Fig.1.2 (d)**. These cracks are attributed to wedging action of tensile bar to the transverse dowel force (dowel action) **Fig.1.2 (e).**

1.3.2 Shear Transfer mechanism in RC beam:

There are numerous ways by which shear is transferred between two adjacent plane in a RC beam. Noticeable among these are analysed from free body diagram of a section divided by flexural crack as shown in Fig. 1.3

The transverse (external) shear force is designated as V (is maximum near supports). It is resisted by various forces acting on crack surface, they are:

1. Shear resistance (V_c) by uncracked concrete in compression
2. Vertical component of shear interface (V_a)
3. Dowel force due to dowel action (V_d)
4. Shear resistance carried by the transverse reinforcement (V_s)

The equilibrium of vertical forces from **Fig. 1.3**, results in the relation:

$$\mathbf{V = V_c + V_a + V_s + V_d} \text{ ----------------------------- } \mathbf{Eq\ (1.1)}$$

If fiber are added the same equation is modified as

$$\mathbf{V = V_c + V_a + V_s + V_d + V_f} \text{ ----------------------------- } \mathbf{Eq\ (1.2)}$$

1.4 Recycled aggregate concrete:

Over the years, concrete is one of the preferred and promising material among civil and structural engineers around the globe. It was chosen for its better performance, longer life and low maintenance cost. For achieving rapid urbanization, every small structures are demolished and newer bigger ones are constructed. These demolished materials of which majority is concrete are often dumped in to landfills which creates huge amount of land and environmental pollution. Similarly, due to depletion of natural resources such as natural coarse and fine aggregates, scientist and engineers around the world are looking at sustainable and reusable materials in concrete. One such material is recycled aggregate concrete [J D Brito et al, 2012]. The use of recycled concrete aggregates as a replacement of natural aggregates is well established fact, but still it is considered as inferior compared to normal aggregates in terms of its structural properties [Katkhuda et al, 2017].

Recycled aggregates are obtained by crushing old concrete and then the coarse portion of crushed aggregates is used as partial or full replacement of natural coarse aggregates and the remaining finer portion is used as replacement of natural fine aggregates in concrete making process.

Some of the advantages of using recycled concrete aggregate are:

- ✓ Reduces the use of normal aggregates hence reduces the excavation natural resources.

- ✓ By using recycled aggregates, significant reduction in construction cost can be achieved.
- ✓ Use of RCA conserves the landfills and protects from land and environmental pollution.
- ✓ Crates more employment opportunities in recycling industry.

Limitation of using Recycled concrete aggregates.

- ✓ Recycled aggregates have high water absorption capacity,
- ✓ Use of recycled aggregates as replacement of normal aggregates can reduce the compressive strength by 10-20%.
- ✓ There are no standard guideline and specifications on use of recycled aggregates in concrete.

1.4.1 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). Moreover, the major constituent of construction and demolishing process is concrete. The waste produced from construction and demolishing process is getting accumulated as landfills. 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.

1.4.2 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. From the literature it is established that by way of using 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, its uses are still limited.

There is considerable amount of work available in the literature on the use of recycled aggregates as partial replacement up of normal aggregates up to 50 %. In the present context, natural aggregates (both coarse and fine) are completely replaced (100% replacement) with recycled aggregates in SCC. The shear 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 liner 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 date for analysis, and it also used for defining, preparing and visualizing all the input data for numerical simulation.

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 Concluding remarks:

Use of SCC has numerous advantages as the name itself suggest that it does not require any external compaction, it compact under its own weight. Usage of steel fiber 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. Steel fiber can also partially replace shear reinforcement (stirrup) there by reducing the congestion of reinforcement in critical section such as beam column joints. 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 also sustainable way of constriction. Finite element modeling using ATENA- GID software helps in understanding the behaviour of reinforced concrete (RC) beam, such as concrete cracking, yielding of reinforcement and also supports in analyzing the behaviour of fiber reinforce concrete beams.

A thorough literature review was planned to understand the behaviour of reinforced concrete especially in shear and furthermore the influence of steel fiber on shear 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 shear behaviour of reinforced concrete is also planned in the present study.

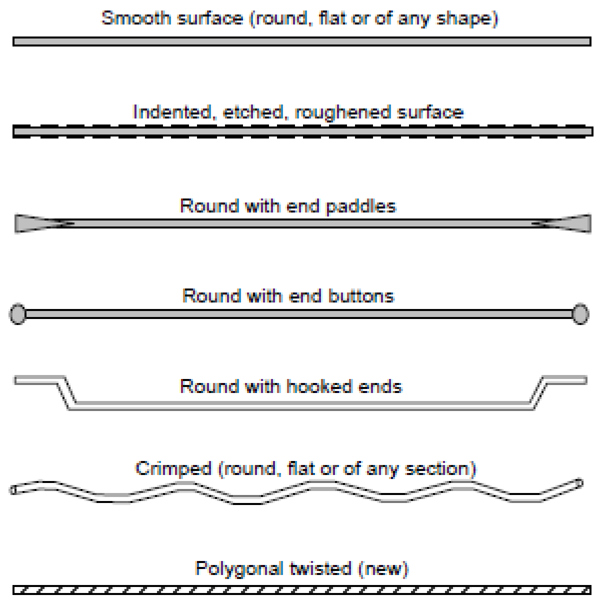
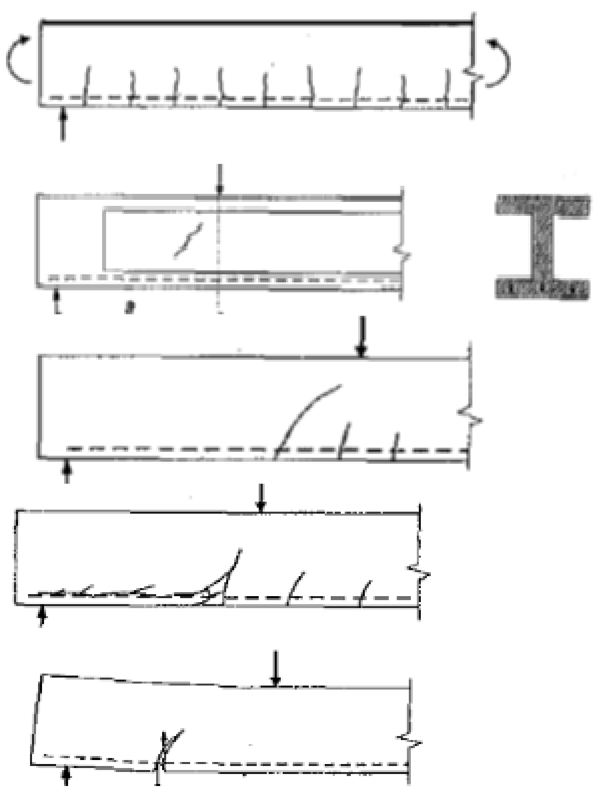


Fig.1.1 Commonly available deformed steel fiber.



(a) Flexural Cracks

(b) Web Shear Cracks or Diagonal tensile cracks

(c) Flexural – shear cracks

(d) Secondary or splitting cracks

e) Dowel Forces in bar

Fig. 1.2 Modes of Failure of a RC beam

[S. Unnikrishna Pillai and Devdas Menon, 2003]

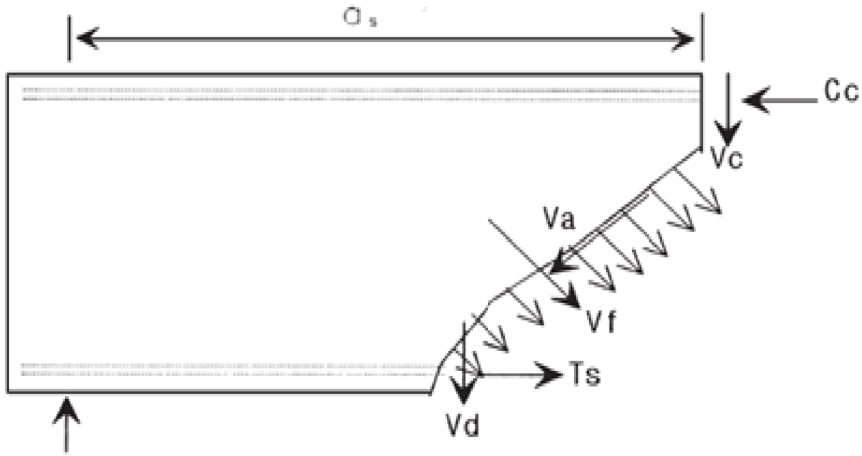


Fig.1.3 Internal forces acting at a flexural shear-crack

CHAPTER 2

LITERATURE REVIEW

2.0 General

In order to understand the role of steel fibers on strength and shear behaviour of SCC, and moreover to recognize the effect of recycled concrete aggregates on strength properties of SCC, a thorough literature review is planned in the present chapter. Similarly, to acquire an in-depth awareness of various software package available on the modelling of fibrous concrete in visualization of cracking, yielding of reinforcement 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.

Self-compacting concrete is considered as a concrete which can be placed and compacted on its own weight without any means of external effort and at the same time it should remain cohesive enough to resist segregation and bleeding. Self-compacting concrete was first announced in Japan to overcome the problems associated with compacting in congested reinforcement and to achieve durable concrete. **Hajime Okamura in the year 1989** proposed a new type of concrete which can settle in to each corner of form work simply by its own weight. He had fixed the ratio of coarse aggregate as 50% of total volume of concrete and fine aggregates as 40% of mortar volume so that self compactability can be achieved by means of varying the water to binder ratio and super plasticizer dosage only. After Okamura started his investigation in 1989, other researcher have started to work on this new type of concrete.

Ozawa etal [1995] has carried out work on self-compacting concrete. He was the first to succeed in achieving the Selfcompating concrete. By using the locally available materials he has proposed first prototype on SCC. By using different super plasticizers he examined the workability of concrete and developed the concrete which was super workable and later it was named as Selfcompating concrete. Also he varied the dosage of mineral admixture (flyash and blast furnace slag) and studied the workability of SCC. After trying for different mix proportions, he concluded that 10-20% of flyash and 25-45% of GGBS by mass has shown better results pertaining to flowability and segregation resistance of SCC.

Kuroiwa [1993] 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.

Nansu et al [2001] suggested a simple mix design methodology for self-compacting concrete. In this mix design, a step by step procedure was proposed to design SCC. The first step is to determine the amount of coarse aggregate required and second is find the amount of binder content required. This paste binder content is then filled in to the voids of the aggregates to ensure that the concrete thus obtained has flowability, self compactability and other desired properties. This method was also involved in determining the aggregate Packing Factor (PF) which influenced the strength, flow ability and Self-compatibility ability of concrete.

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.

Rao, et.al [2010], developed standard and high strength self-compacting concrete 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 10mm and 31 % fly ash is optimal for high strength SCC.

Rao, et.al [2013] their infestation 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 significate change in mix proportions with respect to packing factor, size of aggregates, fine aggregates to total aggregate ratio, cement content , flyash content and water content on SCC. A simplified and direct mix deign method was proposed by modifying the Nansu method of mix deign. This rational mix deign method can be adopted to design any grade of self-compacting concrete with minimum number of trails.

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.

Ramamurthy and Gumaste [1998], in their research work they have 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. From the experimental results it was noticed that compressive strength of recycled aggregate concrete is relatively lower compared with normal concrete. They have also found that the strength of the parent concrete is main governing factor in deciding the strength properties of recycled aggregate concrete.

Limbachiya and Leelawat [2000] in their experimental studies they found that recycled aggregates possess 7 to 9% lower relative density and 2 to 3 time higher 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.

Poon CS et al [2001] from their experimental results they reported that there is no much effect on compressive strength of concretes made from recycled aggregates up to a replacement of 20% to 30% of coarse aggregates with recycled coarse aggregates. They have also found that with the replacement of normal aggregates by recycled aggregates beyond 30% there is reduction in compressive strength of that concrete.

Chakarborty and Gupta [2002] have also found that there is not much decrease in compressive strength in concrete made with recycled aggregates up to a replacement of 30% with normal aggregates. As the replacement of recycled aggregates is beyond 30% the compressive strength of concrete is decreased. They also concluded that the strength characteristics of recycled aggregate concrete are slightly inferior compared with normal concrete.

Kumar et al [2001] in their experimental research work, they have used construction demolished waste as partial replacement of coarse aggregate. 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 and also to enhance the strength and durability of hardened 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%.

Vivian W Y Tam 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 they examined the effect of recycled aggregates on four different compressive strengths via 20 MPa, 30Mpa, 40MPa 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 any use of recycled aggregates.

Khaldoun Rahal [2007], has carried out the experimental work on replacing the normal aggregates with recycled aggregates and studied the strength properties of recycled aggregate concrete. A total of 10 mixes of concrete were prepared with target compressive strength ranging from 20 MPa to 50 MPa for both normal and recycled aggregate concretes. It was found that the target compressive strength was achieved for all the mixes except for 40 to 50 MPa strength concretes. The cub and cylindrical compressive strength of RCA was about 90 % of NAC for similar mix proportions.

Prasad and Kumar [2007] in their research work they used the construction demolished waste (CDW) as replacement of both fine and coarse aggregates. They have replaced the normal aggregates by 0%, 50% and 100 % with recycled aggregates. They used glass fibers to overcome the brittleness in concrete by usage of recycled aggregates. The studies have concluded that RCA can be used as complete replacement of normal aggregates and it was confirmed that recycled aggregates are no way substandard to normal aggregates in concrete. The addition of glass fibers not only enhanced the compressive strength of RCA but also it has increased the split tensile, flexural strength and modulus of elasticity of RCA.

Oliveria et al [2009] carried out the research work on partial replacement of natural coarse aggregates with recycled aggregates. Their study revealed that the replacement of normal coarse aggregates up to 40 % gave better results. They also proven that the performance of recycled aggregates depends upon water absorption and specific gravity.

J De 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 RA 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 M 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 RA with NA 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.

Lima et al [2013], studied the behaviour of recycled aggregate concrete. In their study they have replaced the normal coarse aggregates with recycled aggregates by 30%, 60 % and 100% percentage by weight. The experiments were carried out on 12 different mixes made with recycled aggregates. In their work they also replaced cement partially with flyash. The results have shown that as the percentage replacement of recycled aggregates are increased, the compressive and split tensile strength of recycled aggregates have reduced. Similarly, with increase in percentage replacement of recycled of aggregates, there was increase in water absorption and permeability of recycled aggregate concrete and thereby recycled aggregate concrete is prone to chloride ion penetration and finally resulted in reduced durability characteristics.

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.

Rui Vasco 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.

2.3 Literature review on Recycled aggregate based Self-compacting concrete.

Kou and Poon [2009], carried out the research work on effect of recycled aggregate on self-compacting concrete. In their study, normal coarse aggregates was completely replaced with recycled aggregates and examined the fresh and hardened properties of self-compacting concrete. 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 Jure Grdic 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 self-compacting concrete 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 Nanthagoplan and Manu Santhanam [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 (20-60MPa) compressive strength concrete can be achieved by using M-sand. The results also proven that M-sand can be used in producing SCC.

Panda and Bal [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 RA with NA.

The study also suggested that the 30% replacement of natural coarse aggregates with recycled concrete aggregates produces better results.

Pereira de 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 (SCC). The results have also proven that the permeability of SCC with RCA didn't effect much when compared with SCC with natural coarse aggregates.

Manzi et al [2013], studied the effect of complete (100%) replacement of both natural coarse and fine aggregates with recycled coarse and fine aggregates on fresh and hardened properties of SCC. The main aim of their study is to obtain SCC of medium to high compressive strength using complete replacement of both natural fine and coarse aggregates with recycled fine and coarse aggregate. The basic mechanical properties were carried out on SCC using recycled aggregate performed reasonably well when compared with conventional concrete and SCC without recycled aggregates.

Erhan Guneyisi et al [2014], carried out the research work on SCC using recycled aggregate with surface treatment before using them in concrete. The recycled aggregates were presoaked in HCl solution for 24 hours at 20º C temperature. By presoaking the recycled aggregates the in HCl solution it was found that the adhered cement mortar present on the surface of recycled coarse aggregates was lost, which in turn helps in enhancing the strength properties of SCC. The experimental results revealed that properties RCA such as density and water absorption gave improved when compared with untreated RCA.

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 X. H. 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%. The experimental results showed that compressive and split tensile strengths decreases as the percentage replacement of recycled aggregate 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.

2.4 Literature on review steel fiber reinforced SCC

Buquan Miao et al [2003], carried out the research work on mix design and mechanical properties of steel fiber reinforced self-compacting concrete. Three different dosage of steel fibers via 0.5%, 1% and 1.5% by volume of concrete was varied and mechanical properties like compressive, split tensile and flexural strength were studied on SFRSCC. By using superplasticizers and mineral admixtures such as flyash and GGBS, fresh properties were satisfied without any bleeding and segregation. From the experimental results it was proven that as the dosage of steel fiber increased there was drastic decrease in the flow properties of SCC. From the experimental results it shows that with increasing steel fiber content could improve the flexural strength and toughness of self-compacting SFRC even though its compressive strength reduced due to the increase of air content in SFRSCC.

Mustafa Sahmaran et al [2005], carried the work on hybrid fiber reinforced self-compacting concrete with Fly ash. The fresh and mechanical properties were evaluated by incorporating steel fibers along with High Volume Fly Ash (HVFA). High range water reducing admixture and viscosity modifying admixture were used to achieve the fresh properties of SCC. In the SCC mixes cement was replaced by 50% with flyash. Two different type of steel fiber with aspect ratio 30 and 55 hookend and straight end were used in combination and maintaining total fiber content at 60 kg/m^3. Fresh properties such as slump flow, V- funnel, J-ring and L-box tests were performed. Compressive, split tensile and ultra-sonic pulse velocity test were performed on the hardened concrete. From the experimental result it was concluded that the fiber geometry effects the SCC properties in fresh and hardened state.

Ponikiewski et al [2011], studied the effect of steel fibers on self-compacting concrete 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.

Abbas Al- Ameeri et al [2013] studied the fresh and hardened properties of SCC with steel fibers. The results of the investigation revealed that all the mixes are satisfying the SCC requirements. The mechanical properties such as split tensile and flexural strength of SCC increased with increase in the dosage of steel fibers, whereas compressive strength and modulus of elasticity increased moderately. Ultrasonic pulse velocity was decreased in SCC in the presence of steel fibers.

2.5 Review of literature on shear behaviour of fiber reinforced concrete.

There is significantly respectable amount of literature available on use of steel fibers to study the behaviour of reinforced concrete in shear. **Narayana and Darwish** in the year 1989 studied the shear behaviour of deep beams by using steel fibers. The parameters varied in the study are fiber volume fraction, aspect ratio of the fibers, shear span to depth ratio (a/d) and concrete compressive strength. A total of twelve beams were cast and tested without using any web reinforcement (stirrups). From the experiential results proposed a model to predict the shear strength of fiber reinforce concrete and also concluded from the experimental results that steel fibers can be used as partial shear reinforcement.

Lim and Oh [1999], carried out the research work on shear behaviour of steel fiber reinforced concrete. A total of nine beams were cast and tested to study the influence of steel fibers on shear behaviour of reinforced concrete and evaluated the mechanical properties of steel fibers reinforced concrete. The parameters varied in their study are fiber volume fraction and stirrups ratio. From the experimental results it was concluded that first crack shear strength increased significantly as the dosage of steel fibers increased and also there is marginal improvement in the ultimate shear strength. The combination of stirrups and steel fibers increased the mechanical behaviour of SCC. From the theoretical studies an analytical model to predict the shear strength of fiber reinforced concrete was proposed and also validated with some experimental results.

Madan et al [2007], studied the shear behaviour of RC deep beams using steel fibers**.** The parameters varied in the study are fiber volume fraction and shear span to depth ratio. Three dosage of steel fibers were considered in their study via 0% (plain beam), 0.5 %, 1% and 1.5 % and similarly three shear span to depth ratios 0.75, 1 and 1.25 were considered. A total of 18 beams were cast and tested. The experimental results have shown that addition of steel fiber have substantial improvement on shear strength of reinforced beams (RC). It was also observed that shear strength was decreased as shear span to depth ratio increased and noticed that steel fibers can partly replace web reinforcement (stirrups).

Dinh, H.H et al. [2009], studied the effect of steel fiber on reinforced concrete beams without any shear reinforcement in shear portion. The possibility of using steel fibers as minimum shear reinforcement was evaluated. A total of 28 beams were cast and tested. The target compressive strength of concrete used in the study was 40 MPa. The parameters varied are fiber volume fraction, fiber aspect ratio, and longitudinal reinforcement ratio. From the experimental test results it was revealed that as the dosage of steel fibers increased there is considerable increase in the shear strength of fiber reinforced concrete. It was also found from the experimental results that hooked steel fiber performed better when compared with straight end steel fibers and also established steel fibres can be used as minimum shear reinforcement.

Shah D.L. and Modhera C.D. [2010], evaluated the shear strength of SCC deep beams for both without and with steel fibers for various shear span to depth ratios. The grade of concrete was M30 which was achieved by conducing various trails. The obtained results were compared with empirical formulas provided in ACI 318-14 code and Tie- Strut model. From the experimental results it was revealed that diagonal cracks became more prominent as the depth of the beam increased, also inclusion of steel fibers in concrete deep beams improved the crack and deformation characteristics. The results also suggested that shear span to depth ratio has considerable influence on the ultimate shear strength. Due to the presence of steel fibers, the crack pattern of the RC beams has changed from brittle failure mode to ductile mode. The empirical formulas provided in codes are more conservative, while Strut and Tie Model of ACI 318-14 predicted fairly satisfactory results.

Yining Ding et al [2011], studied the combined effect of stirrups and steel fibers on the hear behaviour of self-compacting concrete (SCC). In this research work, varied parameters are the dosage of steel fibers and stirrup ratio and studied the shear behaviour of SCC. From the experimental results it was observed that shear strength was increased substantially with increase in dosage of steel fibers. It was also noticed that the failure mode of SFRSCC beams changed due to adequate percentage of steel fibers. It was also demonstrated that steel fibers can partly substitute stirrups. The shear strength noted experimentally was compared with various formulas available in the literature and the correlation was satisfactory.

Emma Slater et al [2012], studied the shear behaviour of steel fiber reinforced self-compacting concrete. From the existing experimental results available on shear behaviour of self-compacting concrete, an empirical formula to predict the shear strength of steel fiber reinforced SCC was proposed. From the large date of experimental results of 222 beams were grouped in to six sub groups based on shear span (a/d) ratio, grade of concrete, type of steel fibers i.e. hooked and crimped. The proposed empirical formula was based on linear and non-linear regression analysis and statistical analysis was performed to compare the proposed equation with the already available models in the literature.

Kang Su Kim et al [2012], experimental work on the effect of steel fiber on shear behaviour of self-compacting concrete without using any transverse reinforcement (stirrups) was done. They have proposed an empirical formula to predict shear strength of SFRSCC without any web reinforcement. The proposed equation was certified with experimental results available in the literature on steel fiber reinforced beams and panels. The proposed empirical equation was in well agreement with experimental results.

Hwang et al [2013], studied the shear behaviour of self-compacting concrete by incorporating steel fibers and have suggested an empirical formula to predict shear strength of self-compacting concrete by modifying the softened truss model. In their study have considered steel fibers as individual reinforcing material and fibers are distributed randomly based on fiber volume fraction. To validate the proposed empirical formula, they have collected data from the literature of the beams failed in shear whose shear span to depth ratio is less than 2.5. A total of 85 beams specimens failure details were collected from the literature for validation of the proposed empirical formula. The proposed formula based on modified softened truss model shows a good level of accurateness on the shear strength of SFRC beams and the validation of proposed empirical equation was is good agreement with existing empirical equations collected from previous studies.

Sahoo and Sharma [2014], carried out the research work on the combined effect of stirrups and steel fibers on shear behaviour of SCC beam for both with and without stirrups. A total of 12 shear deficient beams were designed, cast and tested until failure. In their experimental work they have studied the shear and flexural strengths, failure mechanisms and ductility responses of SFRSCC beams. The various constraints considered in their study are grade of concrete, shear span to depth ratio, percentage of longitudinal tensile reinforcement and fiber volume fraction. The fiber dosages are 0%, 0.5%, 1% and 1.5%. From the experimental result it was found that minimum 0.5% of steel fibers is required to partially replace stirrups.

Cuenca et al [2015], studied the influence of concrete matrix and type of fiber on the shear behaviour of fiber reinforced self-compacting concrete. In their experimental study they studied the behaviour of 12 SFRSCC I-section beams. They have maintained similar geometry of fiber and also the dosage is kept constant at 50 kg/m^3. The parameters varied in their study are concrete compressive strength and type of steel fiber. From the experimental results it was found that type of fiber significantly effects the shear behaviour of SFRSCC beams and even design codes also specified the same. They have also concluded that the combination of high strength concrete and lower strength steel fibers does not seems to be efficient.

Sahoo and Reddy [2016], experimentally studied the effect of shear span to depth ratio on the ultimate shear resistance and failure modes of steel fiber reinforced concrete T-beams. In their study they varied the steel fiber from 0 to 1.5 % in 0.5 % interval. They have considered three shear span to depth ratio i.e. 1.6, 2.5 and 3 respectively. From the experimental results it was concluded that steel fiber reinforced concrete beams exhibited higher ultimate resistance, displacement ductility and flexural toughness as compared with RC beams without steel fiber and it remained same for all shear span to depth ratios (a/d). It was also witnessed from the experimental results that the failure mode of the beams with fibers changed from diagonal shear failure to ductile flexural model and the exhibited similar type of behaviour for all the a/d ratios.

Ali Amin and Foster [2016] done the research work on the combined effect of stirrups and steel fibers on behaviour of reinforced concrete beams subjected to four point loading. A total 10 beams were experimentally studied, by varying the steel fibers and transverse reinforcement (stirrups). From the experimental results it was concluded that steel fibers could substitute the transverse reinforcement stirrups as minimum shear reinforcement. They have also compared there experimental results with various exiting models available in the literature and the comparison was satisfactory and CEB-FIB [2010] model code was comparatively nearer to the experimental results.

Gali and Subramaniuam [2017], studied the influence of steel fibers of different volume fraction (0.5% and 0.75%) on shear behaviour of fiber reinforced concrete beams. The shear span to depth ratio was fixed at 1.8. In this study they have evaluated the cracking behaviour of RC beams using digital image correlation (DIC) technique. From the analysis of the beams it was noticed that full depth shear cracks were formed in the RC beams before the beam reached the peak load carrying capacity. It was also observed that with increase in the fiber dosage from 0.5 to 0.75%, there was an increased resistance to crack opening until peak load. It was also noticed from the experimental results that failure in shear in the RC beam occurs when crack opening control provided by flexural reinforcement and steel fibers is insufficient to sustain the aggregate interlock.

2.6 Literature review on Shear Behaviour of Recycled Aggregate based Reinforced Concrete:

The research work on the use of recycled aggregates as a replacement of natural aggregates is carried out by few researches in past few years. The literature available on the effect of replacement of natural aggregates with recycled aggregates in studying the shear behaviour is reasonably less. Some of the existing literature was discussed in the subsequent paragraphs.

Gonza and Fonteboa [2007], did research work on the effect of replacement of natural aggregates with recycled concrete aggregates on the behaviour of reinforced concrete beams under shear. Normal aggregates are replaced with recycled aggregates by up to 50%. The parameters varied in their work are compressive strength of concrete, percentage replacement of normal aggregates with recycled aggregates and also longitudinal reinforcement ratio. The stirrup spacing was varied in the shear span, three stirrup spacing were considered, (1) minimum shear reinforcement, (2) more than minimum shear reinforcement and 3) less than the minimum shear reinforcement. The dimension of the beams are 200mm wide, 350mm deep and effective length was 3000mm with shear span to depth ratio 3.3. Based on the experimental results it was concluded that the ultimate load carrying capacity of recycled aggregate beams are relatively higher compared with conventional concrete beams. From the experimental results an empirical formula to predict shear strength was proposed based on Modified Compression Field Theory (MCFT). The predicted shear strength vas are relatively closer to experimental results.

H B Choi et al [2010], the experimental research work was carried out on the behaviour of reinforced concrete beams by replacing natural aggregates with recycled concrete aggregates in shear. The various percentage replacements of natural aggregates with recycled aggregates considered in their study are 30%, 50% and 100%. Three shear span to depth ratios were considered are 1.5, 2.5 and 3. The effect of stirrups was not considered. The beams were designed, cast and tested without any shear reinforcement so as to ensure that beams are failed in shear only. A total of 20 beam were cast and tested. From the experimental results it was noticed that the ultimate shear strength was deceased as the percentage replacement of recycled concrete aggregates was increased.

Zahara et al [2011], did research on the effect of recycled concrete beams on the shear behaviour of RC beams. A total of 12 beams were cast and tested by replacing normal aggregates by 50% and 100% with recycled concrete aggregates. They have also varied the longitudinal reinforcement ratio by 0.3% and 0.5%. It was observed from the test results that the failure of the beam specimens without any shear reinforcement was sudden and brittle. In addition to that as the shear span to depth ratio increase, the ultimate shear strength was decreased. The ultimate shear strength was decreased as the percentage replacement of recycled aggregates was increased.

Do Yun et al [2011] studied the effect of recycled aggregates on the shear behaviour of reinforced concrete beam. The percentage replacements of recycled aggregates are 30%, 60% and 100%. It was concluded from their experimental results that due to use of recycled aggregates in place of natural aggregates, there is considerable amount of decrease in the ultimate shear strength and also, crack pattern of recycled concrete beams are relatively similar with normal concrete beams.

Adam and Kumara [2014], carried out the research work on the shear and flexural behaviour of RC beams with use of recycled aggregates as partial replacement of natural aggregates. Three percentage replacements of recycled aggregates via 0%, 50% and 100% are considered. Shear reinforcement (stirrups) was not provided, so to ensure that beams fail in shear only. The experimental results are compared with various international codes (ACI, Euro code) available in the literature, the comparison was satisfactory.

Hasan Kantdu et al [2016], experimental work done on the shear behaviour of recycled aggregate concrete beams. Recycled aggregate are treated by presoaking in HCl and H_2SO_4 acid solutions. By presoaking the recycled aggregates in acid solutions, the adhered mortar that is present on the surface of the recycled aggregates was removed which ensures perfect boning and also enhances the shear strength. All the beams were cast without using any shear reinforcement (stirrups). Normal coarse aggregates were replaced by 50% and 100% with recycled aggregates. Also studied the effect of untreated recycled aggregates on shear behaviour of RC beams. Two shear span to depth ratios were considered in their experimental work 2 and 3. The behaviour of the shear deficient beams were studied through load–deflection curves, ultimate shear responses and failure patterns. From the experimental results it was found that by using untreated recycled concrete aggregates, the shear strength values decreased considerably when compared with conventional concrete beams. While using treated recycled aggregate in beams have shown almost similar results when compared with that of normal aggregates concrete beams. The experimental shear strength values were compared with various international codes available in the literature and the correlation was reasonable good with experimental results.

Sara Khedr et al [2017], studied the shear behaviour of steel fiber reinforced recycled aggregate concrete beams by replacing natural aggregates with recycled concrete aggregates by 15%, 30% and 45 % respectively. The fiber volume fraction was varied by 1%, 1.5% and 2 % respectively. The size of the beams was fixed at 150mmx 300mmx 2000mm. All the beams were tested for shear span to depth ratio 2 under two point loading. In their study they, one side of the beam was not provided with any stirrups so as to confirm that the beam fail in shear and also to study the effect of steel fibers in improving the shear strength. The other side of the beam were provided with 8 mm diameter rods at 100 mm spacing. The target compressive strength of all the beam was 25 MPa. From the experimental result they have concluded with increase in percentage replacement of recycled aggregates the shear strength of the beams was decreased. The addition of fibers have improved the shear strength of and also changed the sudden diagonal shear failure of the beams.

Ivan Igavatonic et al [2017], studied the shear behaviour of recycled concrete aggregates beams without using any stirrups. A total of 9 full scaled beams were cast and tested until failure under four point loading. In their study they have considered three different replacement ratios of normal coarse aggregates with recycled aggregates(0%, 50 % and 100%) and also three different shear reinforcement ratios (0% 0.14% and 0.19%) were considered respectively. From the experimental results it was found that first crack shear strength of NAC and RAC beams were occurred at relatively same load. It was also found that the shear strength of RCA beams with 100% replacement was decreased by 15 % when compared with normal concrete beams.

2.7 Literature review on Analytical modeling of RC beams using finite element software in shear

Mehmet Ozcan et al [2009], carried out experimental and finite element analysis on the steel fiber-reinforced concrete beams. The finite element analysis was done using ANSYS v8.0 software. Four SFRC beams of size 250mm x 350mm x 2000mm wear cast and tested until failure with different steel fiber content of 30, 40, 50 and 60 kg/m^3. The longitudinal reinforcement consist of 2-12mm Ø+ 1-8mm dia bars and compression steel consist of 2-8mm Ø whereas 2 legged 8mm dia stirrups are used as shear reinforcement. In ANSYS concrete is modelled as eight-nodded solid brick elements whereas reinforcement is modeled by using 3D spar elements. The experimental results were compared with finite element model crated using ANSYS software and the comparison of finite element model with experimental is in good agreement.

Dahmani et al [2010], carried out the research work on nonlinear finite element analysis of RC beams using ANSYS v8.0 software. An eight node solid elements (SOLID 65) was used to model the concrete. The solid element had eight nodes with three degree of freedom at each node. The element was capable of plastic deformations, cracking in orthogonal directions and crushing. The reinforcing steel is simulated as spar elements and the geometric properties similar to original material. Input data of the materials such as modulus of elasticity, ultimate compressive, tensile strength, modulus of rupture, Poissons ratio and uniaxial stress –strain relationship of concrete are given before the analysis was performed. The model is capable of predicting the failure criteria of concrete. The analytical results were compared with theoretical values. The load applied at initial cracking was correlating the theoretical value.

Modeling of concrete using Finite Element Code ABAQUS was carried out by

Chaudhari and Chakrabarti [2012], in their work 3D model of a concrete cube is prepared using smeared crack model and concrete damage plasticity approach. A concrete cube of size 150 mm is modeled in ABAQUS v6.10 using C3D8 element. A steel plate of thickness 25 mm was placed on top and at the bottom of the cube to ensure the uniform distribution of the compressive load applied. The grade of concrete used was M30 with average compressive stress, σcu = 30 MPa, ultimate strain, ε_{cu} = 0.0035, and the strain at pick stress, ε'_0 = 0.002. From the results it was found that smeared cracked model gives desired results. The material model is validated with theoretical results.

Islam et al [2013], carried out the research work on finite element analysis of steel fiber reinforced concrete using ANSYS v10.0 with SOLID 65 element. The main of their research work is to investigate the shear capacity enhancement of three different types of beams. All the beams were tested in 1000kN universal testing machine and the strain data are taken from digital image correlation technique. The experimental results showed that shear capacity increase by 30% for SFRSC specimens. The finite element model created using ANSYS software is used to validate the experimental results. The finite element model has shown the similar the structural response and failure modes as that of experimental results.

Maher A. Adam et al [2016], carried out the research on shear behaviour of steel fiber reinforce self-compacting concrete deep beams**.** In their experimental work they have cast and tested 12 SFRSCCC beams until failure under four pint load bending test. The fiber content was varied as 0% (plain), 0.5%, 0.75% and 1 %. The dimensions of the beam adopted was 150mm wide x 450mm deep and 1250 mm in length. The shear span to depth ratio was varied from 0.6 to 1. Three different longitudinal reinforcement ratios (1, 1.6 and 2.20 was considered as variables in their study. From the experimental results was noted that that steel fiber enhanced the shear performance of SFRSCC beams by 40% with 1/% dosage of steel fibers. It was also observed that the ultimate shear capacity was increased by about 47% by increasing the longitudinal steel ratio from 1.0% to 2.2%. To validate the experimental results a nonlinear finite element was performed using ANYSY v10.0 software. The analysis of the tested beams was carried out in terms of crack pattern and load deflection behavior. From the comparison of experimental and numerical model was concluded experimental and numerical model are in good correlation with each other.

2.8 Concluding remarks:

From a detailed literature review on SCC, it was evident that SCC is new type of concrete that can be compacted 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, and also influence of steel fibers on SCC was studied. The literature available on the shear behaviour of steel fiber reinforced SCC is very limited. The studies on the shear behaviour of recycled aggregate based steel fiber reinforced SCC are very less.

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

CHAPTER 3
SCOPE AND OBJECTIVES OF INVESTIGATION

3.0 General

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

- Self-Compacting Concrete has numerous advantages including concreting in difficult environments and congested reinforcements. This type of special concrete has large scope in structural applications.
- From the detailed literature review it is evident that the use of steel fibers in self-compacting concrete not only improves the load carrying capacity but also changes the failure pattern from brittle behaviour to ductile mode.
- Effect of steel fibers on shear behaviour of Self-compacting concrete can be studied.
- Recycled aggregates can be used as replacement of natural aggregates and can be used in self-compacting concrete for studying the shear behaviour.
- Effect of stirrup diameter and spacing of stirrups on shear behaviour of SFRSCC can be studied.
- Analytical modelling using finite element based software can be used in studying the shear behaviour of SFRSCC beams for both natural and recycled aggregates.
- Studies on shear behaviour of steel fibers are limited to normal concretes. Studies on Shear behaviour of SCC and SFRSCC is scant and the available models in the literature on vibrated concretes needs to be checked for SCC based on experimental work.

3.1 Scope and Objectives of the Investigation

The scope of the present investigation includes:

- Evaluation of strength properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers (0%, 0.25%, 0.5%, 0.75% and 1% by volume of concrete) for three grades of SCC i.e. 30 MPa, 50 MPa and 70 MPa and thus maximize the dosage of steel fibers.

- ❖ Develop analytical model for predicting shear strength of natural aggregate based steel fiber reinforced self-compacting concrete (NASFRSCC).
- ❖ Develop analytical model for predicting shear strength of recycled aggregate based steel fiber reinforced self-compacting concrete (RASFRSCC).
- ❖ Numerical modelling of steel fiber reinforced self-compacting concrete using a finite element software ATENA for both NASCC and RASCC of 30 MPa and 70 MPa concrete strength and validate based on experimental results.

The following broad objectives have been formulated to study and validate the use of steel fibers in self-compacting concrete to evaluate the shear behaviour.

1. To evaluate the fresh and hardened properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers for three grades i.e. 30 MPa, 50 MPa and 70 MPa and maximize the dosage of steel fibers based on fresh and hardened properties.
2. To investigate the shear behaviour of steel fiber reinforced self-compacting concrete for 30 MPa (low strength concrete) and 70 MPa (high strength concrete) and propose an analytical model to predict the ultimate shear strength.
3. To investigate the shear behaviour of recycled aggregate based steel fiber reinforced self-compacting concrete for 30 MPa (low strength concrete) and 70 MPa (high strength concrete) and propose an analytical model to predict the ultimate shear strength.
4. To validate the proposed model with results obtained through finite element software ATENA for both NASFRSCC and RASFRSCC.

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.

Phase - I:

Studies on fresh and hardened properties of steel fiber reinforced self-compacting concrete for various dosages of steel fibers (0%, 0.25%, 0.5%, 0.75 % and 1% by volume of concrete) for three grades i.e. 30MPa, 50MPa and 70MPa and maximize the dosage of steel fibers based on fresh and hardened properties. The fresh properties include Slump flow test, V-funnel test, V-funnel at T_5 minutes and J-ring test. The mechanical properties include compressive strength, split tensile strength and flexural strength. Some pilot studies were conducted to investigate the shear behaviour of Vibrated Concrete (VC) and Self-Compacting Concrete (SCC).

Phase - II:

Studies on shear behaviour of natural aggregate based self-compacting concrete for three shear span depth ratios (a/d= 2, 2.5 and 3) with different stirrup diameter (6mm and 8mm) and spacing of stirrups for different strengths(30 MPa and 70 MPa) for both without and with steel fibers. An Analytical model is proposed to predict the ultimate shear strength of NASCC and correlate the experimental and predicted shear strength based on various models available in literature on vibrated concrete.

Phase - III:

Studies on shear behaviour of recycled aggregate based self-compacting concrete for three shear span depth ratios (a/d= 2, 2.5 and 3) with different stirrup diameter (6mm and 8mm) and spacing of stirrups for different strengths(30 MPa and 70 MPa) for both without and with steel fibers. An Analytical model is proposed to predict the ultimate shear strength of RASCC and correlate the experimental and predicted shear strength with the various models available in literature on vibrated concrete.

Phase - IV:

Numerical modelling of shear behaviour of steel fiber reinforced self-compacting concrete using Finite Element Software (ATENA) and validate the proposed model for NASCC and RASCC without and with steel fibers for 30 MPa and &70 MPa strength.

The parameters of investigation include

- Grade of concrete - SCC 30, 50 and 70 concretes for (preliminary study was conducted to maximize the dosage of steel fibers.)
- Dosage of steel fibers - 0%, 0.25%,0.5%,0.75% and 1 % by volume of concrete
- Strength of concrete - 30 MPa and 70 MPa (adopted for casting of beams)
- Type of aggregate - Natural aggregate and Recycled concrete aggregate

- Shear Span to depth ratio (a/d) - 2, 2.5 and 3
- Diameter of Stirrup (Ø) - 6 mm and 8 mm
- Spacing of stirrups (s_v) - $\mathbf{a}$, $\frac{\mathbf{a}}{\mathbf{2}}$ (where a is shear span)
- Dosage of steel fiber - 0% and 0.5%

A schematic diagram of the research methodology adopted along with the variables considered in each phase is shown in **Figure 3.1**.

A detailed experimental program keeping these parameters in mind is planned and explained in chapter4

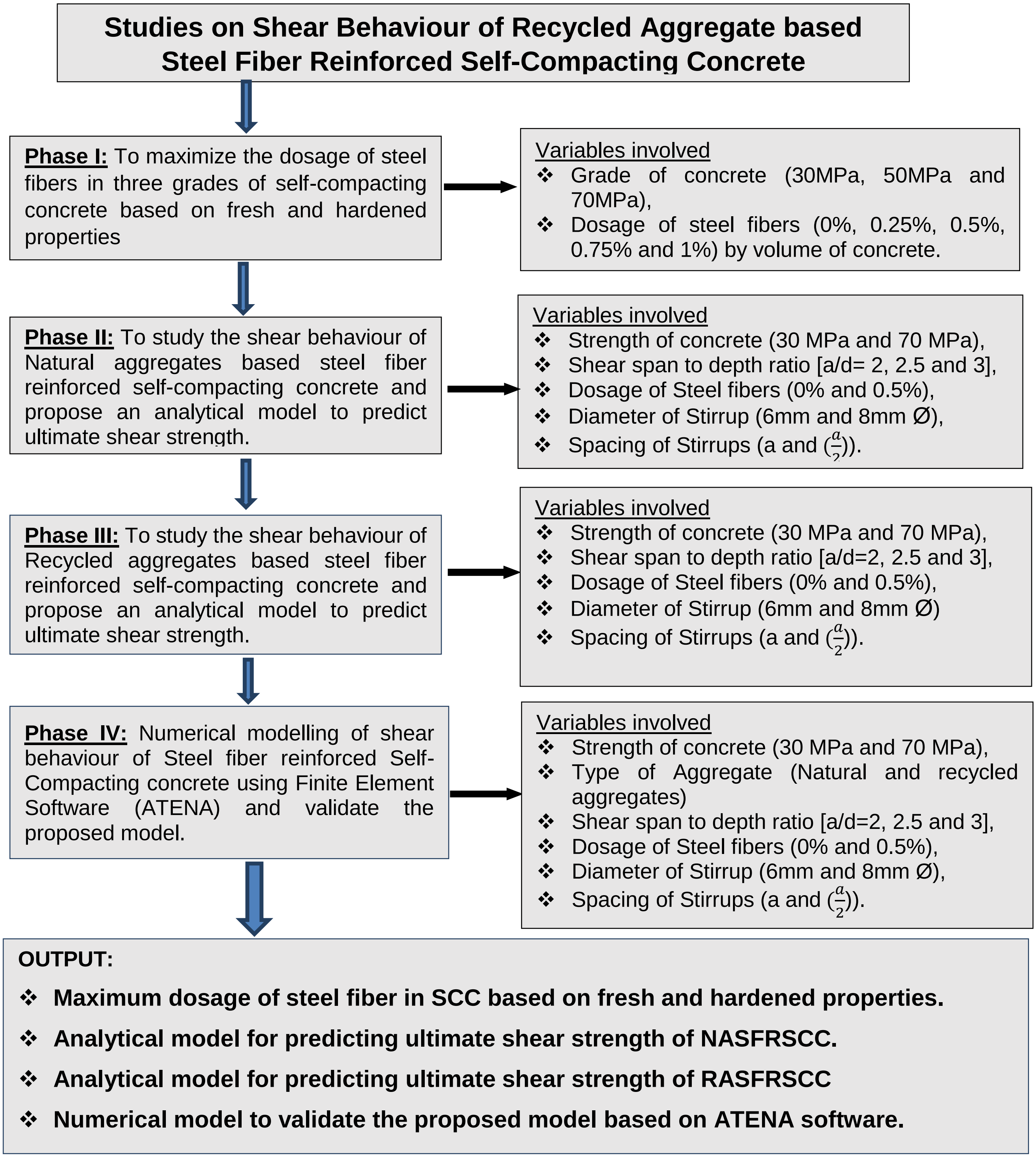


Figure: 3.1 Schematic Diagram of the Research work

CHAPTER 4

MECHANICAL PROPERTIES OF STEEL FIBER REINFORCED SCC

4.0 General

Based on objectives defined in the previous chapter, the entire research work is divided into 3 three phases. The first phase of work is aimed at maximizing the dosage of steel fiber ranging from 0 % to 1% by volume of concrete for three different grades of concrete (SCC30, SCC50 and SCC70). In the present chapter, mechanical behaviour of steel fiber reinforced self-compacting concrete is presented.

4.1 Mechanical Properties of Steel fiber reinforced Self-compacting concrete

4.1.1 Stage 1: Development of Self-Compacting Concrete.

In the first stage, self-compacting concrete was developed using rational method of mix design and fresh and hardened properties were evaluated. SCC was developed by varying the super plasticizer content till the fresh properties were achieved. Fresh properties such as slump flow, V-funnel, J-ring tests were done to check SCC properties according to EFNARC specifications. The details of these test procedures are presented in subsequent paragraphs. Three grades of concrete SCC30, SCC50 and SCC70 were considered in the present study. For studying the mechanical properties such as compressive, split-tensile and flexural strength, standard cube mould of size 150x150mm for compressive strength, 150mm diameter and 300mm height cylinders for split tensile strength and 100x100x500mm prisms specimens for studying the modulus of rupture were considered.

4.1.2 Stage 2: Development of steel fiber reinforced self-compacting concrete.

In the second stage, steel fiber reinforced SCC was developed for different dosages of steel fibers such as 0%, 0.25%, and 0.5% 0.75% and 1% by volume of concrete for three different grades of concrete i.e. M30, M50 and M70. Table 4.1 shows the details of specimens cast. Fresh properties were evaluated for each dosage of steel fiber. It was noted that as the dosage of fibers increased, fresh properties decreased. The hardened properties such as compressive, split tensile and flexural strength are evaluated.

4.2 Materials Used:

4.2.1 Cement: Cement used in the study was 53 grade Ordinary Portland cement confirming to Indian Standard IS-12269 **[BIS, 2013]**. The specific gravity of cement was 2.94, the specific surface area was 225 m^2/g and the initial and final setting times were 45 min and 560 min respectively.

4.2.2 Fly Ash: Fly ash used in the experiments was obtained from Ramagundam thermal power station (NTPC) was sieved by 90 micron sieve and confirmed to Indian Standard IS-3812 **[BIS, 2013]**. The specific gravity was 2.2 and specific surface area of 450 m^2/g. The fly ash had a silica content of 63.99%, silica+ alumina +iron oxide content of 92.7%, pH value was 10 and the loss on ignition was 2.12.

4.2.3 Fine Aggregate (FA): The fine aggregate used in the present study was conforming to Zone-II according to Indian Standards 383 **[BIS, 2002].** It was obtained from a nearby river source. The specific gravity was 2.65, while the bulk density of sand was 1.45 gram/c.c.

4.2.4 Coarse Aggregate (CA): Crushed granite was used as coarse aggregate. Coarse aggregates of 20 mm maximum nominal size was obtained from a local crushing unit which was well graded aggregate according to Indian Standard IS-383 **[BIS 2002].**The specific gravity was 2.8, while the bulk density was 1.5 gram/c.c.

4.2.5 Water: Potable water was used in the experimental work for both mixing and curing of specimens.

4.2.6 Silica Fume: It is an amorphous (non-crystalline) polymorph of silicon dioxide, according to Indian Standards IS-15388 **[BIS, 2003**]. It is an ultrafine powder collected as a by-product of the silicon and ferrosilicon alloy production and consists of spherical particles with an average particle diameter of 150 nm. Micro Silica or silica fume is an ultrafine material with spherical particles less than 1 μm in diameter, the average being about 0.15 μm. This makes it approximately 100 times smaller than the average cement particle. The bulk density varied from 130 to 600 kg/m^3. The specific gravity of silica fume is 2.1 and specific surface area is 15,000 m^2/kg.

4.2.7 Super plasticizer (SP): High Range Water Reducing (HRWR) admixture confirming to ASTM C494 **[ASTM, 2005]** commonly called as super plasticizers was used for improving the flow or workability for decreased water-cement ratio without sacrifice in the compressive strength. These admixtures when they disperse in cement agglomerates significantly, decreases viscosity of the paste forming a thin film around the cement particles. In the present investigation, water-reducing admixture Chyrso fluid optima p-77 (poly carboxylic ether based) obtained from Chyrso Chemicals, India was used.

4.2.8 Steel fiber: Crimped steel fiber confirming to Indian Standards IS-1786 [**BIS, 2008**] with nominal diameter of the fiber 0.5mm and cut length 30mm with aspect ratio of 60 were used. The Tensile strength and modulus of elasticity of this fiber is 850 MPa and 2.1×10^5 MPa respectively.

4.2.9 Mix Proportioning: The mix proportions for Self-Compacting Concrete are obtained by using Rational Mix design method **[Rao et al, 2013]**. 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 **[EFNARC, 2005].**

4.3 Experimental Work:

4.3.1 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 the 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 the SCC to flow through tight openings such as space 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.

4.3.2 Slump flow test and T_{50} Slump flow fest (Reference method for filling ability):

The slump flow test measures the flow spread and flow time T_{50}. 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_{50} cm time) from the time the cone is lifted is noted **(Figure 4.1)**.

4.3.3 V-Funnel Test (Alternative method to T_{50} 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.

4.3.4 L - Box Test Method (Reference method for filling and/or passing ability):

The method aims at investigating the passing and filling ability of SCC. It measures the reached height of fresh SCC after passing through the specified gaps of steel bars and flow within a defined flow distance. With this reached height, the passing or blocking behavior of SCC can be estimated. Uniformity of the mix was also examined by inspecting the sections of concrete in the horizontal section of 'L' box Apparatus as shown in **Figure 4.3.** It consists of a rectangular box section in the shape of 'L'. Concrete was made to pass through the obstructions of known clearances. The vertical section was filled with concrete, and then the gate was lifted to let the concrete flow into the horizontal section through vertically placed reinforcements. When the flow is stabilized, the height of concrete h_1 (at obstructions) and h_2 (at the end of horizontal section of 'L') with respect to base are measured. The ratio of h_2 and h_1 referred to as blocking value, a measure of passing ability of SCC, was calculated. The blocking value of a stable concrete ranging between 0.8 -1.0 indicates better passing ability.

4.3.5 U Box Test (Reference method for filling ability):

This test is conducted to measure the filling ability of SCC. The equipment has 'U' shape that is divided by a middle wall into two compartments as shown in **Figure 4.4.** An opening with a sliding gate is fitted between the two compartments with vertical reinforcements as obstructions. Concrete was made to flow through the obstruction and the level difference between the top surfaces of concrete in both components was measured. Concrete was filled in one compartment up to the top. After one minute, the sliding gate was lifted to allow the concrete to flow into the other compartment through reinforcement obstacles. After the concrete comes to rest, the difference in height was measured. If filling ability of concrete was good, difference in height is minimum.

4.3.6 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 4.5**. 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.

Table 4.3, 4.4 and 4.5 shows the fresh properties of SCC30, SCC50 and SCC70 with and without steel fibers.

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

The addition of steel fibers to SCC mix affects the fresh properties due to both the large surface area of fibers, which requires a higher volume of fluid paste or mortar to be properly surround and lubricate, and the significant inter-particle friction and interlocking among the fibers as well as between the fibers and aggregates. It was observed during the experimental study that, addition of steel 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 were decreased drastically. But fresh properties have satisfied as per EFNARC guidelines up to a dosage of 0.5% and then decreased. **Figures 4.6- 4.8** shows the plot among dosage of steel fibers vs slump flow and V-funnel. As the dosage of steel fibers increased, slump flow was reduced, similarly for V- funnel time increased.

4.5 Hardened properties of SCC:

After satisfying the fresh properties of SCC, the hardened properties of these three grades of concrete (M30, M50 and M70) were determined. A total of 60 specimens each for compressive, split tensile and flexural strength were cast and tested for different dosage of steel fibers for three grades of concrete.

a) **Compressive strength:** After 28 days of curing the specimens were taken from curing tank and kept outside till the moisture content on surface of the cube is evaporated. The cube specimens were then tested in a standard compression testing machine of capacity 200 tones until failure. The specimen was placed in the machine in such a manner that the load was applied to opposite sides of the cubes as casted that is, not top and bottom. The load applied was increased continuously at a constant rate until the resistance of the specimen to the increasing load breaks down and no longer can be sustained. The maximum load applied on the specimen was recorded. The rate of loading and testing procedure was as per IS 516 [1956]

b) **Split Tensile Strength:** The bearing surface of the casting was wiped clean, in case of cylindrical specimens the test was carried out by placing the specimen horizontally between the loading surfaces of the compression testing machine for split tensile strength and the axis of the specimen was carefully aligned with centre of the loading frames. The load was applied and increased continuously till the specimen breaks. The failure load was recorded. The test was performed as per IS: 516 [1956]. The formula to calculate the split tensile strength is given below.

$$f_t = \frac{2P}{\pi * l * d} \qquad \text{Eq (4.1)}$$

Where, P = Max. Load in kN applied to the specimen

l = length of the cylindrical specimen

d = diameter of the cylinder.

c) Flexural Strength: The flexural strength of the specimen is also expressed as the modulus of the rupture. The method used in testing is third point loading. 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 points between the supports. The strength in the bearing is the extreme fibre stress on the tensile side at the point of the failure. The test was performed as per IS: 516 [1956].

If ‘a’ equals the distance between the line of fracture and the nearer support, measured on the centered line of the tensile side of the specimen, in cm, is calculated to the nearest 0.05 MPa as follows.

$$f_b = \frac{P * l}{b * d^2} \qquad \text{Eq (4.2)}$$

when ‘a’ is greater than 20.0 cm for 15 cm specimen or greater than 13.3 cm for a 10.0 cm specimen, or

$$f_b = \frac{3P * a}{b * d^2} \qquad \text{Eq (4.3)}$$

when ‘a’ is less than 20.0 cm but greater than 17 cm for 15 cm specimen, or less than 13.3 cm but greater than 11 cm for a 10 cm specimen where

b = measured width in cm of the specimen,

d = measured depth cm of the specimen at the point of the failure,

l = length in cm of the span on which the specimen was supported, and

P = Max. Load in kN applied to the specimen.

If ‘a’ is less than 17 cm for a 15 cm specimen, or less than 11 cm for a 10 cm specimen, the results of the test be discarded.

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

The results of compressive, split tensile and flexural strength of the tested specimens are presented in the Tables 4.6, 4.7 and 4.8. From the test results it can be noticed that as the dosage of steel fiber increased from 0% to 1%, compressive strength increased slight by 1.8% and 4.7% for 0.25% and 0.5% of steel fibers and then decreased by 10% and 16% for 0.75% and 1% dosage of steel fibers. The decrease in the compressive strength can be attributed to the balling effect that has taken place in the concrete cube due to the larger volume of steel fiber which has resulted in creating local voids. Similarly, as the dosage of steel fibers increased, Split tensile and flexural strength increased constantly. But fresh properties were not satisfying beyond the dosage of 0.5%. Based on fresh and hardened properties it can be concluded that 0.5 % dosage of steel fibers by volume of concrete was maximum for self-compacting concrete. **Figures 4.9, 4.10 and 4.11** shows the variation of compressive, split tensile and flexural strength for different dosages and for three grades of SCC.

4.7 Pilot Study:

A preliminary study was carried out to know the difference on shear behaviour of SCC and NC. For this purpose six number of shear deficient beams were designed with different stirrup spacing via 160mm, 200mm and 250mm, with shear span to depth ratio (a/d) 2, 2.5 and 3. The dimension of the beams are fixed as 100mm x 100mm x 500mm and longitudinal reinforcement consisted of 2-8mm Ø bars was and 2 legged 4mm Ø GI rod was used as shear reinforcement (stirrups). The grade of concrete considered for the study was M30. The mix design for normal concrete was done based on IS: 10262-2009 whereas SCC was designed by using rational method of mix design. The details of mix proportion for M30 normal concrete is presented in Table 4.9. A plot is drawn among shear strength to shear span to depth ratio (a/d) for SCC and NC is shown in figure 4.12. Tables 4.10 and 4.11 shows the shear strength of NC and SCC.

Based on the preliminary study, the following observations are made.

1. As spacing of stirrups increased, failure mode of the beam has changed from flexural failure to shear (Diagonal tension) failure.
2. As the shear span to depth ratio (a/d) increased there is a decrease in shear strength.
3. Shear strength (V_{uc}) was slightly higher in case of SCC compared to Normal concrete.
4. The crack pattern of Normal concrete (NC) and Self-compacting concrete (SCC) are relatively similar.
5. Therefore for the detailed study three a/d ratios 2, 2.5 & 3 are fixed and spacing of stirrups was varied in the Shear span.

4.8 Conclusions from the present study:

Based on the preliminary study the following are conclusions:

1. Due to addition of steel fiber, fresh properties of SCC30, SCC50 & SCC70 has decreased.
2. Addition of fibers has 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 maximum dosage for self-compacting concrete.

4. As the dosage of steel fibers has increased beyond 0.5 % by volume of concrete, balling effect was observed during mixing of concrete and it resulted in decrease in compressive strength for all grades of SCC.
5. Due to use of steel fibers, split and flexural strengths was increased gradually as the dosage of fibers increased, this increase can be due to the fibres bridging the crack propagation and resulted in increased ultimate load carrying capacity of the specimens and also delaying the failure of the specimens.
6. Shear Strength (V_{uc}) was slightly higher in case of SCC compared to Normal concrete.

Table 4.1: Details of SFRSCC specimens cast

Grade of concrete	Dosage of steel fibers (% by volume of concrete)	Specimens cast		
		Cubes	Cylinders	Prisms
M30	0%	6	3	3
	0.25%	6	3	3
	0.5%	6	3	3
	0.75%	6	3	3
	1%	6	3	3
	Sub -Total	**30**	**15**	**15**
M50	0%	6	3	3
	0.25%	6	3	3
	0.5%	6	3	3
	0.75%	6	3	3
	1%	6	3	3
	Sub -Total	**30**	**15**	**15**
M70	0%	6	3	3
	0.25%	6	3	3
	0.5%	6	3	3
	0.75%	6	3	3
	1%	6	3	3
	Sub-Total	**30**	**15**	**15**

Table 4.2: Mix proportions of SCC30, SCC50 & SCC70 grade SCC

Mix	Cement (kg/m^3)	Fly ash (kg/m^3)	Silica fume (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	w/b	SP (kg/m^3)
M30	350	324	-	746	945	203	0.30	5.73
M50	500	270	-	775	868	223	0.29	5.69
M70	600	226	48	780	874	245	0.28	6.03

Table: 4.3 Fresh properties of SCC30 without and with steel fiber

Grade of Concrete	30 MPa					EFNARC 2005	
Dosage of Fibers	0%	0.25%	0.5%	0.75%	1%	Min.	Max.
Slump Test, (mm)	750	700	680	600	570	550	800
T_{50} Slump flow, (sec)	3	5	5	7.5	8	2	5
V funnel, sec	6	7.5	8.5	16	19	6	12
V funnel @ T_5 min, (sec)	6.5	7	9.3	20	23	6	15
J-ring	3	8	8	12	13	0	10

Table: 4.4 Fresh properties of SCC50 without and with steel fiber

Grade of Concrete	50 MPa					EFNARC 2005	
Dosage of Fibers	0%	0.25%	0.5%	0.75%	1%	Min.	Max.
Slump Test, (mm)	750	660	620	600	570	550	800
T_{50} Slump flow, (sec)	2.3	3	6	8	11	2	5
V funnel, (sec)	6	6.9	7.5	21	22	6	12
V funnel @ T_5 min, (sec)	7.5	8	10	23	25	6	15
J-ring	3	8	8	12	13	0	10

Table: 4.5 Fresh properties of SCC 70 without and with steel fiber

Grade of Concrete	70 MPa					EFNARC 2005	
Dosage of Fibers	0%	0.25%	0.5%	0.75%	1%	Min.	Max.
Slump Test, (mm)	720	710	680	640	450	550	800
T_{50} Slump flow, (sec)	2.5	3.25	4	5	24	2	5
V funnel, (sec)	10.5	10.5	11.8	12	15	6	12
V funnel @ T_5 min, (sec)	12	12.6	14	15	20	6	15
J-ring	3	4	7	9	12	0	10

Table 4.6: Hardened properties of M30 grade SCC for different dosages of steel fibers at 28 days

Dosage of Fibers	**0%**	**0.25%**	**0.5%**	**0.75%**	**1%**
Compressive strength (MPa)	39.67	40.41	**41.65**	36.06	34.2
Split tensile strength (MPa)	3.67	4.3	**4.34**	4.28	4.25
Flexural Strength (MPa)	3.982	4.33	**4.87**	5.16	5.25

Table 4.7: Hardened properties of M50 grade SCC for different dosages of steel fibers at 28 days

Dosage of Fibers	**0%**	**0.25%**	**0.5%**	**0.75%**	**1%**
Compressive strength (MPa)	60.70	61.51	**62.3**	60.7	58.7
Split tensile strength (MPa)	4.66	5.25	**5.63**	5.85	5.23
Flexural Strength (MPa)	4.87	5.16	**5.58**	5.75	5.98

Table 4.8: Hardened properties of M70 grade SCC for different dosages of steel fibers at 28 days

Dosage of Fibers	0%	0.25%	0.5%	0.75%	1%
Compressive strength (MPa)	78.25	78.9	**83.35**	77.25	66.25
Split tensile strength (MPa)	7.036	7.47	**7.85**	7.41	7.32
Flexural Strength (MPa)	6.09	6.49	**7.41**	7.47	7.67

Table 4.9: Mix proportions of M30 Normal Concrete (NC)

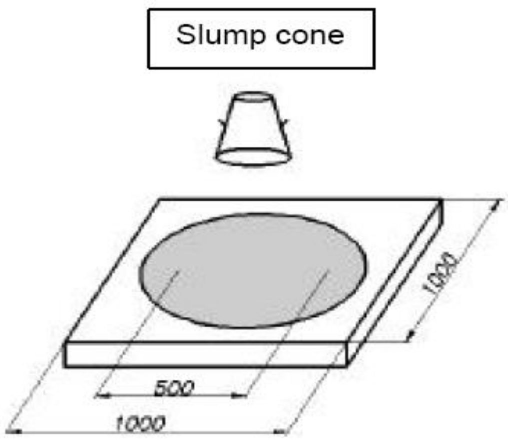
Mix	Cement (kg/m^3)	CA (kg/m^3)	FA (kg/m^3)	Water (kg/m^3)	Water to cement ratio (w/c)
M30	300	878	774	200	0.4

Table 4.10 Shear strength of Normal concrete of M30

S.No.	Ultimate Load (kN)	Shear Strength (N/mm^2)	Mode of Failure
a/d=2,			
1	30.02	1.87	Flexural Failure
2	31.34	1.95	
Average		1.91	
a/d=2.5,			
1	22.95	1.43	Shear Failure
2	22.15	1.40	
Average		1.41	
a/d=3,			
1	21.80	1.09	Shear Failure
2	21.64	1.08	
Average		1.085	

Table 4.11 Shear strength of Self-Compacting Concrete of M30

S.No.	Ultimate Load (N)	Shear Strength (N/mm^2)	Mode of Failure
a/d=2,			
1	31.78	1.98	Flexural Failure
2	32.67	2.04	
Average		2.01	
a/d=2.5,			
1	22.95	1.43	Shear Failure
2	22.07	1.37	
Average		1.40	
a/d=3,			
1	21.20	1.06	Shear Failure
2	22.06	1.103	
Average		1.08	



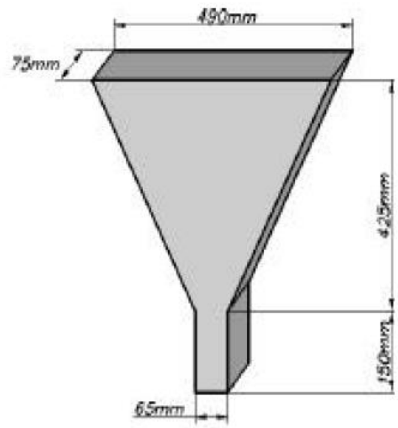
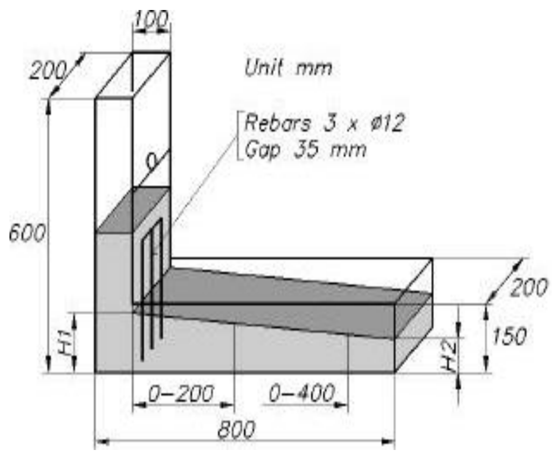


Fig 4.1 Base plate and Abrams cone **Fig 4.2 V funnel test**



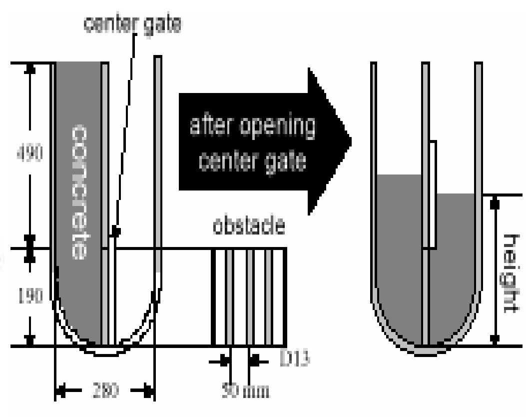


Fig 4.3 L-Box test apparatus **Fig 4.4 U-Box test apparatus**

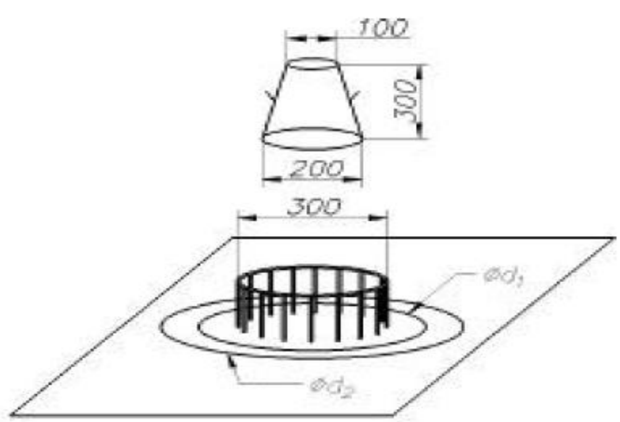


Fig 4.5 J-Ring Test

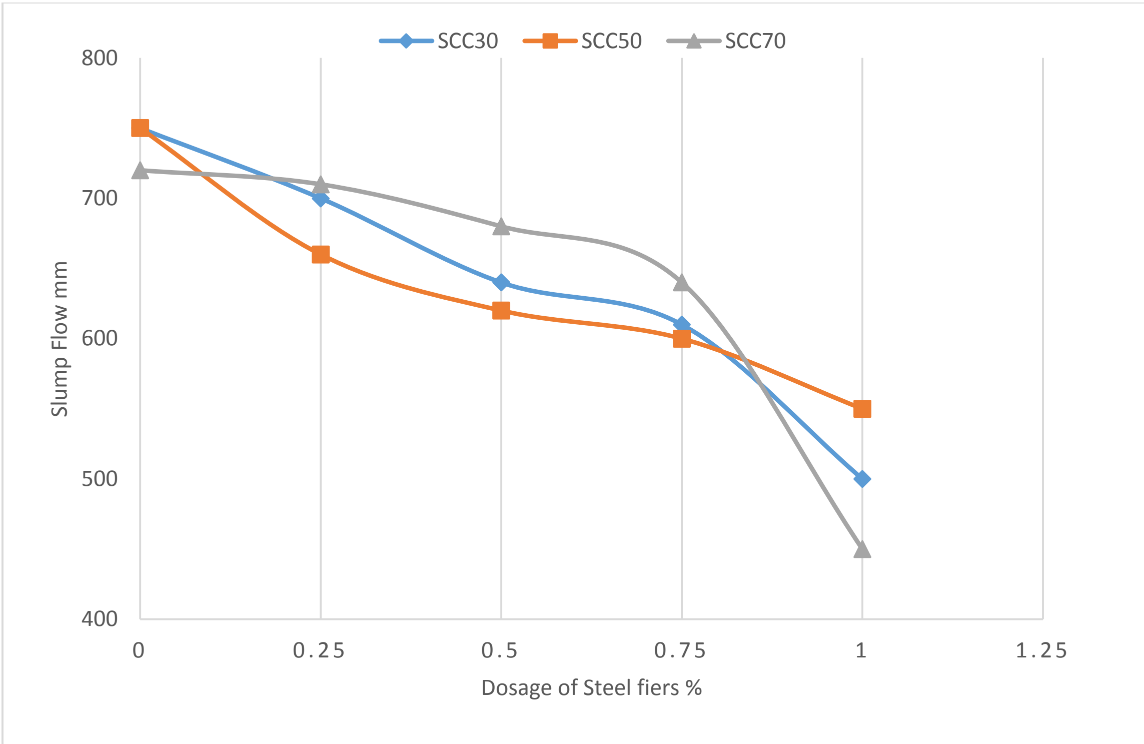


Figure 4.6: Slump Flow vs Dosage of steel fibers

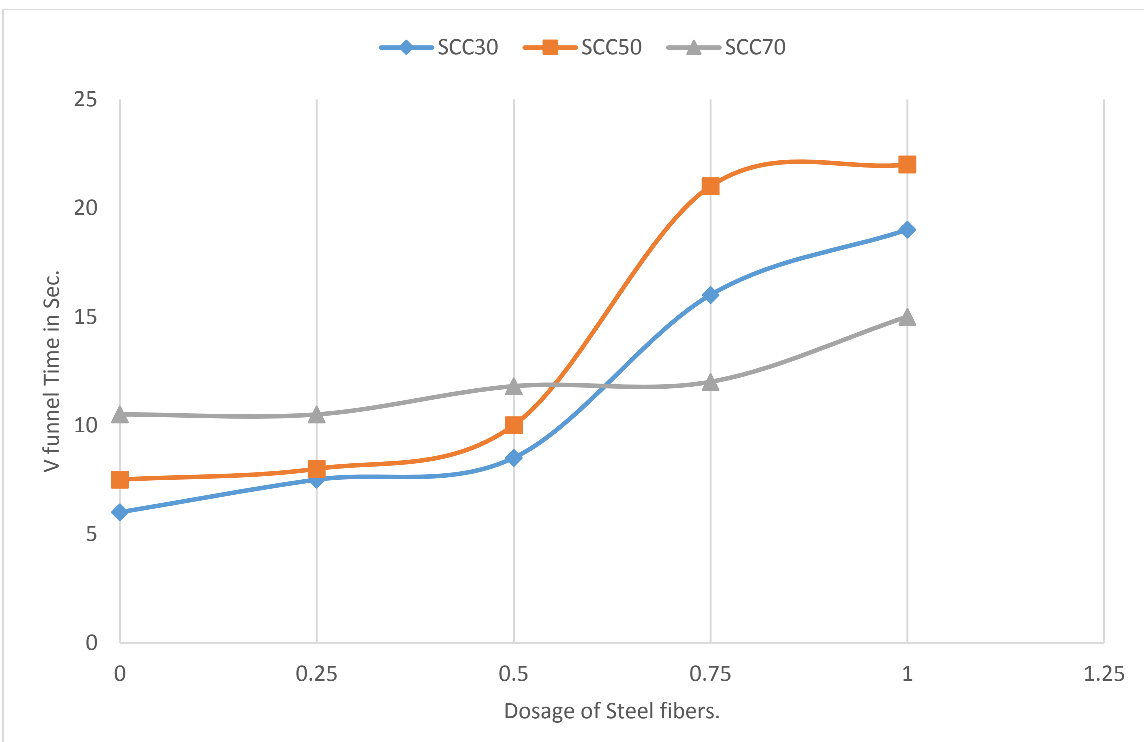


Figure 4.7: V- Funnel (time) vs Dosage of Steel Fibers

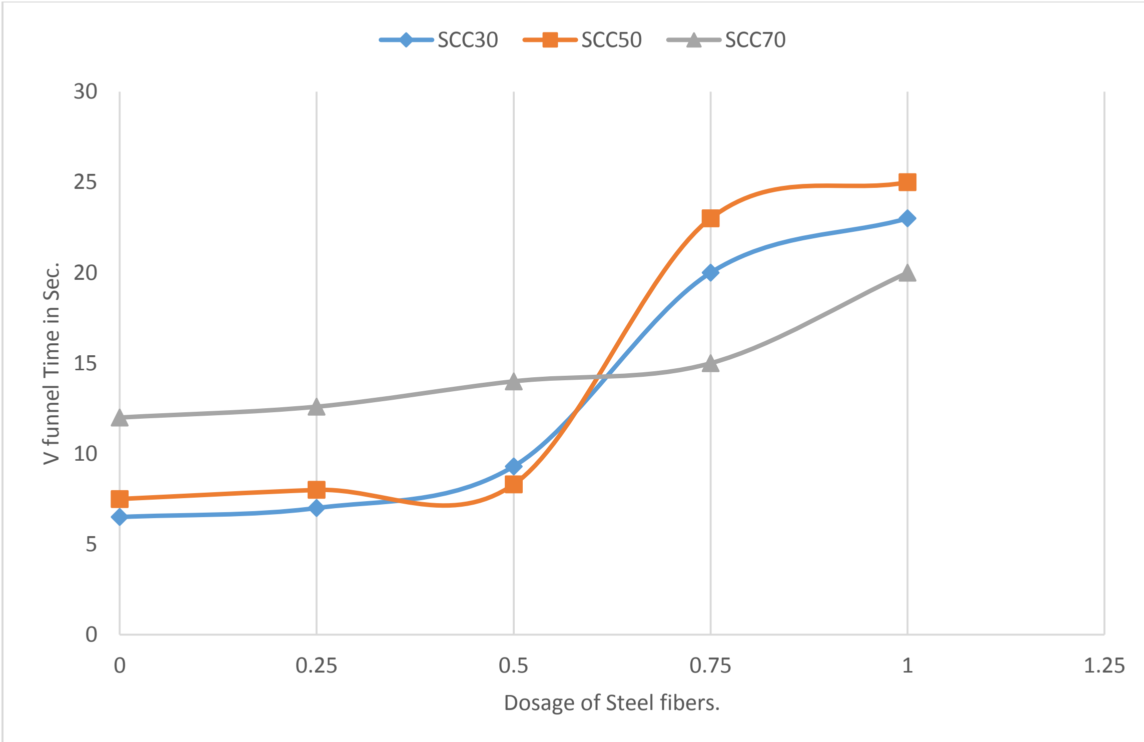


Figure 4.8: V- Funnel at 5minutes (time) vs Dosage of Steel Fibers

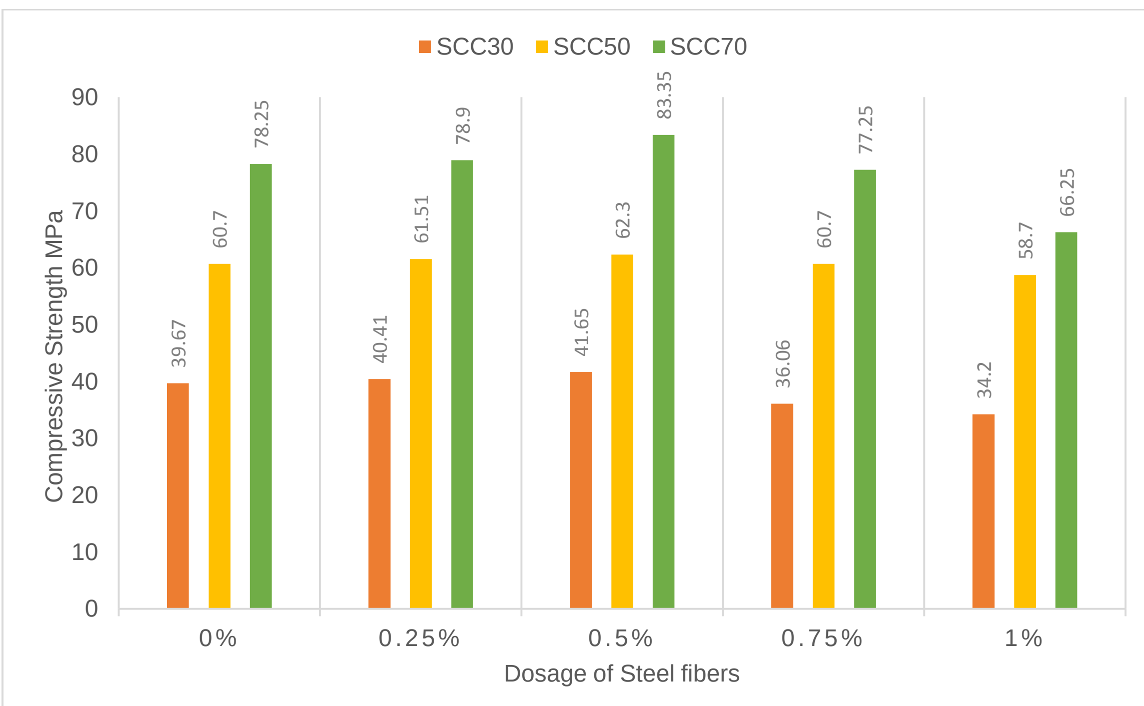


Figure 4.9: Compressive strength vs dosage of steel fibers

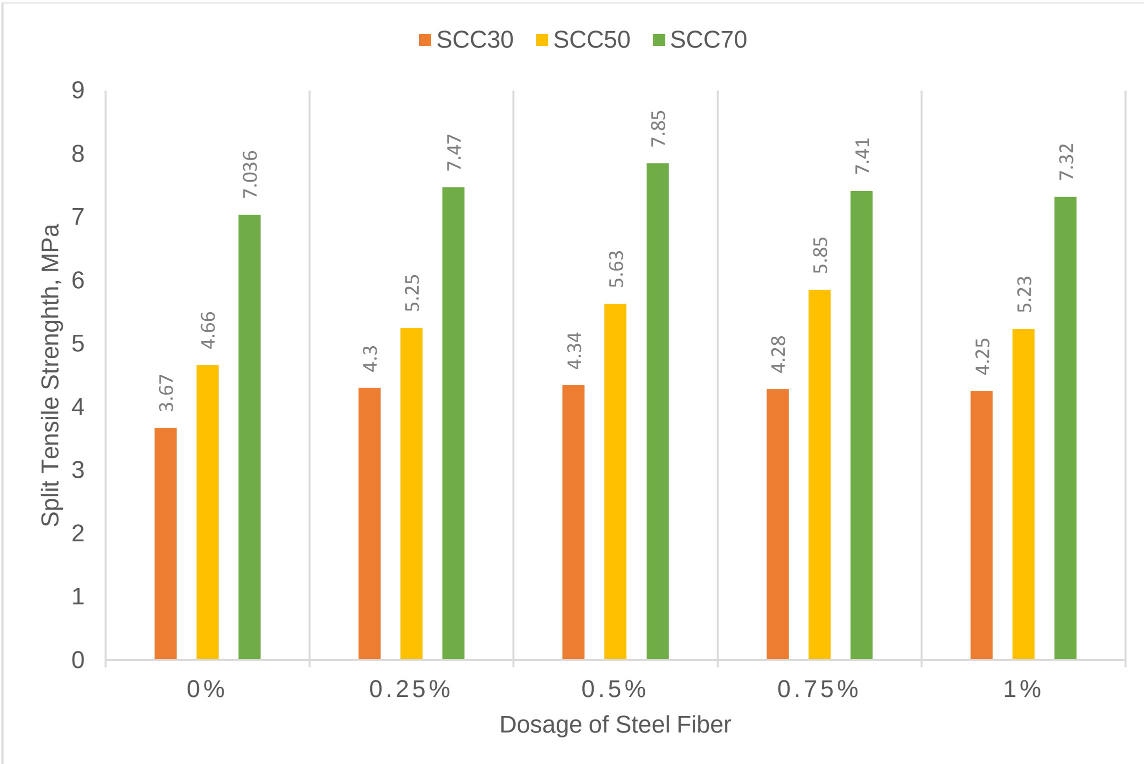


Figure 4.10: Split Tensile strength vs dosage of steel fibers

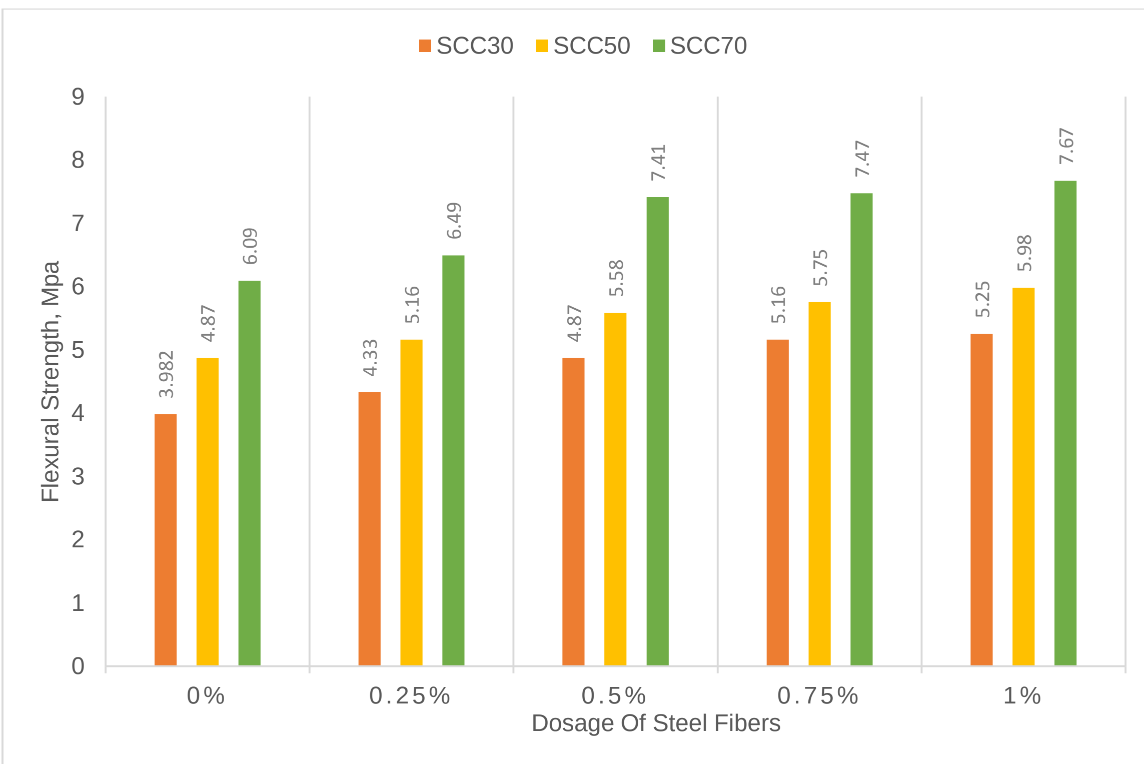


Figure 4.11: Flexural strength vs dosage of steel fibers

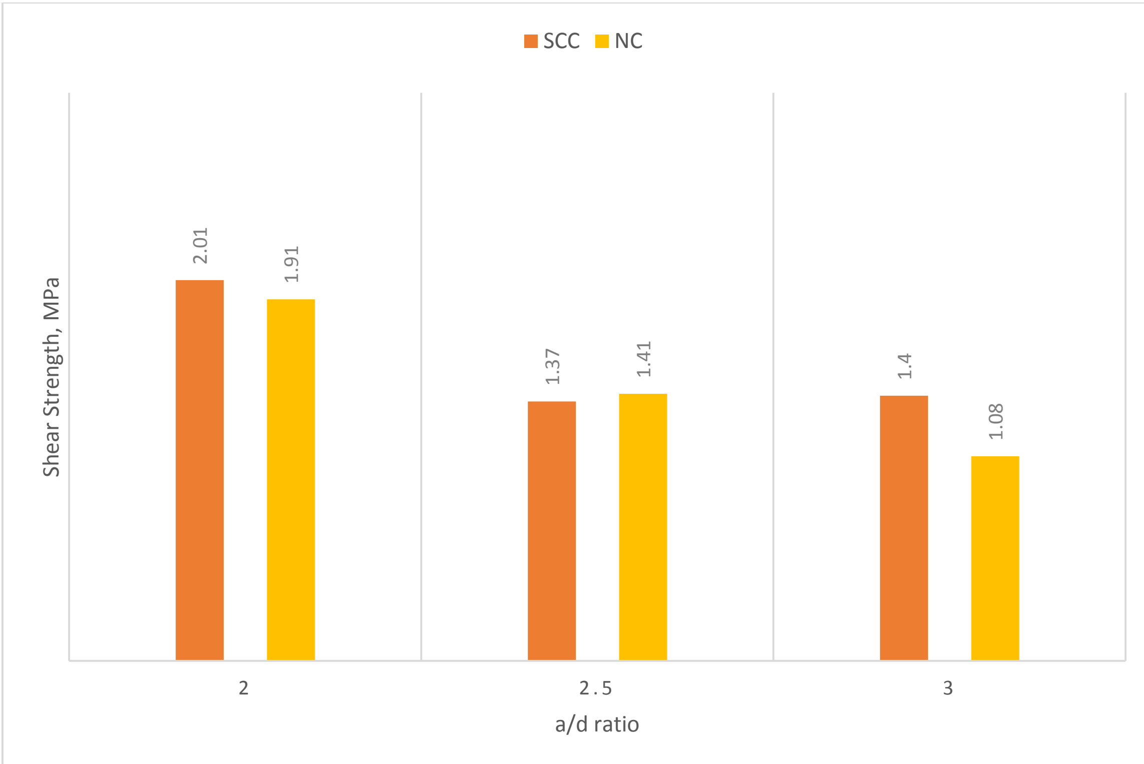


Figure 4.12 Shear strength vs a/d ratio for M30 SCC and NC

CHAPTER 5

SHEAR BEHAVIOUR OF STEEL FIBER REINFORCED SELF-COMPACTING CONCRETE

5.0 General

Chapter 4 dealt with the mechanical properties of steel fiber reinforced SCC for various dosages of steel fibers. The studies concluded that due to use of steel fibers, sudden failure of the specimens can be avoided. There is an increases in the split tensile and flexural strength. 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 shear behaviour of self-compacting concrete for without and with steel fibers.

5.1 Shear Behaviour of steel fiber reinforced self-compacting concrete.

Shear failure of conventional reinforced concrete beams usually occurs by tensile failure of concrete in the shear span. For this reason, shear failure in general is sudden and brittle, and in practice shear reinforcement in the form of stirrups are incorporated to prevent this type of failure, and to increase the shear strength of the beams. [**Ta'an and Feel, 1990**]. 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. Steel fibers are used to increase the shear capacity of concrete and to partially replace the lateral ties (stirrups) in RC structural members. The addition of steel fibers to an RC beam can increase its shear strength, and if sufficient amount of steel fibers are added a brittle shear failure can be modified to a ductile behavior and also reduces the crack width [**Yining Ding et.al, 2011**].

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 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, especially on the shear behaviour of SFSCC, is still limited. The present study focuses on the shear behaviour of steel fiber reinforced self-compacting concrete in shear.

Numerous studies [Narayana and Darwish,(1989); Lim and Oh, (1999) ; Dinh H et al, (2009); Shah D.L. and Modhera C.D, (2010); Yining Ding et al, (2011); Kang Su Kim et al, (2012); Hwang et al, (2013), Cuenca et al, (2015); Ali Amin and Foster (2016); Gali and Subramaniuam, (2017)] were reported in literature regarding the shear behaviour of fiber reinforced concrete. The major factors considered in their studies are: 1) shear span-to effective depth ratio (a/d), 2) concrete compressive strength (fc), 3) longitudinal tensile reinforcement ($\boldsymbol{\rho}_t$), 4) Spacing of stirrups (S_v) and 5) Diameter of stirrups. When fibers are also included, parameters like fiber volume fraction (V_f) or fiber type (material, dimensions shape, etc.), also affect the shear performance of SCC**.**

5.2 Experimental Programme.

The experimental program was designed to study the shear behaviour of steel fiber reinforced self-compacting concrete by casting and testing of 100x200x1200mm beams. The scheme of casting the specimens was done in two stages. The first stage includes studies on the shear behaviour of steel fiber reinforced self-compacting concrete using 6mm Ø stirrup. The second stage involves studies on the shear behaviour of steel fiber reinforced self-compacting concrete using 8mm Ø stirrup. The variables in the study are shear span to depth ratio (a/d), grade of concrete (f_c), Spacing of stirrups (S_v), volume of steel fibers (V_f) and diameter of stirrup ($Ø_d$).

In each set a total of 36 beams were cast and tested by varying above parameters. In the present study two grades were considered i.e. M30 and M70. The stirrups spacing's was varied in the shear span. Three shear span to depth ratios were considered (a/d= 2, 2.5 and 3). 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. Hence, in casting of beams only maximum dosage of steel fibers was used i.e. 0.5% by volume of concrete. In each set three standard cubes, cylinders and prisms of sizes 150x150x150mm, 150mm diameter x 300mm height and 100x100x50mm were cast and tested for obtaining the compressive, split tensile and flexural strengths respectively. These specimens are companion specimens.

To study the behaviour of self-compacting concrete in shear, the beams are designed to fail in shear only. To make the beams as shear deficient, higher stirrup spacing was considered. For each a/d ratio six beams were cast, of which two beams are of plain ones i.e. without stirrups. In those two one is of no stirrups and no fibers and other one is no stirrups and with steel fibers.

Similarly, for remaining four beams two stirrup spacing's were considered i.e. a and $\frac{a}{2}$. The details of the beams cast for two grades of SCC are presented in Table 5.1. The experimental programme is same for two stages with only variation is diameter of stirrup i.e. 6mm and 8mm Ø.

The above beams were cast using 6mm diameter stirrup. Similarly, remaining 36 beams were cast and tested using 8mm diameter stirrup.

5.2.1 Materials Used:

The details of the various materials used such are cement, flyash, fine aggregates, coarse aggregates, silica fume and steel fibers are presented in chapter 4.

a) ***Tension reinforcement:*** TMT bars of 12 mm & 16 mm diameter of grade Fe 500 confirming to IS: 1786 -2008 whose yield strength F_y = 500 N/mm^2 of length 1160mm were used as tension reinforcement and 6mm Ø mild steel bars whose yield strength F_y= 290 N/mm^2 was used as top compression reinforcement.

b) Web Reinforcement: Two legged 6mm and 8mm dimeter stirrups whose yield strength of 290 MPa and 415 MPa was used as web reinforcement***.***

5.2.2 Moulds and Equipment

5.2.2.1 Cubes: Standard cube moulds of 150 x150 x 150mm made of cast iron were used for casting the specimens for conducting compression test on concrete.

5.2.2.2 Cylinders: Standard cylinders of 150 mm diameter and 300 mm height, made of cast iron were used for casting the specimens for conducting split tensile strength on concrete.

5.2.2.3 Prisms: Standard cast iron moulds of size 100x100x500mm were used for casting and the specimens are used for finding flexural strength of concrete.

5.2.2.4 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.

5.2.2.5 Preparation of specimens and Fabrication process

The required length of the longitudinal steel bars were cut and straightened. Similarly, for stirrups, 6 and 8 mm diameter mild steel bars was cut from the lots, straightened and bent into the proper shape. The stirrups were placed at required spacing and were tied to the longitudinal steel with binding wire.

5.2.2.6 Reinforcement Details.

The dimensions and typical reinforcement details for both grades of SCC M30 & M70 and for different shear span to depth (a/d) ratios are shown in Figures 5.1 to 5.6. The stirrups spacing was varied in the shear span, for each a/d ratio two stirrup spacing were considered. M30 grade SCC beams consist of 2-12mm Ø TMT bars as longitudinal reinforcement, 2-6mm Ø mild steel bars as top compression reinforcement. Similarly, M70 grade SCC beams consist of 2-16 mm and 1-12mm Ø bars as longitudinal reinforcement, 2-6mmØ mild steel bars as top compression reinforcement and two legged 6mm and 8mm Ø bars are used as stirrups for both SCC30 & SCC70 grades concrete.

5.2.2.7 Casting of beams

The required number of beam moulds was assembled on smooth concrete flooring with an oilpaper in between the bottom of the channels and the flooring. The inner side of the mould was lubricated properly. Cover blocks of proper thickness were placed below the bottom of the cage so that the required effective depth of the beam is maintained. The required quantities of the materials for casting one batch of beams were mixed thoroughly on a platform to get a uniform mix. First the reinforcement cage was kept on cover blocks in the mould. Then the concrete is placed in the beam. The beam moulds were stripped 24 hours after concreting. The specimens were numbered with water proof ink.

5.2.2.8 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 specimen were kept under shade.

5.2.3 Testing of the beams.

5.2.3.1 Preparation of Test Specimens: One day before the testing of the cured beams were white washed. The capping is done with the help of glass plate and spirit level.

5.2.3.2 Testing machine: The testing of the beams were done on 1000KN Dynamic Testing Machine under flexure. The beams were tested under strain control, with a loading rate of 0.1mm/min.

5.2.3.2 Measurement of deflections: The deflections were measured at the centre of the beam. The dynamic testing machine gives the load and deflections values directly.

5.3 Results and Discussion:

5.3.1 Discussion on Shear behaviour of Self-compacting concrete using 6mm Ø stirrups:

In this section, the behaviour 36 simply supported beams for shear span to depth ratio 2, 2.5 and 3 tested is discussed. The results of these beams are presented in Tables 5.2, 5.3 and 5.4.

a) Effect of shear reinforcement (stirrups) on Shear behaviour of SCC Beams:

It can be observed from the Tables 5.2, 5.3 & 5.4 that as the spacing of stirrups increases, ultimate load and ultimate shear strength decreased.

1. SCC30-0 beam with no stirrups and steel fibers has shown lower load carrying capacity and brittle failure pattern compared to the beam with stirrups i.e. SCC30-180, with provision of stirrups , ultimate shear strength increased by 54%. Similarly for the beam SCC30-360 with stirrup at 360 mm, ultimate shear strength increased by 39.3%.
2. For higher grade concrete, SCC70-0 beam with no stirrups has shown lower load carrying capacity compared with beams with stirrup at 180 mm and 360 mm spacing. Due to provision of stirrup the ultimate shear strength increased by 31% and 26% for SCC70-180 and SCC70-360 beams respectively.
3. Similarly, for beams tested for shear span 2.5, with provision of stirrup at 225 and 450 mm, ultimate shear strength increased by 39% and 20% for beams SCC30-225 and SCC30-450 compared with plain beams without stirrups. For higher grade concrete beams with provision of stirrups at 225 and 450 mm, ultimate load increased by 42% and 25% compared with plain beam without stirrup.
4. For beams tested for shear span 3, the ultimate shear strength is increased by 28% and 5.2% respectively for SCC30-270 and SCC30-540 beams compared with SCC30-0 beam without any stirrups. Similar trend was observed even in case of higher grade concrete beams.

Finally, it can concluded that with provision of stirrups, the ultimate load carrying capacity of the beams will be increased, but with increased spacing of stirrups will affect the load carrying capacity of beams which will result in early failure of the beams. It was also noticed that by providing stirrups at larger spacing with inclusion of steel fibers can improve the shear performance of SFRSCC beams. By providing steel fibers, stirrup spacing can be increased their by steel fibers can partially replacing the stirrups. Figures 5.7, 5.8 &5.9 shows the variation of Shear Strength with Spacing of Stirrups for SCC with grades M30 and M70 for both non fibrous and fibrous SCC.

b) Influence of Steel fiber on shear strength:

Figures 5.10-5.15 shows the comparison of load deflection curves of SCC30 and SCC70 grade concrete among SCC and SFSCC beams for different shear span to depth ratios (a/d) 2, 2.5 & 3. It can be observed that.

1. The SCC30-0 beam with no stirrups and steel fibers has failed suddenly in shear, due to addition of steel fibers the load carrying capacity of SFRSCC30-0 beams has

increased by 24%. The beam with stirrups and steel fibers i.e. SFRSCC30-180, has shown higher load carrying capacity and the failure mode has changed from brittle failure to ductile mode. Due to combined effect of steel fiber and stirrups, the ultimate shear strength in increased by 90%.

2. The similar behaviour was observed in the case of higher grade (SCC70) concrete.
3. The SCC30-180 beam shows both lower load carrying capacity and brittle failure patter compared to the SFRSCC30-180, addition of steel fibers has increased the load bearing capacity by 23.25 % and also maximum deflection corresponding to ultimate load increased by 65.07%.
4. Similarly, the SCC30-360 beam also shows both lower load carrying capacity (F_u =86.77 KN) and brittle failure pattern compared to the beam with steel fibers (SFSCC30-360).
5. In case of high grade concrete (SCC 70), addition of steel fibers has increased the Ultimate Shear strength by 38.07% and also maximum deflection corresponding to ultimate load increased by 19.91%. Due to the combination of stirrups and steel fibers, the ultimate shear strength is increased by 80.7%. Same behaviour was observed for both the a/d ratios 2.5 & 3.
6. From the above observations it can be concluded that the addition of steel fibers can increase the load carrying capacity and can greatly enhance the ductility and also change the failure pattern of the beam from brittle shear failure to ductile flexural-shear failure. The SCC beam without steel fibers failed soon after first diagonal crack has occurred.

c) ***Effect of shear span to depth (a/d) ratio on Shear behavior of SCC beams for different stirrup spacing:***

It can be observed from the Table 5.2, Table 5.3 and Table 5.4 that as the shear span to depth (a/d) ratio increased, the ultimate load and ultimate shear strength decreased. This may be attributed to the increase in the principal tensile stresses in the shear span causing diagonal tension cracks which decrease the shear resistance of the beam. The addition of steel fibers improves the ductility and change the failure mode from a brittle shear collapse into a ductile flexural-shear failure. By keeping the stirrup spacing constant and adding steel fibers, ultimate shear strength increased because of the confining effect of steel fiber which will play a significant role before and after cracking. The combination of steel fibers and stirrups show a positive hybrid effect on shear behaviour and enhances the shear resistance of beam. Also, steel fibers can partially replace stirrups and ensure more ductility. As the grade of concrete increased, ultimate strength increased because the shear resistance of beam has increased. Figure 5.16(a) and 5.16(b) shows the variation of shear strength with shear span to depth ratio (a/d) for plain beams without stirrups and for beams with different stirrups spacing.

d) Effect of Stirrups and Steel fibers on Toughness of SCC beams with 6mm Ø stirrup.

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 load deflection curve. In the present study toughness of the beams is measured by calculating the area under load- deflection curve. Addition of Steel fibers not only improved the shear performance of SCC beams but there is also enhancement in the toughness. Due to inclusion of steel fibers for plain beams without stirrups, there an increment of 35% in toughness of the SFRSCC30-0 beam when compared with the identical beam without steel fiber. Similarly, in case of higher grade concrete beams, due to addition of fibers the toughness of the plain beam SFRSCC70 increased by 92%. Due to the combined effect of stirrups and steel fibers, toughness of SFRSCC30-180 beam with steel fibers and stirrups at 180 mm spacing is increased by 98%, compared with identical beam without steel fibers and also in case of higher grade concrete for SFRSCC70-180 beam there is an increment of 44% compared with identical beam without fibers. Similar trend was observed in case of beams tested for shear to depth ratio 2.5 and 3 for both grades of concrete.

Figures 5.17-5.19 show the variation of toughness with respect to stirrup spacing for both grades of concrete and for with and without steel fiber beams for three a/d ratios.

5.3.2 Discussion on Shear behaviour of Self-compacting concrete using 8mm Ø stirrups:

The second stage involves studies on shear behaviour of steel fiber reinforced self-compacting concrete using 8mm Ø stirrup. In this section, a total of 36 simply supported beams were cast and tested for three shear span to depth ratio (a/d= 2, 2.5 and 3) is discussed. The results of these beams are presented in Tables 5.5, 5.6 and 5.7.

a) Effect of stirrup spacing's on shear behaviour of SCC Beams:

It can be observed from the Tables 5.5, 5.6 &5.7 that as the spacing of stirrups increases, ultimate load and ultimate shear strength decreased.

1. The SCC30-0 beam with no stirrups and fibers has shown lower load capacity and brittle failure pattern compared to the beam SCC30-180 with 8mm Ø stirrup. Due to provision of stirrups at 180 mm spacing, the ultimate load carrying capacity of the beam increased by 82% and also the failure mode has changed from sudden brittle failure to ductile mode, for shear span to depth ratio a/d=2.
2. For higher grade concrete SCC70, due to provision of 8mm Ø stirrup at 180 mm spacing, the ultimate load carrying capacity of the beam is increased by 97%. This increase in shear strength can be attributed to the increase in area of shear reinforcement in the shear span, which enables the beam to resist heavier loads and avoids sudden diagonal shear failure.
3. For increase in stirrups spacing from 180 to 360 mm for a/d=2, the ultimate load carrying capacity of the beam reduced by 12% and 18% for SCC30 and SCC70 grades respectively.
4. Similarly, for shear span to depth ratio (a/d) 2.5, for increase in stirrup spacing from 225 to 450, the ultimate load is reduced by 15% and 35.38% for SCC30 and SCC70 respectively.
5. For shear span to depth ratio (a/d=3), as the spacing of stirrup increased from 270 to 540, the ultimate load decreased by 17.6% and 25% for SCC30 and SCC70 respectively.

Finally, it can concluded that irrespective of diameter of stirrup, ultimate shear strength decreased as the spacing of stirrup increased for any shear span to depth ratio and this is true for both lower and higher grades of concrete. The variation of shear strength vs spacing of stirrups for three shear span to depth ratio (2, 2.5 and 3) is shown in Figures 5.26-5.28

b) Influence of steel fibers on shear strength of SFRSCC Beams:

Addition of steel fiber not only improve the flexural tensile behaviour of SCC but also increase the ultimate load carrying capacity of SCC beams. Figures 5.29-5.30 Shows the load vs deflections graphs for SCC30 and SCC70 for three shear span to depth ratios (a/d= 2, 2.5 & 3).

1. The SCC30-0 plain beam with no fibers and stirrups, has shown lower load carrying capacity and brittle failure pattern compared to SFSRCC30-0 beam with steel fibers and no stirrups. Due to addition of steel fibers, the ultimate load carrying capacity of the beam increased by 24%. Similarly, due to the combined effect of stirrups and steel fibers the ultimate load carrying capacity of the beam SFRSCC30-180 is increased by 104%.
2. For higher grade concrete, due to addition of steel fiber the ultimate load carrying capacity of the beam SFRSCC70-0 i.e. the beam with steel fibers and without stirrups is increased by 15% and due to the combination of stirrups and steel fibers for the beam SFRSCC70-180, the ultimate load carrying capacity is increased by 125%, and for the beam SFSCC70-360 with increased stirrup spacing from 180 to 360 mm the ultimate load carrying capacity of the is increased by 79%. The addition of steel fibers can partially increase the stirrup spacing their by reducing the area of shear reinforcement.
3. Similarly, for shear span to depth ratio 2.5 due to addition of steel fiber, the ultimate shear strength of the SFRSCC30-0 increased by 18 % compared to the beam with no fibers and stirrups i.e. SCC30-0. For higher grade concrete the ultimate load carrying capacity of the beam SFSCC70-0 increased by 11.5 %. Due to the combined effect of stirrups and steel fibers the ultimate load carrying capacity of the beams SFRSCC30-225 and SFRSCC70-225 is increased by 85% and 117% respectively. And also with increase in spacing of stirrups from 225 to 450 and with addition of steel fibers, the ultimate load carrying capacity of the beams is increased by 55% and 79% for SFRSCC30-450 and SFRSCC70-450 compared to with plain beams with no stirrups and no steel fibers respectively.
4. For shear span to depth ratio a/d=3, due to the inclusion of steel fibers, the ultimate load carrying capacity of the beam SFRSCC30-0 is increased slightly by 5% compared to plain beam with no fibers and stirrups i.e. SCC30-0. Similarly, for higher grade concrete with addition of fibers the ultimate load carrying capacity of the beam is increased marginally by 4.2%. Due to the combination for stirrups and steel fibers,

the ultimate load carrying capacity of the beams SFRSCC30-270 and SFRSCC70-270 increased by 94% and 91.6% compared to the plain beam with no stirrups and fibers i.e. SCC30-0 and SCC70-0 respectively.

5. Due to inclusion of Steel fibers, the toughness of the beam increased by 35% for the beam SFRSCC30 compared to the plain beam without steel fibers i.e.SCC30-0 and also due to the combination of stirrups and steel fibers, the toughness of the beam SFRSCC30-180 is increased by 287% and with only stirrups the toughness is increased by 124%. This shows that steel fibers play vital role in improving the toughness of the beam before and after cracking.
6. Similarly for higher grade concrete for the beam SFRSCC70-0, toughness increased by 93% and due to the combined effect of stirrups and steel fibers, toughness of the beam SFRSCC70-180 is increased by 590% compared to plain beam without steel fibers and stirrups. Similar behaviour was observed for shear span to depth ration 2.5 and 3.

For the above discussion it can be concluded that the addition of steel fibers can greatly influence the shear strength of SCC beam and also the combination of stirrups and steel fibers increased the ultimate shear strength by more than 100% in almost all the cases. Steel fibers can also partially replace the stirrups by increasing the spacing of stirrups their by reducing the area of shear reinforcement required.

c) Effect of shear span to depth ratio on shear behaviour of SCC Beams:

As observed in the case of beams with 6mm diameter stirrups that as shear span to depth ratio (a/d) increased from 2 to 3 ultimate shear strength was decreased. The same type of behaviour was observed in the case of beams with 8 mm diameter stirrup. From the tables 5.4 to 5.6 it can be observed that irrespective of grade of concrete the ultimate shear strength decreased as a/d ratio increased. The load carrying capacity of SCC30-0 beam of shear span to depth ratio a/d=2 with no stirrups and steel fibers is higher by 5 % and 22% compared with the similar beam SCC30-0 tested for shear span to depth ratio of 2.5 and 3. This decrease in shear strength is due to increase in the shear span, which increases the principal tensile stresses in the shear span causing early diagonal tension cracks and results in lower load carrying capacity. Similarly, for higher grade concrete for the beam SCC70-0 with no stirrups and fibers, the ultimate shear strength is higher by

19.5% and 22.54% for similar type of beam tested for shear span 2.5 and 3 respectively. Due to the combination of stirrups and steel fibers also a similar type of behaviour was noted. The figures 5.31(a) and 5.32(b) shows the variation of shear strength and shear span to depth ratio (a/d) for plain beams without stirrups and for beams with stirrups.

d) Effect of Stirrup diameter on shear behaviour of SCC beams:

Diameter of stirrup is the one of the important parameter that effects the shear strength of concrete. In the present study two stirrup diameters were used to the effect of stirrup diameter (6mm and 8 mm). Figure 5.33 shows the variation of shear strength to diameter of stirrup for three shear span to depth ratios (a/d= 2, 2.5 and 3). From the figures it can be noticed that as the stirrup diameter increased, the ultimate shear strength also increased. This is due to increase in the area of shear reinforcement in the shear span causing increased confining effect on concrete as result of which there is an increase in shear strength of SCC beams. For similar beam with identical spacing of stirrup, the ultimate shear strength increased by 18.8% for SCC30-180 beam with 8mm Ø stirrup compared to that the beam with 6mm Ø stirrup. Similarly, due to the combination of stirrups and steel fibers, shear strength of the beam SFRSCC30-180 with 8mm Ø stirrup, is increased by 7.6% compared to the similar beam with 6mm Ø stirrup. In case of higher grade concrete, the shear strength of SCC70-180 beam with 8mm Ø is increased by 33.8% compared with that of the similar beam with 6mm Ø stirrup. Similarly, the percentage increase in ultimate shear strength of SFRSCC70-180 beam with combination of stirrups and steel fibers and with 8mm diameter stirrup is 19.7% compared to that of identical beam with 6mm dimeter stirrup. This shows that due to the use of steel fibers, the percentage increase in ultimate shear strength is higher compared to that of plain beams without fibers i.e. steel fibers help in bridging the crack propagation and also improves the ultimate load carrying capacity of the beam.

In case of the beams tested under shear span 2.5 and 3, the percentage increase of ultimate shear strength is lower in case of lower grade concrete i.e. SCC30 beams. For instance SCC30-225 beam with 8mm stirrup diameter, ultimate shear strength is increased slightly by 9.6%. But for higher grade concrete, the percentage increase is higher. The ultimate shear strength of SCC70-225 beam is higher by 30.6% compared to identical beam with 6mm stirrup diameter. Similarly in case of shear span to depth ratio a/d=3, the ultimate shear strength of the beam SCC30-270 with 8mm diameter beam is higher by 8.54% compared with similar beam with 6mm diameter stirrup and for higher grade concrete the ultimate shear strength of the beam SCC70-270 with 8mm diameter stirrup is higher by 16% compared with similar beam with 6mm diameter. This indicates that, as the shear span to depth ratio is increased from 2 to 3, there is a decrease in ultimate shear strength and it holds good even in the case of 8mm Ø stirrup.

The use of steel fibers can reduce the area of shear reinforcement without compromising the shear strength of concrete. The ultimate shear strength of SFRSCC30-180 beam with 6mm diameter stirrup is slightly higher by 3.6% compared with SCC30-180 beam without fibers and with 8mm diameter stirrup and also in the case of higher grade concrete, the ultimate shear strength of SFRSCC70-180 beam with 6mm diameter stirrup is slightly lower by 9.31% compared with SCC70-180 beam without fibers and with 8 mm stirrup diameter. Similar trend was observed in case of a/d ratio 2.5 and 3. This behaviour indicates that steel fibers play a vital role before and after cracking and also it can reduce the area of shear reinforcement required if present in sufficient quantity.

From this discussion it can be concluded that by using 8mm diameter stirrup, the ultimate shear strength will be improved due to increase in area of shear reinforcement. Due to use of steel fibers the area of shear reinforcement can be reduced, thereby reducing the congestion of reinforcement by which cost of reinforcing steel can be reduced.

e) Influence of stirrups and steel fiber on Toughness of SFRSCC Beams with 8mm Ø stirrup.

Toughness is defined as the amount of energy per unit volume that a material can absorb before failure. In can also be defined as area under load deflection curve. In the present study toughness of the beams is measured by calculating the area under load-deflection curve. Addition of steel fiber has not only improved the shear performance of SCC beam but also it has increased the toughness of the beams. Due to addition of steel fibers toughness of the beam SFRSCC30 is increased by 35% compared to plain beam SCC30-0 without steel fibers. In case of higher grade concrete beams due to inclusion of steel fibers, toughness of the beam SFRSCC70-0 increased by 93%. The combined effect of stirrup and steel fibers has shown much better performance than plain beams. Figure 5.34 shows the variation of toughness with respect to stirrup spacing.

5.4 Angle of inclination (ϴ)

From the failure pattern of the beams, the crack angle is measured for SCC30 and SCC70 beams with both 6 mm and 8 mm diameter stirrup. The details of these are presented in the Tables 5.8-5.9. It can be observed that as the shear span to depth ratio increased, the crack angle has reduced. This can be attributed to increase in the crack length as the shear span to depth ratio increased from a/d 2 to 3.

5.5 Prediction of Theoretical shear strength.

From the crack angle (ϴ) obtained, a plot between the crack angle vs shear span to depth ratio is plotted. Figure 5.35(a) shows the variation of crack angle (ϴ) with respect to shear span to depth ratio whereas, Figure 5.35(b) shows the variation of average crack angle (ϴ) with respect to shear span to depth ratio. The cracked portion of the beam is shown in Figure 5.36. As the type of failure is split tensile failure. Assuming the crack inclination is "ϴ", and the force acting on the surface of the crack as split tensile force (F_t). By way of resolving the force F_t along the y-direction, the vertical component of force F_t is "$F_t * \mathrm{Cos}\theta$". Shear force (V_u) at the support is equivalent to $\mathbf{V_u = V_{uc} + V_{us}}$. Where V_{uc} = shear force taken by uncracked concrete and $\mathbf{V_{us}}$ **=** shear force taken by vertical stirrup.

Shear force taken by uncracked concrete is given by, $V_{uc} = \mathrm{x}' * \mathrm{b} * \mathrm{F_t} * \mathrm{Cos}\theta$ **Eq (5.1)**

Where. F_t = Split tensile Strength of Concrete, b = width of the beam, $\mathrm{x}' =$ length of the crack, $\mathrm{x}' = \frac{\mathrm{d}}{\mathrm{Sin}\theta}$; d= depth of the beam and angle of inclination θ = 50.574-3.2838(a/d) is obtained from the Figure 15(b); a/d= shear span to depth ratio.

Therefore, substituting the value of $\mathrm{x}' = \frac{\mathrm{d}}{\mathrm{Sin}\theta}$ in above Eq (5.1)

$$\mathbf{V_{uc} = x' * b * F_t * Cos\theta} \qquad \textbf{Eq (5.2)}$$

$$\mathbf{V_{uc} = \frac{d}{Sin\theta} * b * F_t * Cos\theta} \qquad \textbf{Eq (5.3)}$$

$$\mathbf{\frac{V_u}{d * b} = \frac{F_t\, Cos\theta}{Sin\theta}} \qquad \textbf{Eq (5.4)}$$

Shear strength of uncracked concrete is given by

$$\tau_c = \frac{F_t}{Tan\theta} \quad \text{Eq (5.5)}$$

Similarly, Shear force taken by vertical stirrup (V_{us}) is given by

$$V_{us} = \frac{0.87 * f_y * A_{sv}}{Cos\theta} \quad \text{Eq (5.6)}$$

Where; F_y = Yield strength of the stirrup;

A_{SV} = Area of the shear reinforcement;

Therefore, Predicted Theoretical Shear Strength is given by:

$$V_u = V_{uc} + V_{us} \quad \text{Eq (5.7)}$$

$$V_u = Eq(5.3) + Eq(5.6) \quad \text{Eq (5.8)}$$

$$V_u = \left\{\frac{d}{Sin\theta} * b * F_t * Cos\theta\right\} + \left\{\frac{0.87 * f_y * A_{sv}}{Cos\theta}\right\} * k_1 \quad \text{Eq (5.9)}$$

$k_1 = 0$, when crack does not cross the stirrup and $k_1 = 1$ **,** when crack crosses the stirrup.

5.5.1 Comparison of Theoretical and Experimental Shear Strength:

The theoretical shear strength obtained by predicted equation is compared with experimental results. The correlation among experimental and predicted shear strength is in good agreement. Tables 5.10 and 5.11 shows the Experimental and Theoretical Shear Strength for SCC30 and SCC70 for 6mm dia stirrup and 8 mm dia stirrup and percentage error. The percentage error in all the cases is less than 15 % with an average ratio of theoretical and experimental shear strength as 1.02. Figure 5.37 shows the plot among experimental and theoretical shear strength, the equation between experiential and theoretical shear strength is given by **y = 0.9451x + 0.1722; with an R^2 = 0.9612**

5.6 Predicted Analytical Shear Strength based on Non-linear regression analysis:

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

V_u = (0.3*f_{ck})+(0.016*A_{sv})-(0.001*S_v)-(0.038*A_{st})-(0.712*a/d) + (0.8*V_f) Eq (5.10)

Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5). A comparison is made among experimental and analytical predicted shear strength using. From the comparison it was observed that experimental results are close to predicted shear strength. Tables 5.12-5.13 shows the comparison of experimental and analytical shear strength. Figure 5.38 shows the comparison of experimental and analytical shear strength.

5.7 Comparison of test results with various models from Literature:

In this section, the experimental results obtained for ultimate shear strength of non-fibrous SCC and fibrous SCC beams are compared with shear strength models available in the literature for vibrated concrete.

5.7.1 Non-Fibrous SCC

1. **Russo et al. [2004]** after detailed investigation on High Strength Concrete (HSC) beams with stirrups as shear reinforcement, an equation has been proposed to calculate the average shear strength. The parameters varied in their investigation are concrete compressive strength f_c shear span to depth ratio a/d, and stirrup ratio. For beams without shear reinforcement the shear stress is due to arch and beam action.

$$V_{uc} = V_a + V_b \qquad \text{Eq(5.11)}$$

$$V_{uc} = \xi[0.97\rho_s^{0.46} f_c'^{\frac{1}{2}} + 0.2\rho_s^{0.91} f_c'^{0.38} f_{y1}^{0.96}(a/d)^{-2.33}] \qquad \text{Eq(5.12)}$$

$$\text{Where, } \xi = 1/\sqrt{1 + d/(25d_a)} \qquad \text{Eq(5.13)}$$

$$\rho_s = A_s / (bd) \qquad \text{Eq(5.14)}$$

Where v_a *and* v_b are the shear stresses due to the arch and beam actions respectively, ξ is the factor for taking into account of size effect. d is the effective depth of the beam. d_a is the maximum size of coarse aggregate. f'_c is the compressive strength of the circular cylinder. ρ_s is the longitudinal reinforcement ratio. f_{y1} is the yielding strength of the longitudinal reinforcement. a/d is the shear span-to-depth ratio. A third term must be added to equation (1) when stirrups are present.

$$V_u = V_{uc} + V_s \qquad \text{Eq(5.15)}$$

$$V_s = 1.75 I_b \rho_{st} f_{yst} \qquad \text{Eq(5.16)}$$

$$\text{Where, } I_b = \frac{0.97\,\rho_s^{0.46} f_c'^{1/2}}{0.97\,\rho_s^{0.46} f_c'^{1/2} + 0.2\rho_s^{0.91} f_c'^{0.38} f_{y1}^{0.96}(a/d)^{-2.33}} \qquad \text{Eq(5.17)}$$

$$\rho_s = A_s / (bd) \qquad \textbf{Eq(5.18)}$$

Where V_s is the shear stress due to the stirrups, I_b is the index of beam action, f_{yst} is the yielding strength of the stirrup, and ρ_{st} is the stirrup ratio evaluated with reference to the spacing s.

2. **Chinese Code for Design of Concrete Structure, GB50010–2002**

After detailed investigation on Beams with different grades of concrete and Stirrups ratio, Chinese code for design of concrete structures has proposed an equation for vibrated concrete to calculate the shear strength and is given by**.**

$$V_U = \frac{1.75}{1+\lambda} f_t bd + f_{yst} \frac{A_{st}}{s} d \, , \qquad \textbf{Eq(5.19)}$$

$$v_u = \frac{V_u}{bd} \qquad \textbf{Eq(5.20)}$$

Where V_u , is the shear load of the RC member, f_t is the tensile strength of the prism, λ is the shear span-to-depth ratio and v_u is the shear strength of the RC member and s is spacing of stirrups.

3. ACI code 318-14

After detailed investigation on beams with different grades of concrete, different yield strength and stirrups ratio ACI committee has given an equation to calculate shear strength for vibrated concrete.

$$v_u = \frac{1}{7}\left[\sqrt{f'_c} + 120\,\rho_s\left(\frac{d}{a}\right)\right] + \rho_{st} f_{yst} \qquad \textbf{Eq(5.21)}$$

Where v_u is the shear strength, f'_c is the average compressive strength of concrete, ρ_s is the longitudinal reinforcement ratio. f_{yst} is the yielding strength of the longitudinal reinforcement and a/d is the shear span-to-depth ratio.

5.7.2 Fibrous SCC:

1. Narayanan and Darwish

By using steel fibers as shear reinforcement, Narayanan and Darwish has proposed a formula for shear stress due to fiber (v_f).The parameters varied in their investigation were volume fraction (F) of the fibers, fiber aspect ratio (l/d), concrete compressive strength f_{cu}, amount of longitudinal reinforcement(ρ_{st}), and the shear span/effective depth ratio a/d..

$$v_f = 0.41\tau F \qquad \textbf{Eq(5.23)}$$

Were $F = (\frac{l_f}{d_f})\, V_f k_f$ where V_f is shear stress due to steel fibers, τ is the average fibre matrix interfacial bond stress, and τ = 4.15 MPa. F is the fibre factor. $(\frac{l_f}{d_f})$ is the fibre aspect ratio. k_f is the bond factor that accounts for differing bond characteristics of the fibre, it is assigned a relative value of 0.5 for round fibers, 0.75 for crimped fibers, and 1.0 for indented fibers. In the present paper the value of k_f *is taken as* 0.75 as crimped fibers.

2. Ta'an and Feel

A Model was proposed to predict the ultimate shear strength of fibre-reinforced concrete rectangular beams by **Ta'an and Feel.** A total of 89 beams were tested, all the beams have failed in shear. The factors influencing the shear strength of fibre concrete beams were found to be the shear span-to-depth ratio, main reinforcement volume, dimensions, and type.

$$v_f = \frac{8.5}{9} k V_f \frac{l_f}{d_f} \qquad \textbf{Eq(5.24)}$$

Where k is a factor reflecting the fibre shape. For crimped fibers, k = 0.75, V_f is the fibre volume fraction and $(\frac{l_f}{d_f})$ is the fibre aspect ratio.

3. Swamy et al

To assess the effectiveness of steel fibers used as shear reinforcement in lightweight concrete beams **Swamy et al** in their research work has proposed a truss model to predict the ultimate shear strength,

$$v_f = 0.37\tau V_f (\frac{l_f}{d_f}) \qquad \textbf{Eq(5.25)}$$

Where τ is equal to 4.15 MPa as suggested by Narayanan and Darwish and V_f is the fibre volume fraction. $(\frac{l_f}{d_f})$ is the fibre aspect ratio.

2. Lim and Oh

An analytical model to predict shear strength of fiber reinforced concrete was proposed by **Lim and Oh.** A total of nine beams were cast by varying volume fraction of steel fibers and ratio of stirrups to the required shear reinforcement.

$$v_f = 0.5\tau V_f \frac{l_f}{d_f} \cot\alpha \qquad \text{Eq(5.26)}$$

Where α is the inclination between the longitudinal reinforcement and the shear crack, and is equal to 45°and τ is equal to 4.15 MPa as suggested by Narayanan and Darwish and V_f is the fibre volume fraction.

3. Chinese Guidelines for FRC, CECS 38:2004

After detailed investigation on beams with different grades of concrete and stirrups ratio Chinese code has proposed an equation for fiber reinforced concrete.

$$V_{uf} = \frac{1.75}{1+\lambda} f_t bd(1 + \beta_v \lambda_f) + f_{yst} \frac{A_{st}}{s} d \qquad \text{Eq(5.27)}$$

$$v_{uf} = \frac{V_{uf}}{bd}, \qquad \text{Eq(5.28)}$$

Where V_{uf} is the shear load of the fiber reinforced RC member, and β_v is the influence coefficient it is taken as 0.75 for crimped fibre of the steel fibers, λ_f is fiber factor equals to $= V_f(\frac{l_f}{d_f})$ and v_{uf} is shear strength of fiber reinforced RC member.

Tables 5.14 and 5.15 shows the comparison of shear strength values of various models and experimental results and analytical shear strength of SCC30 and SCC70 for both non fibrous and fibrous concrete beams with 6mm Ø stirrup as shear reinforcement. Based on the comparison it is concluded that the shear strength predicted by Russo et al. is relatively close to that of the experimental values. Figures 5.39-5.41 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete. From the above results it can be found that the values predicted by Narayanan and Darwish model for fiber reinforced concrete are relatively close to experimental values. Figures 5.42-5.44 shows the variation of shear strength for various models and experiential results for fibrous SCC30 and SCC70 grade concrete.

5.7.3 Comparison of experimental results with various models for 8mm Ø stirrup.

In this section, experimental results of beams cast with 8mm Ø stirrup were compared with various model as presented above. It is found that as the area of shear reinforcement is increased, ultimate shear strength also increased. Tables 5.16-5.17 show the shear strength values of beams cast with 8 mm Ø stirrup for both non-fibrous and fibrous concretes. From the results it can be concluded that the shear strength predicted by

Russo et al. and Chinese code are relatively close to that of the experimental values. Figures 5.45-5.47 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete. From the results it can be concluded that the shear strength predicted by Narayana and Darwish model is relatively close to that of the experimental values. Figures 5.44-5.46 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete.

5.8 Conclusions from Phase-II:

Based on the detailed studies on Shear behaviour of SCC and SFRSCC Beams using 6mm and 8mm diameter bars as stirrups following conclusions were made.

1. Due to addition of steel fibers, the ultimate shear strength is increased and also the failure mode is changed from sudden brittle failure to ductile behaviour, this is true for both stirrup diameters (6mm and 8mm) and for both grades of concrete SCC30 and SCC70.
2. As the shear span to depth ratio increased from 2 to 3, ultimate shear strength is reduced and similar behaviour was observed in case of both fibrous and non-fibrous concrete for both 6mm and 8mm stirrup and for both grades of concrete SCC30 and SCC70.
3. As the area of shear reinforcement increased, ultimate shear and toughness of the beams also increased.
4. Addition of steel fibers has improved toughness of the beams.
5. As the Spacing of stirrups increased, there is a decrease in ultimate shear strength of the beams.
6. Steel fibers can partially replace stirrups their by reducing the area of shear reinforcement required.
7. As the shear span to depth ratio (a/d) increased, there is a decrease in the crack angle (ϴ).
8. A comparison was made between experimental, analytical shear strength values with various models available on vibrated concrete. It was noticed that the ultimate shear strength predicted by Russo etal model for plain SCC beams and Narayana and

Darwish model for FRSCC are relatively close with experimental values for beams with 6mm and 8 mm diameter stirrup.

Table: 5.1 Beam details

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Fiber content Kg/m^3
1.	**SCC30-0**	2	-	-	-
2.	**SFRSCC30-0**	2	-	-	38
3.	**SCC30-180**	2	180	6	-
4.	**SCC30-360**	2	360	6	-
5.	**SFRSCC30-180**	2	180	6	38
6.	**SFRSCC30-360**	2	360	6	38
7.	**SCC70-0**	2	-	-	-
8.	**SFSCC70-0**	2	-	-	38
9.	**SCC70-180**	2	180	6	-
10.	**SCC70-360**	2	360	6	-
11.	**SFRSCC70-180**	2	180	6	38
12.	**SFRSCC70-360**	2	360	6	38
13.	**SCC30-0**	2.5	-	-	-
14.	**SFRSCC30-0**	2.5	-	-	38
15.	**SCC30-225**	2.5	225	6	-
16.	**SCC30-450**	2.5	450	6	-
17.	**SFRSCC30-225**	2.5	225	6	38
18.	**SFSCC30-450**	2.5	450	6	38
19.	**SCC70-0**	2.5	-	-	-
20.	**SFRSCC70-0**	2.5	-	-	38
21.	**SCC70-225**	2.5	225	6	-
22.	**SCC70-450**	2.5	450	6	-
23.	**SFRSCC70-225**	2.5	225	6	38
24.	**SFRSCC70-450**	2.5	450	6	38
25.	**SCC30-0**	3	-	-	-
26.	**SFRSCC30-0**	3	-	-	38
27.	**SCC30-270**	3	270	6	-
28.	**SCC30-540**	3	540	6	-
29.	**SFRSCC30-270**	3	270	6	38
30.	**SFRSCC30-540**	3	540	6	38
31.	**SCC70-0**	3	-	-	-
32.	**SFRSCC70-0**	3	-	-	38
33.	**SCC70-270**	3	270	6	-
34.	**SCC70-540**	3	540	6	-
35.	**SFRSCC70-270**	3	270	6	38
36.	**SFRSCC70-540**	3	540	6	38

Table 5.2: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=2 for 6mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
NASCC30				
SCC30-0	62.28	1.73	3.74	112.42
SFRSCC30-0	85.24	2.34	5.18	152.03
SCC30-180	95.67	2.66	4.18	234.27
SCC30-360	86.77	2.41	4.12	182.2
SFRSCC30-180	117.92	3.28	6.90	464.1
SFRSCC30-360	102.35	2.84	5.21	328
NASCC70				
SCC70-0	88.43	2.45	3.58	228.50
SFRSCC70-0	101.69	2.55	4.08	440.70
SCC70-180	115.70	3.21	4.92	365.7
SCC70-360	109.7	3.04	3.54	212.2
SFRSCC70-180	159.75	4.44	5.90	525.03
SFRSCC70-360	138.83	3.86	5.40	483.46

Table 5.3: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=2.5 for 6mm Ø stirrup

Designation	Ultimate Load KN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN mm)
NASCC30				
SCC30-0	59.16	1.64	3.54	106.79
SFRSCC30-0	69.89	1.94	5.58	142.03
SCC30-225	82.32	2.29	4.59	213.4
SCC30-450	71.20	1.98	4.25	187.9
SFRSCC30-225	101.46	2.82	6.60	438.25
SFSCC30-450	91.20	2.53	5.45	300.59
NASCC70				
SCC70-0	71.10	1.97	3.38	218.29
SFRSCC70-0	79.25	2.20	4.18	387.11
SCC70-225	100.69	2.80	5.08	318.92
SCC70-450	88.77	2.47	4.02	188
SFRSCC70-225	128.15	3.56	5.97	446
SFRSCC70-450	117.48	3.26	5.59	393.08

Table 5.4: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=3 for 6mm Ø stirrup

Designation	Ultimate Load (KN)	Ultimate Shear Strength MPa	Max. Deflection (mm)	Toughness (kN-mm)
NASCC30				
SCC30-0	48.42	1.34	3.84	101.45
SFRSCC30-0	50.84	1.41	5.68	134.89
SCC30-270	77.12	2.14	4.16	167.50
SCC30-540	50.95	1.42	5.18	100.83
SFRSCC30-270	93.45	2.60	6.55	359.40
SFRSCC30-540	80.99	2.25	5.50	285.60
NASCC70				
SCC70-0	68.49	1.90	3.48	208.29
SFRSCC70-0	71.32	1.98	4.48	374.11
SCC70-270	100.44	2.79	3.66	197.70
SCC70-540	72.10	2.10	2.34	156.02
SFRSCC70-270	131.27	3.65	5.40	440.70
SFRSCC70-540	91.67	2.55	4.08	398.50

Table 5.5: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=2 for 8mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
NASCC30				
SCC30-0	62.28	1.73	3.74	112.42
SFRSCC30-0	85.24	2.34	5.18	152.03
SCC30-180	113.62	3.16	3.9	252
SCC30-360	100.65	2.80	3.64	144
SFRSCC30-180	127.04	3.53	5.24	436
SFRSCC30-360	122.57	3.40	4.52	318
NASCC70				
SCC70-0	88.43	2.45	3.58	228.50
SFRSCC70-0	101.59	2.55	4.08	440.70
SCC70-180	174.59	4.85	9.82	1471
SCC70-360	143.15	3.98	5.2	513
SFRSCC70-180	199.06	5.53	5.63	1588
SFRSCC70-360	158.80	4.41	5.32	586

Table 5.6: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=2.5 for 8mm Ø stirrup

Designation	Ultimate Load KN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN mm)
NASCC30				
SCC30-0	59.16	1.64	3.54	106.79
SFRSCC30-0	69.89	1.94	5.58	142.03
SCC30-225	90.52	2.51	5.32	248
SCC30-450	76.94	2.14	2.78	109.2
SFRSCC30-225	109.60	3.04	6.18	457.38
SFRSCC30-450	91.70	2.55	3.87	296.4
NASCC70				
SCC70-0	71.10	1.97	3.38	218.29
SFRSCC70-0	79.25	2.20	4.18	387.11
SCC70-225	145.38	4.04	5.52	518
SCC70-450	93.94	2.61	3	140
SFRSCC70-225	154.78	4.30	7.4	1441
SFRSCC70-450	127.49	3.54	3.7	487

Table 5.7: Ultimate load and shear strength of fibrous and non-fibrous NASCC beams for a/d=3 for 8mm Ø stirrup

Designation	Ultimate Load (KN)	Ultimate Shear Strength MPa	Max. Deflection (mm)	Toughness (kN-mm)
NASCC30				
SCC30-0	48.42	1.34	3.84	101.45
SFRSCC30-0	50.84	1.41	5.68	134.89
SCC30-270	84.51	2.34	3.98	168.36
SCC30-540	55.92	1.55	2.8	112.68
SFRSCC30-270	93.94	2.61	4.49	347.68
SFRSCC30-540	87.39	2.42	3.9	296
NASCC70				
SCC70-0	68.49	1.90	3.48	208.29
SFRSCC70-0	71.32	1.98	4.48	374.11
SCC70-270	110.65	3.07	4.1	315
SCC70-540	75.57	1.99	2.3	279.84
SFRSCC70-270	150.75	4.19	5.2	1114
SFRSCC70-540	95.65	2.80	3.5	468

Table: 5.8 Crack Angle for NASCC30 beams with 6mm Ø stirrup

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Crack Angle (Θ)
1.	**SCC30-0**	2	-	-	**43.60**
2.	**SRFSCC30-0**	2	-	-	**43.47**
3.	**SCC30-180**	2	180	6	**43.60**
4.	**SCC30-360**	2	360	6	**42.27**
5.	**SRFSCC30-180**	2	180	6	**44.29**
6.	**SRFSCC30-360**	2	360	6	**43.88**
				Average:	**43.52**
7.	**SCC30-0**	2.5	-	-	**42.27**
8.	**SFRSCC30-0**	2.5	-	-	**43.74**
9.	**SCC30-225**	2.5	225	6	**42.93**
10.	**SCC30-450**	2.5	450	6	**41.63**
11.	**SFRSCC30-225**	2.5	225	6	**43.60**
12.	**SFRSCC30-450**	2.5	450	6	**42.02**
				Average:	**42.70**
13.	**SCC30-0**	3	-	-	**36.53**
14.	**SFRSCC30-0**	3	-	-	**40.40**
15.	**SCC30-270**	3	270	6	**40.28**
16.	**SCC30-540**	3	540	6	**41.01**
17.	**SFRSCC30-270**	3	270	6	**43.33**
18.	**SFRSCC30-540**	3	540	6	**41.26**
				Average:	**40.47**
			SCC70		
1.	**SCC70-0**	2	-	-	**43.60**
2.	**SFRSCC70-0**	2	-	-	**44.43**
3.	**SCC70-180**	2	180	6	**44.57**
4.	**SCC70-360**	2	360	6	**44.01**
5.	**SFRSCC70-180**	2	180	6	**44.71**
6.	**SFRSCC70-360**	2	360	6	**43.88**
				Average:	**44.20**
7.	**SCC70-0**	2.5	-	-	**41.76**
8.	**SFRSCC70-0**	2.5	-	-	**42.27**
9.	**SCC70-225**	2.5	225	6	**42.93**
10.	**SCC70-450**	2.5	450	6	**42.27**
11.	**SFRSCC70-225**	2.5	225	6	**44.57**
12.	**SFRSCC70-450**	2.5	450	6	**42.14**
				Average:	**42.66**
13.	**SCC70-0**	3	-	-	**39.81**
14.	**SFRSCC70-0**	3	-	-	**40.52**
15.	**SCC70-270**	3	270	6	**40.89**
16.	**SCC70-540**	3	540	6	**40.04**
17.	**SFRSCC70-270**	3	270	6	**42.14**
18.	**SFRSCC70-540**	3	540	6	**40.76**
				Average:	**40.69**

Table: 5.9 Crack Angle for NASCC beams with 8mm Ø stirrup

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Crack Angle (ϴ)
1.	**SCC30-0**	2	-	-	**44.10**
2.	**SRFSCC30-0**	2	-	-	**43.97**
3.	**SCC30-180**	2	180	8	**44.10**
4.	**SCC30-360**	2	360	8	**42.77**
5.	**SRFSCC30-180**	2	180	8	**44.79**
6.	**SRFSCC30-360**	2	360	8	**44.38**
7.	**SCC70-0**	2	-	-	**45.07**
8.	**SFRSCC70-0**	2	-	-	**45.21**
9.	**SCC70-180**	2	180	8	**45.07**
10.	**SCC70-360**	2	360	8	**43.56**
11.	**SFRSCC70-180**	2	180	8	**45.21**
12.	**SFRSCC70-360**	2	360	8	**44.10**
13.	**SCC30-0**	2.5	-	-	**42.77**
14.	**SFRSCC30-0**	2.5	-	-	**44.24**
15.	**SCC30-225**	2.5	225	8	**43.43**
16.	**SCC30-450**	2.5	450	8	**42.13**
17.	**SFRSCC30-225**	2.5	225	8	**44.10**
18.	**SFRSCC30-450**	2.5	450	8	**42.52**
		SCC70			
19.	**SCC70-0**	2.5	-	-	**42.26**
20.	**SFRSCC70-0**	2.5	-	-	**42.77**
21.	**SCC70-225**	2.5	225	8	**43.43**
22.	**SCC70-450**	2.5	450	8	**42.77**
23.	**SFRSCC70-225**	2.5	225	8	**45.07**
24.	**SFRSCC70-450**	2.5	450	8	**42.64**
25.	**SCC30-0**	3	-	-	**37.03**
26.	**SFRSCC30-0**	3	-	-	**40.90**
27.	**SCC30-270**	3	270	8	**40.78**
28.	**SCC30-540**	3	540	8	**41.51**
29.	**SFRSCC30-270**	3	270	8	**43.83**
30.	**SFRSCC30-540**	3	540	8	**41.76**
31.	**SCC70-0**	3	-	-	**40.31**
32.	**SFRSCC70-0**	3	-	-	**41.02**
33.	**SCC70-270**	3	270	8	**41.39**
34.	**SCC70-540**	3	540	8	**40.54**
35.	**SFRSCC70-270**	3	270	8	**42.64**
36.	**SFRSCC70-540**	3	540	8	**41.26**

Table: 5.10 Experimental vs Theoretical Shear Strength for NASCC30

Designation	Experimental		Theoretical		% Error	Theoretical/ experimental
	Load kN	Shear Strength, MPa	Load kN	Shear Strength, MPa		
			6 mm Ø			
SCC30-0	62.28	1.7	69.36	1.93	**11.37**	
SFRSCC30-0	85.24	2.4	82.41	2.29	**3.31**	1.11
SCC30-180	95.67	2.7	97.93	2.72	**2.36**	0.97
SCC30-360	86.77	2.4	81.97	2.28	**5.53**	1.02
SFRSCC30-180	117.92	3.3	118.63	3.30	**0.60**	0.94
SFRSCC30-360	102.35	2.8	105.2	2.92	**2.78**	1.01
SCC30-0	59.16	1.6	56.87	1.58	**3.87**	1.03
SFRSCC30-0	69.89	1.9	70.98	1.97	**1.57**	0.96
SCC30-225	82.32	2.3	99.79	2.77	**2.69**	1.02
SCC30-450	71.2	2.0	74.31	2.06	**4.38**	1.21
SFRSCC30-225	101.46	2.8	101.71	2.83	**0.25**	1.04
SFRSCC30-450	91.2	2.5	86.71	2.41	**4.92**	1.00
SCC30-0	46.81	1.3	43.67	1.21	**6.69**	0.95
SFRSCC30-0	48.59	1.3	48.06	1.33	**1.09**	0.93
SCC30-270	67.33	1.9	77.95	2.17	**15.77**	0.99
SCC30-540	57.56	1.6	59.42	1.65	**3.30**	1.16
`SFRSCC30-270	95.66	2.7	102.49	2.85	**7.14**	1.03
SFRSCC30-540	75.1	2.1	77.42	2.15	**3.09**	1.07
			8 mm Ø			
SCC30-0	62.28	1.7	64.54	1.79	**3.64**	1.03
SFRSCC30-0	85.24	2.4	80.98	2.25	**4.99**	1.04
SCC30-180	113.62	3.2	113.46	3.15	**0.14**	0.95
SCC30-360	100.65	2.8	99.70	2.77	**0.94**	1.00
SFRSCC30-180	127.04	3.5	123.99	3.44	**2.40**	0.99
SFRSCC30-360	122.57	3.4	112.31	3.12	**8.37**	0.98
SCC30-0	59.16	1.6	57.88	1.61	**2.16**	0.92
SFRSCC30-0	69.89	1.9	80.22	2.23	**14.78**	0.98
SCC30-225	90.52	2.5	78.72	2.19	**13.04**	1.15
SCC30-450	76.94	2.1	73.02	2.03	**5.09**	0.87
SFRSCC30-225	109.6	3.0	106.33	2.95	**2.98**	0.95
SFRSCC30-450	91.7	2.5	94.71	2.63	**3.29**	0.97
SCC30-0	48.42	1.3	49.027	1.36	**1.25**	1.03
SFRSCC30-0	50.84	1.4	59.08	1.64	**16.21**	1.01
SCC30-270	84.51	2.3	76.58	2.13	**9.38**	1.16
SCC30-540	55.92	1.6	56.40	1.57	**0.86**	0.91
SFRSCC30-270	93.94	2.6	90.40	2.51	**3.77**	1.01
SFRSCC30-540	87.39	2.4	87.50	2.43	**0.13**	0.96
					Average	**1.02**

Table: 5.11 Experimental vs Theoretical Shear Strength for NASCC70

Designation	Experimental		Theoretical		% Error	Theoretical/ experimental
	Load kN	Shear Strength, MPa	Load kN	Shear Strength, MPa		
6 mm Ø						
SCC70-0	88.2	2.5	92.08	2.56	**4.40**	1.04
SFRSCC70-0	91.8	2.6	106.17	2.95	**15.65**	1.16
SCC70-180	115.56	3.2	112.09	3.11	**3.00**	0.97
SCC70-360	109.44	3.0	104.13	2.89	**4.85**	0.95
SFRSCC70-180	159.84	4.4	162.54	4.52	**1.69**	1.02
SFRSCC70-360	138.96	3.9	148.18	4.12	**6.63**	1.07
SCC70-0	70.92	2.0	79.53	2.21	**12.14**	1.12
SFRSCC70-0	79.2	2.2	87.50	2.43	**10.48**	1.10
SCC70-225	100.8	2.8	97.52	2.71	**16.60**	0.97
SCC70-450	88.92	2.5	99.79	2.77	**12.23**	1.12
SFRSCC70-225	128.16	3.6	126.89	3.52	**0.99**	0.99
SFRSCC70-450	117.36	3.3	116.36	3.23	**0.86**	0.99
SCC70-0	68.4	1.9	68.84	1.91	**0.65**	1.01
SFRSCC70-0	71.28	2.0	80.74	2.24	**13.27**	1.13
SCC70-270	100.44	2.8	104.78	2.91	**4.32**	1.04
SCC70-540	75.6	2.1	78.74	2.19	**4.16**	1.04
SFRSCC70-270	131.4	3.7	129.37	3.59	**1.55**	0.98
SFRSCC70-540	91.8	2.6	92.30	2.56	**0.55**	1.01
8 mm Ø						
SCC70-0	88.2	2.5	90.48	2.51	**2.59**	1.03
SFRSCC70-0	91.8	2.6	97.29	2.70	**5.98**	1.06
SCC70-180	174.6	4.9	177.78	4.94	**1.82**	1.02
SCC70-360	143.28	4.0	133.24	3.70	**7.01**	0.93
SFRSCC70-180	199.08	5.5	191.63	5.32	**3.74**	0.96
SFRSCC70-360	158.76	4.4	145.8	4.05	**8.17**	0.92
SCC70-0	70.92	2.0	72.78	2.02	**2.63**	1.03
SFRSCC70-0	79.2	2.2	80.00	2.22	**1.01**	1.01
SCC70-225	145.44	4.0	147.21	4.09	**1.22**	1.01
SFRSCC70-225	154.8	4.3	165.2	4.59	**6.72**	1.07
SCC70-450	93.96	2.6	90.48	2.51	**3.70**	0.96
SFRSCC70-450	127.44	3.5	114.34	3.18	**10.28**	0.90
SCC70-0	68.4	1.9	75.30	2.09	**10.09**	1.10
SFRSCC70-0	73.08	2.0	85.20	2.37	**16.60**	1.17
SCC70-270	110.52	3.1	102.95	2.86	**6.85**	0.93
SCC7-540	85.32	2.4	83.00	2.31	**2.71**	0.97
SFRSCC70-270	150.84	4.2	153.42	4.26	**1.71**	1.02
SFRSCC70-540	115.56	3.2	120.01	3.33	**3.85**	1.04

Table: 5.12 Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 6mm diameter stirrup.

Designation	Experimental	Analytical	Exp/Analytical
	SCC30		
SCC30-0	1.73	1.77	0.98
SFRSCC30-0	2.14	2.17	0.99
SCC30-180	2.66	2.49	1.07
SCC30-360	2.41	2.31	1.04
SFRSCC30-180	3.28	2.89	1.13
SFRSCC30-360	2.84	2.71	1.05
SCC30-0	1.64	1.42	1.15
SFRSCC30-0	1.94	1.82	1.07
SCC30-225	2.29	2.09	1.10
SCC30-450	1.98	1.86	1.06
SFRSCC30-225	2.82	2.49	1.13
SFRSCC30-450	2.53	2.26	1.12
SCC30-0	1.34	1.06	1.26
SFRSCC30-0	1.41	1.46	0.97
SCC30-270	1.73	1.69	1.02
SCC30-540	1.42	1.41	1.01
SFRSCC30-270	2.6	2.56	1.02
SFRSCC30-540	2.25	2.19	1.03
	SCC70		
SCC70-0	2.45	2.6	0.94
SFRSCC70-0	2.55	3	0.85
SCC70-180	3.21	3.31	0.97
SCC70-360	3.04	3.13	0.97
SFRSCC70-180	4.44	3.71	1.20
SFRSCC70-360	3.86	3.53	1.09
SCC70-0	1.97	2.24	0.88
SFRSCC70-0	2.2	2.64	0.83
SCC70-225	2.8	2.91	0.96
SCC70-450	2.47	2.68	0.92
SFRSCC70-225	3.65	3.31	1.10
SFRSCC70-450	3.26	3.08	1.06
SCC70-0	1.9	1.88	1.01
SFRSCC70-0	1.98	2.28	0.87
SCC70-270	2.79	2.51	1.11
SCC70-540	2.1	2.24	0.94
SFRSCC70-270	3.56	3.36	1.06
SFRSCC70-540	2.55	2.63	0.97

Table: 5.13 Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 8mm diameter stirrup.

Designation	Experimental	Analytical	Exp/Pre
SCC30-0	1.73	1.77	0.98
SFRSCC30-0	2.34	2.17	1.08
SCC30-180	3.16	3.19	0.99
SCC30-360	2.8	3.01	0.93
SFRSCC30-180	3.53	3.59	0.98
SFRSCC30-360	3.4	3.4	1.00
SCC30-0	1.64	1.42	1.15
SFRSCC30-0	1.94	1.82	1.07
SCC30-225	2.51	2.79	0.90
SCC30-450	2.14	2.56	0.84
SFRSCC30-225	3.04	3.19	0.95
SFRSCC30-450	2.55	2.96	0.86
SCC30-0	1.34	1.06	1.26
SFRSCC30-0	1.41	1.46	0.97
SCC30-270	2.34	2.39	0.98
SCC30-540	1.55	2.11	0.73
SFRSCC30-270	2.61	2.78	0.94
SFRSCC30-540	2.42	2.51	0.96
SCC70			
SCC70-0	2.45	2.6	0.94
SFRSCC70-0	2.55	3	0.85
SCC70-180	4.85	4.78	1.01
SCC70-360	3.98	3.83	1.04
SFRSCC70-180	5.53	4.41	1.25
SFRSCC70-360	4.41	4.23	1.04
SCC70-0	1.97	2.24	0.88
SFRSCC70-0	2.2	2.64	0.83
SCC70-225	4.04	3.61	1.12
SCC70-450	2.61	3.38	0.77
SFRSCC70-225	4.3	4.01	1.07
SFRSCC70-450	3.54	3.78	0.94
SCC70-0	1.9	1.88	1.01
SFRSCC70-0	2.03	2.28	0.89
SCC70-270	3.07	3.21	0.96
SCC70-540	2.37	2.93	0.81
SFRSCC70-270	4.19	3.61	1.16
SFRSCC70-540	2.8	3.33	0.84

Table 5.14 Shear strength of SCC beams without steel fibers for 6mm Ø stirrup.

Type	Russo et al. V_u MPa	Chinese Code V_u MPa	ACI code 318-14 V_u MPa	Experimental V_u MPa	Analytical V_u MPa
a/d=2					
SCC30-0	1.64	2.32	1.01	1.73	1.65
SCC70-0	3.84	3.12	1.51	2.45	2.47
SCC30-180	2.30	3.23	2.57	2.66	2.62
SCC70-180	4.40	4.03	2.97	3.21	3.44
SCC30-360	1.97	2.78	1.46	2.41	2.29
SCC70-360	4.12	3.57	1.96	2.6	3.11
a/d=2.5					
SCC30-0	1.3	1.99	0.99	1.64	1.32
SCC70-0	2.8	2.67	1.46	1.97	2.14
SCC30-225	1.94	2.72	1.71	2.29	2.2
SCC70-225	3.42	3.40	2.19	2.8	3.02
SCC30-450	1.60	2.35	1.35	2.03	1.79
SCC70-450	3.12	3.03	1.82	2.47	2.61
a/d=3					
SCC30-0	1.1	1.74	0.97	1.34	1.28
SCC70-0	2.3	2.34	1.43	1.90	1.81
SCC30-270	1.73	2.35	1.58	1.73	1.79
SCC70-270	2.91	2.94	2.03	2.41	2.61
SCC30-540	1.39	2.04	1.27	1.42	1.29
SCC70-540	2.61	2.64	1.73	2.10	2.12

Table 5.15 Shear strength of steel fibre reinforced SCC beams for 6 mm Ø stirrup.

Type	Narayanan and Darwish V_{uf} MPa	Ta'an and Feel V_{uf} MPa	Swamy et al V_{uf} MPa	Lim and Oh V_{uf} MPa	Chines code for FRC V_{uf} MPa	Experimental V_{uf} MPa	Analytical V_{uf} MPa
a/d=2							
SFRSCC30-0	2.56	2.15	2.74	3.13	3.58	2.34	2.14
SFRSCC70-0	4.76	4.36	4.95	3.85	4.80	2.55	2.96
SFRSCC30-180	3.22	2.81	3.40	3.79	4.49	3.28	3.11
SFRSCC70-180	5.32	4.91	5.50	5.89	5.71	4.44	3.93
SFRSCC30-360	2.89	2.48	3.08	3.47	4.03	2.84	2.78
SFRSCC70-360	5.04	4.63	5.23	5.62	5.25	3.86	3.6
a/d=2.5							
SFRSCC30-0	2.17	1.76	2.36	2.75	3.06	1.94	1.81
SFRSCC70-0	3.74	3.33	3.93	4.32	4.11	2.20	2.63
SFRSCC30-225	2.86	2.45	3.05	3.43	3.79	2.82	2.69
SFRSCC70-225	4.34	3.93	4.53	4.91	4.84	3.56	3.52

SFRSCC30-450	2.51	2.11	2.70	3.09	3.43	2.53	2.28
SFRSCC70-450	4.04	3.63	4.23	4.62	4.48	3.26	3.11
			a/d=3				
SFRSCC30-0	1.97	1.56	2.16	2.55	2.68	1.41	1.48
SFRSCC70-0	3.22	2.81	3.41	3.80	3.60	1.98	2.3
SFRSCC30-270	2.65	2.24	2.84	3.23	3.29	2.60	2.28
SFRSCC70-270	3.83	3.42	4.02	4.41	4.20	3.65	3.1
SFRSCC30-540	2.31	1.90	2.50	2.89	2.98	2.25	2.19
SFRSCCC70-540	3.53	3.12	3.71	4.10	3.90	2.55	2.61

Table 5.16 Shear strength of SCC beams without steel fibers for 8 mm Ø stirrup.

Type	Russo et al. V_u MPa	Chinese Code V_u MPa	ACI code 318-02 V_u MPa	Experimental V_u MPa	Analytical V_u MPa
			a/d=2		
SCC30-0	1.64	2.32	1.01	1.73	1.65
SCC70-0	3.84	3.12	1.51	2.45	2.47
SCC30-180	2.81	3.94	2.63	3.16	3.15
SCC70-180	4.82	4.73	3.13	4.85	3.97
SCC30-360	2.23	3.13	1.82	2.80	2.92
SCC70-360	4.34	3.92	2.32	3.98	3.74
			a/d=2.5		
SCC30-0	1.30	1.99	0.99	1.64	1.32
SCC70-0	2.80	2.67	1.46	1.97	2.14
SCC30-225	2.48	3.29	2.28	2.51	2.76
SCC70-225	3.88	3.97	2.75	4.04	3.58
SCC30-450	1.86	2.64	1.63	2.14	2.47
SCC70-450	3.35	3.32	2.11	2.61	3.29
			a/d=3		
SCC30-0	1.1	1.74	0.97	1.34	1.28
SCC70-0	2.3	2.34	1.43	1.90	1.81
SCC30-270	2.27	2.82	2.05	2.05	2.37
SCC70-270	3.39	3.42	2.51	2.80	3.19
SCC30-540	1.66	2.28	1.51	1.55	2.02
SCC70-540	2.85	2.88	1.97	1.99	2.85

Table 5.17 Shear strength of steel fibre reinforced SCC beams for 8 mm Ø stirrup.

Type	Narayanan and Darwish V_{uf} MPa	Ta'an and Feel V_{uf} MPa	Swamy et al V_{uf} MPa	Lim and Oh V_{uf} MPa	Experimental V_{uf} MPa	Chines code for FRC V_{uf} MPa	Analytical V_{uf} MPa
			a/d=2				
SFRSCC30-0	2.56	2.15	2.74	3.13	2.34	3.58	2.14

SFRSCC70-0	4.76	4.36	4.95	3.85	2.55	4.80	2.96
SFRSCC30-180	3.28	3.32	3.91	4.30	3.53	5.19	3.64
SFRSCC70-180	5.74	5.33	5.93	6.32	5.53	6.42	5.37
SFRSCC30-360	3.14	2.74	3.33	3.72	3.40	4.38	3.41
SFRSCC70-360	5.25	4.85	5.44	5.83	4.41	5.61	4.23
a/d=2.5							
SFRSCC30-0	2.17	1.76	2.36	2.75	1.94	3.06	1.81
SFRSCC70-0	3.74	3.33	3.93	4.32	2.20	4.11	2.63
SFRSCC30-225	2.82	2.99	3.58	3.97	3.04	4.36	3.25
SFRSCC70-225	3.56	4.39	4.99	5.38	4.30	5.41	4.07
SFRSCC30-450	2.78	2.37	2.97	3.36	2.55	3.71	2.96
SFRSCC70-450	4.27	3.86	4.46	4.85	3.54	4.76	3.78
a/d=3							
SFRSCC30-0	1.97	1.56	2.16	2.55	1.41	2.68	1.48
SFRSCC70-0	3.22	2.81	3.41	3.80	1.98	3.60	2.3
SFRSCC30-270	3.18	2.78	3.37	3.76	2.61	3.76	2.86
SFRSCC70-270	4.31	3.90	4.49	4.88	4.19	4.68	3.68
SFRSCC30-540	2.58	2.17	2.76	3.15	2.42	3.22	2.52
SFRSCCC70-540	3.76	3.36	3.95	4.34	2.80	4.14	3.34

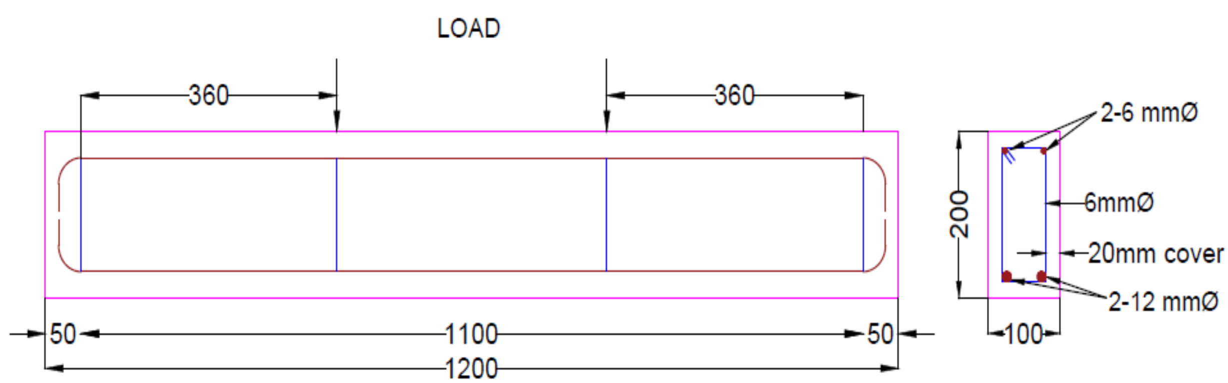


Figure: 5.1(a)

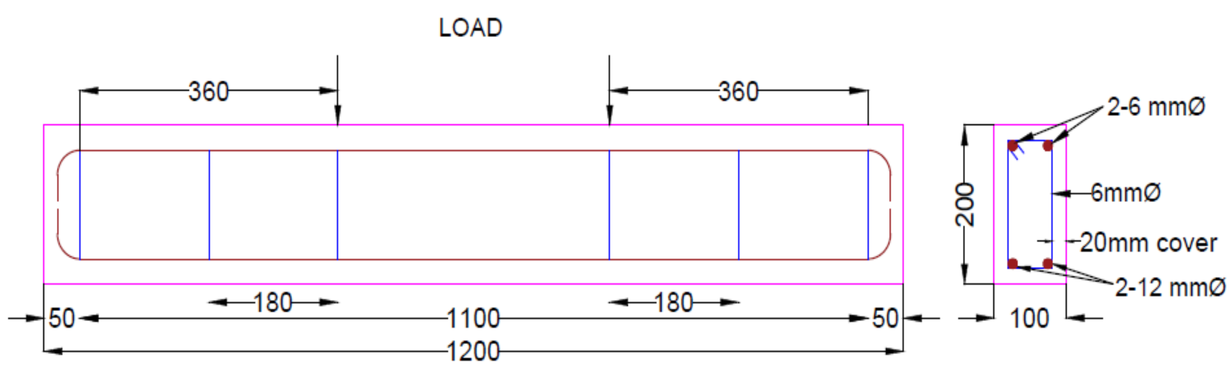


Figure: 5.1(b)

Figure: 5.1 Details of reinforcement for M30 mix with a/d=2

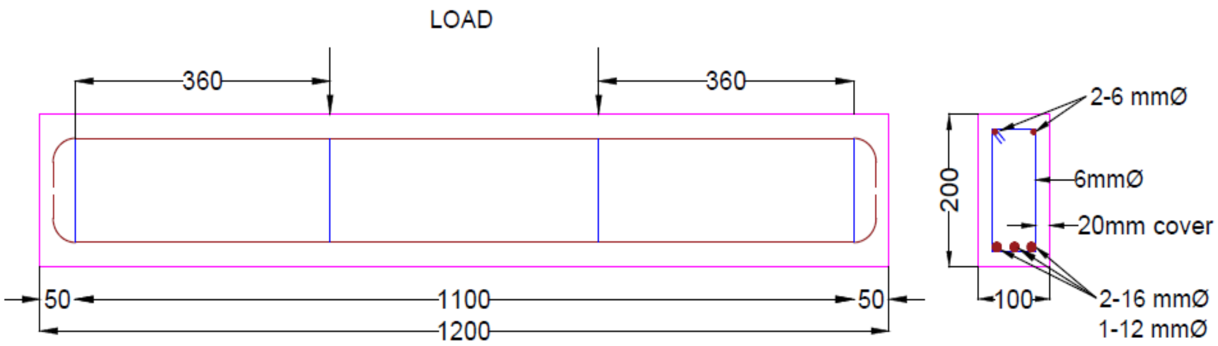


Figure: 5.2(a)

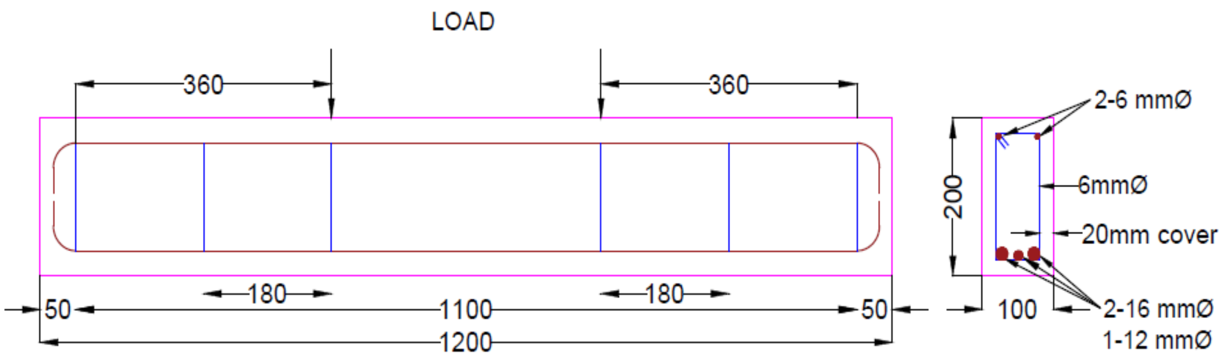


Figure: 5.2(b)

Figure: 5.2 Details of reinforcement for M70 Mix with a/d=2

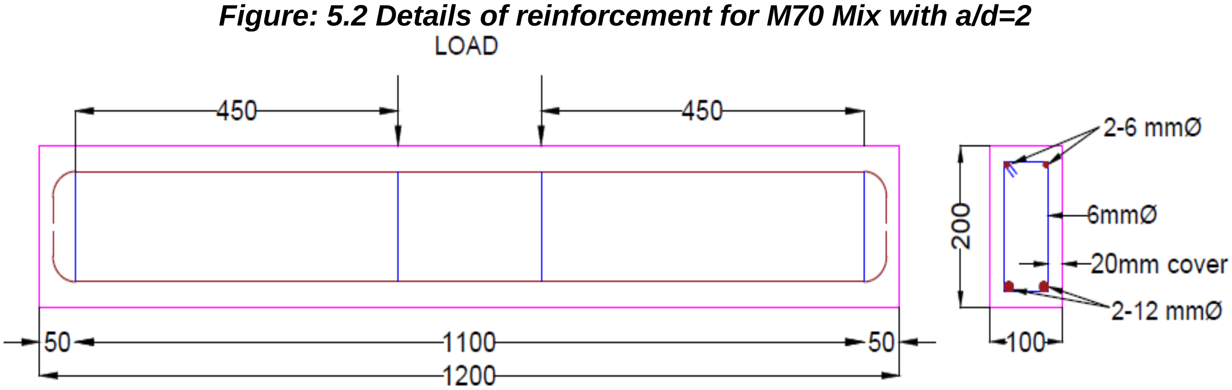


Figure: 5.3(a)

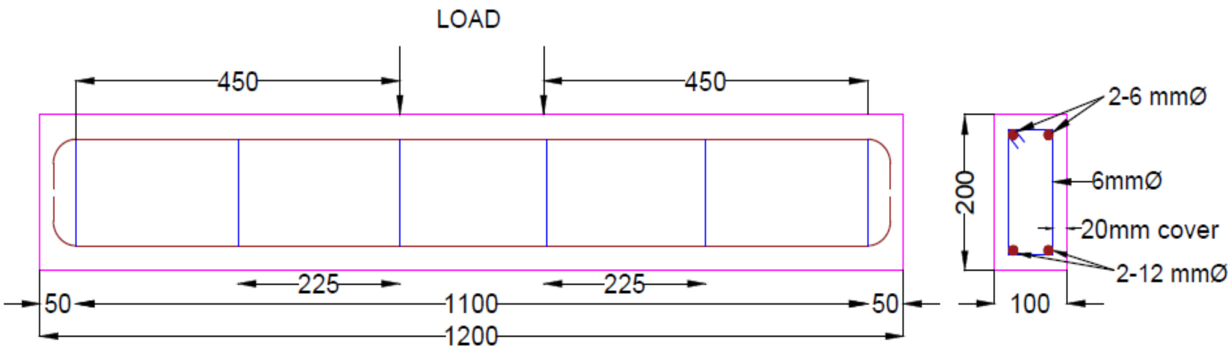


Figure: 5.3(b)

Figure: 5.3 Details of reinforcement for M30 Mix with a/d=2.5

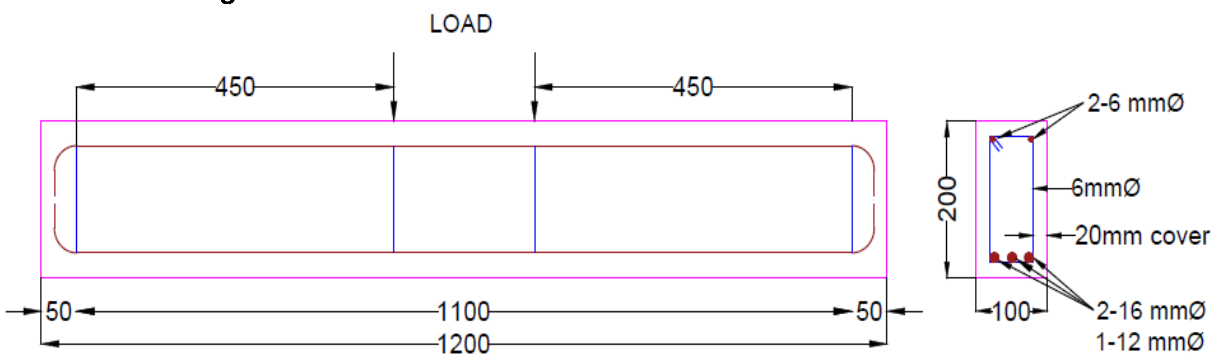


Figure: 5.4(a)

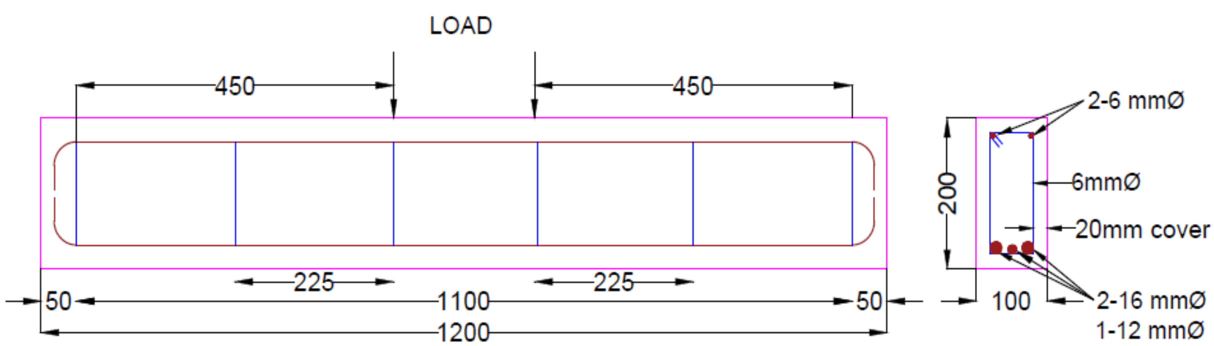


Figure: 5.4(b)

Figure: 5.4 Details of reinforcement for M70 Mix with a/d=2.5

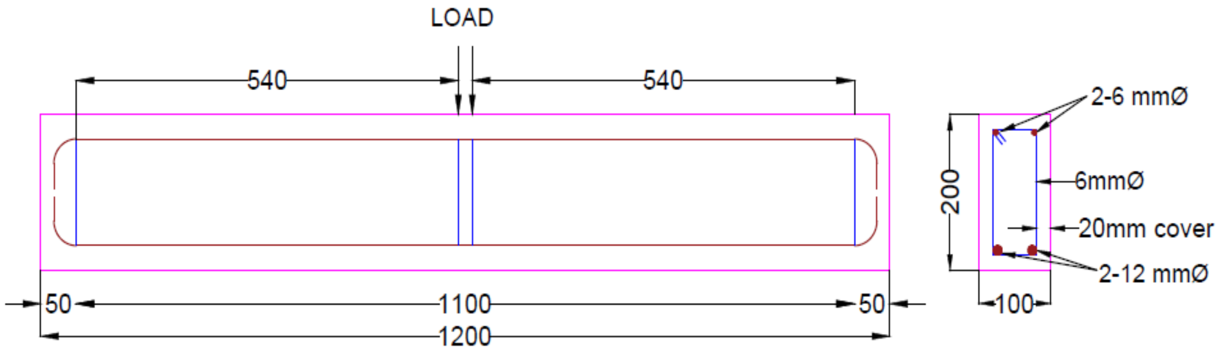


Figure: 5.5(a)

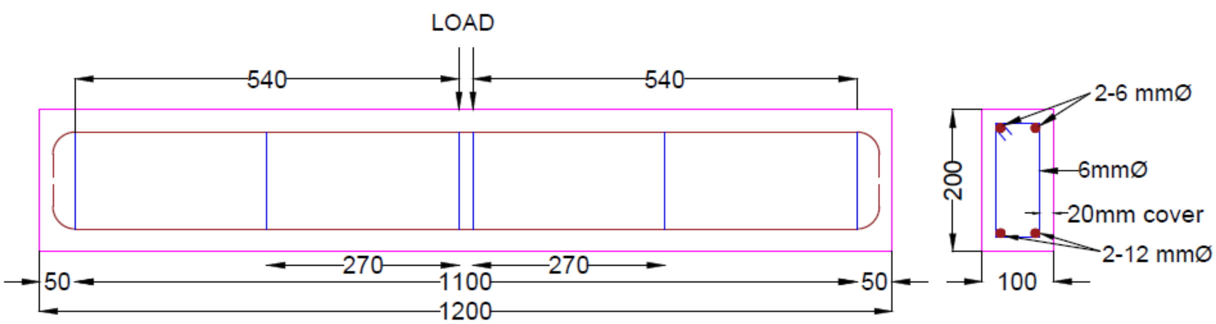


Figure: 5.5(b)

Figure: 5.5 Details of reinforcement for M30 Mix with a/d=3

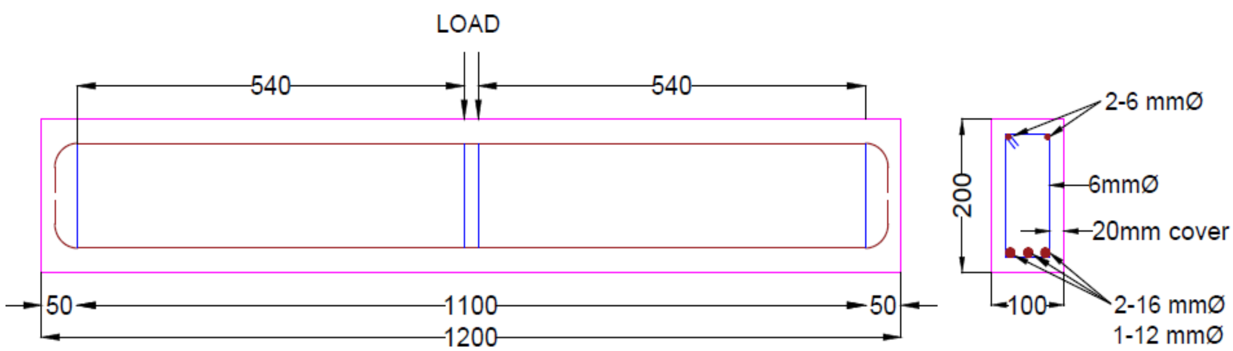


Figure: 5.6(a)

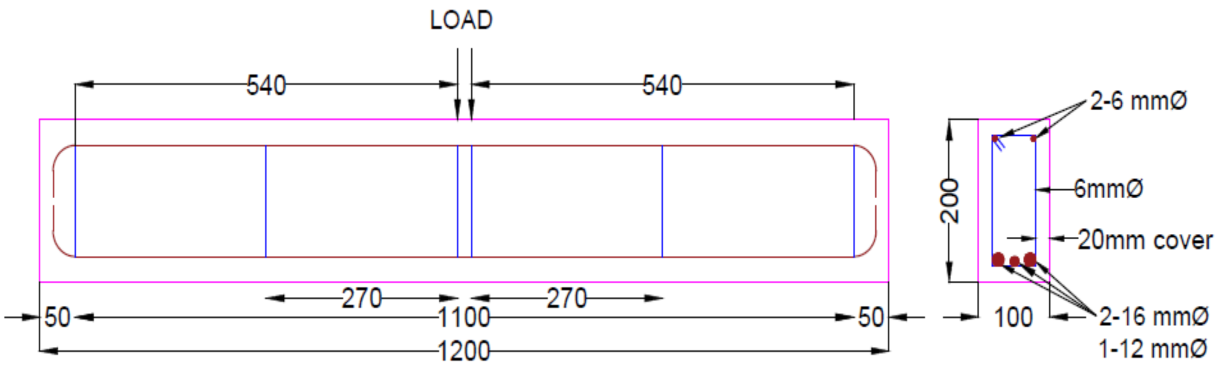


Figure: 5.6(b)

Figure: 5.6 Details of reinforcement for M70 Mix with a/d=3

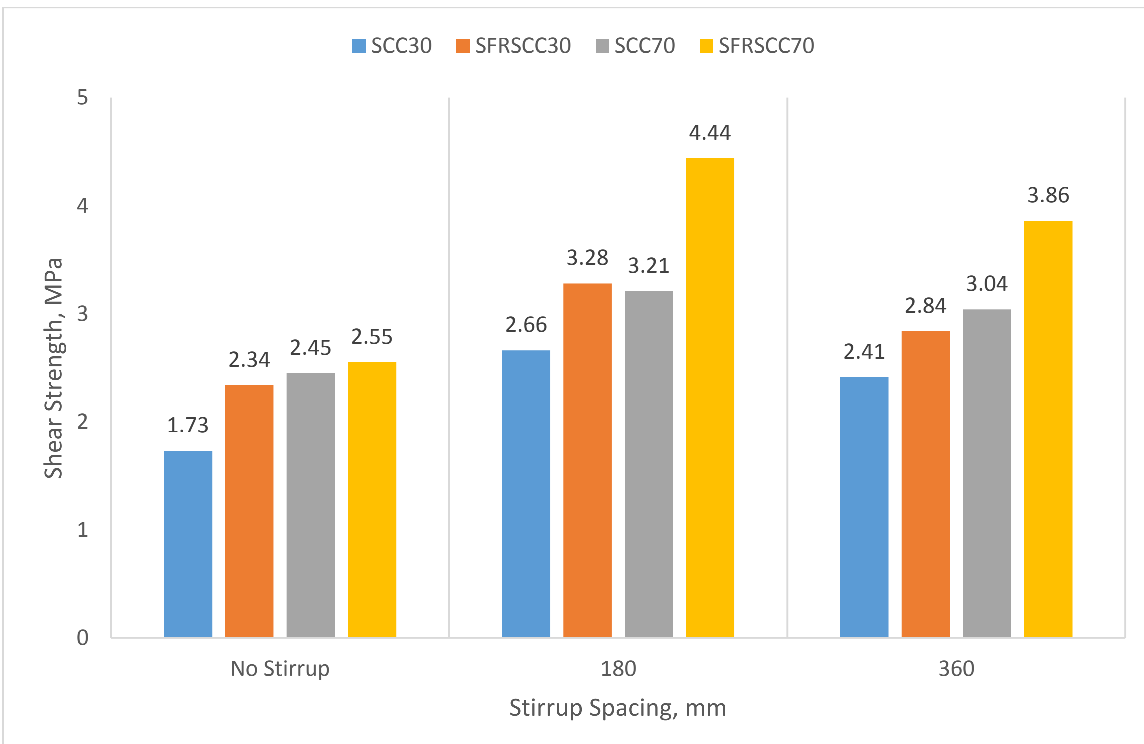


Figure 5.7: Shear Strength Vs Spacing of Stirrups for (SCC30 & SCC70, a/d=2)

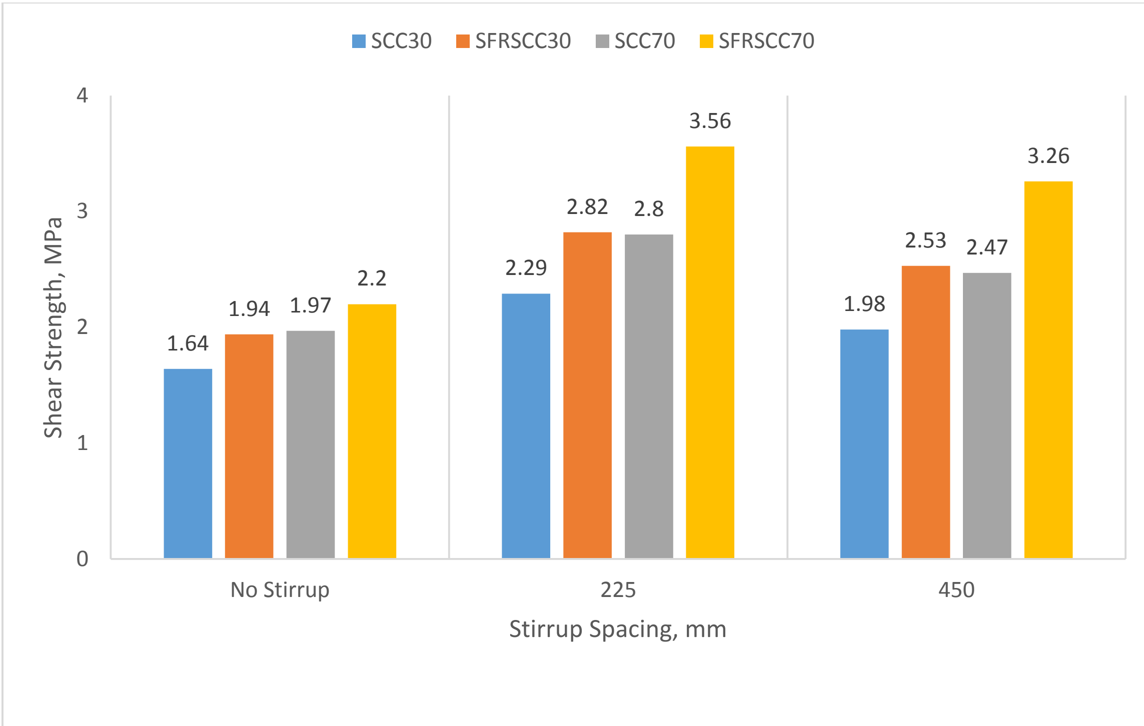


Figure 5.8: Shear Strength Vs Spacing of Stirrups for (SCC30 & SCC70, a/d=2.5)

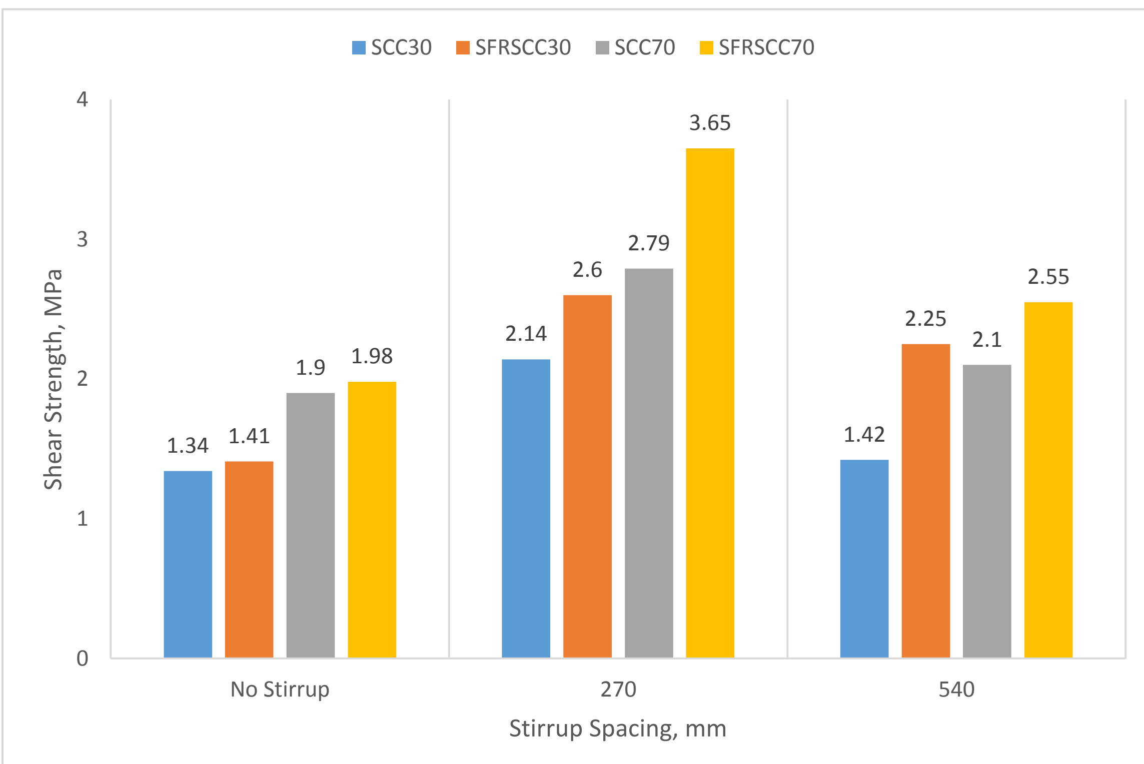


Figure 5.9: Shear Strength Vs Spacing of Stirrups for (SCC30 & SCC70, a/d=3)

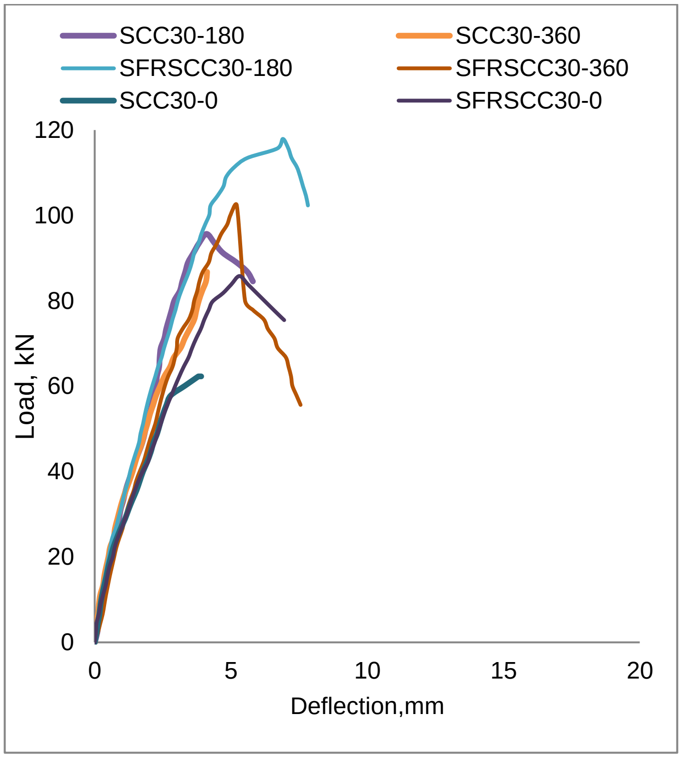


Figure 5.10 : Load vs Deflection for SCC30 a/d=2

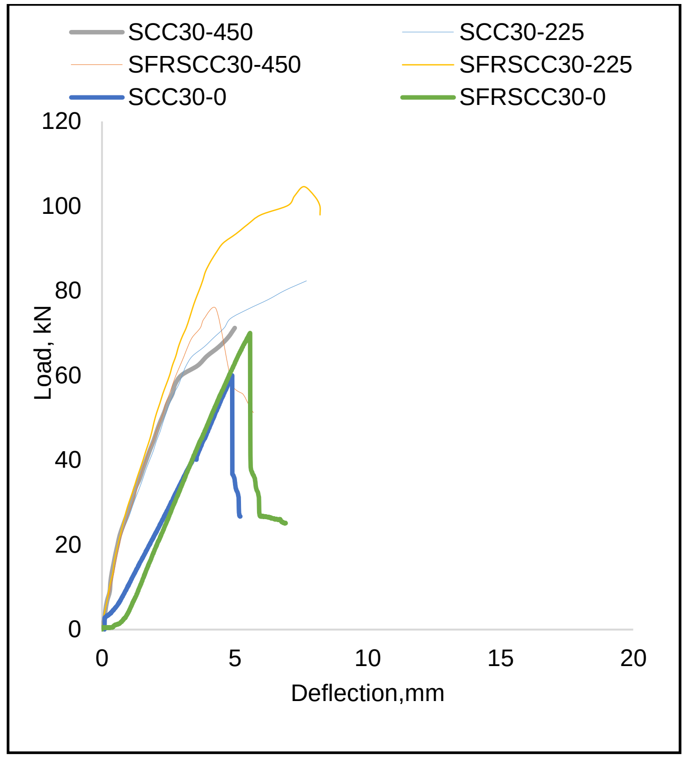


Figure 5.11: Load vs Deflection for SCC30 a/d=2.5

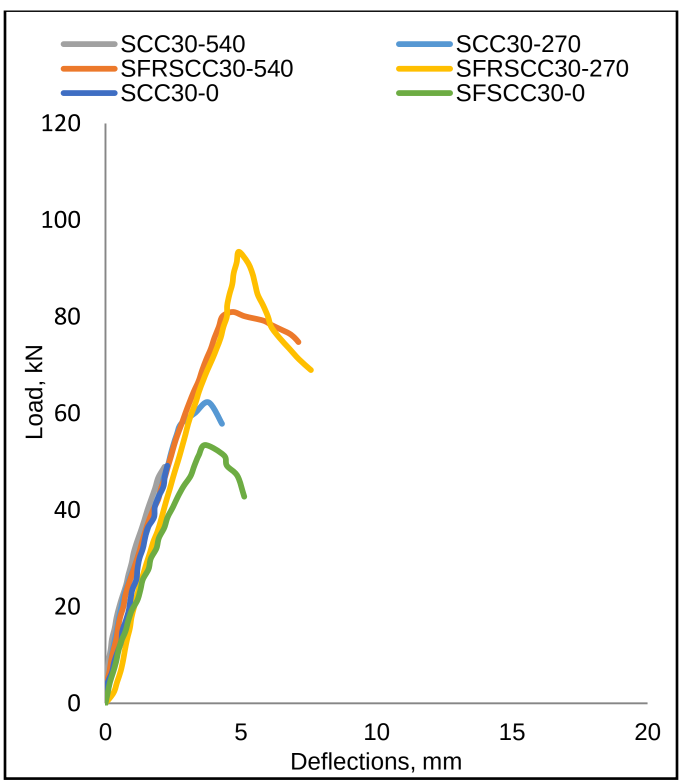


Figure 5.12: Load vs Deflection for SCC30 a/d=3

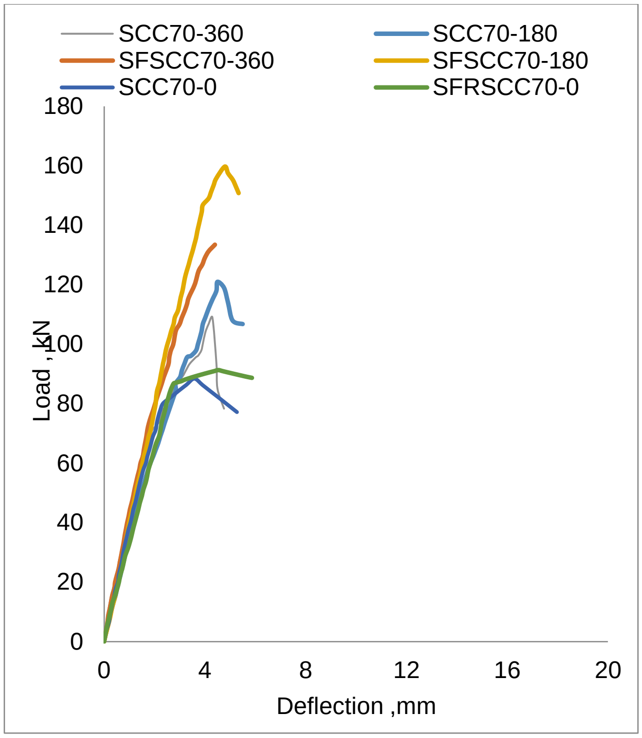


Figure 5.13: Load vs Deflection for SCC70 a/d=2

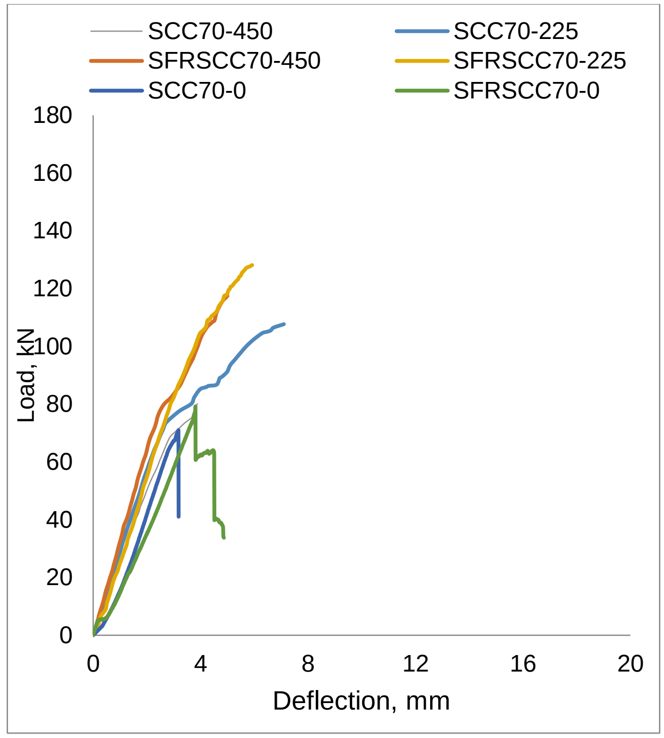


Figure 5.14: Load vs Deflection for SCC70 a/d=2.5

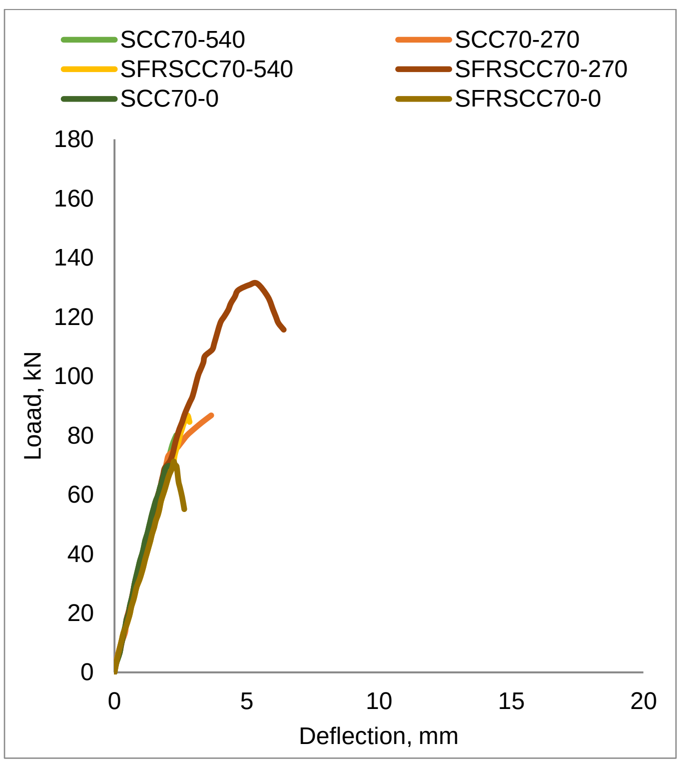


Figure 5.15: Load vs Deflection for SCC70 a/d=3

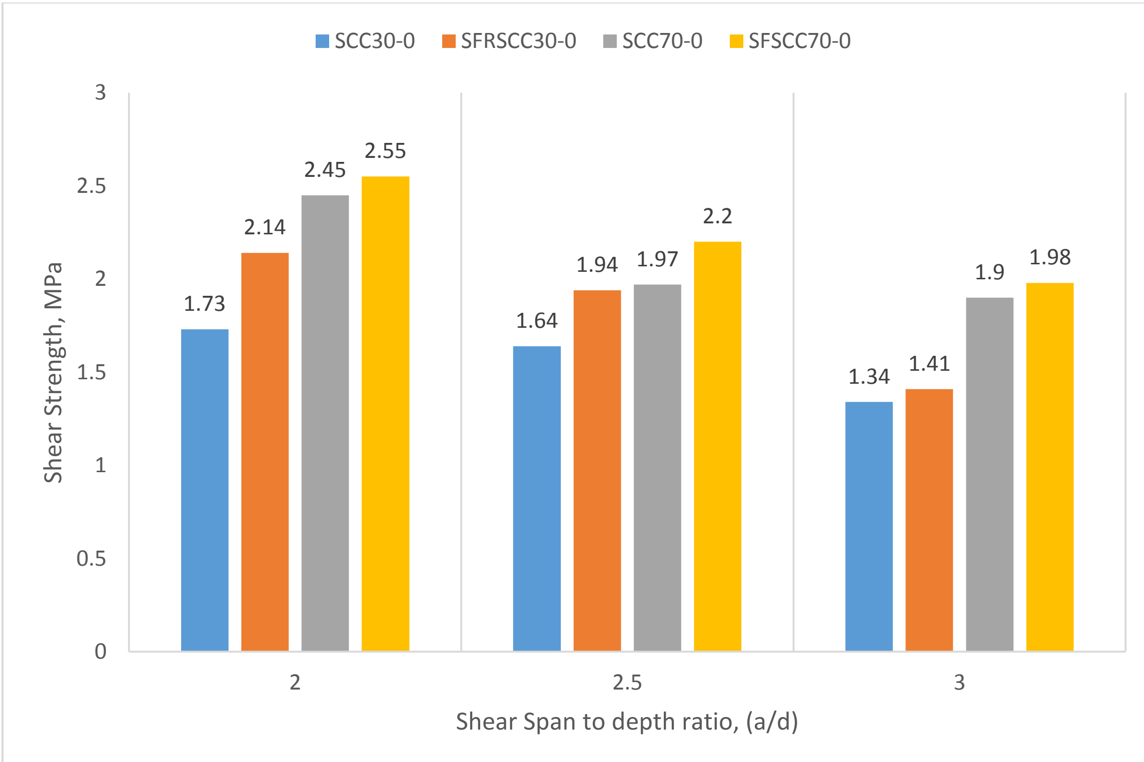


Figure 5.16 (a): Shear Strength Vs Shear Span to depth ratio (a/d) for Plain beams

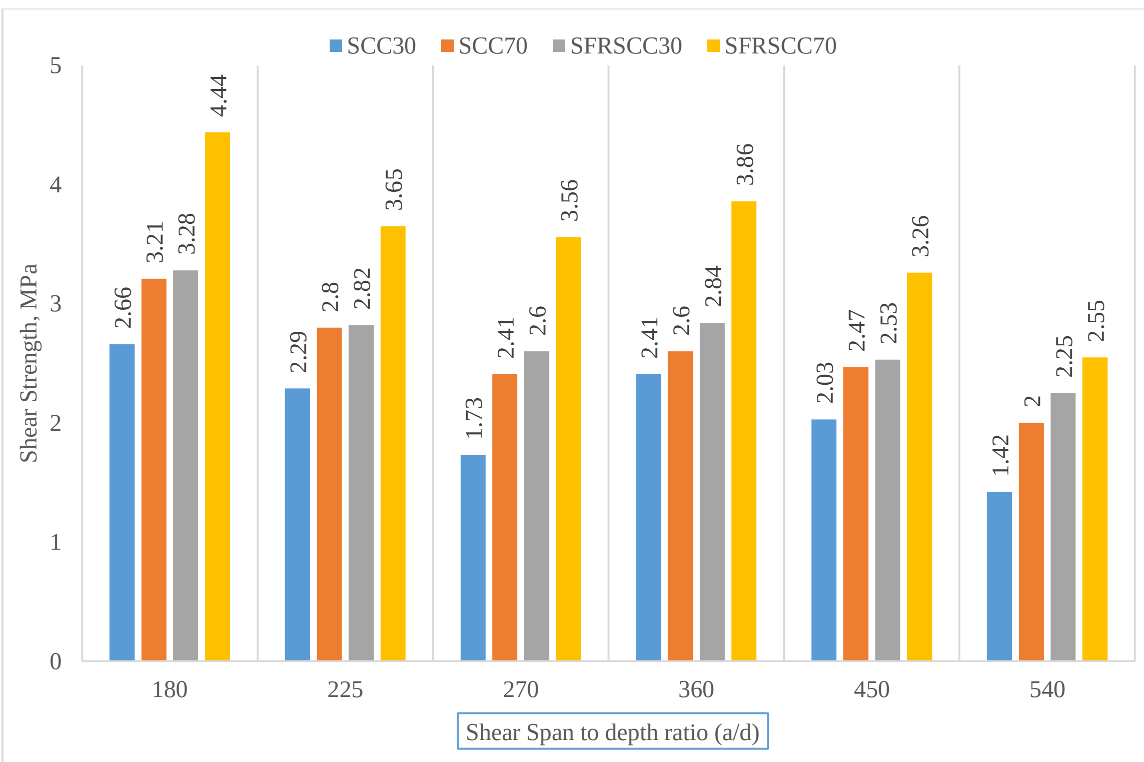


Figure 5.16(b): Shear Strength Vs Shear Span to depth ratio (a/d) for beams with stirrups

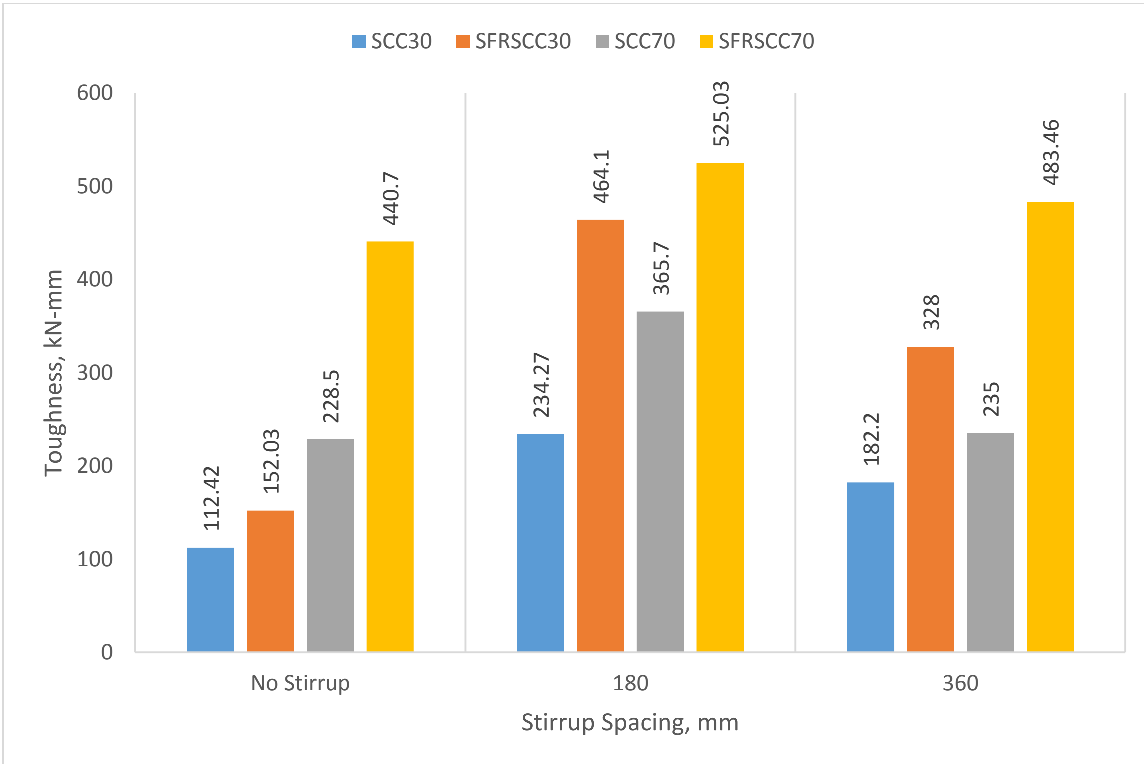


Figure: 5.17 Toughness vs Stirrup Spacing for a/d=2

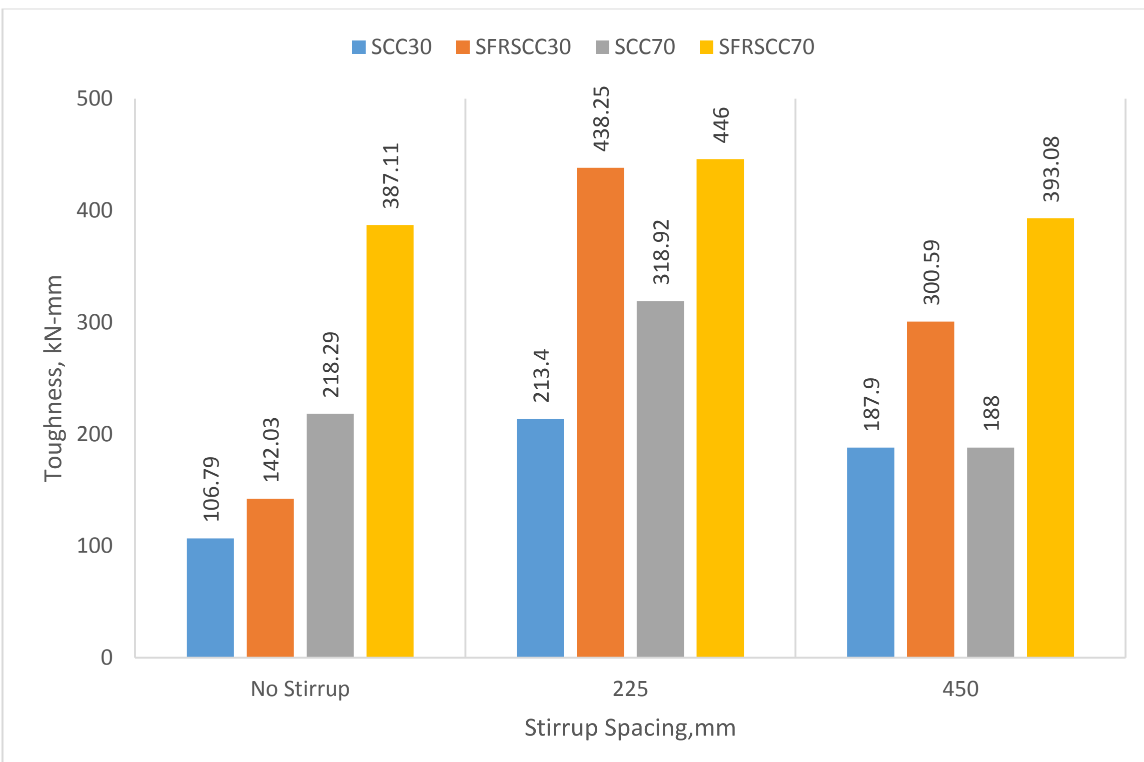


Figure: 5.18 Toughness vs Stirrup Spacing for a/d=2.5

Figure: 5.19 Toughness vs Stirrup Spacing for a/d=3

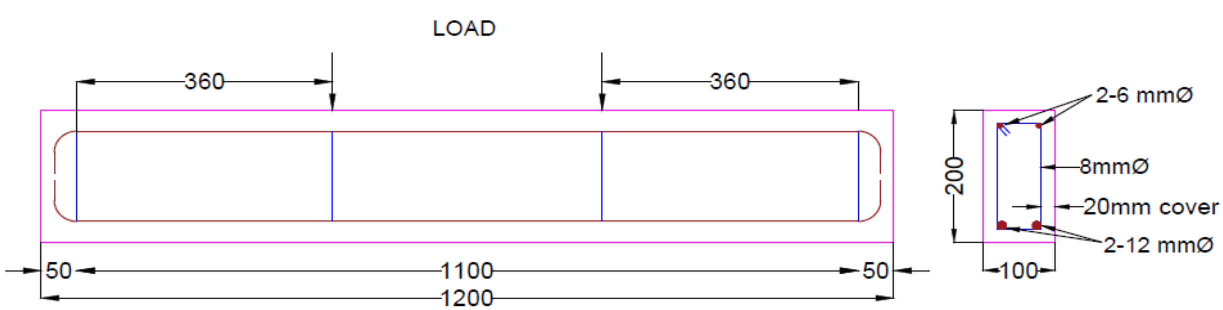


Figure: 5.20(a)

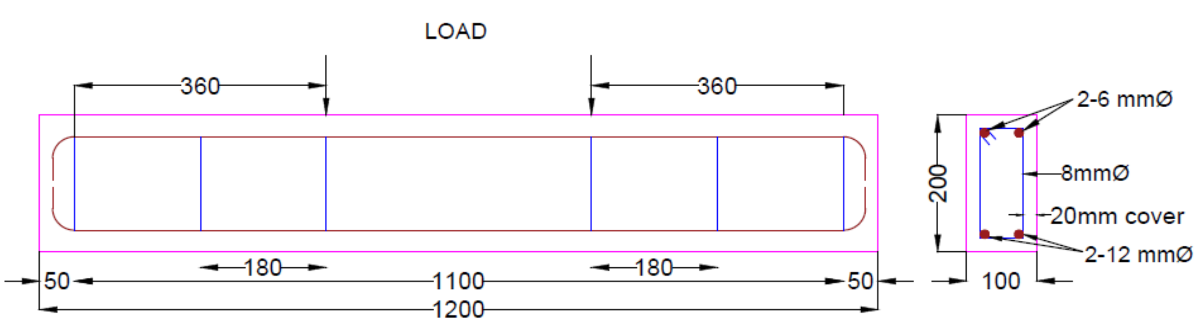


Figure: 5.20(b)

Figure: 5.20 Details of reinforcement for M30 mix with a/d=2 for 8mm Ø stirrup

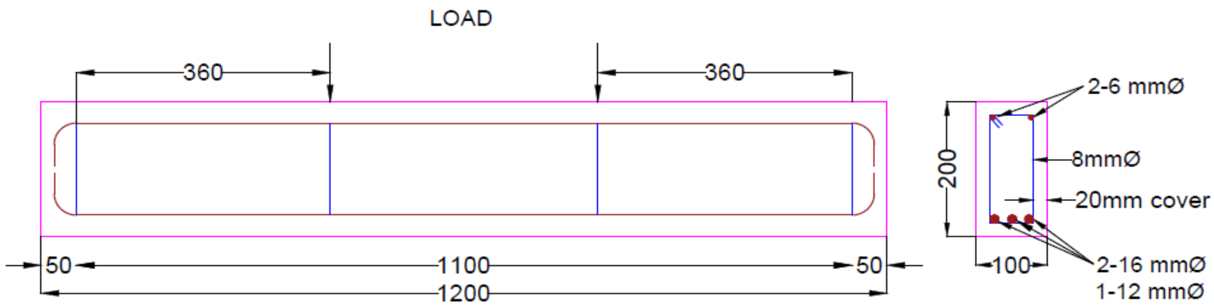


Figure: 5.21(a)

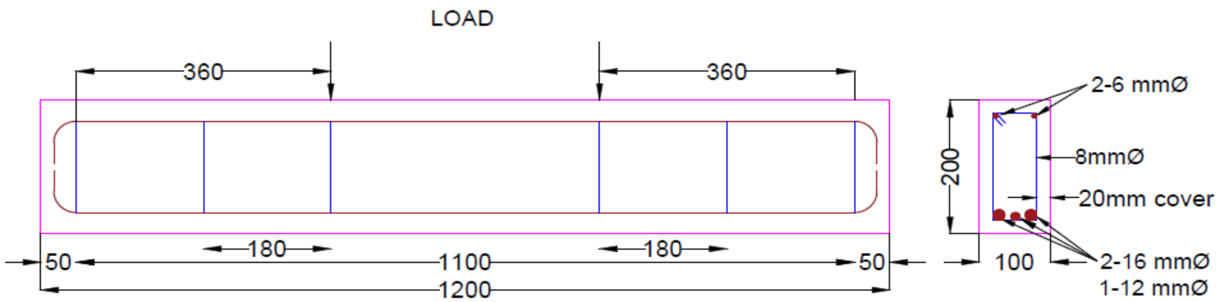


Figure: 5.21(b)

Figure: 5.21 Details of reinforcement for M70 mix with a/d=2 for 8mm Ø stirrup

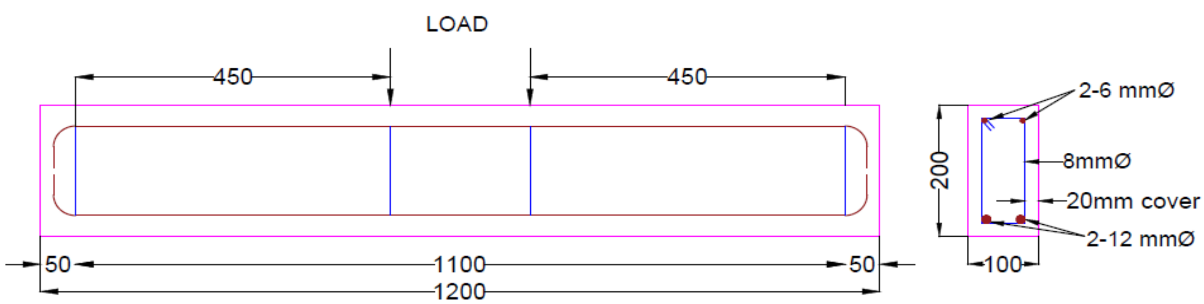


Figure: 5.22(a)

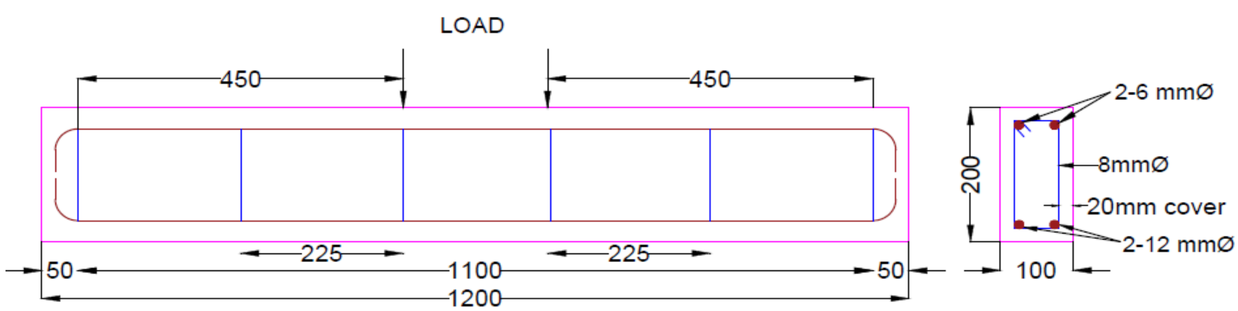


Figure: 5.22(b)

Figure: 5.22 Details of reinforcement for M30 mix with a/d=2.5 for 8mm Ø stirrup

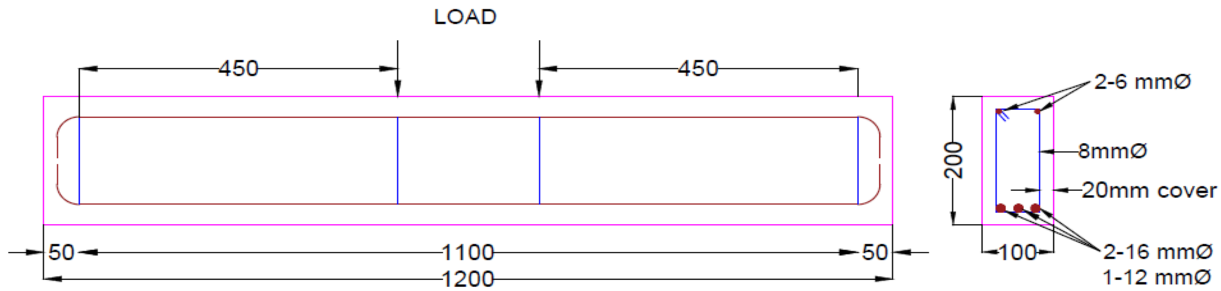


Figure: 5.23(a)

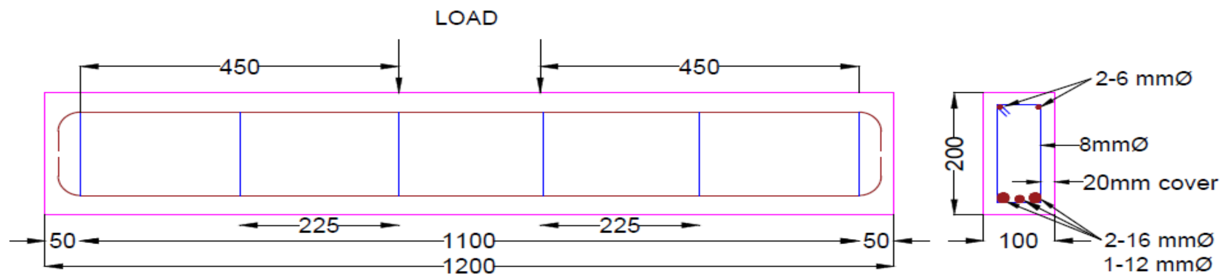
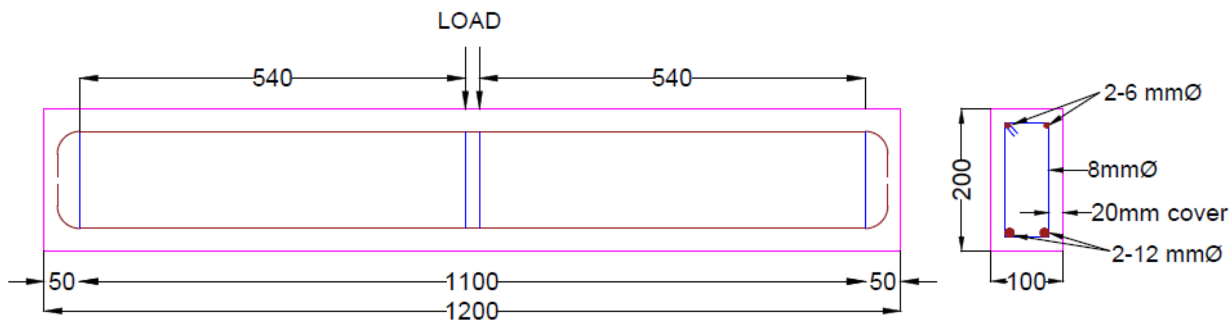


Figure: 5.23(b)

Figure: 5.23 Details of reinforcement for M70 mix with a/d=2.5 for 8mm Ø stirrup



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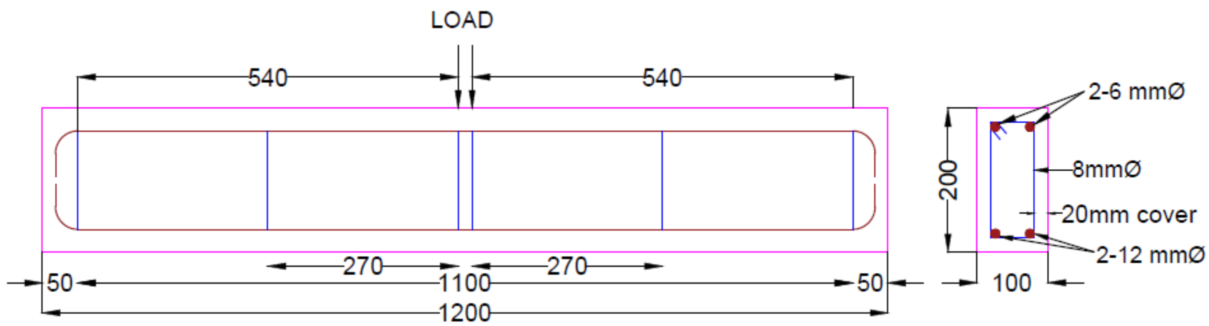


Figure: 5.24(b)

Figure: 5.24 Details of reinforcement for M30 mix with a/d=3 for 8mm Ø stirrup

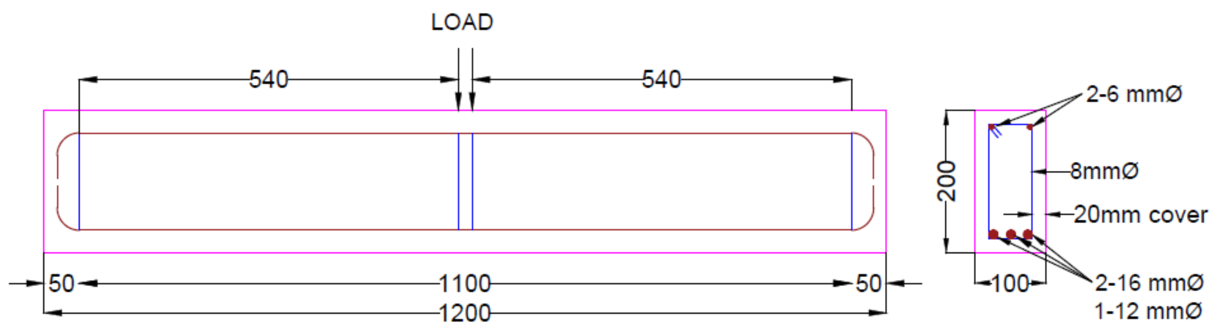


Figure: 5.25(a)

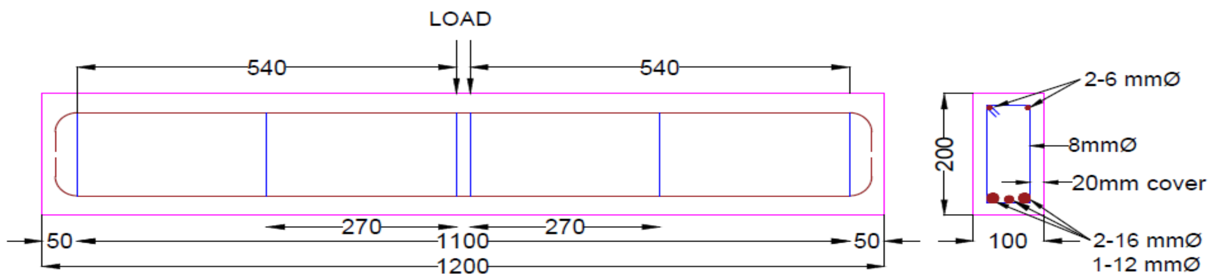


Figure: 5.25(b)

Figure: 5.25 Details of reinforcement for M70 mix with a/d=3 for 8mm Ø stirrup

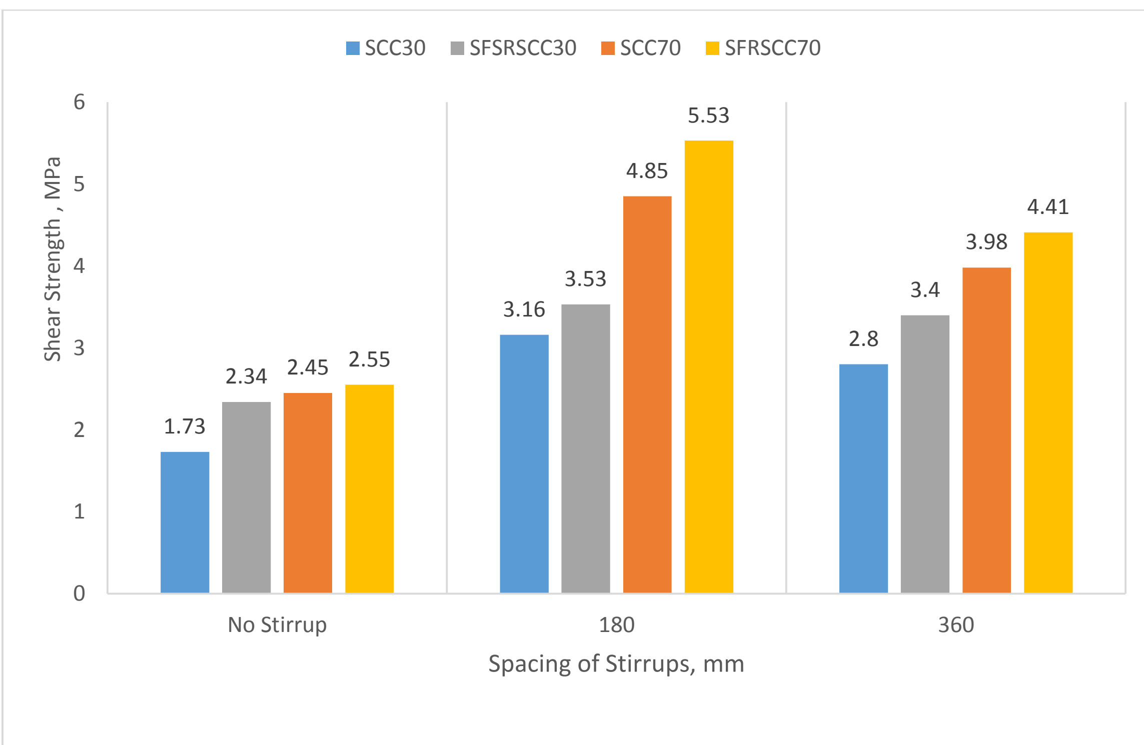


Figure 5.26: Shear Strength Vs Spacing of Stirrups using 8mm Ø stirrup for (SCC30 & SCC70, a/d=2)

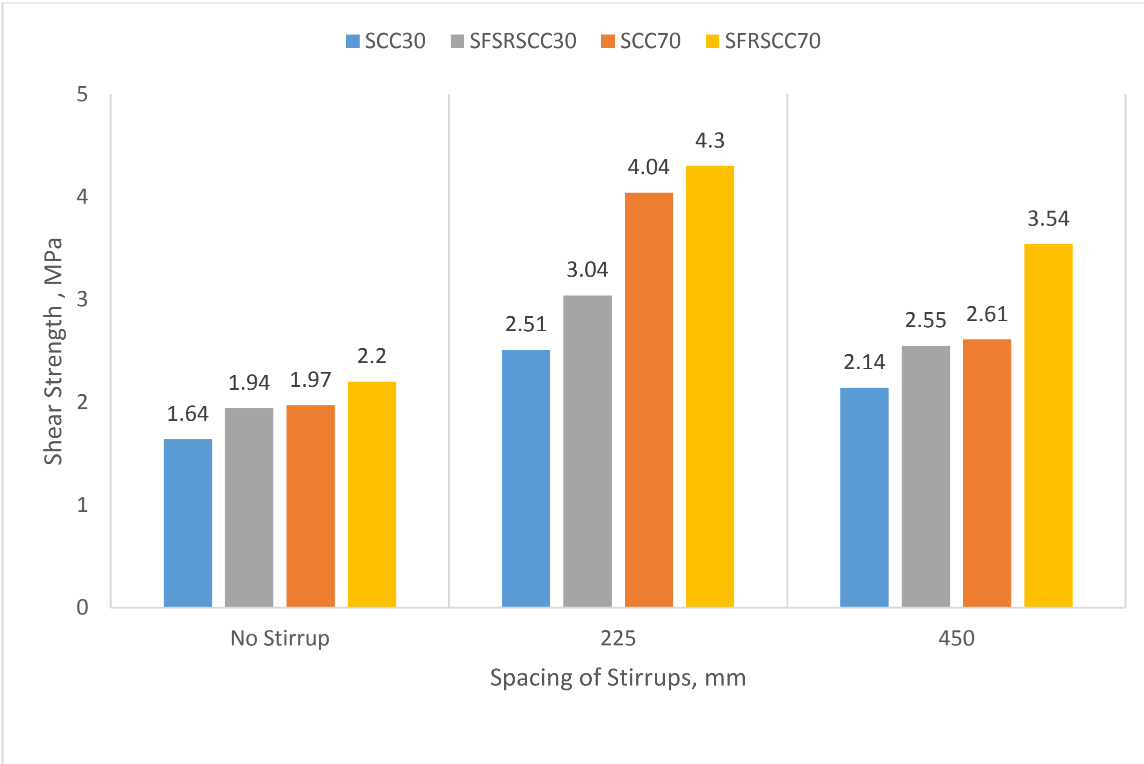


Figure 5.27: Shear Strength Vs Spacing of Stirrups using 8mm Ø stirrup for (SCC30 & SCC70, a/d=2.5)

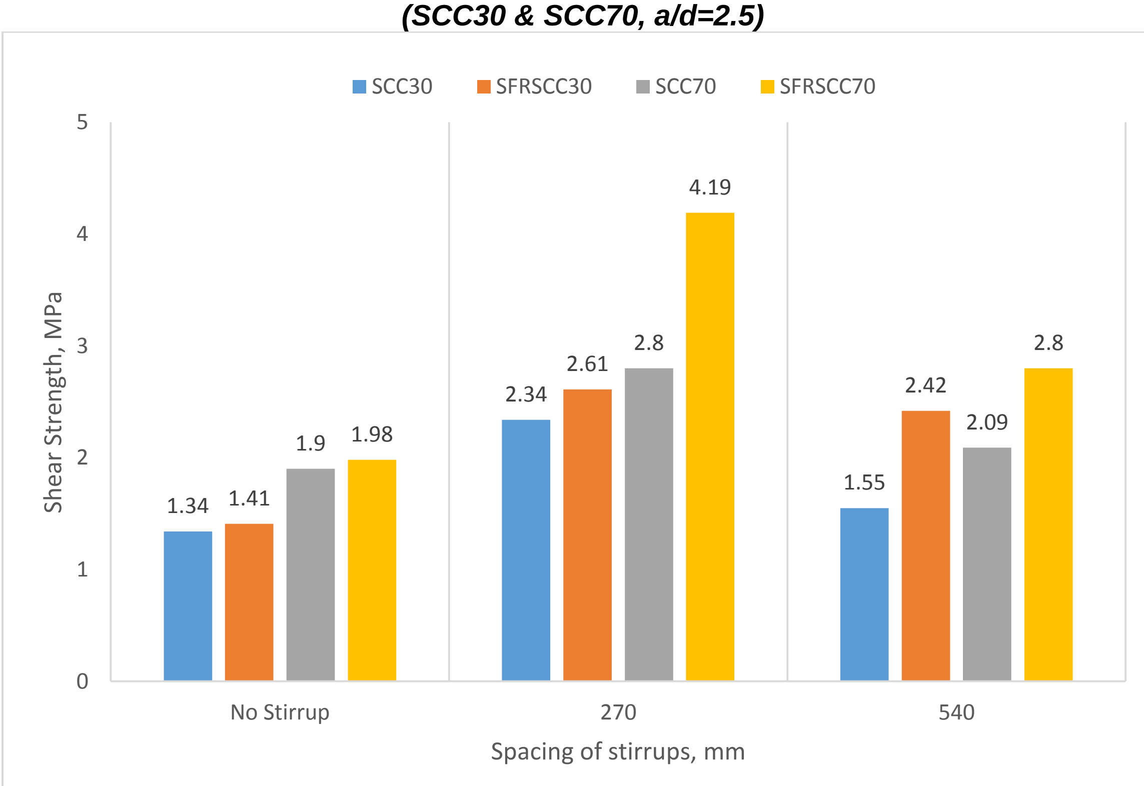


Figure 5.28: Shear Strength Vs Spacing of Stirrups using 8mm Ø stirrup for (SCC30 & SCC70, a/d=3)

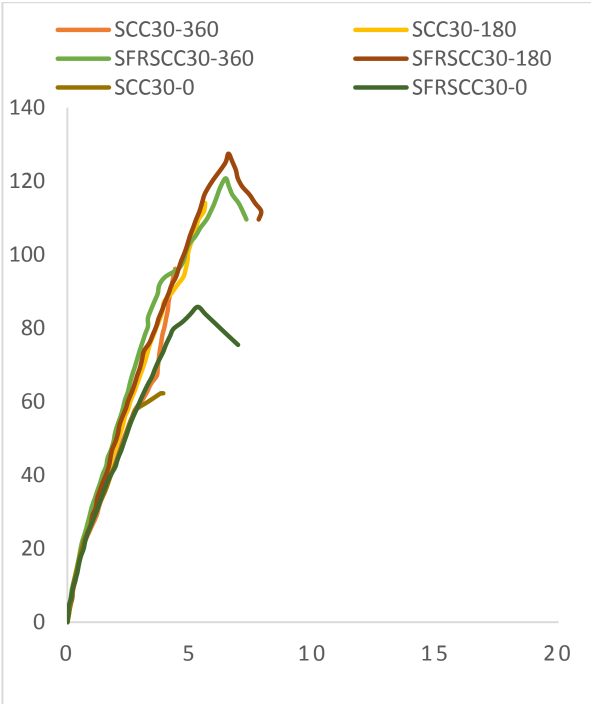


Figure 5.29(a): Load vs Deflection for SCC30 a/d=2 for 8mm Ø Stirrup

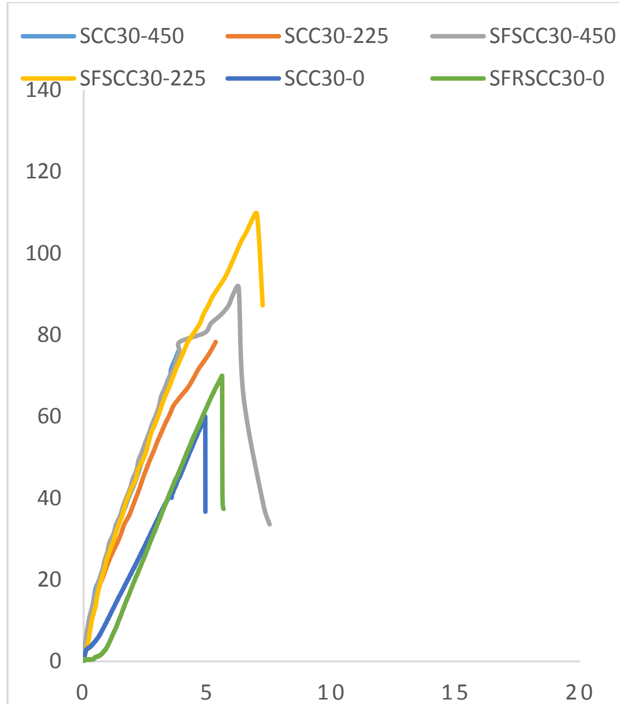


Figure 5.29(b): Load vs Deflection for SCC30 a/d=2.5 for 8mm Ø Stirrup

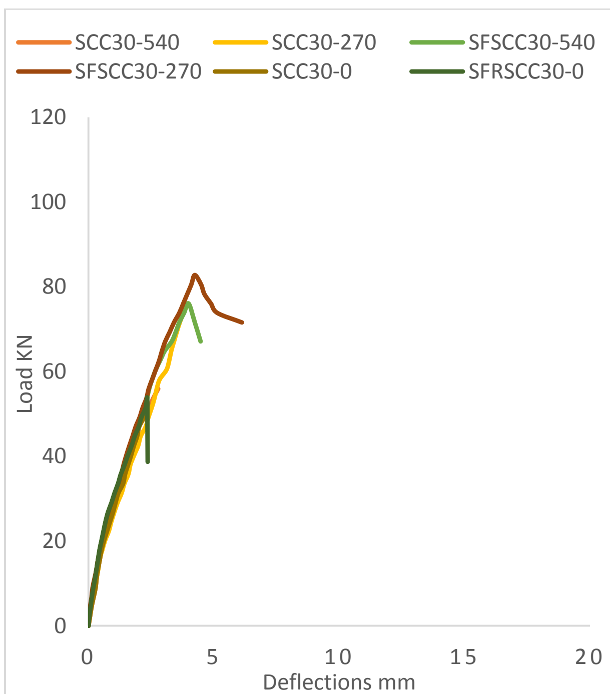


Figure 5.29(c): Load vs Deflection for SCC30 a/d=3 for 8mm Ø Stirrup

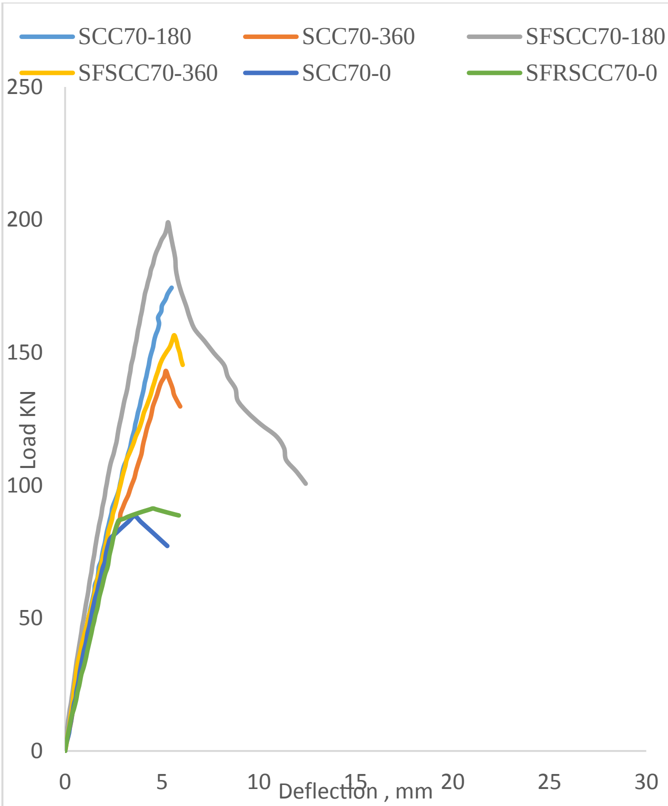


Figure 5.30(a): Load vs Deflection for SCC70 a/d=2 for 8mm Ø Stirrup

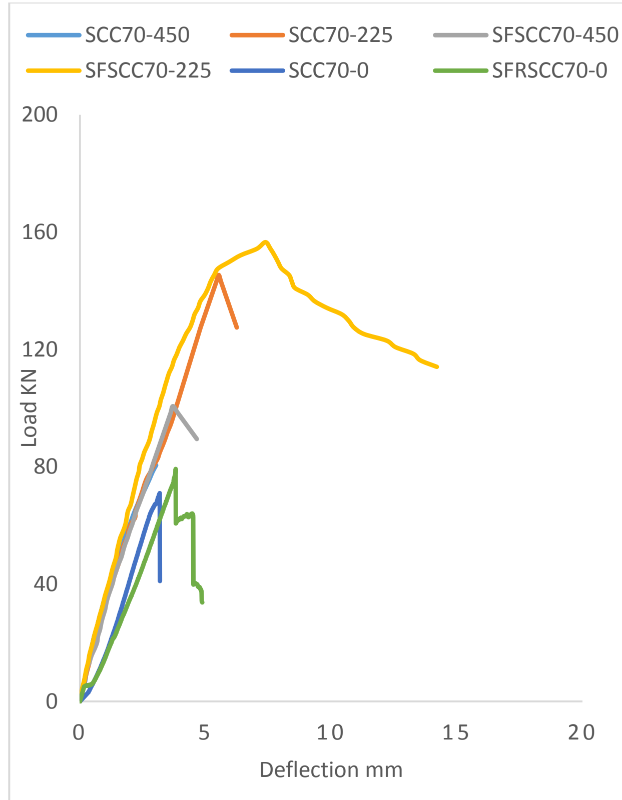


Figure 5.30(b): Load vs Deflection for SCC70 a/d=2.5 for 8mm Ø Stirrup

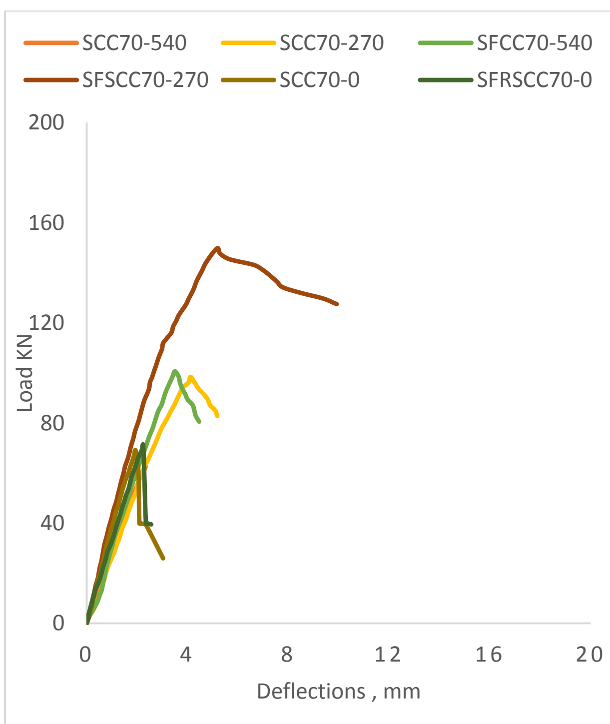


Figure 5.30(c) Load vs Deflection for SCC70 a/d=3 for 8mmØ Stirrup

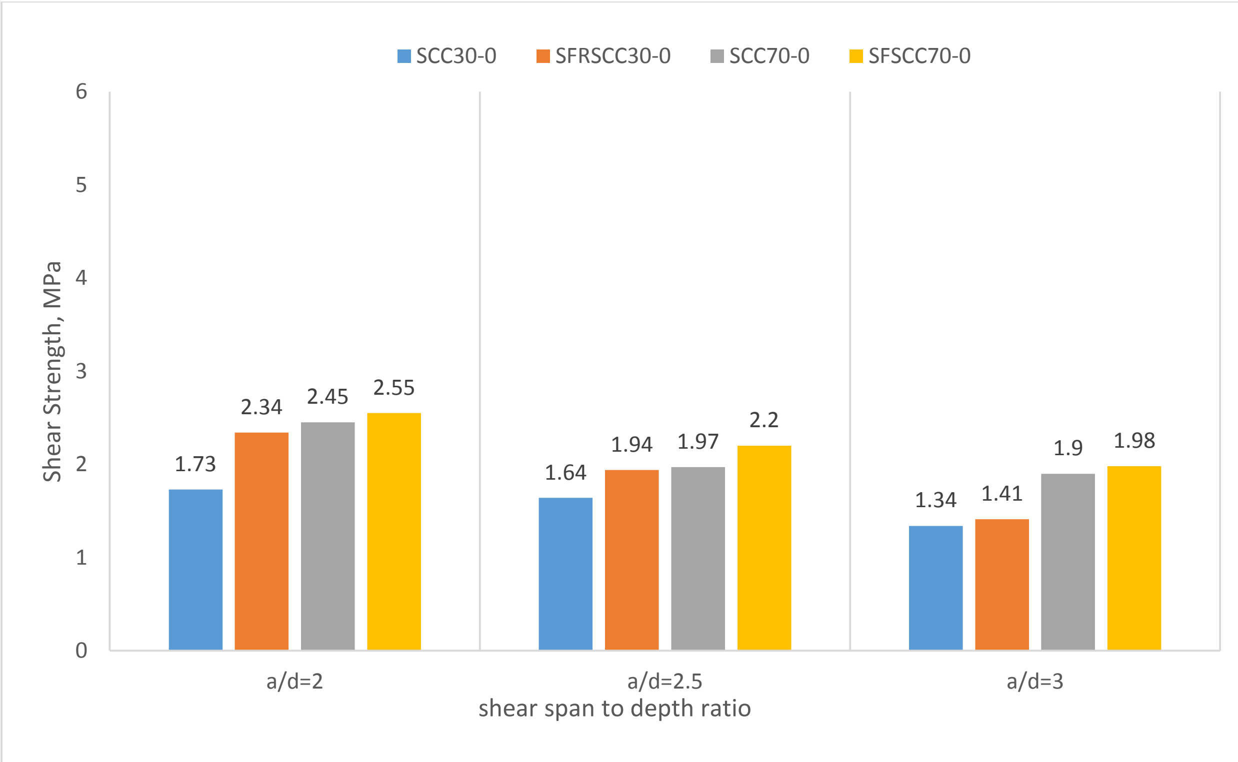


Figure: 5.31(a) Shear Strength vs a/d ratio for plain beams

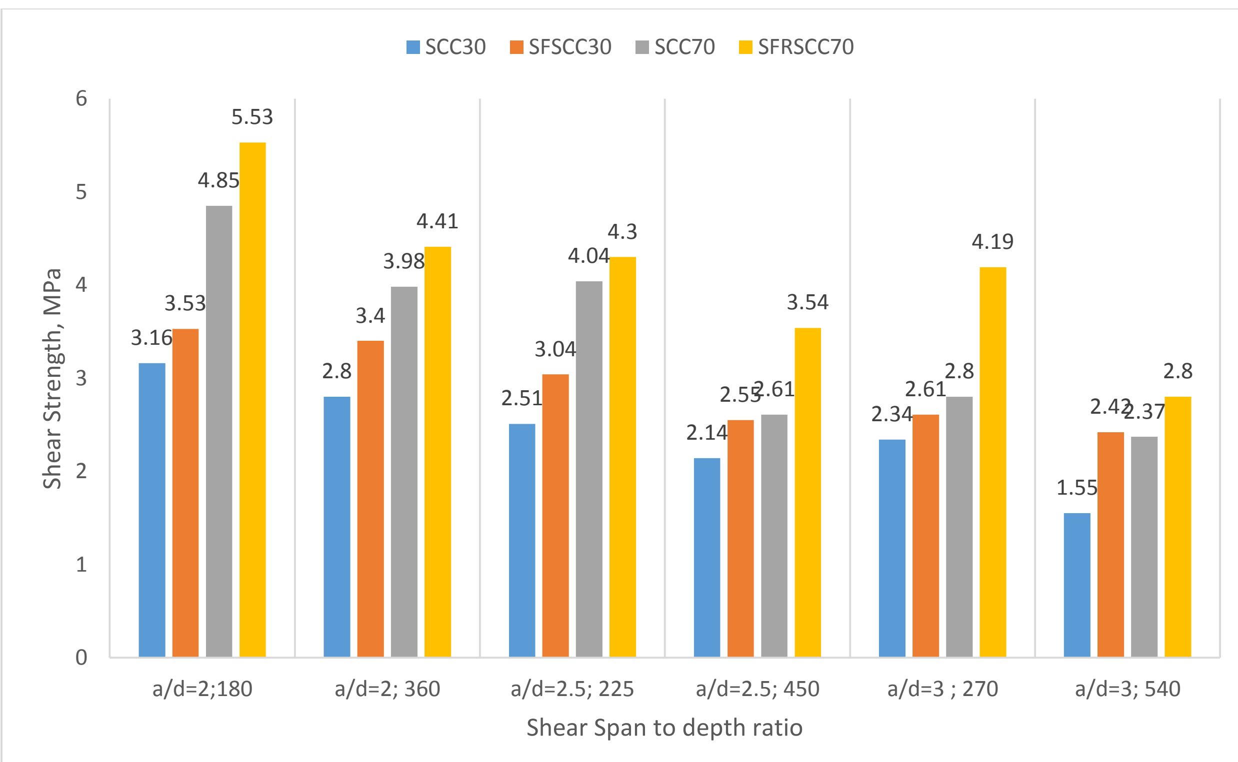


Figure: 5.32(b) Shear Strength vs a/d ratio for beams using Stirrups.

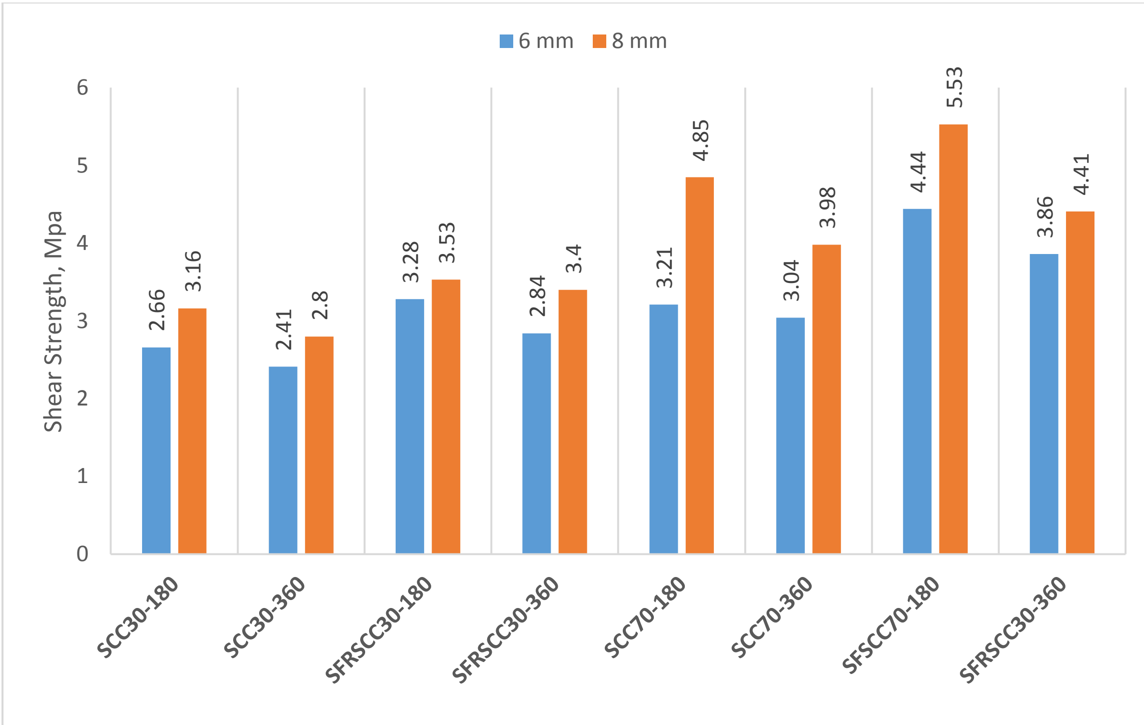


Figure: 5.33(a) Shear Strength Vs Diameter of Stirrup, for a/d=2

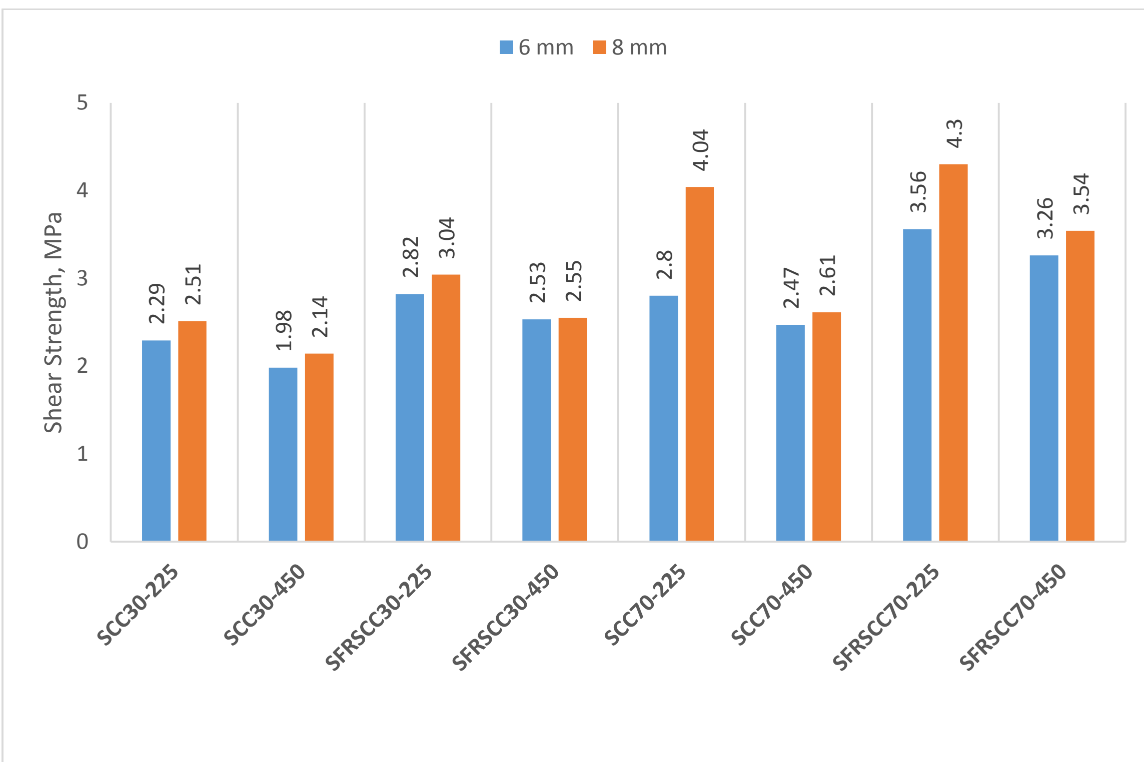


Figure: 5.33(b) Shear Strength Vs Diameter of Stirrup, for a/d=2.5

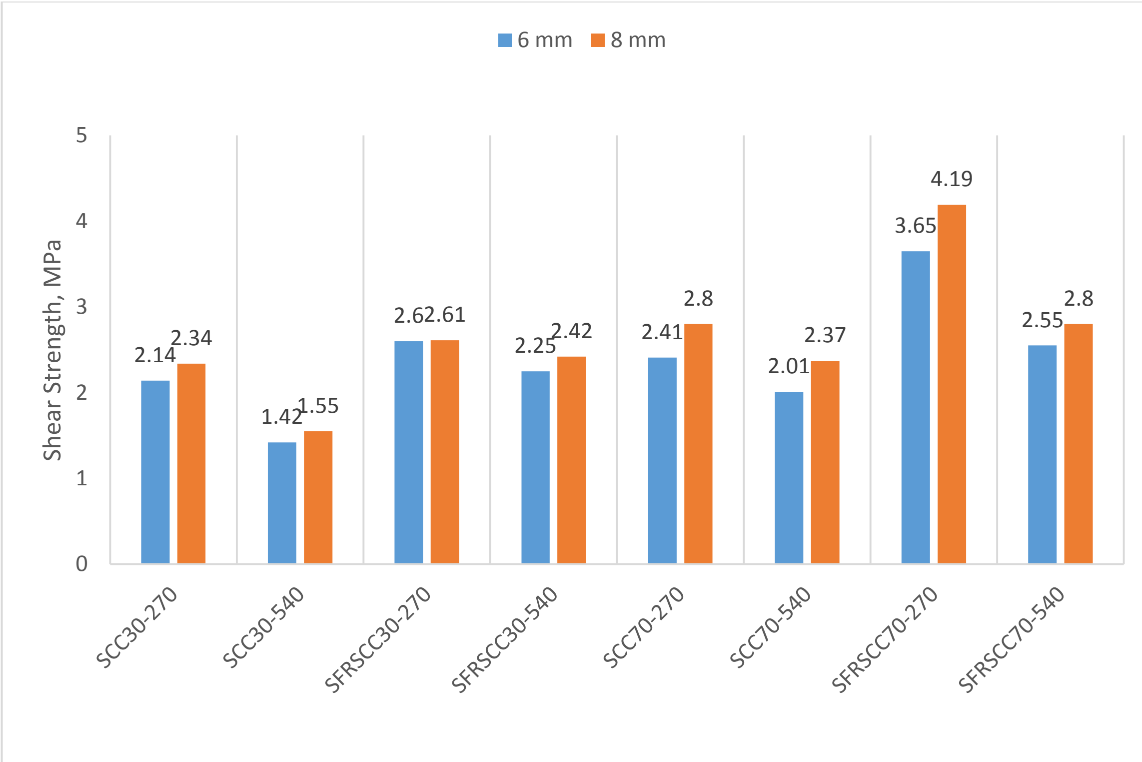


Figure: 5.33(c) Shear Strength Vs Diameter of Stirrup, for a/d=3

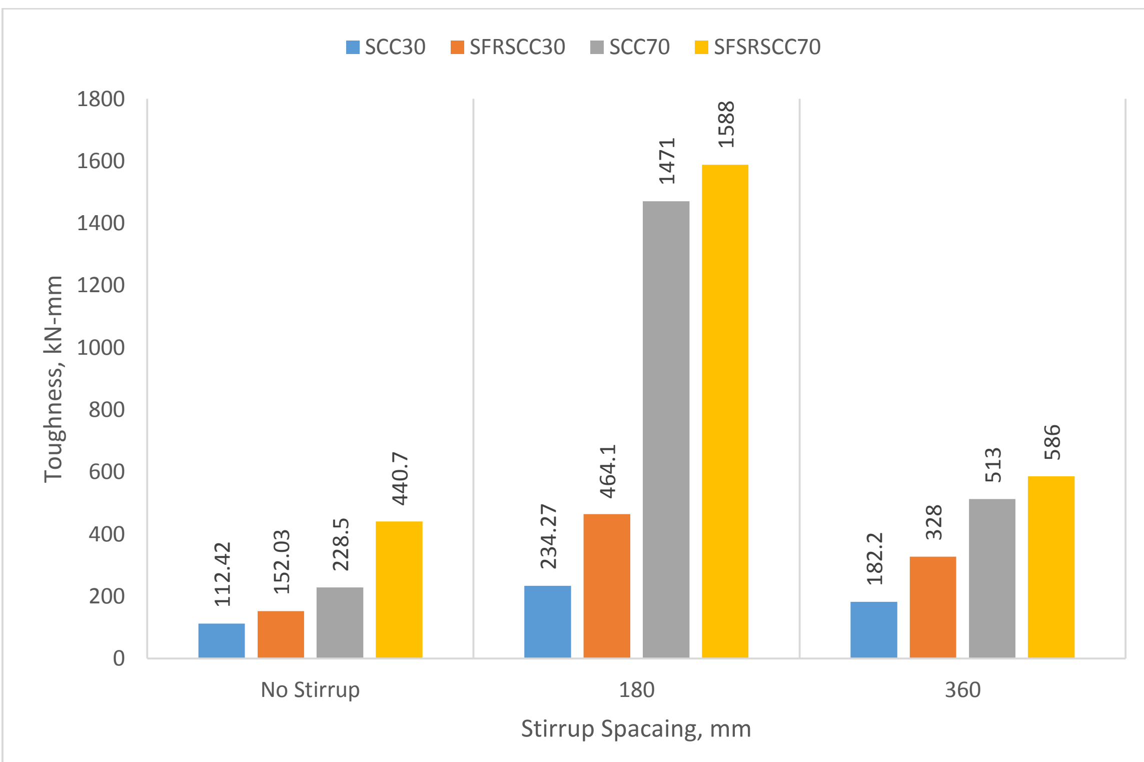


Figure: 5.34(a) Toughness Vs Spacing of Stirrup, for a/d=2

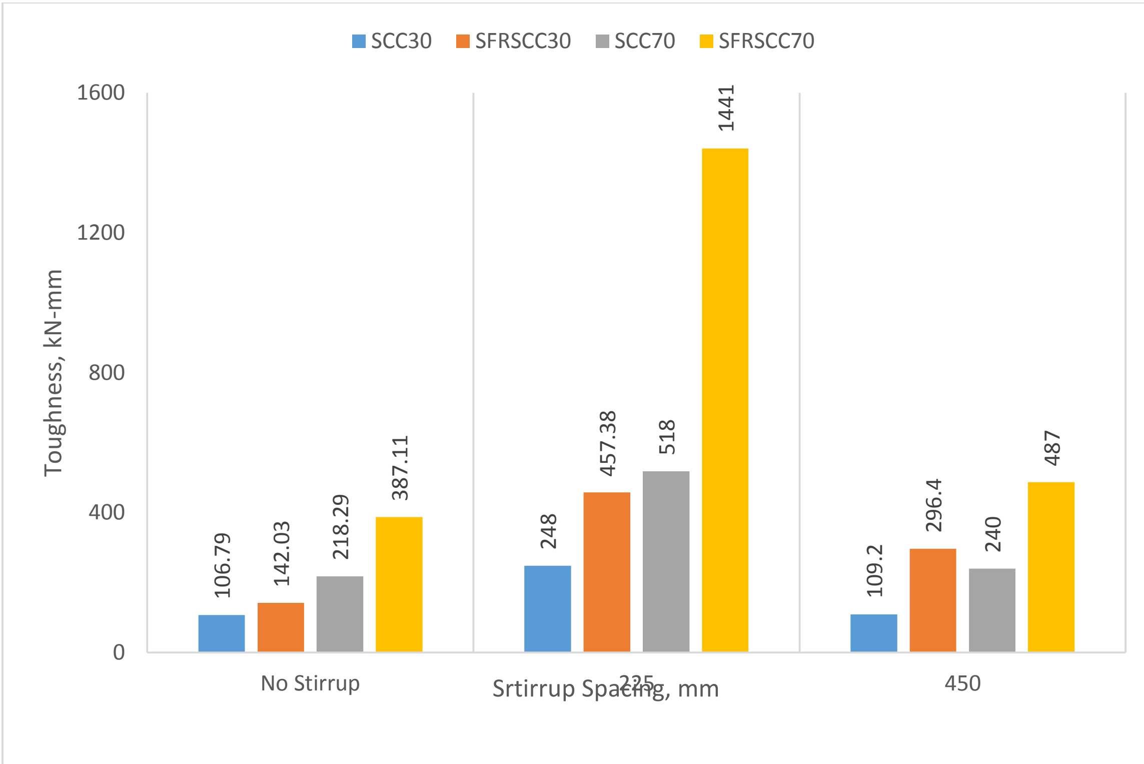


Figure: 5.34(b) Toughness Vs Spacing of Stirrup, for a/d=2.5

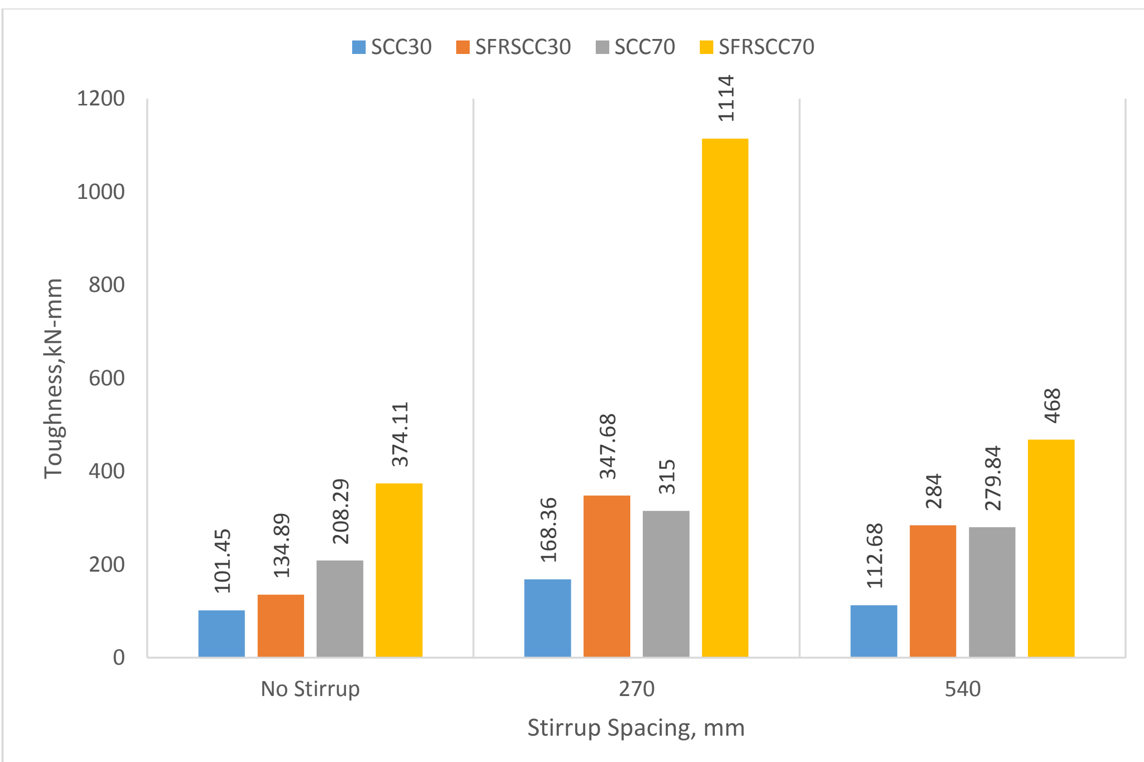


Figure: 5.34(c) Toughness Vs Spacing of Stirrup, for a/d=3

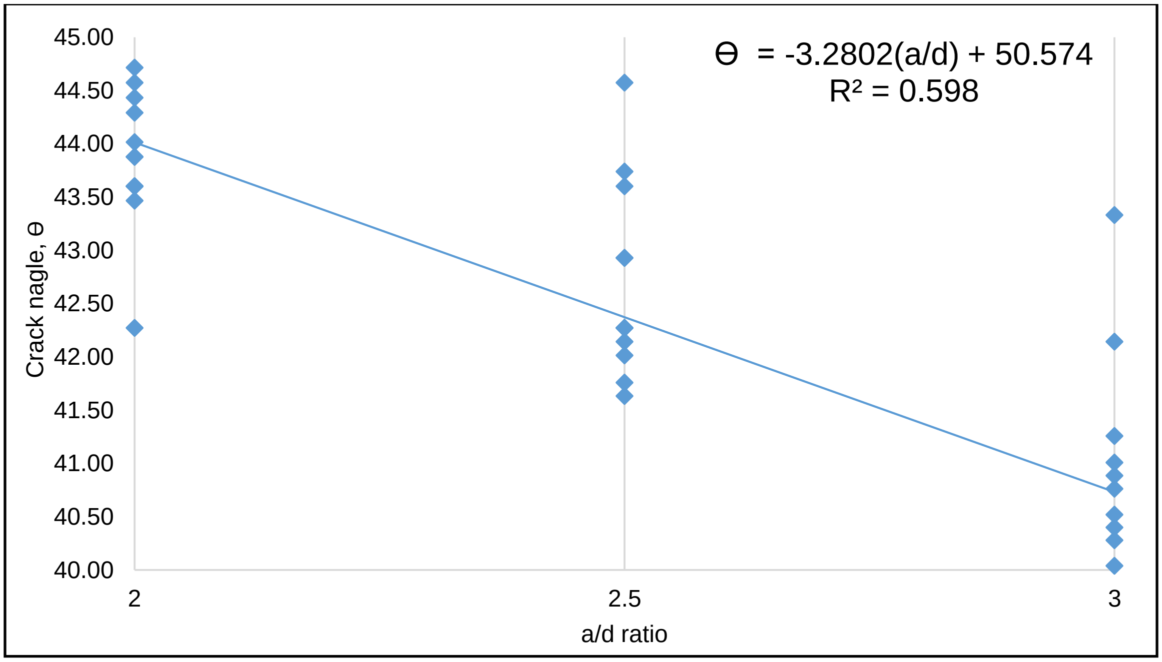


Figure 5.35(a): Crack angle vs a/d ratio

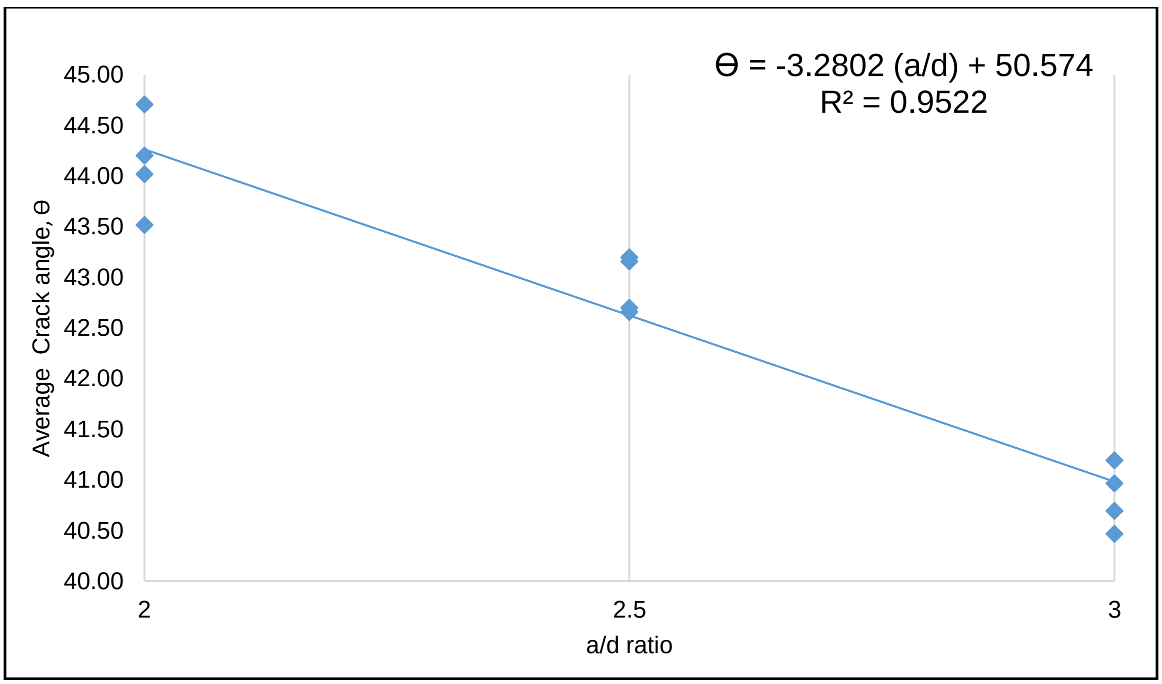


Figure 5.35(b): Average Crack angle vs a/d ratio

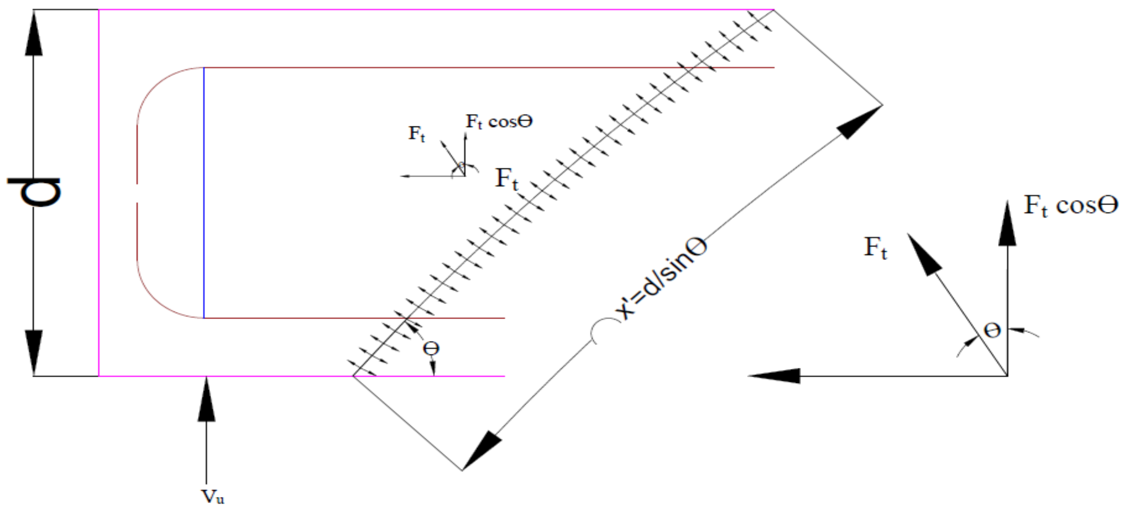


Figure 5.36: Cracked portion of the beam

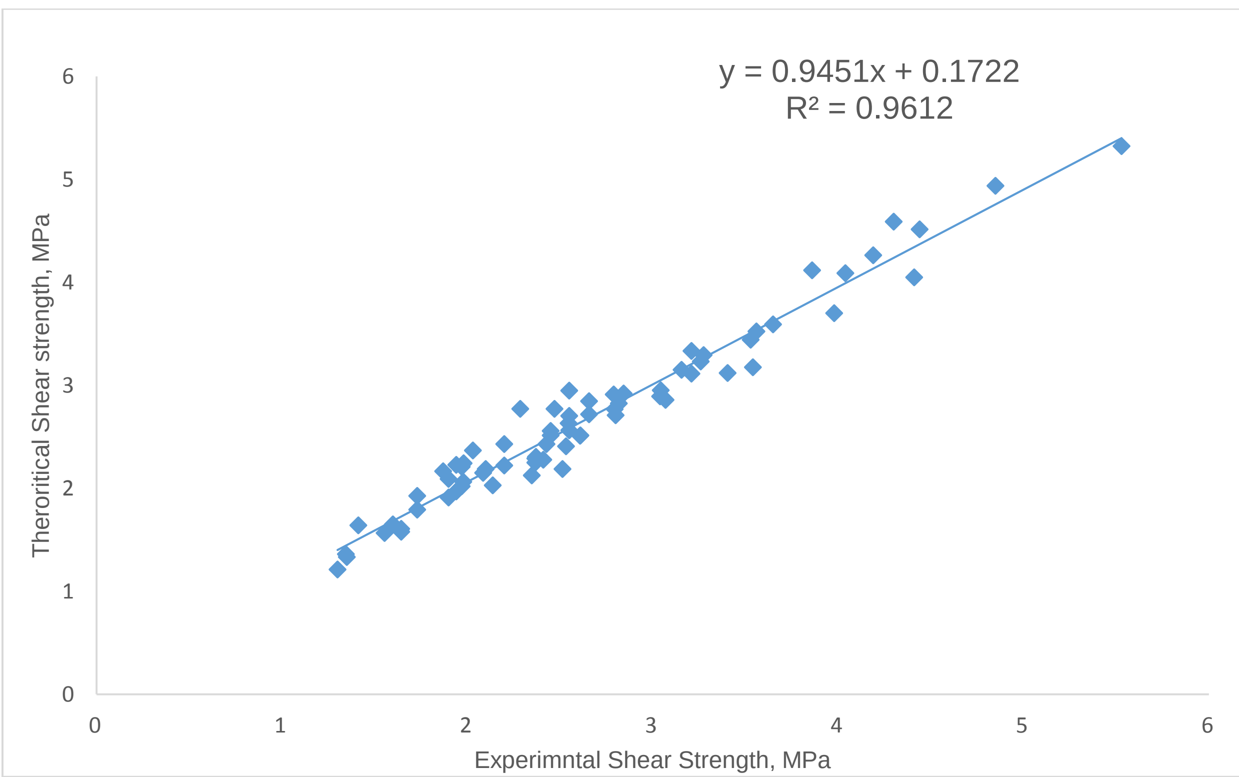


Figure 5.37: Experimental vs Theoretical Shear Strength for SCC30 and SCC70

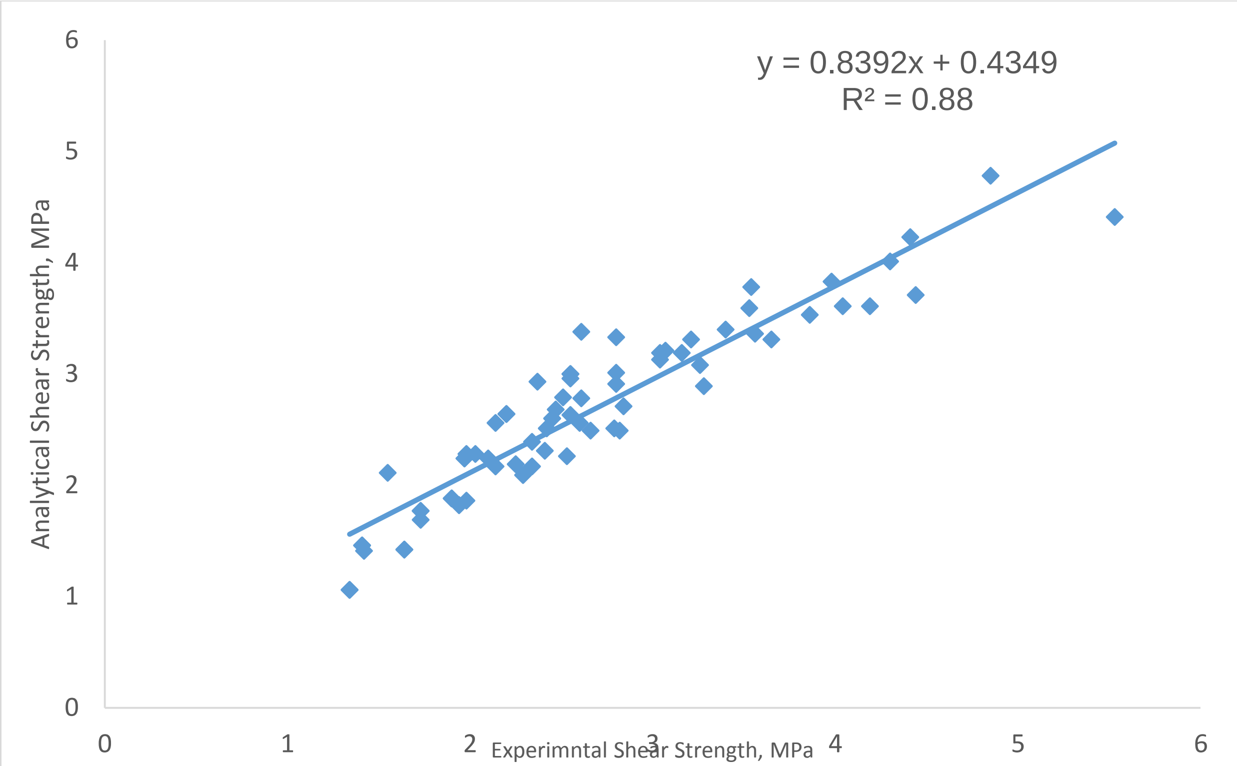


Figure 5.38: Experimental vs Analytical Shear Strength for SCC30 and SCC70

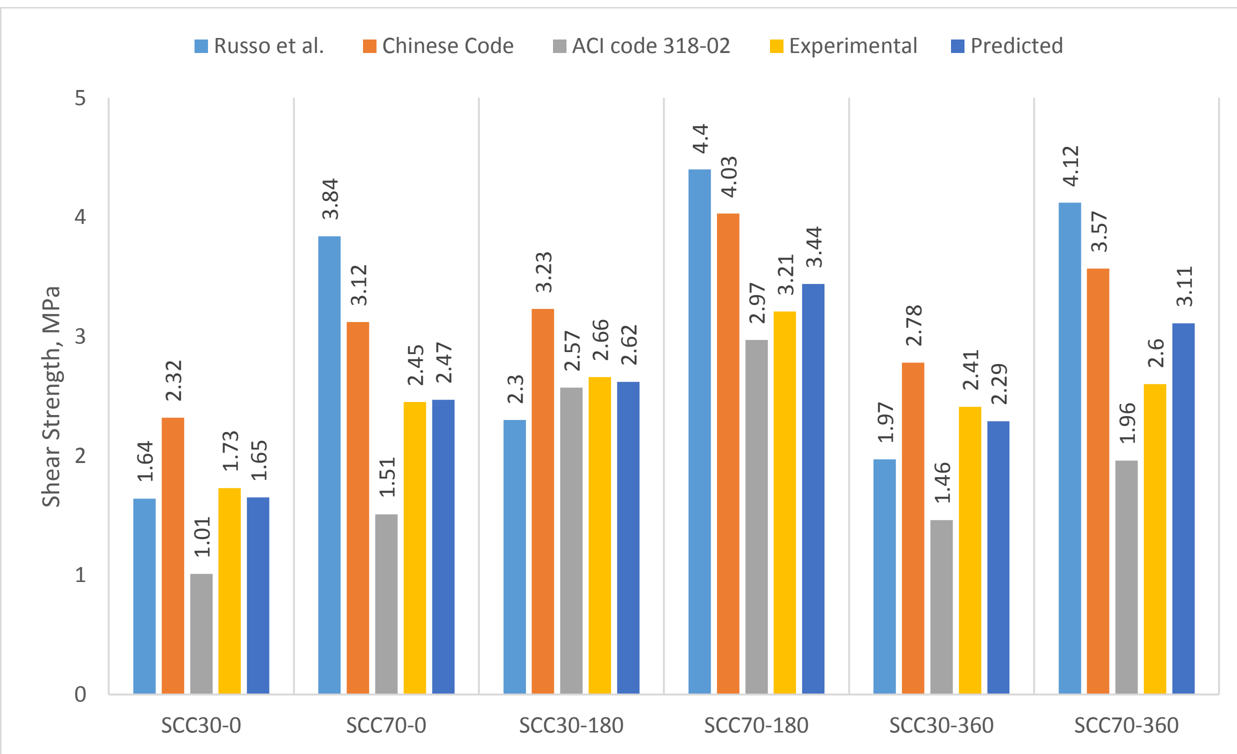


Figure: 5.39 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete (a/d=2).

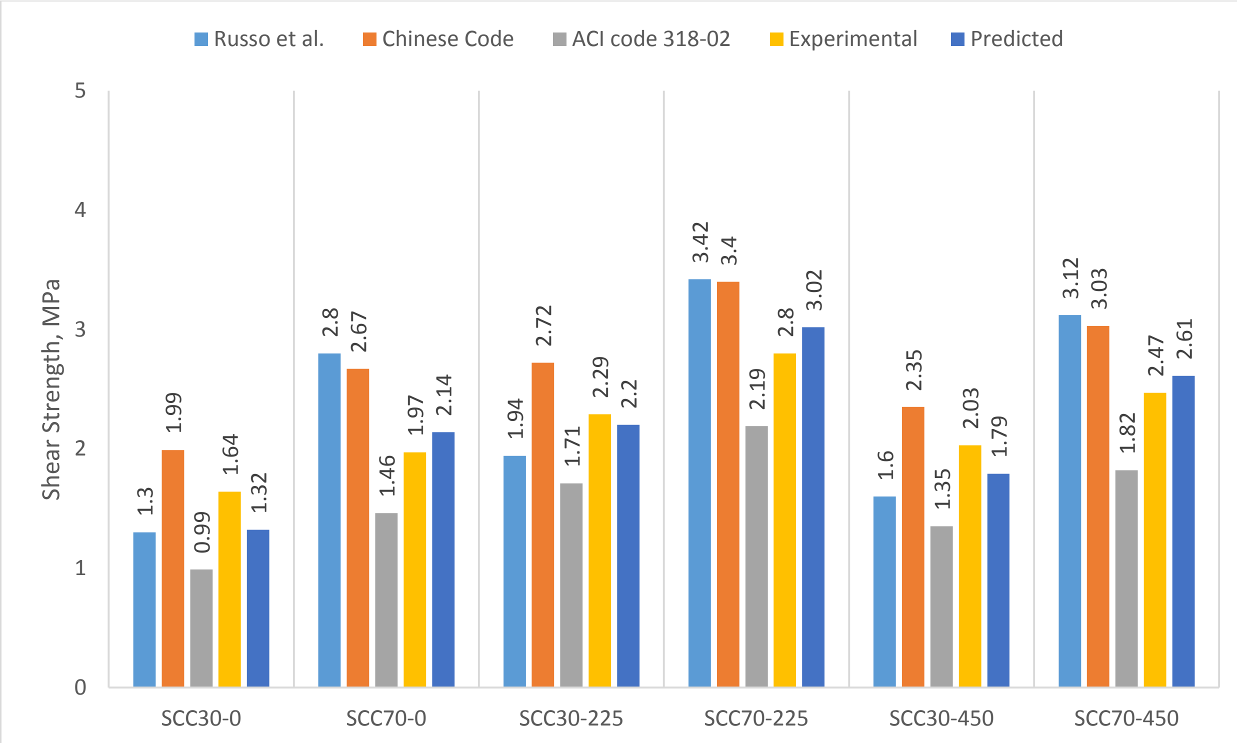


Figure: 5.40 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete (a/d=2.5).

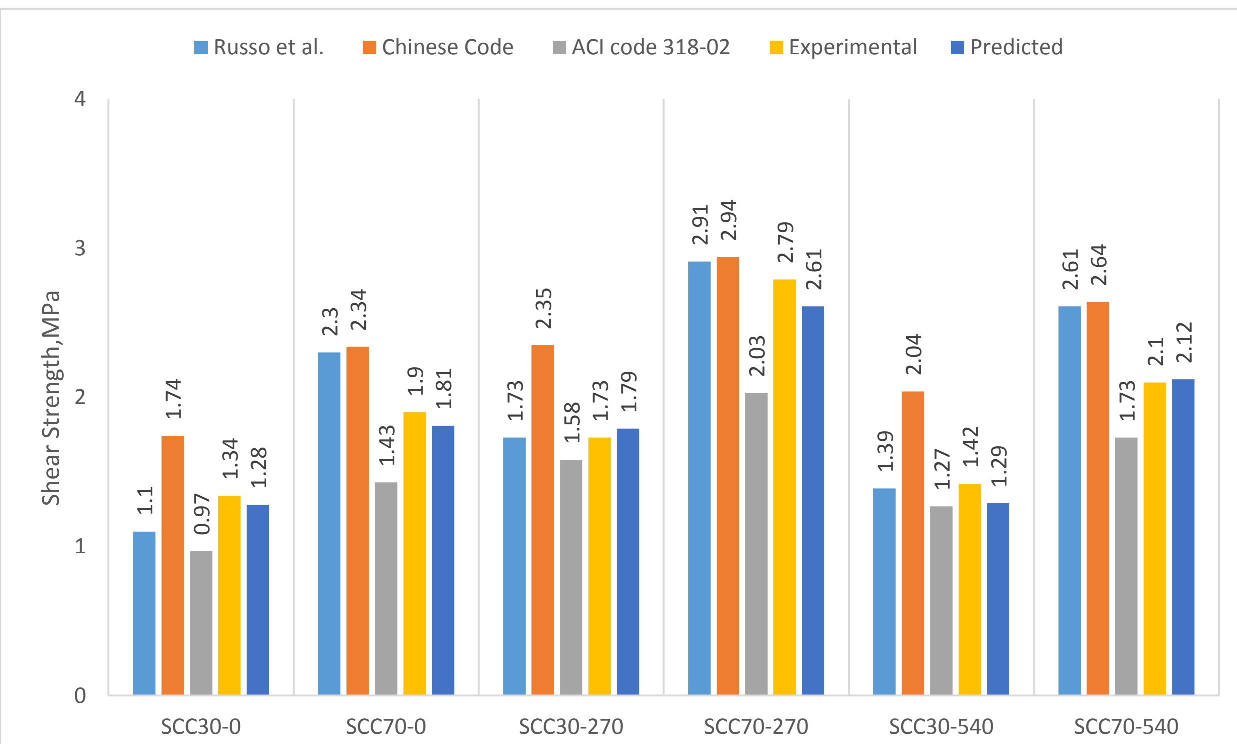


Figure: 5.41 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete (a/d=3).

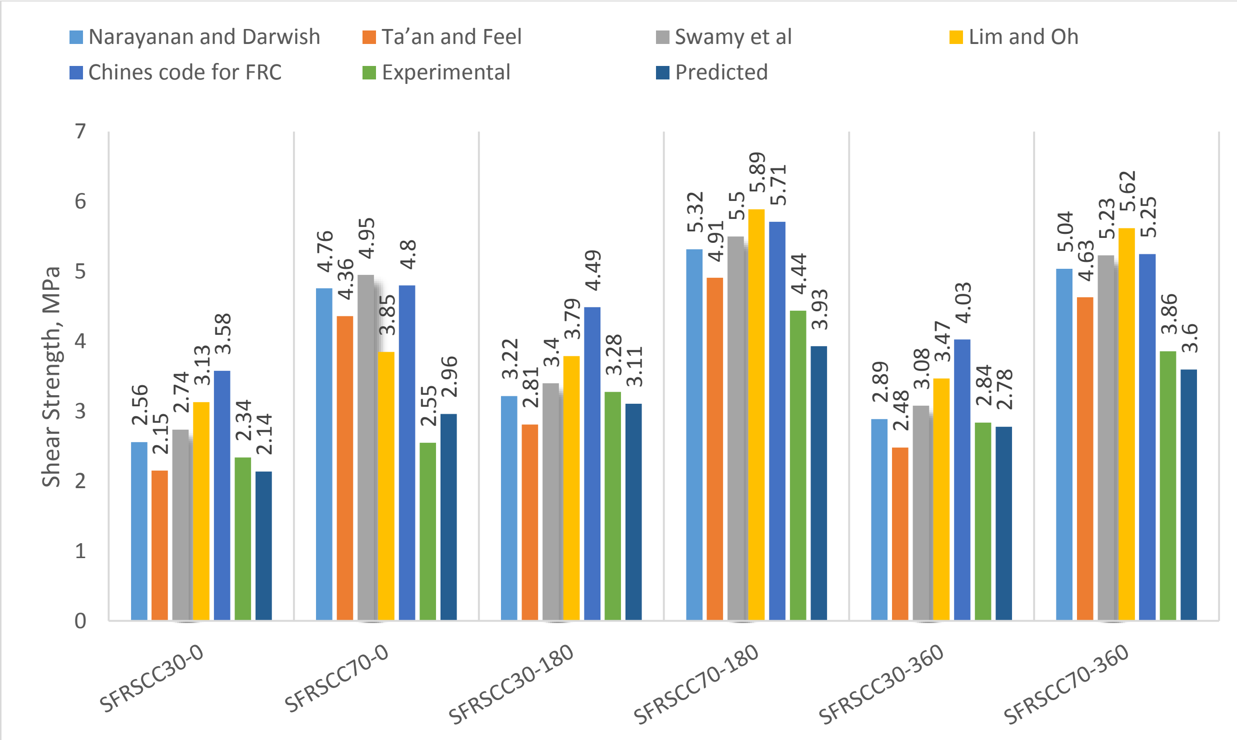


Figure: 5.42 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2).

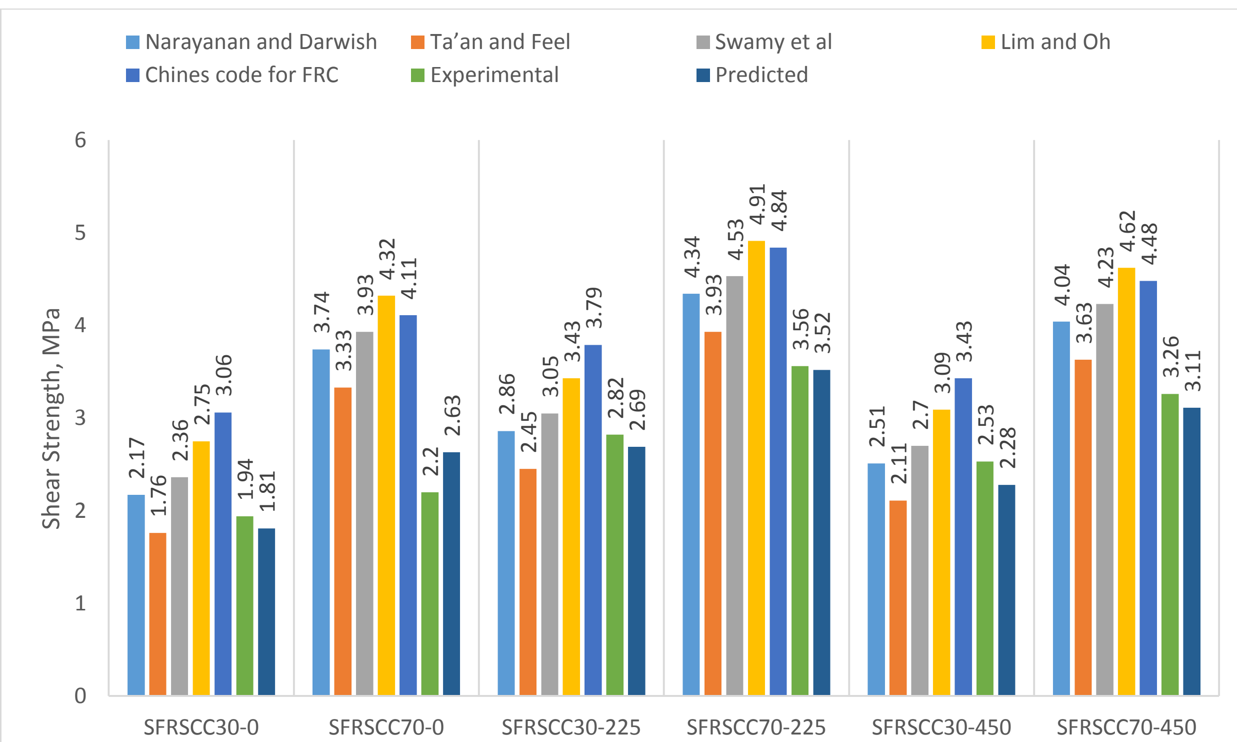


Figure: 5.43 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2.5).

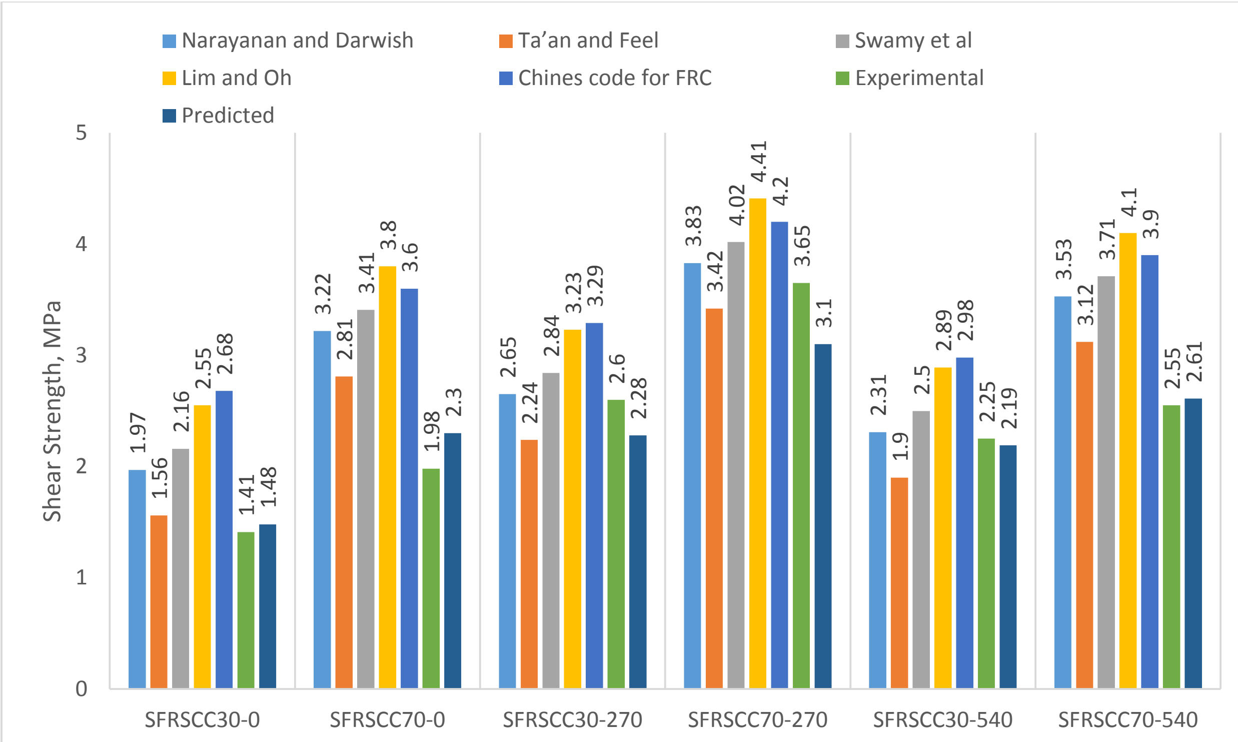


Figure: 5.44 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=3).

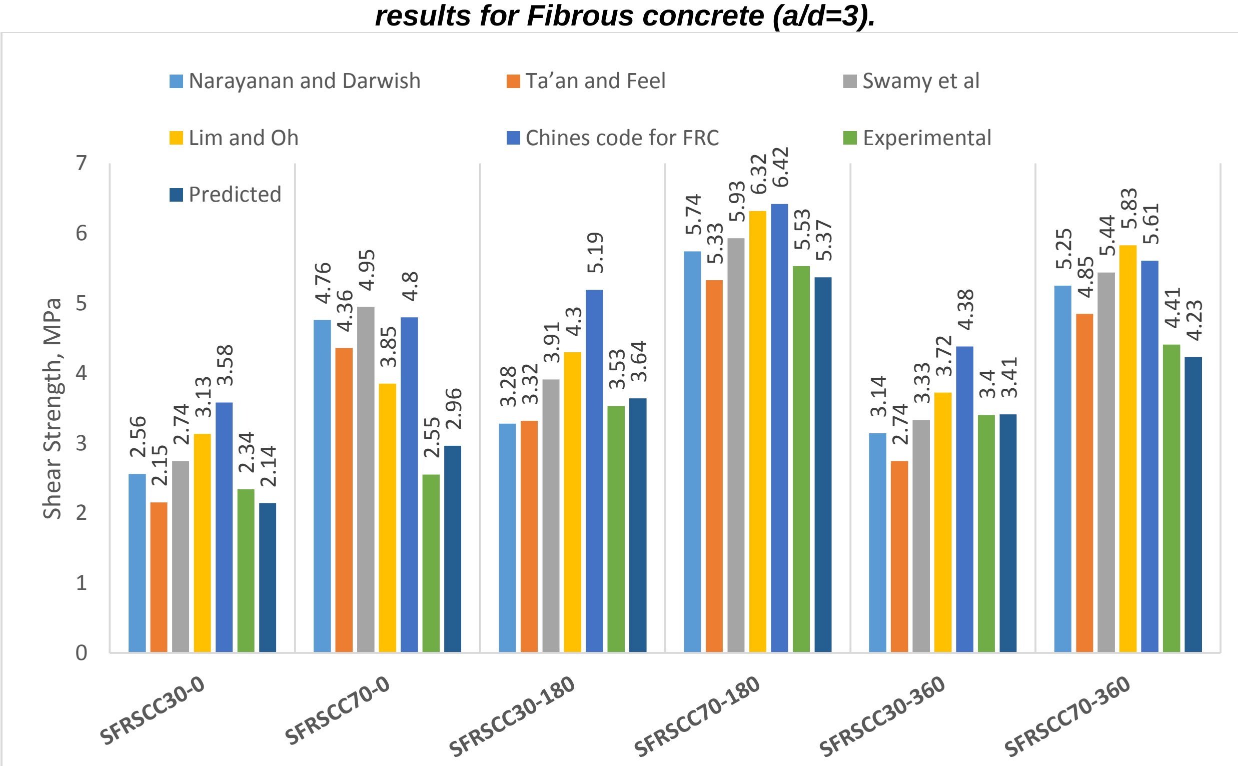


Figure: 5.45 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2) (8mm Ø)

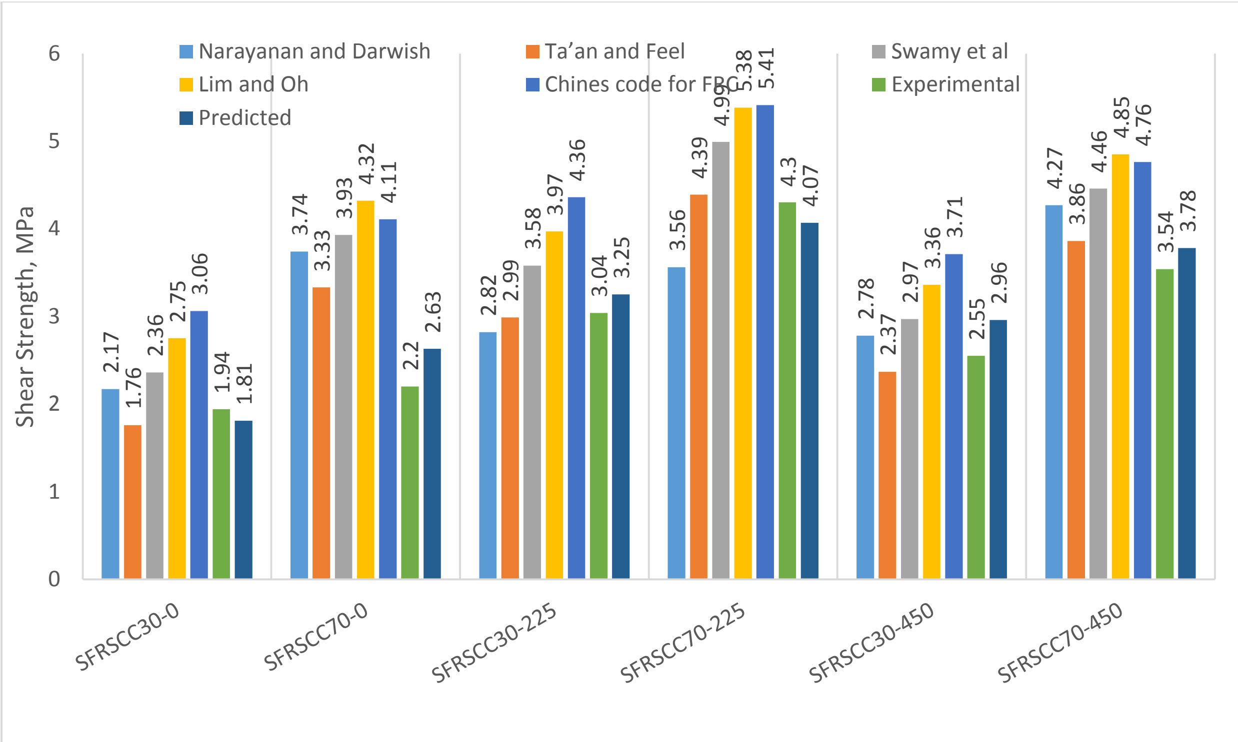


Figure: 5.46 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2.5) (8mm Ø)

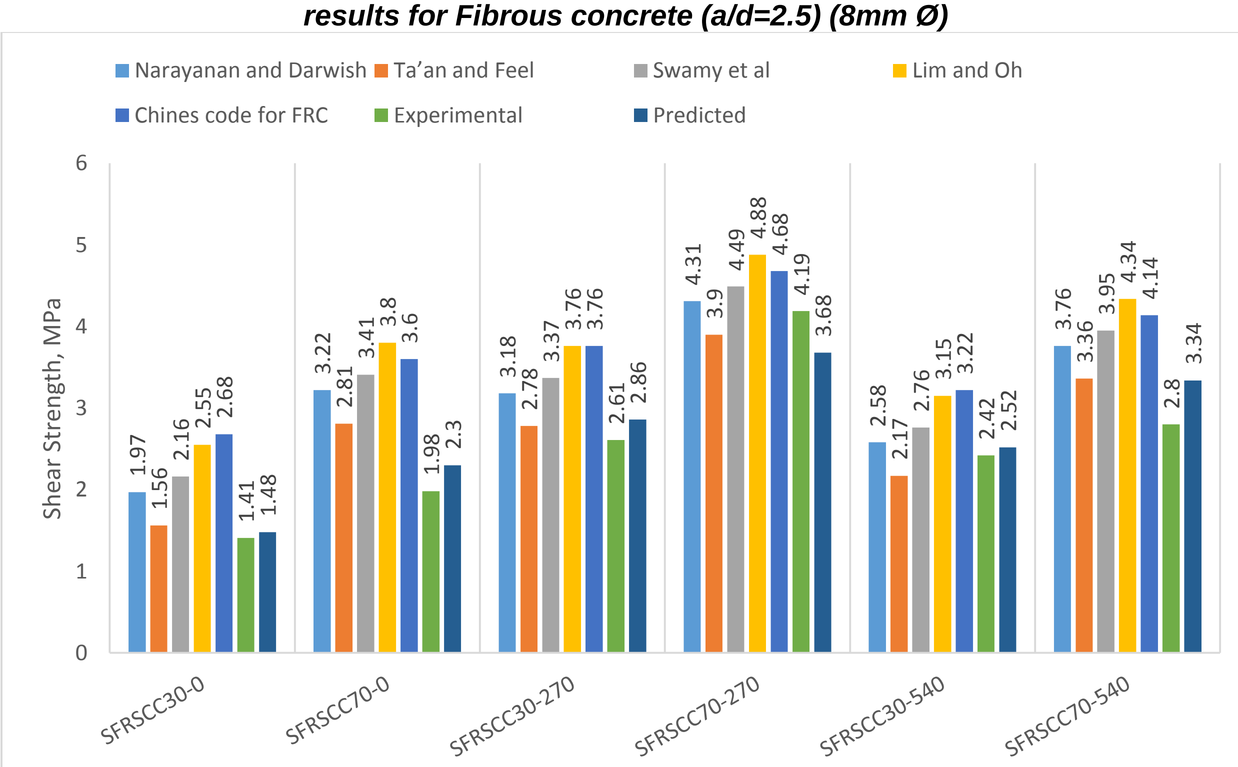


Figure: 5.47 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=3) (8mm Ø)

CHAPTER 6
SHEAR BEHAVIOUR OF RECYCLED AGGREGATE STEEL FIBER REINFORCED SCC

6.0 General

The previous chapter dealt with shear behaviour of steel fiber reinforced self-compacting concrete for both 6mm and 8mm diameter stirrups by using natural aggregate. The studies concluded that steel fiber plays a very important role in crack arresting mechanism and also improves the shear performance of self-compacting concrete. It was also noticed that addition of steel fibers can partially replace stirrups there by providing larger spacing for stirrups in SCC. As the shear span to depth ratio increased from 2 to 3 ultimate shear strength decreased irrespective of grade and type of concrete. From the experimental results it was found that as spacing of stirrups increased, shear strength decreased. Further, it is noticed that due to increase in the area of shear reinforcement by using 8mm diameter stirrup, there was an increase in ultimate shear resisting capacity of the beams and also comparison of experimental results with various model available in the literature on vibrated concrete was done and the correlation was satisfactory.

This chapter focuses on the shear behaviour of self-compacting concrete for both without and with steel fibers by completely replacing natural aggregates (both coarse and fine aggregates) with recycled aggregates.

6.1 Introduction

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 the 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. 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. 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 overcome by using steel fibers and use of steel fibers in self-competing concrete can change the brittle failure nature to a ductile behaviour especially in shear. The present chapter focuses to study the shear behaviour of recycled aggregate based self-compacting concrete without and with fibers.

As we know that 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 and the remaining finer fraction can be used as fine aggregates in the concrete production process.

Several researches have studied the effect of recycled aggregates on mechanical, durability and structural properties by replacing up to 50% of natural aggregates. In the present study, natural aggregates are completely replaced with recycled coarse and fine aggregates and mechanical properties and shear behavior of self-compacting concrete 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 shear behaviour recycled aggregate based self-compacting concrete for both with out and with steel fibers are presented in the following sections. The parameters varied are a) Grade of concrete 30 MPa and & 70 MPa b) Shear Span to depth ratio (a/d) 2,2.5 and 3 c) Spacing of stirrup d) Diameter of stirrup (6 & 8 mm) e) volume of steel fiber 0% and 0.5% by volume of concrete.

6.2 Experimental Program:

The experimental program is similar to that presented in the chapter 5. Experimental programme was designed to study the shear behaviour of recycled aggregate based steel fiber reinforced self-compacting concrete by casting and testing 100x200x1200mm shear deficit beams. The scheme of casting the specimens was done in two stages. The First stage includes studies on shear of steel fiber reinforced self-compacting concrete using 6mm Ø stirrup. The second stage involves studies on shear of steel fiber reinforced self-compacting concrete using 8mm Ø stirrup. The variables in the study are shear span to depth ratio (a/d), grade of concrete (fc), Spacing of stirrups (Sv), volume of steel fibers (V_f) and diameter of stirrup and type of aggregate.

In each stage, a total of 36 beams were cast and tested by varying above parameters. In the present study two mixes were considered i.e. 30 MPa and 70 MPa strength concrete. The stirrups spacing's was varied in the shear span. Three shear span to depth ratios were considered (a/d= 2, 2.5 and 3). From the preliminary study presented in chapter 4, based on the fresh and hardened properties on SCC it was found that 0.5% dosage of steel fibers by volume of concrete is optimal, beyond which fresh properties were not satisfying the EFNARC criteria. Hence in casting of beams only optimal dosage of steel fibers was used i.e. 0.5% by volume of concrete. In each set three standard cubes, cylinders and prisms of sizes 150x150x150mm, 150mm diameter 300mm height and 100x100x500mm were cast and tested for obtaining the compressive, split tensile and flexural strengths. These specimens are companion specimens.

To study the behaviour of self-compacting concrete in shear, the beams are designed to fail in shear. To make the beams as shear deficient, larger stirrup spacing was considered. For each a/d ratio six beams were cast, of which two beams are of plain ones i.e. without stirrups. In those two one is of no stirrups and no fibers and other one is no stirrups and with fibers.

Similarly, for remaining four beams two stirrup spacing were considered i.e. a and $\frac{a}{2}$. The details of the beams cast for two grades of SCC are presented in table 6.1. The experimental programme is same for both the stages of casting, only difference being 8mm Ø stirrup was used instead of 6mm Ø stirrup.

6.2.1 Materials Used and Methods:

The details of the various materials used such are cement, flyash, fine aggregates, coarse aggregates, silica fume and steel fibers and reinforcement details are presented in chapter 4 and 5.

a) ***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 below.

b) ***Recycled Fine Aggregate (RFA):*** The finer fraction obtained after crushing of concrete cubes and can be used as fine aggregates in the concrete. The aggregates were washed with water to remove any unwanted substances, and presoaked for 30 minutes and then they were air-dried and brought to saturated surface dry condition and used

d) ***Water:*** Potable water was used in the experimental work for both mixing and curing of specimens and it is confirming to IS456-2000.

6.2.2 Mix Proportions

Self-Compacting Concrete (SCC) mixes are designed using the rational mix design method (**Rao etal, 2013**). The details of mix proportions are presented in Table 6.4. Trial mixes were carried out by varying super Plasticizer dosage and binder content and the fresh properties were evaluated as per EFNARC Specifications via, Slump flow, $T_{50\ mm}$, L-Box, V-Funnel, $T_{5\ mins}$ and J ring tests.

6.2.3 Fresh Properties of RASCC30 & RASCC70 for both without and with steel fibers:

The details of fresh properties of RASCC30 and RASCC70 without and with steel fiber were shown in Table 6.5. It can be seen from Table **6.5** that, addition of steel fibers has reduced the flow properties but all the properties are satisfied according to EFNARC specifications.

6.2.4 Hardened properties of Self-compacting concrete without and with steel fiber:

The details of hardened properties of 30 MPa and 70 MPa RASCC without and with steel fiber at the age of 28 days were shown in Tables 6.6. All the tests were done as per IS: 516-2004 specifications. Due to use of recycled aggregate, there is slight decrease in the mechanical properties of RASCC compared with that of natural aggregate SCC. Due to use of recycled aggregates, compressive strength of RASCC30 is reduced by 8.68% compared to that of NASCC30. Similarly for higher grade concrete, the compressive strength is reduced by 9%. Figures 6.1-6.3 show the variation of compressive strength, split tensile strength and flexural strength of 30 and70 MPa NASCC and RASCC and for both without and with steel fiber.

6.3 Moulds and Equipment

6.3.1 Cubes: Standard cube moulds of 150 x150 x 150mm made of cast iron were used for casting and testing specimens for compression as per IS 10086-2008.

6.3.2 Cylinders: Standard Cylinders of 150 mm diameter and 300 mm height, made of cast iron were used, for casting and testing specimens for split tensile strength as per IS 10086-2008.

6.3.3 Prisms: Standard cast iron moulds of size 100x100x500mm were used for casting and testing specimen for flexural strength of concrete as per IS 10086-2008.

6.3.4 Beams: Casting of beams consisted of two channel sections 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 were kept in between the two channels to maintain the spacing (equal to the width of beam). The entire casting was done on a level platform. The ends of the moulds 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 were used.

6.3.5 Preparation of specimens and Fabrication process

The required lengths of the longitudinal steel bars were cut and straightened. Similarly, for stirrups, 6 and 8 mm diameter mild steel rods are was cut from the lots, straightened and bent into the proper shape. The stirrups were placed at required spacing and were tied to the longitudinal steel bars with binding wire.

6.3.6 Reinforcement Details.

The dimensions and typical reinforcement detail for both mixes 30 & 70 MPa and for different shear span to depth (a/d) ratios are shown in Figures 6.4 to 6.9. The stirrups spacing was varied in the shear span, for each a/d ratio two stirrup spacing were considered. For Mix A (30 MPa) SCC beams consist of 2-12mm Ø TMT bars as longitudinal reinforcement, 2-6mm Ø mild steel bars as top compression reinforcement. Similarly, for Mix B (70MPa) SCC beams consists of 2-16 mm and 1-12mm Ø bars as longitudinal reinforcement, 2-6mmØ mild steel bars as top compression reinforcement and two legged 6mm and 8mm Ø bars was used as stirrups for both 30 and 70MPa concrete.

6.3.7 Casting of beams

The required number of beam moulds were assembled on smooth concrete flooring with an oilpaper in between the bottom of the channels and the flooring. The inner side of the mould was lubricated properly. Cover blocks of proper thickness were placed below the bottom of the cage so that the required effective depth of the beam is maintained. The required quantities of the materials for casting one batch of beams were mixed thoroughly in a concrete mixer to get a uniform mix. First, the reinforcement cage was kept on cover blocks in the mould. Then the concrete is placed in the mould. The beam moulds were stripped 24 hours after concreting. The specimens were numbered with water proof ink.

6.3.8 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 specimen were kept under shade.

6.3.9 Testing of the beams.

6.3.10 Preparation of Test Specimens: One day before the testing, the beams were white washed. The capping is done with the help of glass plate and spirit level.

6.3.11 Testing machine: The beams were tested on 1000kN Dynamic Testing Machine under flexure, with strain control of 0.1mm/min.

6.3.12 Measurement of deflections: The deflections were measured at the centre of the beam.

6.4 Results and Discussion:

6.4.1 Discussion on Shear behaviour of Self-compacting concrete using 6mm Ø stirrups:

In this section, the behaviour of 36 simply supported beams with 6 mm Ø stirrup for shear span to depth ratio 2, 2.5 and 3 has been discussed. The results of these beams are presented in Tables 6.7, 6.8 and 6.9. The behaviour of these beams are discussed in detail in the following sections.

a) Effect of Spacing of Stirrups on shear behaviour of RASCC Beams

It can be observed from above Tables 6.6, 6.7 and 6.8 that as spacing of stirrup increased for any shear span to depth (a/d) ratio, ultimate shear strength has been decreased.

1. RASCC30-0 plain beam with no stirrup has shown lower load carrying capacity and brittle failure pattern compared to similar beam with stirrup spacing at 180mm and 360mm. due to provision of stirrup the ultimate shear strength of the beam RASCC30-180 and RASCC30-360 is increased by 52.45% and 29.19% compared to plain beam. As the spacing increased from 180mm to 360mm the ultimate shear strength decreased by 18%. This decrease in shear strength with increase in spacing of stirrups can be attributed to reduced shear resistance of the beam which results in early failure at relatively lower load.
2. Higher grade concrete RASCC70-0 beam with no stirrup also failed early at lower load compared to similar beam with stirrup spacing at 180 mm and 360 mm. Due to provision of stirrups, the ultimate shear strength increased by 52.9% and 45.4%

respectively. As the spacing of stirrup increased from 180 to 360 mm, shear strength decreased marginally by 4.91%.

3. Similarly, for shear span to depth ratio a/d=2.5, RASCC30-225 beam with stirrup spacing at 225 mm has shown higher load carrying capacity compared to plain beam with no stirrup. Due to provision of stirrup at 225 mm spacing, ultimate shear strength increased by 40.6% and also for the beam RASCC30-450 with stirrup spacing at 450mm, ultimate shear strength increased slightly by 28.15% compared with plain beam with no stirrup. As the spacing of stirrup increased from 225 to 450 there is slight decrees in shear strength by 21%.
4. For higher grade concrete, for shear span to depth ratio a/d=2.5, RASCC70-225 has shown higher load carrying capacity compared with plain beam without stirrups. Due to provision of stirrups at 225 and 450 mm spacing, ultimate shear strength is increased by 53.65% and 23.8% respectively.
5. Similar trend was observed in the case of beams with shear span to depth ratio a/d= 3.

Figures 6.10, 6.11and 6.12 shows the variation of shear strength with respect to spacing of stirrups.

b) Effect of Shear Span to depth ratio (a/d) on Shear Behaviour of RASCC beams

Shear span to depth ratio is one of the important parameter which effects the shear behaviour of reinforced concrete beams. To study the effect of shear span to depth ratio on shear behaviour of RASCC, in the present study three span to depths were selected, i.e. a/d= 2, 2.5 and 3. From Tables 6.7-6.9, it clearly shows that as the shear span to depth ratio increased from 2 to 3 there is decrease in ultimate shear strength of self-compacting concrete. This decrease in ultimate shear strength can be attributed to increase in shear span causing early diagonal cracks at lower loads, resulting in lower load carrying capacity of the beam. From the shear strength results following points can be observed.

For the plain beam RASCC30-0 without stirrups and steel fibers, tested for shear span to depth ratio a/d=2, the ultimate load carrying capacity of the beam is 54.68 kN, as the shear span to depth ratio (a/d) increased from 2 to 2.5 and 3, the ultimate load carrying capacity of the beam is reduced to 40.64kN and 39.15kN respectively. The percentage decrease in ultimate shear strength is 25.67% and 28.4% respectively compared to beam with no stirrups and no fibers. Addition of steel fibers, has increased the load carrying capacity of the beam and reduced the percentage decrease in ultimate shear strength. With the presence of steel fibers for the beam tested for shear span 2.5 and 3, the ultimate shear strength was decreased slightly by 2.83% and 11.4% respectively.

Similarly, for higher grade concrete beam as the shear span to depth ratio (a/d) increased from 2 to 2.5 and 3, the ultimate shear strength of plain beams RASCC70-0 is decreased by 7.02% and 20.2% respectively and also addition of steel fibers has increased the load carrying capacity and percentage decrease in ultimate shear strength is reduced by 2.46% and 7.41% compared with a/d=2. This shows that steel fibers plays an important role in crack arresting and there by delaying the failure of the specimen and finally increases the ultimate load carrying capacity of the beam. Figure 6.13and 6.14 shows the variation of shear strength with respect to a/d ratio for plain beams without stirrups and beams with stirrups. Similar type of behaviour was seen in the case of beams provided with stirrups.

c) Influence of Steel fiber on Shear Behaviour of RASCC beams:

Addition of steel fibers in SCC not only helps in crack arresting mechanism but also improves the ultimate load carrying capacity by delaying the crack propagation. From the experimental results presented in Tables 6.7-6.9 it shows the same. The following observations were made based on the experimental results.

1. The plain beam RASCC30-0 with no stirrups and steel fiber has shown lower load carrying capacity and brittle failure pattern compared with RASFRSCC30-0 beam with steel fibers. Due to addition of steel fibers, the ultimate load carrying capacity of the beam increased by 11.5%. Similarly for higher grade concrete beam RASCC70-0 with no stirrups and steel fibers has shown brittle failure pattern and lower load carrying capacity compared to RASFRSCC70-0 beam with steel fibers. Due to addition of steel fibers, ultimate load carrying capacity of the beam is increased by 10.5%.
2. The combination of stirrups and steel fiber has shown a hybrid effect on shear performance of RASFRSCC beams. Due to the combined effect of stirrups and steel fibers, the ultimate load carrying capacity of the beams RASFRSCC30-180 and RASFRSCC30-360 tested for shear span (a/d) 2 increased by 92% and 72.2%

compared with plain beam. With increase in stirrup spacing there is a slight decrease in shear strength was observed. As the spacing is increased from 180mm to 360mm the shear strength decreased by 15.2%, whereas with steel fibers it is decreased by 10.4%. This show that addition of steel fibers can helps in improving shear strength for larger spaced stirrups as well.

3. For higher strength (70 MPa) concrete beams, with combination of stirrups and steel fibers has shown better performance on shear behaviour on RASCC beams. Due to the combined effect of stirrups and steel fiber on RASFRSCC70-180 and RASFRSCC70-360 beams the ultimate shear strength is increased by 96.3% and 65% respectively compared to plain beam. As spacing of stirrups increased from 180 to 360 mm there is a slight decrease in shear strength was noticed. With increase in stirrup spacing, shear strength decreased by 16.07%.
4. The beams tested for shear span to depth ratio 2.5, the shear strength of RASFRSCC30-0 is increased by 30.7% compared with plain beam with no stirrups and steel fibers and for higher grade concrete beams with addition of steel fibers, shear strength is increased by 15.4%.
5. With combination of stirrups and steel fibers, the ultimate shear strength is increased by 134% and 105% respectively for RASFRSCC30-225 and RASFRSCC30-450 beam compared with plain beam with no stirrup and steel fibers. As the stirrup spacing is increased, there is a slight decrease in shear strength by 17.3% for beam without steel fibers, and for the beam with steel fibers shear strength is decreased by 12.6%.
6. Similarly for higher grade concrete beam with combination of stirrup and steel fibers, ultimate shear strength is increased by 80.6% and 35% respectively for RASFRSCC70-225 and RASFRSCC70-450. With increase in stirrup spacing, shear strength is decreased by 19.4% for beam without steel fibers, whereas for the beam with steel fibers percentage decrease in shear strength is 8.8% respectively.
7. Similar trend is observed in the case of beams tested for shear span to depth ratio (a/d) 3 for both 30 and 70 MPa RASCC and RASFRSCC.

From the above discussion it can be concluded that addition of steel fibers play an important role in improving the shear performance of self-compacting concrete made with recycled aggregates. The combination of stirrups and steel fibers has shown hybrid effect on self-compacting concrete and also steel fiber can partially replace the stirrups their by increasing the spacing of stirrups in RASFRSCC beams without effecting the shear performance. Figures 6.15-6.20 shows the comparison of load vs deflection curves for Both RASCC30 and RASCC70 with and without steel fibers.

d) Influence of stirrups and steel fibers on Toughness of RASCC Beams:

Toughness is defined as the amount of energy per unit volume that a material can absorb before failure. In can also be defined as area under load deflection curve. Addition of steel fibers, not only improves the shear strength, but also there is an increment in toughness. Due to addition of steel fibers, toughness of RASFRSCC30-0 beam is increased by 35.2%, similarly, for higher grade concrete due addition of steel fibers toughness of the beam RASFRSCC70-0 is increased by 92.8% and due to provision of stirrups only, toughness of the beams RASCC30-180 and RASCC70-180 is increased by 108.3% and 127.8% respectively. This shows that combination of stirrups and steels fibers has more effect than with provision of stirrups only. Similar behaviour has been observed in case of beams with shear span to depth ratio (a/d) 2.5 and 3. Figures 6.21-6.23 shows the variation of toughness for RASCC and RASFRSCC beams for different a/d ratios.

6.4.2 Discussion on Shear behaviour of Self-compacting concrete using 8mm Ø stirrups:

In this section behaviour of 36 simply supported RASCC beams were cast by using 8 mm Ø stirrup and tested for shear span to depth ratio (a/d) 2, 2.5 and 3 were discussed . The results are presented in Tables 6.10-6.12. Influence of steel fibers and effect of stirrup spacing and stirrup diameter are discussed in detail in the following sections. Figures 6.24-6.29 shows the reinforcement details of 30 MPa and 70 MPa concrete using 8 mm Ø stirrup.

a) Effect of Spacing of stirrups on shear behaviour of RASCC beams:

It can be observed from the studies that as spacing of stirrups increased there is decrease in shear strength. Comparing with plain beams without any stirrups, there is an increase in shear strength with provision of stirrups at 180mm and 360mm spacing for a/d= 2, and similar trend was observed for beams tested for a/d 2.5 and 3. From the experimental results following points are noticed.

1. Plain beam RASCC30-0, has shown lower load carrying capacity and failed suddenly, due to provision of stirrups at 180 mm and 360mm spacing, the ultimate shear strength of RASCC30-180 and RASCC30-360 is increased by 52.7% and 39.2% respectively. As the spacing of stirrups increased from 180 to 360 mm the shear is slightly reduced by 9.6%.
2. Similarly, higher grade concrete beam RASCC70-0 has also failed early at lower loads and suddenly when compared with beams with stirrups at 180 mm and 360 mm spacing. The ultimate shear strength of the beams is increased by 132% and 85% respectively. As the spacing of stirrups is increased from 180 mm to 360 mm there is a slight decrease in shear strength by 20.2%.
3. For shear span to depth ratio (a/d) 2.5, the plain beam failed early at lower load compared to beams with stirrups at 225 mm and 450 mm spacing. Due to provision of stirrups the ultimate shear strength of the beam increased by 82% and 42% respectively. As the spacing of stirrup increased from 225 mm to 450 mm, the ultimate shear strength decreased by 23%. It was also observed that for higher spacing between the stirrups, percentage decrease in shear strength is higher. This shows that by providing stirrups at larger spacing results in early failure of the beam at relatively lower loads.
4. For higher grade concrete beams tested for shear span to depth ratio 2.5, the plain beam with no stirrup failed suddenly at relatively lower load. Due to provision of stirrups at 225 mm and 450 mm spacing, ultimate shear strength is increased by 52% and 29% respectively. It was also observed that the percentage increase in shear strength for larger spacing of stirrups is lower compared to that for closer spacing of stirrups. For increased spacing of stirrups from 225 to 450 mm the ultimate shear strength is decreased by 15%.
5. Similar behaviour was noticed for the beams tested for shear span to depth ratio (a/d) 3 for both grades of concrete (RASCC30 & RASCC70).

Figure 6.30-6.32 shows the variation of shear strength for different spacing of stirrups and for different shear span to depth ratios.

b) Influence of steel fibers on RASFRSCC beams.

Figures 6.33-6.38 shows the load vs deflection curves for RASCC30 and RASCC70 for 8mm diameter stirrup for shear span to depth ratio (a/d= 2, 2.5 and 3). From the experimental results and load – deflection graphs, following points were observed.

1. Plain beam without stirrups and steel fibers RASCC30-0 shown lower load carrying capacity and brittle failure pattern and failed early when compared with RASFRSCC30-0 beam with steel fibers. Due to addition of steel fibers ultimate shear strength increased by 14%. The combination of stirrups and steel fibers has better performance on shear behaviour of RASFRSCC beams. Due to the combined effect of stirrups and steel fibers the ultimate shear strength is increased by 109% and 79% for RASFRSCC30-180 and RASFRSCC30-360 beams respectively, when compared with plain beam.
2. Similarly for RASFRSCC70 beams due to addition of steel fibers, the ultimate shear strength increased by 10%. Due to the combined effect of stirrups and steel fibers, the ultimate shear strength is increased by 148% and 93% for RASFRSCC70-180 and RASFRSCC70-360 beams when compared with plain beam without stirrups and without steel fibers respectively.
3. For the beams tested for shear span to depth ratio a/d=2.5, plain beam without steel fiber and stirrups has failed early at lower load with brittle failure mode. Due to addition of steel fibers, the ultimate shear strength of the plain beam increased by 34% and due to the combined effect of stirrups and steel fibers, the ultimate shear strength of the beam RASFRSCC30-225 and RASFRSCC30-450 increased by 157% and 118% respectively when compared with plain beams without stirrups and steel fibers.
4. Similarly for higher strength concrete beams tested for shear span to depth ratio (a/d=2.5), due to addition of steel fibers the ultimate shear strength of the beam RASFRSCC70-0 increased by 14% and due to the combination of stirrups and steel fibers, the ultimate shear strength of the beam RASFRSCC70-225 and RASFRSCC70-450 increased by 93% and 29% respectively when compared with plain beams with no stirrups and steel fibers. It was observed that as the stirrups spacing increased, percentage increase in ultimate shear strength is reduced.

5. Similar type of behaviour was observed in case of beams tested for shear span to depth ratio (a/d=3). It was also noticed that as the shear span to depth ratio increased from (a/d) 2 to 3, the ultimate shear strength is reduced and in the presence of steel fibers, percentage increase in shear strength is reduced when compared with beams tested for shear span (a/d) 2.

From the above discussion it is evident that steel fibers play a very important role in enhancing the shear performance of RASFSCC and also the combination of stirrups and steel fibers shows the hybrid effect and the ultimate shear strength increased enormously. It was also observed that steel fibers can partially replace the stirrups by increasing the spacing of stirrups there by reducing the area of reinforcing steel near critical sections.

c) Effect of Shear Span to depth ratio (a/d) on shear performance of RASCC.

Shear span to depth ratio is the one of the important parameter effecting the shear strength of concrete. To study this parameter in the present study three shear span to depth ratio (a/d= 2, 2.5 and 3) were selected in the present study. The experimental test results of the beams tested for three shear span to depth ratio (a/d= 2, 2.5 and 3) are presented in the Tables 6.10-6.12. From the experimental results it was observed that as the shear span to depth ratio increased from a/d=2 to 3, ultimate shear strength is decreased. The ultimate load carrying capacity of the plain beam RASCC30-0 without stirrups and steel fibers tested for shear span to depth ratio (a/d) 2 is 54.68 kN as the shear span to depth ratio increased to 2.5 and 3, the ultimate load of the similar beam is decreased to 43 kN and 41 kN respectively. The percentage decrease in shear strength is 28% and 33% respectively in comparison with a/d=2. Even with the combination of stirrups and steel fibers, as the shear span to depth ratio increased, ultimate shear strength decreased for both RASCC30 and RASCC70 concrete beams.

Figure 6.39 and figure 6.40 shows the variation of shear strength with respect to shear span to depth ratio for plain beams and beams with stirrups.

d) Influence of steel fibers and stirrups on toughness of RASFRSCC beams.

Toughness is defined as the amount of energy per unit volume that a material can absorb before failure. In can also be defined as area under load deflection curve. In the present study toughness of the beams is measured by calculating the area under load-deflection curve. Addition of steel fibers not only increased the shear strength but also improved the toughness of the beam. From the experimental results presented in the Tables 6.10-6.12 it is noticed that due to addition of steel fibers, the toughness of the beam improved considerably and also combination of stirrups and steel fibers has shown better improvement in the toughness of RASCC beams for both 30 and 70 MPa concrete. Due to addition of steel fibers, toughness of the plain beam RASFRSCC30-0 is increased by 55% compared with plain beam without stirrups and steel fibers. Similarly for higher strength concrete beams i.e. RASCC70, due to addition of steel fiber the toughness is increased by 75%. Similar behaviour was observed for beam with shear span to depth ratio 2.5 and 3. It was also observed that as the spacing of stirrups increased, percentage increase in toughness due to addition of steel fibers is slightly decreased compared to beams with closer stirrups spacing. Figures 6.41-43 shows the variation of toughness with respect to stirrup spacing for both fibrous and non-fibrous RASCC30 RASCC70.

e) Effect of Stirrup diameter (6mm & 8mm Ø) on shear behaviour of RASCC beams.

Area of shear reinforcement is considered as important parameter which effects the shear behaviour of reinforced concrete on shear behaviour of reinforced concrete. In the present study, two stirrup diameters were considered (6mm and 8mm Ø) to study the effect of shear reinforcement. From the experimental results it is observed that as the area of shear reinforcement increased, there is an increase in ultimate shear strength. For the beams with shear span to depth ratio a/d= 2, for identical spacing of stirrups but with different diameter of stirrup, the ultimate shear strength of the beams with use of 8mm diameter stirrup for 30 MPa concrete is increased slightly compared with beams tested with 6mm Ø stirrup. Whereas with use of steel fibers, the ultimate shear strength is increased by 8.5%. Similarly for 70 MPa concrete, due to use of 8 mm Ø stirrups, the ultimate shear strength is increased by 34.12% and in the presence of steel fibers, the ultimate shear strength is increased by 20.72% when compared with similar beams and identical stirrup spacing but with use of 6 mm diameter stirrup. Similar trend was observed for beams tested for shear span to depth ratio 2.5 and 3. Figures 6.44 -6.46 shows the variation of shear strength with respect to diameter of stirrup (6mm and 8mm) for shear span to depth ratio 2, 2.5 and 3 for both 30 MPa and 70 MPa concrete.

6.4.3 Comparison of Shear Strength of NASCC beams and RASCC beams.

a) Comparison of shear strength for 6mm dimeter stirrup

To study the shear performance of self-compacting, a comparison is made with self-compacting concrete beams cast with normal aggregates and with self-compacting concrete beams cast with recycled aggregates as complete replacement of natural aggregates. Due to use of recycled aggregates, shear strength decreased by 12% and 10.2% for 30 and 70 MPa plain SCC beams. Similarly in case of fibrous SCC beams, due to use of recycled aggregates, shear strength reduced by 2.36% and 6.98% for 30 MPa and 70 MPa concrete. In the presence of stirrups the ultimate shear strength of RASCC beams is decreased by 13.15% and 4.36% for 30 MPa and 70 MPa concrete. Due to combination of stirrups and steel fibers, the ultimate shear strength is reduced by 10.36% and 11.26% for 30 MPa and 70 MPa concrete respectively for beam tested for shear span to depth ratio (a/d) 2. Similar type of behaviour was observed in case of beams tested for shear span to depth ratio 2.5 and 3 respectively. Due to the presence of weak interfacial transition zone in recycled aggregates, failure occurs at relatively lower loads due to which ultimate shear strength of RASCC is reduced when compared with NASCC beams. In the presence of steel fibers, the percentage decrease in ultimate shear is less compared to plain RASCC beams.

Figures 6.47-6.52 shows the comparison of shear strength among NASCC and RASCC 30 and 70 MPa concretes for shear span to depth ratio (a/d) 2, 2.5 and 3.

(b) Comparison of shear strength for 8mm dimeter stirrup

To study the effect of recycled aggregates on shear behaviour of self-compacting concrete beams cast with 8mm diameter stirrup as shear reinforcement, a comparison was made between NASCC beams cast using 8mm diameter stirrups with that of RASCC beams cast with 8mm diameter stirrups as shear reinforcement. From the experimental results it was observed that irrespective of diameter of stirrups, with the use of recycled aggregates as replacement of natural aggregates there is decrease in the shear strength. Figures 6.53-6.58 shows the variation of shear strength among NASCC and RASCC for 30 and 70 MPa concrete using 8mm diameter stirrup for three shear span to depth rations (a/d) 2, 2.5 and 3.

6.5 Angle of Inclination (ϴ):

From the failure pattern of the beams, crack angle is measure for SCC30 and SCC70 beams for both 6 mm and 8 mm diameter stirrup. The details of these are presented in the Tables 6.13-6.14. It was observed that as the shear span to depth ratio increased, crack angle is reduced. This can be attributed to increase in the crack length as the shear span increased from a/d 2 to 3.

6.5.1 Prediction of Theoretical shear strength.

From the obtained crack angle (ϴ), a plot among crack angle and vs shear span to depth ratio is plotted. Figure 6.59(a) shows the variation of crack angle (ϴ) with respect to shear span to depth ratio whereas, Figure 6.60 (b) shows the variation of average crack angle (ϴ) with respect to shear span to depth ratio. The cracked portion of the beam is shown in Figure 6.61. As the type of failure is split tensile failure. Assuming the crack inclination is as "ϴ", and the force acting on the surface of the crack as split tensile force (F_t). By way of resolving the force F_t along the y-direction, the vertical component of force F_t is "$F_t * \mathrm{Cos}\theta$". Shear force (V_u) at the support is equivalent to $\mathbf{V_u = V_{uc} + V_{us}}$. Where V_{uc} = shear force taken by uncracked concrete and $\mathbf{V_{us}}$ **=** shear force taken by vertical stirrup.

Therefore, Predicted Theoretical Shear Strength fir RASCC is given by:

$$\mathbf{V_u = V_{uc} + V_{us}} \qquad \textbf{Eq (6.1)}$$

$$\mathbf{V_u = \left\{\frac{d}{Sin\theta} * b * F_t * Cos\theta\right\} + \left\{\frac{0.87 * f_y * A_{sv}}{Cos\theta}\right\} * k_2} \; ; \qquad \textbf{Eq (6.2)}$$

Where F_t = Split tensile strength of RASCC or RASFRSCC and θ = 50.459 - 3.2838(a/d). $k_2 = 0$, when crack does not cross the stirrup and $k_2 = 1$ **,** when crack crosses the stirrup

6.5.2 Comparison of Theoretical and Experimental Shear Strength:

The theoretical shear strength obtained by predicted equation is compared with experimental results. The correlation among experimental and predicted shear strength is in good agreement. Tables 6.15 and 6.16 shows the Experimental and Theoretical Shear Strength for SCC30 and SCC70 for 6mm dia stirrup and 8 mm dia stirrup and percentage error. The percentage error in all the cases is less than 15 % with an average ratio of theoretical and experimental shear strength as 1.03. Figure 6.60 shows the plot among experimental and theoretical shear strength, the equation between experiential and theoretical shear strength is given by **$y = 0.9547x + 0.1633$ with an $R^2 = 0.975$**

6.5.3 Predicted Analytical Shear Strength based on Non-linear regression analysis:

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

$$V_u = (0.35*f_{ck}) + (0.014*A_{sv})-(0.001*S_v)-(0.04*A_{st})-(0.73*a/d) + (0.24*V_f) \quad \text{Eq (6.3)}$$

where, f_{ck} = Compressive strength of RASCC; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5). A comparison is made among experimental and analytical predicted shear strength using. From the comparison it was observed that experimental results are close to predicted shear strength. Tables 6.17-6.18 shows the comparison of experimental and analytical shear strength. Figure 6.61 shows the comparison of experimental and analytical shear strength.

6.6 Comparison of test results with various models available Literature:

6.6.1 For beams cast using 6mm diameter stirrup:

In this section, the experimental results obtained for ultimate shear strength of non-fibrous SCC and fibrous SCC beams are compared with shear strength models available in the literature for vibrated concrete. The model used for comparing NASCC beams are used for comparing experimental results of RASCC beams. The details of the models are presented in the chapter 5.

a) Non Fibrous RASCC:

Table 6.19 shows the shear strength values of various models and experimental results of RASCC30 and RASCC70 of non-fibrous concrete beams with 6mm Ø stirrup as shear reinforcement. From the Table 6.19 it can be concluded that the shear strength predicted by Russo et.al and ACI318-14 are close to that of the experimental values. Figures 6.62-6.64 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete.

b) Fibrous SCC:

Table 6.20 shows the comparison of shear strength values of experimental results and various models of RASFRSCC30 and RASFRSCC70 for 6mm Ø stirrup as shear reinforcement. From the Table 6.20 it can be concluded that the shear strength predicted by Narayana and Darwish for fiber reinforced concrete are close to that of the experimental values. Figures 6.65-6.67 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete.

6.6.2 For beams cast using 8mm diameter stirrup:

a) For Non- Fibrous SCC Beams:

Table 6.21 shows the shear strength values of various models and experimental results RASCC30 and RASCC70 of non-fibrous concrete beams cast using 8mm Ø stirrup as shear reinforcement. From the Table 6.21 it can be concluded that the shear strength predicted by Russo et al model and ACI318-14 are close to that of the experimental values. Figures 6.68-6.70 Shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete.

b) For Fibrous SCC Beams:

Table 6.22 shows the comparison of shear strength values of experimental results and various models of RASFRSCC30 and RASFRSCC70 for 8mm Ø stirrup as shear reinforcement. From the Table 6.22 it can be concluded that the shear strength predicted by Ta’an et al, and Chinese code for fiber reinforced concrete are close to that of the experimental values. Figures 6.71- 6.73 shows the variation of shear strength for various models and experiential results for non-fibrous SCC30 and SCC70 grade concrete

6.7 Conclusions from the Present Study:

Based on the detailed studies on shear behaviour of recycled aggregate based self-compacting concrete for both fibrous and non-fibrous concretes beams using 6mm and 8mm diameter as stirrups following conclusions were made.

1. Due to use of recycled aggregates, the compressive strength is decreased by 7.8 and 8% respectively for 30MPa and 70 MPa concrete.
2. As the shear span to depth ratio increased from 2 to 3, ultimate shear strength is reduced and similar behaviour was observed in case of both fibrous and non-fibrous concrete for both 6mm and 8mm stirrup.

3. The shear strength of the beams using recycled aggregates as complete replacement of natural aggregates is reduced by 12% and 10.2% for 30 and 70 MPa for plain SCC beams.
4. Similarly, in case of fibrous SCC beams, due to use of recycled aggregates, shear strength is reduced by 2.36% and 6.98% for 30 MPa and 70 MPa concrete.
5. For increase in the area of shear reinforcement by increasing the diameter of stirrups there is an increase in the shear strength of both plain and fibrous RASCC30 and RASCC70 beams.
6. A comparison was made between experimental and predicted shear strength with various models available on vibrated concrete. It was noticed that the ultimate shear strength predicted by Russo model and ACI-318 code for plain SCC beams and Narayana and Darwish for SFRSCC are relatively close with experimental values for beams with 6mm and 8mm stirrup.

Table: 6.1 Beam details cast using recycled aggregates

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Fiber content Kg/m^3
1.	**RASCC30-0**	2	-	-	-
2.	**RASFRSCC30-0**	2	-	-	38
3.	**RASCC30-180**	2	180	6	-
4.	**RASCC30-360**	2	360	6	-
5.	**RASFRSCC30-180**	2	180	6	38
6.	**RASFRSCC30-360**	2	360	6	38
7.	**RASCC70-0**	2	-	-	-
8.	**RASFRSCC70-0**	2	-	-	38
9.	**RASCC70-180**	2	180	6	-
10.	**RASCC70-360**	2	360	6	-
11.	**RASFRSCC70-180**	2	180	6	38
12.	**RASFRSCC70-360**	2	360	6	38
13.	**RASCC30-0**	2.5	-	-	-
14.	**RASFRSCC30-0**	2.5	-	-	38
15.	**RASCC30-225**	2.5	225	6	-
16.	**RASCC30-450**	2.5	450	6	-
17.	**RASFRSCC30-225**	2.5	225	6	38
18.	**RASFRSCC30-450**	2.5	450	6	38
19.	**RASCC70-0**	2.5	-	-	-
20.	**RASFRSCC70-0**	2.5	-	-	38
21.	**RASCC70-225**	2.5	225	6	-
22.	**RASCC70-450**	2.5	450	6	-
23.	**RASFRSCC70-225**	2.5	225	6	38
24.	**RASFRSCC70-450**	2.5	450	6	38
25.	**RASCC30-0**	3	-	-	-
26.	**RASFRSCC30-0**	3	-	-	38
27.	**RASCC30-270**	3	270	6	-
28.	**RASCC30-540**	3	540	6	-
29.	**RASFRSCC30-270**	3	270	6	38
30.	**RASFRSCC30-540**	3	540	6	38
31.	**RASCC70-0**	3	-	-	-
32.	**RASFRSCC70-0**	3	-	-	38
33.	**RASCC70-270**	3	270	6	-
34.	**RASRCC70-540**	3	540	6	-
35.	**RASFRSCC70-270**	3	270	6	38
36.	**RASFRSCC70-540**	3	540	6	38

Table: 6.2 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

Table: 6.3 Physical Properties of Recycled Fine aggregates

Properties	
Bulk density(kg/m^3)	1308
Specific gravity	2.16
Fineness Modulus	3.40
Water absorption (%)	5.6

Table: 6.4 Mix proportions of 30 and 70 MPa RASCC

Mix	**Cement (kg/m^3)**	**Fly ash (kg/m^3)**	**Silica fume (kg/m^3)**	**CA (kg/m^3)**	**FA (kg/m^3)**	**Water (kg/m^3)**	**SP (kg/m^3)**	**W/b**
30 MPa	350	324	0	665	782	203	5.73	0.30
70 MPa	600	226	48	695	724	247	6.03	0.28

Table: 6.5 Fresh properties of 30 MPa and 70 MPa SCC without and with fiber

Grade of Concrete	**RASCC30**		**RASCC70**		**EFNARC 2005**	
Dosage of Fibers	**0%**	**0.5%**	**0%**	**0.5%**	**Min.**	**Max.**
Slump Test, mm	730	640	720	680	550	800
T_{50} Slump flow, sec	3	5	3	4	2	5
V funnel, sec	6	7.25	10	12	6	12
V funnel @ T_5 min, sec	7	9.2	8	14	6	15
J-ring, sec	3	8	2	7	0	10

Table 6.6: Hardened properties of 30 and 70 MPa RASCC at 28 days

	30 MPa			**70 MPa**		
Dosage of steel fibers (%)	**Compressive strength (MPa)**	**Split tensile strength (MPa)**	**Flexural Strength (MPa)**	**Compressive strength (MPa)**	**Split tensile strength (MPa)**	**Flexural Strength (MPa)**
0	36.5	3.46	3.68	72.99	6.13	5.89
0.5	38.32	3.92	4.54	78.86	6.63	6.85

Table: 6.7 Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=2 for 6mm Ø stirrup

Designation	**Ultimate Load kN**	**Ultimate Shear Strength (v_u) (MPa)**	**Deflection (mm)**	**Toughness (kN-mm)**
RASCC30				
RASCC30-0	54.68	1.52	2.99	106.80
RASFRSCC30-0	63.72	1.77	5.29	144.43
RASCC30-180	83.36	2.31	5.98	222.56
RASCC30-360	70.64	1.96	4.84	173.09

RASFRSCC30-180	105.12	2.92	6.93	440.90
RASFRSCC30-360	94.16	2.61	5.33	311.60
RASCC70				
RASCC70-0	72.33	2.20	4.87	217.08
RASFRSCC70-0	89.60	2.48	4.43	418.67
RASCC70-180	110.61	3.07	3.54	494.71
RASCC70-360	105.17	2.92	4.41	454.17
RASFRSCC70-180	142.01	3.94	7.67	1168.74
RASFRSCC70-360	119.18	3.31	5.70	667.94

Table 6.8: Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=2.5 for 6mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
RASCC30				
RASCC30-0	40.64	1.13	3.52	103.05
SFRSCC30-0	53.13	1.48	7.29	137.06
SCC30-225	68.42	1.90	5.0	205.93
SCC30-450	56.56	1.57	4.56	181.32
SFRSCC30-225	95.45	2.65	9.51	422.91
SFRSCC30-450	83.36	2.32	4.49	290.07
RASCC70				
RASCC70-0	67.25	1.87	3.01	210.65
RASFRSCC70-0	77.64	2.16	3.74	373.56
RASCC70-225	103.33	2.87	5.27	446.48
RASFRSCC70-225	121.5	3.37	6.25	887.47
RASCC70-450	83.26	2.32	3.71	430.39
RASFRSCC70-450	110.79	3.07	4.79	671.29

Table 6.9: Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=3 for 6mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
RASCC30				
RASCC30-0	39.15	1.09	4.05	95.36
RASFRSCC30-0	48.40	1.34	7.19	126.80
RASCC30-270	62.28	1.73	5.03	157.45
RASFRSCC30-270	84.55	2.35	7.14	337.84
RASCC30-540	51.23	1.42	3.76	94.78
RASFRSCC30-540	61.74	1.72	5.35	268.46
RASCC70				
RASCC70-0	67.70	1.88	3.76	195.79

RASFRSCC70-0	76.97	2.13	4.37	351.66
RASCC70-270	89.71	2.49	5.01	461.18
RASFRSCC70-270	121.65	3.38	8.26	667.94
RASCC70-540	77.10	2.14	6.39	338.29
RASFRSCC70-540	81.08	2.25	3.26	498.18

Table: 6.10 Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=2 with 8mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
RASCC30				
RASCC30-0	54.68	1.43	4.2	192.69
RASFRSCC30-0	63.72	1.77	4.52	299.27
RASCC30-180	83.50	2.32	4.65	358.05
RASCC30-360	76.14	2.12	5.8	306.17
RASFRSCC30-180	114.23	3.17	6.24	768.31
RASFRSCC30-360	98.06	2.72	8.31	592.58
RASCC70				
RASCC70-0	72.33	2.09	4.48	217.11
RASFRSCC70-0	79.60	2.21	4.45	379.11
RASCC70-180	168.1	4.66	5.52	734.60
RASCC70-360	134.09	3.74	4.41	513.26
RASFRSCC70-180	179.1	4.97	9.63	968.75
RASFRSCC70-360	143.43	3.98	7.02	951.66

Table: 6.11 Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=2.5 with 8mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
RASCC30				
RASCC30-0	42.67	1.19	4.12	183.06
RASFRSCC30-0	57.38	1.59	4.42	294.31
RASCC30-225	78.00	2.17	4.65	340.15
RASCC30-450	60.46	1.68	5.68	290.86
RASFRSCC30-225	109.77	3.05	6.54	719.89
RASFRSCC30-450	93.36	2.59	7.11	562.95
RASCC70				
RASCC70-0	70.61	1.96	4.48	211.60
RASFRSCC70-0	80.75	2.24	4.95	323.22
RASCC70-225	107.33	2.98	5.52	697.87
RASCC70-450	90.75	2.52	8.34	497.60
RASFRSCC70-225	136.16	3.78	4.41	920.3

RASFRSCC70-450	111.68	3.10	6.42	704.08

Table: 6.12 Ultimate load and shear strength of fibrous and non-fibrous RASCC beams for a/d=3 for 8mm Ø stirrup

Designation	Ultimate Load kN	Ultimate Shear Strength (v_u) (MPa)	Deflection (mm)	Toughness (kN-mm)
RASCC30				
RASCC30-0	41.11	1.14	4.05	132.82
RASFRSCC30-0	50.34	1.40	7.19	286.42
RASCC30-270	81.75	2.27	5.03	382.98
RASFRSCC30-270	87.93	2.44	7.14	405.98
RASCC30-540	53.28	1.48	3.76	169.98
RASFRSCC30-540	64.21	1.78	5.35	291.88
RASCC70				
RASCC70-0	67.70	1.88	3.76	171.90
RASFRSCC70-0	76.97	2.13	4.37	346.02
RASCC70-270	106.80	2.97	5.01	461.18
RASCC70-540	85.58	2.38	6.39	338.29
RASFRSCC70-270	124.08	3.45	8.26	929.10
RASFRSCC70-540	93.24	2.59	3.26	498.18

Table: 6.13 Crack Angle for RASCC beams with 6mm Ø stirrup

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Crack Angle (θ)
1.	**RASCC30-0**	2	-	-	**42.53**
2.	**RASFRSCC30-0**	2	-	-	**42.80**
3.	**RASCC30-180**	2	180	6	**42.93**
4.	**RASCC30-360**	2	360	6	**41.63**
5.	**RASFRSCC30-180**	2	180	6	**44.71**
6.	**RASFRSCC30-360**	2	360	6	**44.01**
7.	**RASCC70-0**	2	-	-	**42.93**
8.	**RASFRSCC70-0**	2	-	-	**44.43**
9.	**RASCC70-180**	2	180	6	**44.29**
10.	**RASCC70-360**	2	360	6	**44.15**
11.	**RASFRSCC70-180**	2	180	6	**44.86**
12.	**RASFRSCC70-360**	2	360	6	**44.57**
13.	**RASCC30-0**	2.5	-	-	**41.63**
14.	**RASFRSCC30-0**	2.5	-	-	**42.14**
15.	**RASCC30-225**	2.5	225	6	**42.93**
16.	**RASCC30-450**	2.5	450	6	**42.27**
17.	**RASFRSCC30-225**	2.5	225	6	**43.33**
18.	**RASFRSCC30-450**	2.5	450	6	**43.06**
			RASCC70		
19.	**RASCC70-0**	2.5	-	-	**41.76**

20.	**RASFRSCC70-0**	2.5	-	-	**42.53**
21.	**RASCC70-225**	2.5	225	6	**42.93**
22.	**RASCC70-450**	2.5	450	6	**41.89**
23.	**RASFRSCC70-225**	2.5	225	6	**44.43**
24.	**RASFRSCC70-450**	2.5	450	6	**43.74**
25.	**RASCC30-0**	3	-	-	**37.57**
26.	**RASFRSCC30-0**	3	-	-	**40.28**
27.	**RASCC30-270**	3	270	6	**40.52**
28.	**RASCC30-540**	3	540	6	**39.92**
29.	**RASFRSCC30-270**	3	270	6	**43.06**
30.	**RASFRSCC30-540**	3	540	6	**40.89**
31.	**RASCC70-0**	3	-	-	**39.69**
32.	**RASFRSCC70-0**	3	-	-	**40.28**
33.	**RASCC70-270**	3	270	6	**40.04**
34.	**RASRCC70-540**	3	540	6	**39.81**
35.	**RASFRSCC70-270**	3	270	6	**41.76**
36.	**RASFRSCC70-540**	3	540	6	**40.64**

Table: 6.14 Crack Angle for RASCC beams with 8mm Ø stirrup

S.No.	Beam Designation	a/d	Stirrups Spacing , mm	Stirrup Diameter mm	Crack Angle (Θ)
37.	**RASCC30-0**	2	-	-	**42.98**
38.	**RASFRSCC30-0**	2	-	-	**43.25**
39.	**RASCC30-180**	2	180	8	**43.38**
40.	**RASCC30-360**	2	360	8	**42.08**
41.	**RASFRSCC30-180**	2	180	8	**45.16**
42.	**RASFRSCC30-360**	2	360	8	**44.46**
43.	**RASCC70-0**	2	-	-	**43.41**
44.	**RASFRSCC70-0**	2	-	-	**44.91**
45.	**RASCC70-180**	2	180	8	**44.77**
46.	**RASCC70-360**	2	360	8	**44.63**
47.	**RASFRSCC70-180**	2	180	8	**45.34**
48.	**RASFRSCC70-360**	2	360	8	**45.05**
49.	**RASCC30-0**	2.5	-	-	**42.05**
50.	**RASFRSCC30-0**	2.5	-	-	**42.56**
51.	**RASCC30-225**	2.5	225	8	**43.35**
52.	**RASCC30-450**	2.5	450	8	**42.69**
53.	**RASFRSCC30-225**	2.5	225	8	**43.75**
54.	**RASFRSCC30-450**	2.5	450	8	**43.48**
			RASCC70		
55.	**RASCC70-0**	2.5	-	-	**42.18**
56.	**RASFRSCC70-0**	2.5	-	-	**42.95**
57.	**RASCC70-225**	2.5	225	8	**43.35**
58.	**RASCC70-450**	2.5	450	8	**42.31**
59.	**RASFRSCC70-225**	2.5	225	8	**44.85**
60.	**RASFRSCC70-450**	2.5	450	8	**44.16**

61.	**RASCC30-0**	3	-	-	**38.00**
62.	**RASFRSCC30-0**	3	-	-	**40.71**
63.	**RASCC30-270**	3	270	8	**40.95**
64.	**RASCC30-540**	3	540	8	**40.36**
65.	**RASFRSCC30-270**	3	270	8	**43.50**
66.	**RASFRSCC30-540**	3	540	8	**41.32**
67.	**RASCC70-0**	3	-	-	**40.10**
68.	**RASFRSCC70-0**	3	-	-	**40.69**
69.	**RASCC70-270**	3	270	8	**40.45**
70.	**RASRCC70-540**	3	540	8	**40.22**
71.	**RASFRSCC70-270**	3	270	8	**42.17**
72.	**RASFRSCC70-540**	3	540	8	**41.05**

Table: 6.15 Experimental vs Theoretical Shear Strength for RASCC30

Designation	Experimental		Theoretical		% Error	Theoretical/ experimental
	Load kN	Shear Strength, MPa	Load kN	Shear Strength, MPa		
6 mm Ø						
RASCC30-0	54.72	1.52	59.48	1.65	8.70	1.09
RASFRSCC30-0	63.72	1.77	66.06	1.84	3.67	1.04
RASCC30-180	83.16	2.31	82.66	2.30	0.60	0.99
RASCC30-360	70.56	1.96	74.32	2.06	5.33	1.05
RASFRSCC30-180	105.12	2.92	108.60	3.02	3.31	1.03
RASFRSCC30-360	93.96	2.61	98.81	2.74	5.16	1.05
RASCC30-0	40.68	1.13	46.26	1.28	13.71	1.14
RASFRSCC30-0	53.28	1.48	57.43	1.60	7.78	1.08
RASCC30-225	68.4	1.9	71.01	1.97	3.82	1.04
RASCC30-450	56.52	1.57	57.43	1.60	1.60	1.02
RASFRSCC30-225	95.4	2.65	108.60	3.02	13.84	1.14
RASFRSCC30-450	83.52	2.32	84.55	2.35	1.24	1.01
RASCC30-0	39.24	1.09	44.56	1.24	13.55	1.14
RASFRSCC30-0	48.24	1.34	48.00	1.33	0.51	0.99
RASCC30-270	62.28	1.73	63.79	1.77	2.43	1.02
RASFRSCC30-270	84.6	2.35	90.92	2.53	7.47	1.07
RASCC30-540	51.12	1.42	51.61	1.43	0.96	1.01
RASFRSCC30-540	61.92	1.72	61.60	1.71	0.51	0.99
8mm Ø						
RASCC30-0	51.48	1.43	57.43	1.60	11.55	1.12
RASFRSCC30-0	63.72	1.77	66.87	1.86	4.95	1.05
RASCC30-180	83.52	2.32	84.55	2.35	1.24	1.01
RASCC30-360	76.32	2.12	73.15	2.03	4.15	0.96
RASFRSCC30-180	114.12	3.17	116.03	3.22	1.67	1.02
RASFRSCC30-360	97.92	2.72	94.34	2.62	3.65	0.96
RASCC30-0	42.84	1.19	46.26	1.28	7.97	1.08
RASFRSCC30-0	57.24	1.59	59.71	1.66	4.32	1.04
RASCC30-225	78.12	2.17	79.97	2.22	2.36	1.02

RASCC30-450	60.48	1.68	63.02	1.75	4.20	1.04
RASFRSCC30-225	109.8	3.05	111.62	3.10	1.66	1.02
RASFRSCC30-450	93.24	2.59	93.92	2.61	0.73	1.01
RASCC30-0	41.04	1.14	38.14	1.06	7.07	0.93
RASFRSCC30-0	50.4	1.4	55.43	1.54	9.98	1.10
RASCC30-270	81.72	2.27	81.58	2.27	0.17	1.00
RASFRSCC30-270	87.84	2.44	84.55	2.35	3.74	0.96
RASCC30-540	53.28	1.48	56.31	1.56	5.69	1.06
RASFRSCC30-540	64.08	1.78	68.41	1.90	6.75	1.07

Table: 6.16 Experimental vs Theoretical Shear Strength for RASCC70

Designation	**Experimental**		**Theoretical**		**% Error**	**Theoretical/ experimental**
	Load kN	**Shear Strength, MPa**	**Load kN**	**Shear Strength, MPa**		
			6 mm Ø			
RASCC70-0	79.2	2.2	79.54	2.21	0.43	
RASFRSCC70-0	89.28	2.48	85.83	2.38	3.87	1.00
RASCC70-180	110.52	3.07	113.06	3.14	2.30	0.96
RASCC70-360	105.12	2.92	109.20	3.03	3.88	1.02
RASFRSCC70-180	141.84	3.94	143.28	3.98	1.01	1.04
RASFRSCC70-360	119.16	3.31	116.51	3.24	2.22	1.01
RASCC70-0	67.32	1.87	64.61	1.79	4.02	0.98
RASFRSCC70-0	77.76	2.16	75.51	2.10	2.89	0.96
RASCC70-225	103.32	2.87	113.97	3.17	10.31	0.97
RASFRSCC70-225	121.32	3.37	125.90	3.50	3.78	1.10
RASCC70-450	83.52	2.32	93.30	2.59	11.72	1.04
RASFRSCC70-450	110.52	3.07	108.30	3.01	2.01	1.12
RASCC70-0	67.68	1.88	64.55	1.79	4.62	0.98
RASFRSCC70-0	76.68	2.13	77.93	2.16	1.63	0.95
RASCC70-270	89.64	2.49	90.02	2.50	0.43	1.02
RASFRSCC70-270	121.68	3.38	124.56	3.46	2.37	1.00
RASCC70-540	77.04	2.14	75.16	2.09	2.45	1.02
RASFRSCC70-540	81	2.25	87.27	2.42	7.75	0.98
			8 mm Ø			
RASCC70-0	75.24	2.09	77.03	2.14	2.38	1.08
RASFRSCC70-0	89.28	2.48	93.91	2.61	5.19	1.02
RASCC70-180	167.76	4.66	157.98	4.39	5.83	1.05
RASCC70-360	134.64	3.74	133.07	3.70	1.17	0.94
RASFRSCC70-180	178.92	4.97	173.30	4.81	3.14	0.99
RASFRSCC70-360	143.28	3.98	143.82	4.00	0.38	0.97
RASCC70-0	70.56	1.96	70.61	1.96	0.08	1.00
RASFRSCC70-0	80.64	2.24	88.93	2.47	10.28	1.00
RASCC70-225	107.28	2.98	112.31	3.12	4.69	1.10
RASFRSCC70-225	136.08	3.78	135.27	3.76	0.59	1.05
RASCC70-450	90.72	2.52	106.57	2.96	17.47	0.99

RASFRSCC70-450	111.6	3.1	108.29	3.01	2.96	1.17
RASCC70-0	67.68	1.88	64.34	1.79	4.94	0.97
RASFRSCC70-0	76.68	2.13	87.61	2.43	14.25	0.95
RASCC70-270	106.92	2.97	103.62	2.88	3.09	1.14
RASFRSCC70-270	124.2	3.45	124.90	3.47	0.57	0.97
RASCC70-540	85.68	2.38	82.40	2.29	3.83	1.01
RASFRSCC70-540	93.24	2.59	96.61	2.68	3.62	0.96

Table: 6.17 Experimental vs Analytical Shear Strength for RASCC30 and RASCC70 for 6mm diameter stirrup.

Designation	Experimental	Predicted	Exp/Pre
	RASCC30		
RASCC30-0	1.52	1.66	0.92
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.31	2.28	1.01
RASCC30-360	1.96	2.34	0.84
RASFRSCC30-180	2.92	2.4	1.22
RASFRSCC30-360	2.61	2.45	1.07
RASCC30-0	1.13	1.3	0.87
RASFRSCC30-0	1.48	1.41	1.05
RASCC30-225	1.9	1.94	0.98
RASCC30-450	1.57	2.0	0.79
RASFRSCC30-225	2.65	2.56	1.04
RASFRSCC30-450	2.32	2.11	1.10
RASCC30-0	1.09	0.94	1.16
RASFRSCC30-0	1.34	1.05	1.28
RASCC30-270	1.73	1.59	1.09
RASFRSCC30-270	2.35	2.42	0.97
RASCC30-540	1.42	1.48	0.96
	RASCC70		
RASCC70-0	2.2	2.54	0.87
RASFRSCC70-0	2.48	2.65	0.94
RASCC70-180	3.07	3.16	0.97
RASCC70-360	2.92	3.22	0.91
RASFRSCC70-180	3.94	3.27	1.20
RASFRSCC70-360	3.31	3.33	0.99
RASCC70-0	1.87	2.18	0.86
RASFRSCC70-0	2.16	2.29	0.94
RASCC70-225	2.87	2.81	1.02
RASFRSCC70-225	3.37	2.88	1.17
RASCC70-450	2.32	2.52	0.92
RASFRSCC70-450	3.07	2.99	1.03
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.13	1.93	1.10
RASCC70-270	2.49	2.46	1.01
RASFRSCC70-270	3.38	3.28	1.03
RASCC70-540	2.14	2.23	0.96

RASFRSCC70-540	2.25	2.66	0.85

Table: 6.18 Experimental vs Analytical Shear Strength for RASCC30 and RASCC70 for 6mm diameter stirrup.

Designation	Experimental	Predicted	Exp/Pre
RASCC30-0	1.52	1.66	0.92
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.32	2.73	0.85
RASCC30-360	2.12	2.58	0.82
RASFRSCC30-180	3.17	3.12	1.02
RASFRSCC30-360	2.72	2.89	0.94
RASCC30-0	1.19	1.3	0.92
RASFRSCC30-0	1.59	1.45	1.10
RASCC30-225	2.17	2.38	0.91
RASCC30-450	1.68	1.98	0.85
RASFRSCC30-225	3.05	2.49	1.22
RASFRSCC30-450	2.59	2.56	1.01
RASCC30-0	1.14	1.12	1.02
RASFRSCC30-0	1.40	1.05	1.33
RASCC30-270	2.27	2.03	1.12
RASFRSCC30-270	2.44	2.11	1.16
RASCC30-540	1.48	1.58	0.94
RASFRSCC30-540	1.78	2.22	0.80
	RASCC70		
RASCC70-0	2.09	2.54	0.82
RASFRSCC70-0	2.48	2.65	0.94
RASCC70-180	4.66	4.56	1.02
RASCC70-360	3.74	3.66	1.02
RASFRSCC70-180	4.97	4.81	1.03
RASFRSCC70-360	3.98	3.77	1.06
RASCC70-0	1.96	2.18	0.90
RASFRSCC70-0	2.24	2.29	0.98
RASCC70-225	2.98	3.25	0.92
RASFRSCC70-225	3.78	3.67	1.03
RASCC70-450	2.52	2.64	0.95
RASFRSCC70-450	3.10	3.23	0.96
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.13	1.93	1.10
RASCC70-270	2.97	2.91	1.02
RASFRSCC70-270	3.45	2.99	1.15
RASCC70-540	2.38	2.55	0.93
RASFRSCC70-540	2.59	3.10	0.84

Table: 6.19 Shear strength of SCC beams without steel fibers for 6mm Ø stirrup.

Type	Russo et al. V_u MPa	Chinese Code V_u MPa	ACI code 318-14 V_u MPa	Experimental V_u MPa	Predicted V_u MPa
a/d=2					
RASCC30-0	1.59	2.02	1	1.52	1.6
RASCC70-0	3.72	2.41	1.5	2.2	2.48
RASCC30-180	2.24	2.93	1.88	2.31	2.42
RASCC70-180	4.26	3.32	2.37	3.07	3.30
RASCC30-360	1.91	2.47	1.43	1.96	2.40
RASCC70-360	3.99	2.86	1.91	2.92	3.28
a/d=2.5					
RASCC30-0	1.20	1.73	0.90	1.13	1.26
RASCC70-0	2.73	2.07	1.40	1.87	2.14
RASCC30-225	1.89	2.46	1.68	1.90	2.07
RASCC70-225	3.32	2.79	2.14	2.87	2.95
RASCC30-450	1.55	2.09	1.31	1.57	2.04
RASCC70-450	3.02	2.43	1.77	2.32	3.07
a/d=3					
RASCC30-0	1.01	1.51	0.90	1.09	0.92
RASCC70-0	2.22	1.81	1.38	1.60	1.80
RASCC30-270	1.69	2.12	1.54	1.73	1.73
RASCC70-270	2.83	2.41	1.98	2.49	2.60
RASCC30-540	1.35	1.82	1.24	1.42	1.84
RASCC70-540	2.53	2.11	1.68	2.14	2.72

Table: 6.20 Shear strength of steel fibre reinforced SCC beams for 6 mm Ø stirrup.

Type	Narayanan and Darwish V_{uf} MPa	Ta'an and Feel V_{uf} MPa	Swamy et al V_{uf} MPa	Lim and Oh V_{uf} MPa	Chines code for FRC V_{uf} MPa	Experimental V_{uf} MPa	Predicted V_{uf} MPa
a/d=2							
RASFRSCC30-0	2.5	2.1	2.69	3.08	3.11	1.77	1.72
RASFRSCC70-0	4.64	4.23	4.83	5.22	3.71	2.29	2.59
RASFRSCC30-180	3.16	2.75	3.34	3.73	4.02	2.92	2.53
RASFRSCC70-180	5.18	4.77	5.37	5.76	4.62	3.94	3.41
RASFRSCC30-360	2.83	2.42	3.01	3.41	3.56	2.61	2.51
RASFRSCC70-360	4.91	4.50	5.09	5.49	4.17	3.31	3.39
a/d=2.5							
RASFRSCC30-0	2.12	1.72	2.31	2.7	2.66	1.48	1.37
RASFRSCC70-0	3.65	3.24	3.83	4.22	3.18	2.16	2.25
RASFRSCC30-225	2.81	2.40	3.53	3.39	3.39	2.65	2.19
RASFRSCC70-225	4.24	4.29	4.42	4.81	3.91	3.37	3.42

RASFRSCC30-450	2.47	2.06	2.65	3.04	3.03	2.32	2.16
RASFRSCC70-450	3.94	3.53	4.12	4.52	3.54	3.07	3.04
a/d=3							
RASFRSCC30-0	1.93	1.54	2.12	2.51	2.33	1.34	1.03
RASFRSCC70-0	3.14	2.73	3.33	3.72	2.78	1.86	1.91
RASFRSCC30-270	2.61	2.20	2.79	3.19	2.94	2.35	1.73
RASFRSCC70-270	3.75	3.34	3.93	4.32	3.39	3.38	2.60
RASFRSCC30-540	2.27	1.86	2.45	2.85	2.63	1.72	1.80
RASFRSCCC70-540	3.44	3.04	3.63	4.02	3.09	2.25	2.68

Table: 6.21 Shear strength of RASCC beams without steel fibers for 8 mm Ø stirrup.

Type	**Russo et al. V_u MPa**	**Chinese Code V_u MPa**	**ACI code 318-14 V_u MPa**	**Experimental V_u MPa**	**Predicted V_u MPa**
a/d=2					
RASCC30-0	1.59	2.02	1.01	1.52	1.6
RASCC70-0	3.72	2.41	1.50	2.2	2.48
RASCC30-180	2.74	3.64	2.59	2.32	2.71
RASCC70-180	4.69	4.03	3.08	4.66	3.59
RASCC30-360	2.16	2.83	1.78	2.12	2.69
RASCC70-360	4.20	3.22	2.27	3.74	3.57
a/d=2.5					
RASCC30-0	1.20	1.73	0.90	1.13	1.26
RASCC70-0	2.73	2.07	1.40	1.87	2.14
RASCC30-225	2.42	3.03	2.24	2.17	2.36
RASCC70-225	3.78	3.36	2.70	2.98	3.24
RASCC30-450	1.82	2.38	1.60	1.68	2.34
RASCC70-450	3.25	2.71	2.06	2.52	3.22
a/d=3					
RASCC30-0	1.01	1.51	0.90	1.09	0.92
RASCC70-0	2.22	1.81	1.38	1.60	1.8
RASCC30-270	2.22	2.59	2.01	2.27	2.02
RASCC70-270	3.30	2.89	2.46	2.97	2.9
RASCC30-540	1.62	2.05	1.47	1.48	2.13
RASCC70-540	2.76	2.35	1.92	2.4	3.01

Table 6.22 Shear strength of steel fibre reinforced SCC beams for 8 mm Ø stirrup.

Type	Narayanan and Darwish V_{uf} MPa	Ta'an and Feel V_{uf} MPa	Swamy et al V_{uf} MPa	Lim and Oh V_{uf} MPa	Chines code for FRC V_{uf} MPa	Experimental V_{uf} MPa	Predicted V_{uf} MPa
a/d=2							
RASFRSCC30-0	2.5	2.1	2.69	3.08	3.11	1.77	1.72
RASFRSCC70-0	4.64	4.23	4.83	5.22	3.71	2.29	2.59
RASFRSCC30-180	3.66	3.28	3.85	4.24	4.73	3.17	3.26
RASFRSCC70-180	5.61	4.44	5.79	6.18	5.33	4.97	4.72
RASFRSCC30-360	3.08	2.84	3.27	3.66	3.92	2.72	2.81
RASFRSCC70-360	5.12	3.86	5.31	5.70	4.52	3.98	3.68
a/d=2.5							
RASFRSCC30-0	2.12	1.72	2.31	2.7	2.66	1.48	1.37
RASFRSCC70-0	3.65	3.24	3.83	4.22	3.18	2.16	2.25
RASFRSCC30-225	3.34	2.82	3.53	3.92	3.96	3.05	3.12
RASFRSCC70-225	4.70	3.56	4.89	5.28	4.48	3.78	3.68
RASFRSCC30-450	2.73	2.53	2.92	3.31	3.31	2.59	2.46
RASFRSCC70-450	4.17	3.26	4.36	4.75	3.83	3.10	3.33
a/d=3							
RASFRSCC30-0	1.93	1.54	2.12	2.51	2.33	1.34	1.03
RASFRSCC70-0	3.14	2.73	3.33	3.72	2.78	1.86	1.91
RASFRSCC30-270	3.14	2.60	3.33	3.72	3.41	2.44	2.51
RASFRSCC70-270	4.22	3.65	4.41	4.79	3.86	3.45	2.87
RASFRSCC30-540	2.54	2.25	2.72	3.11	2.87	1.78	1.6
RASFRSCCC70-540	3.68	2.55	3.87	4.26	3.32	2.59	2.98

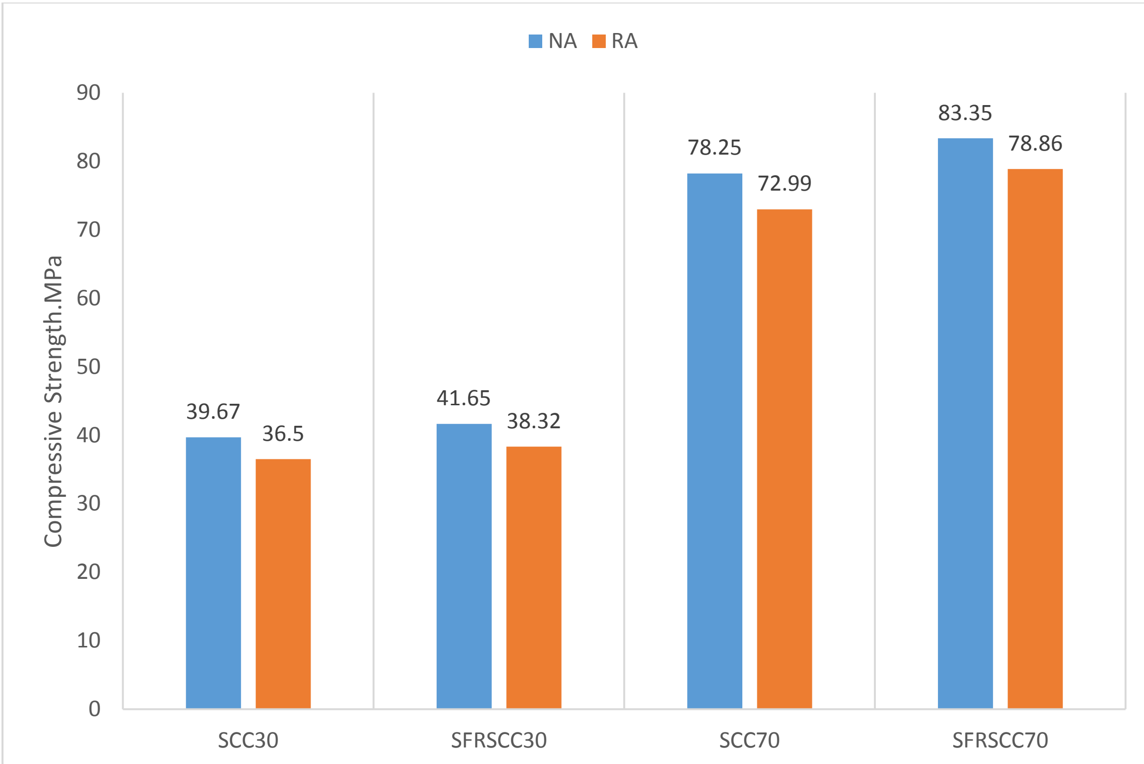


Figure 6.1 Compressive strength vs Type of concrete (NASCC and RASCC)

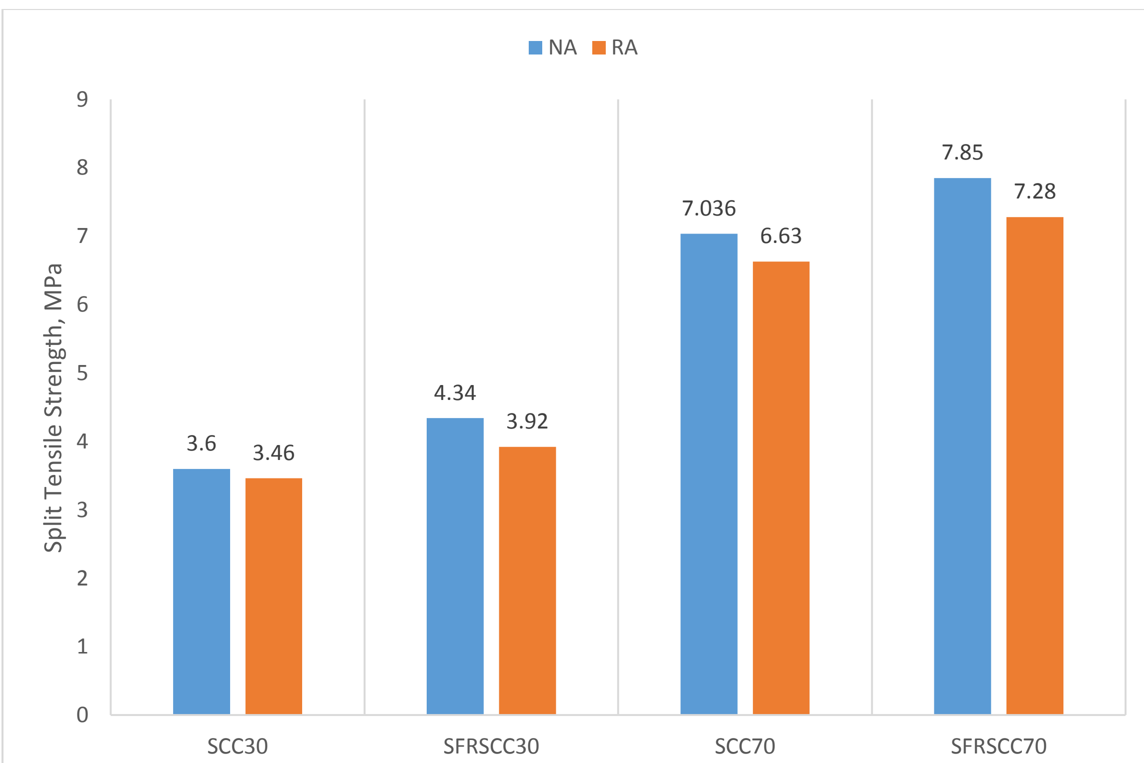


Figure 6.2 Split Tensile strength vs Type of concrete (NASCC and RASCC)

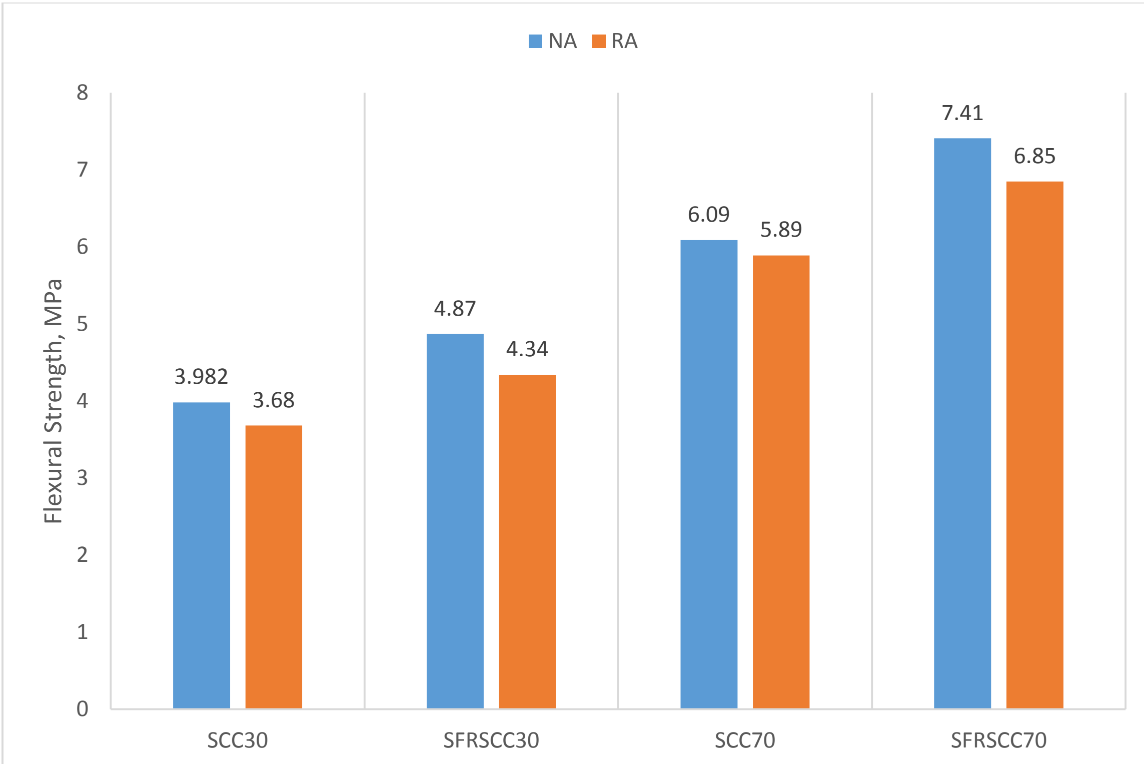


Figure 6.3 Flexural strength vs Type of concrete (NASCC and RASCC)

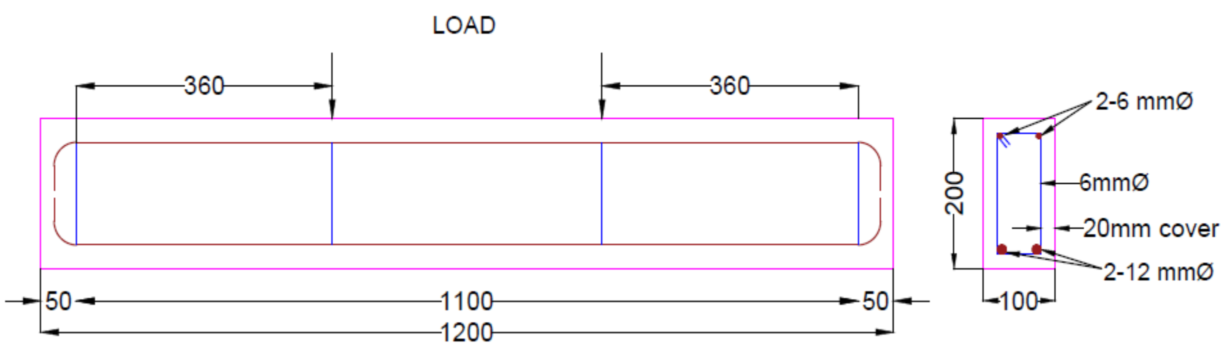


Figure: 6.4(a)

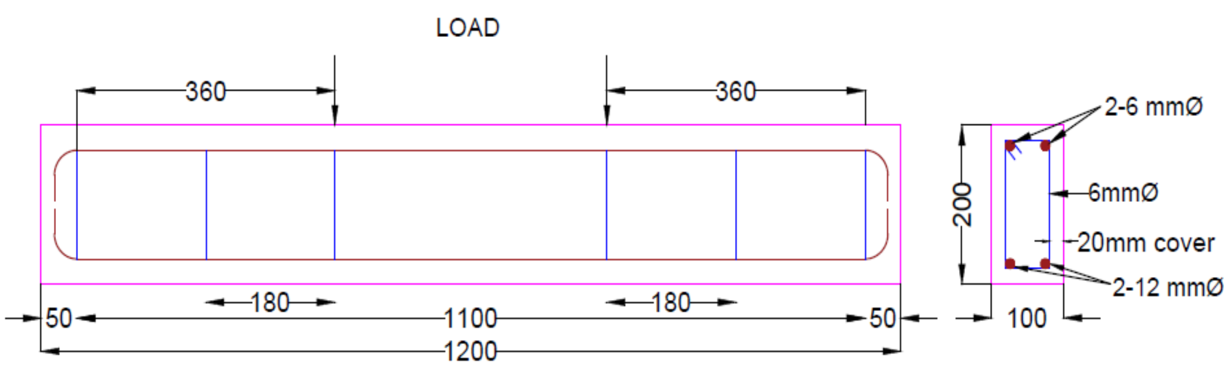


Figure: 6.4(b)

Figure: 6.4 Details of reinforcement for 30MPa mix with a/d=2

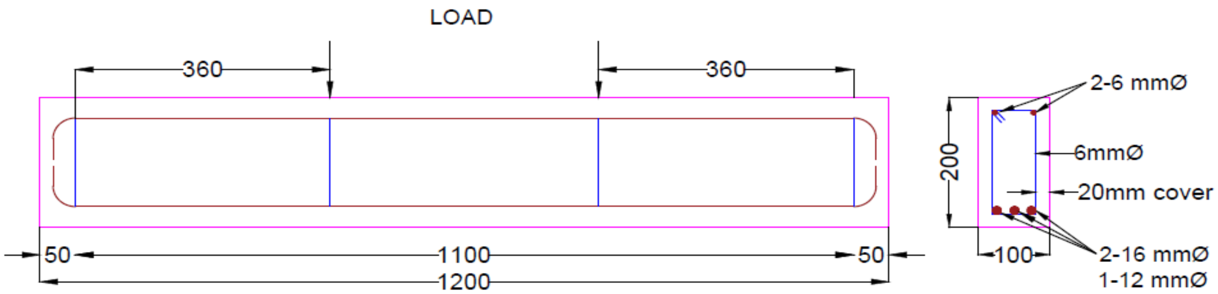


Figure: 6.5(a)

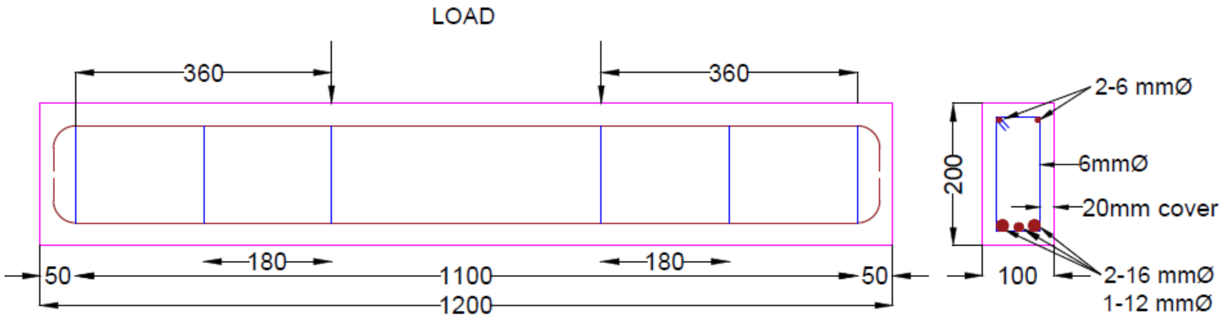


Figure: 6.5(b)

Figure: 6.5 Details of reinforcement for 70MPa Mix with a/d=2

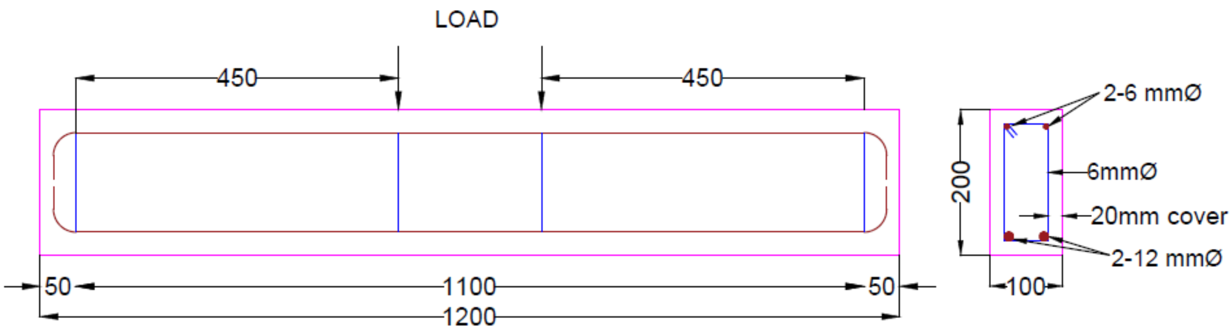


Figure: 6.6(a)

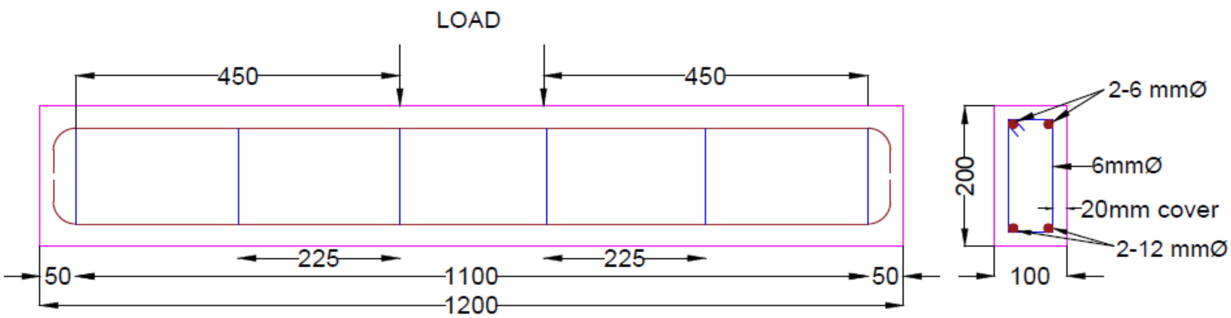


Figure: 6.6(b)

Figure: 6.6 Details of reinforcement for 30MPa Mix with a/d=2.5

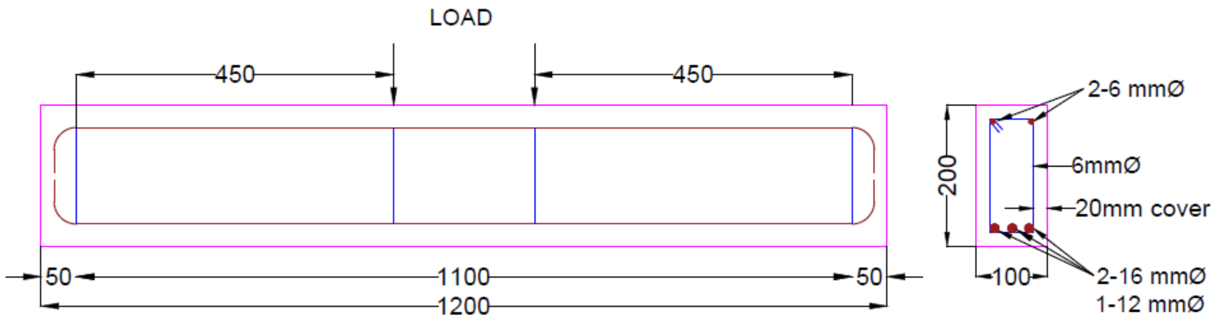


Figure: 6.7(a)

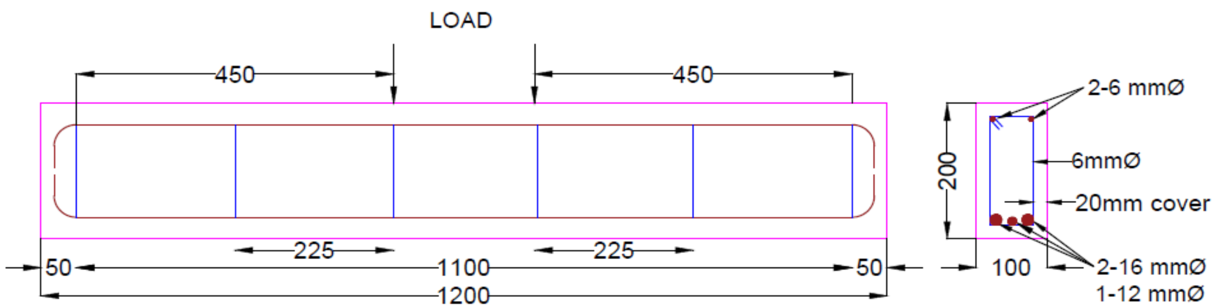


Figure: 6.7(b)
Figure: 6.7 Details of reinforcement for 70MPa Mix with a/d=2.5

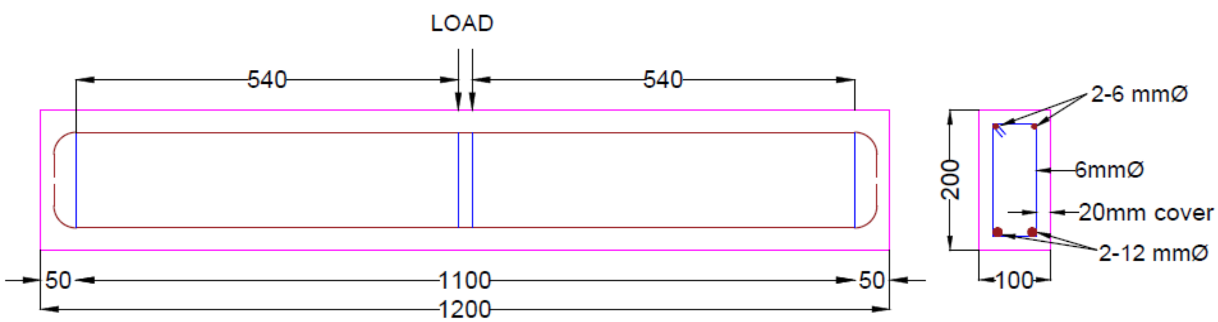


Figure: 6.8(a)

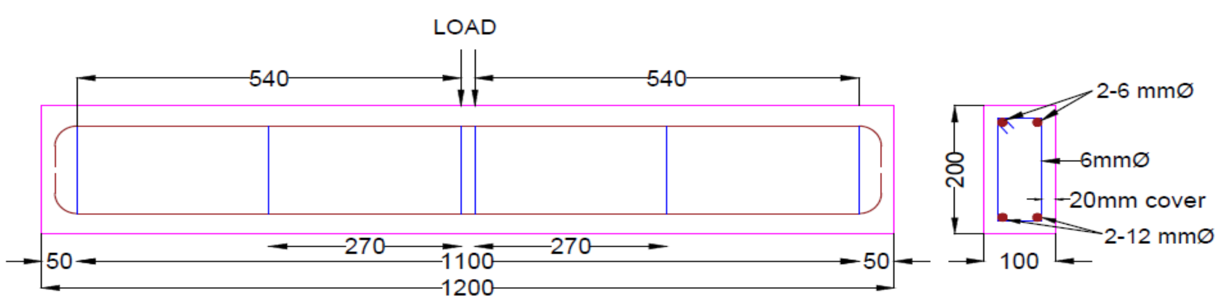


Figure: 6.8(b)
Figure: 6.8 Details of reinforcement for 30MPa Mix with a/d=3

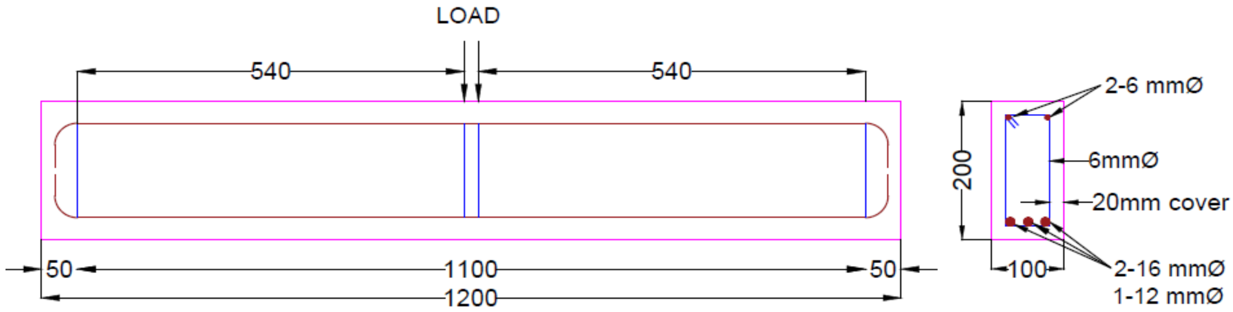


Figure: 6.9(a)

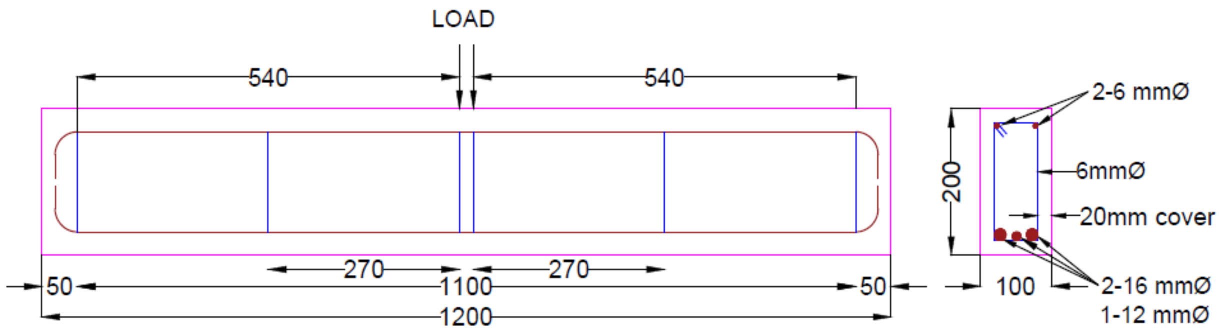


Figure: 6.9(b)

Figure: 6.9 Details of reinforcement for 70MPa Mix with a/d=3

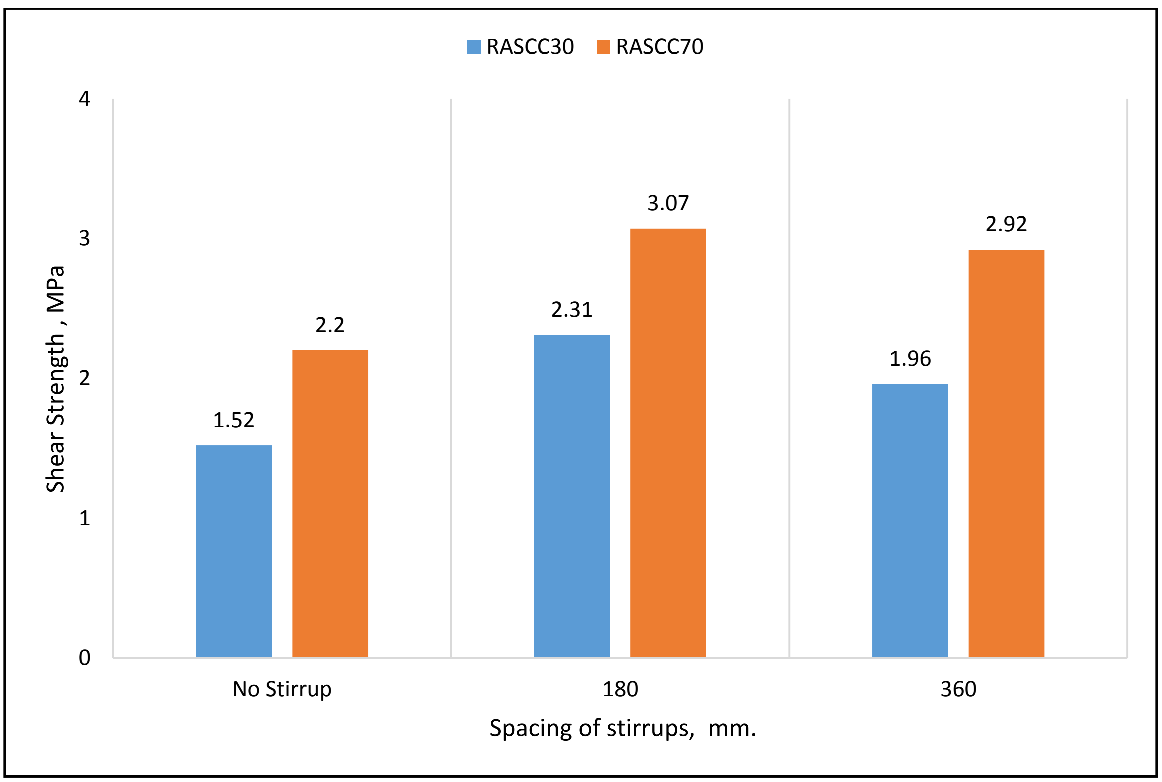


Figure: 6.10 Variation of Shear strength vs Spacing of stirrup for a/d=2

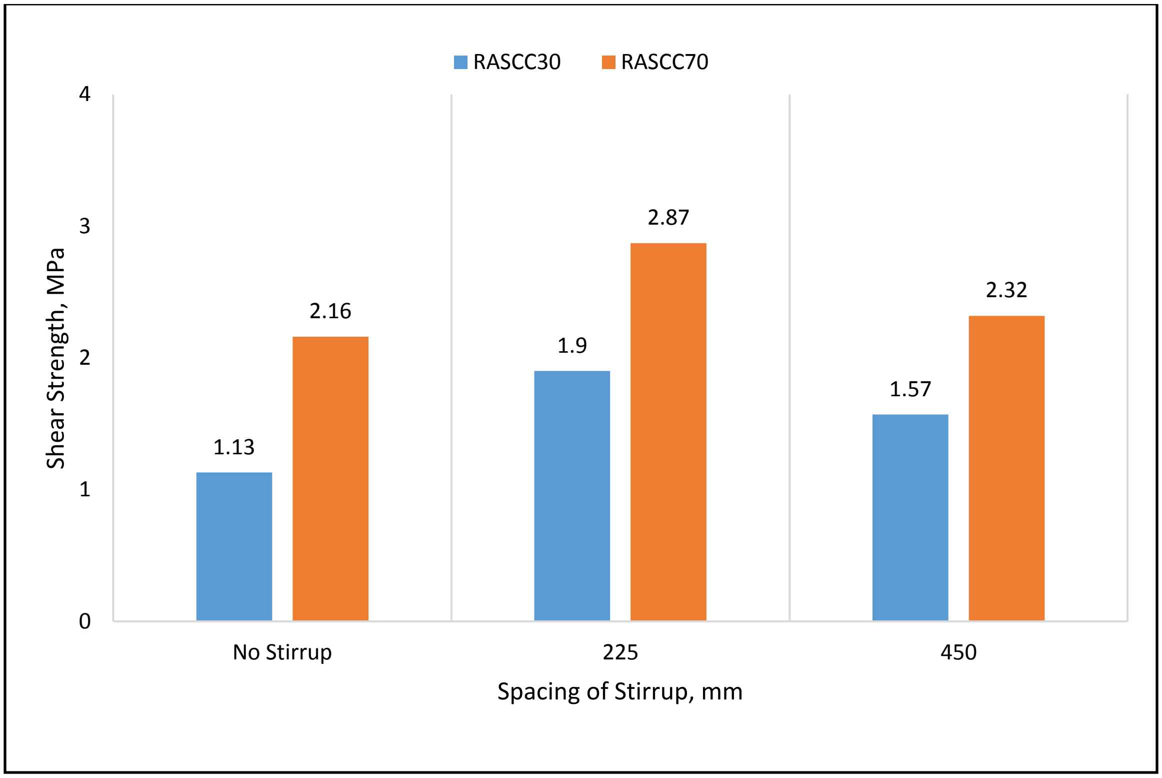


Figure: 6.11 Variation of Shear strength vs Spacing of stirrup for a/d=2.5

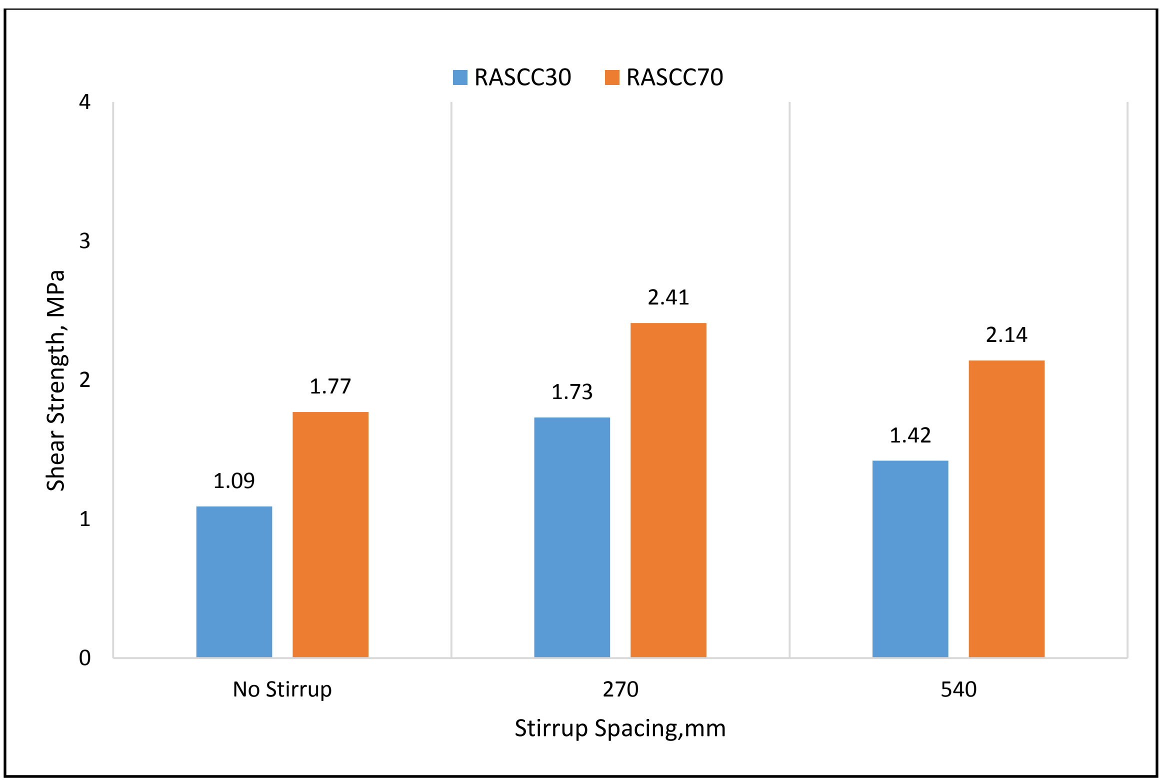


Figure: 6.12 Variation of Shear strength vs Spacing of stirrup for a/d=3

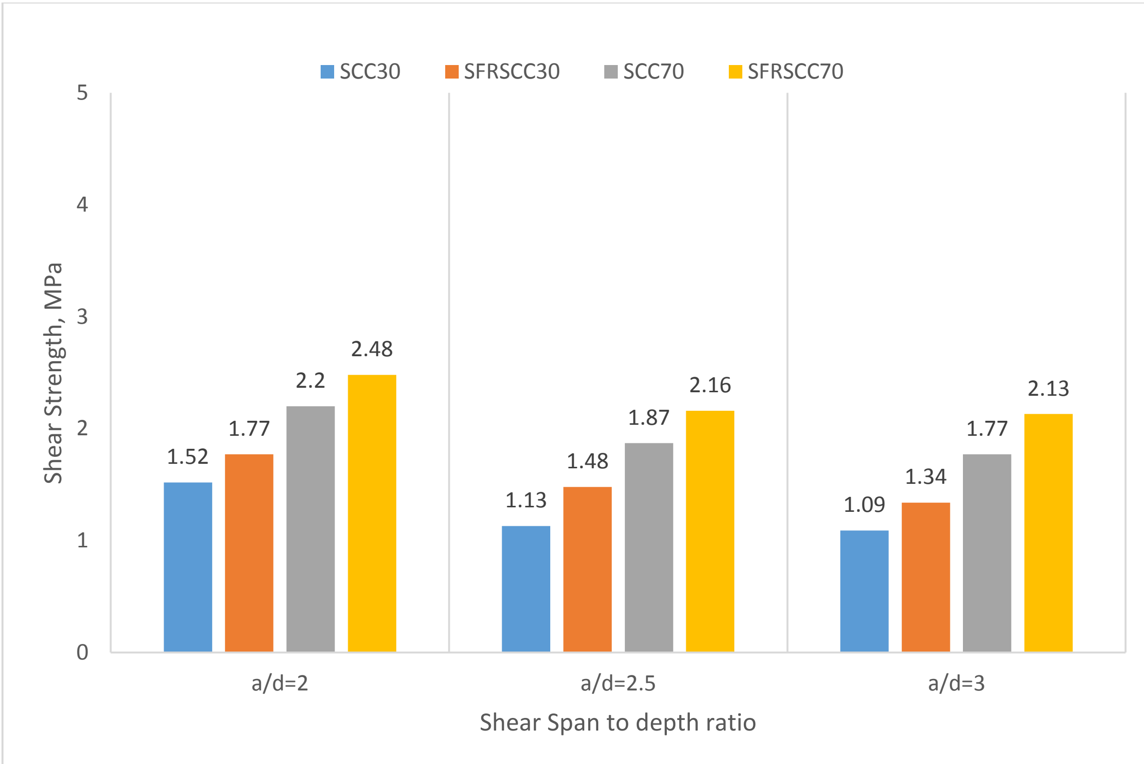


Figure: 6.13 Shear Strength vs shear span to depth ratio for plain RASCC beams

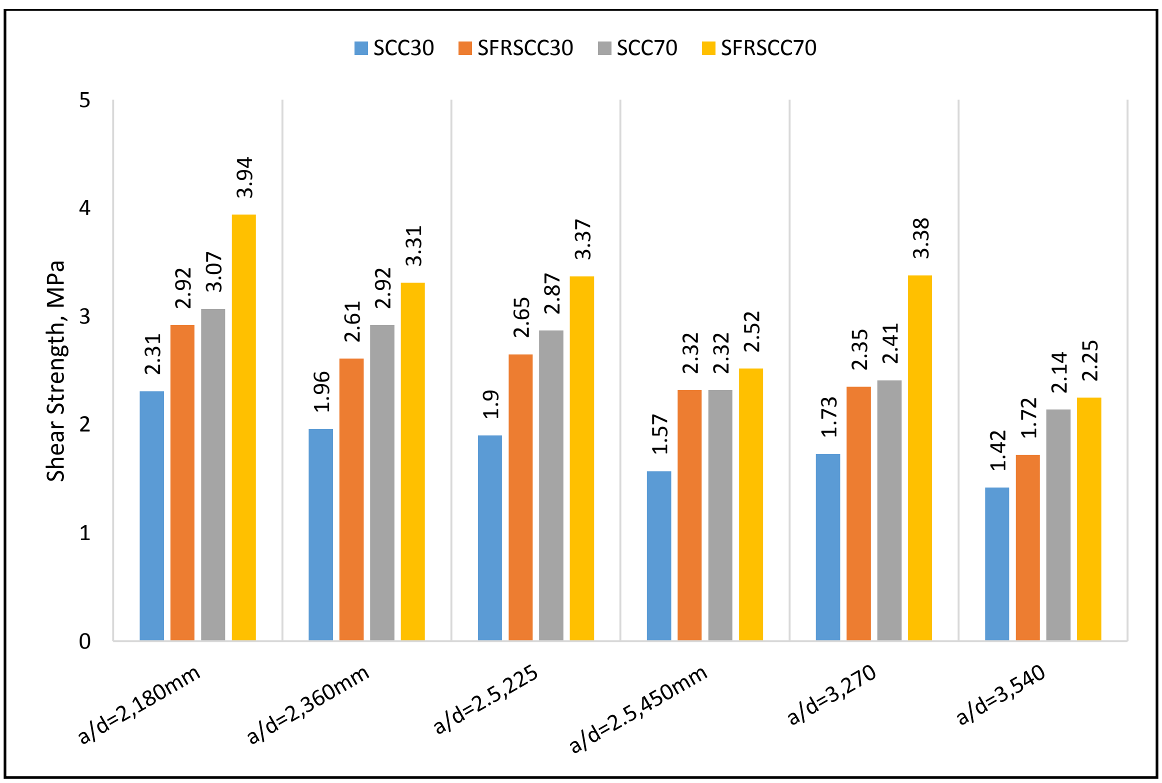


Figure: 6.14 Shear Strength vs shear span to depth ratio for RASCC beams with stirrups

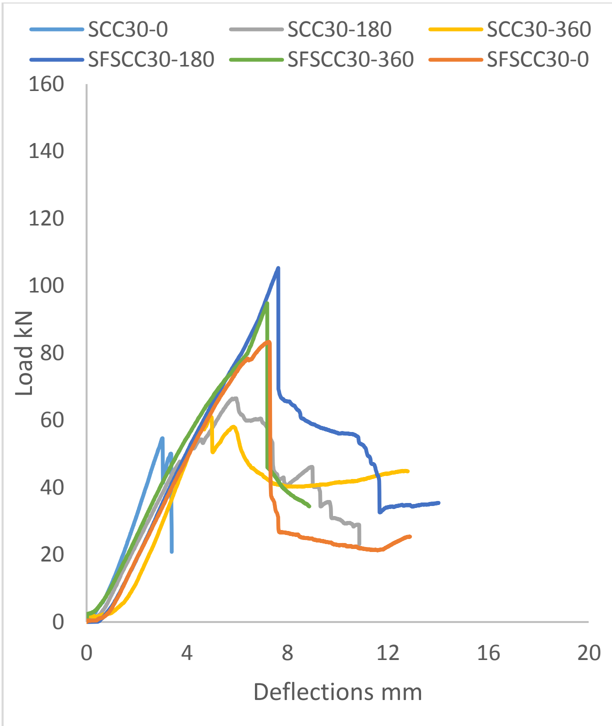


Figure: 6.15 Load vs Deflection for RASCC30 a/d=2

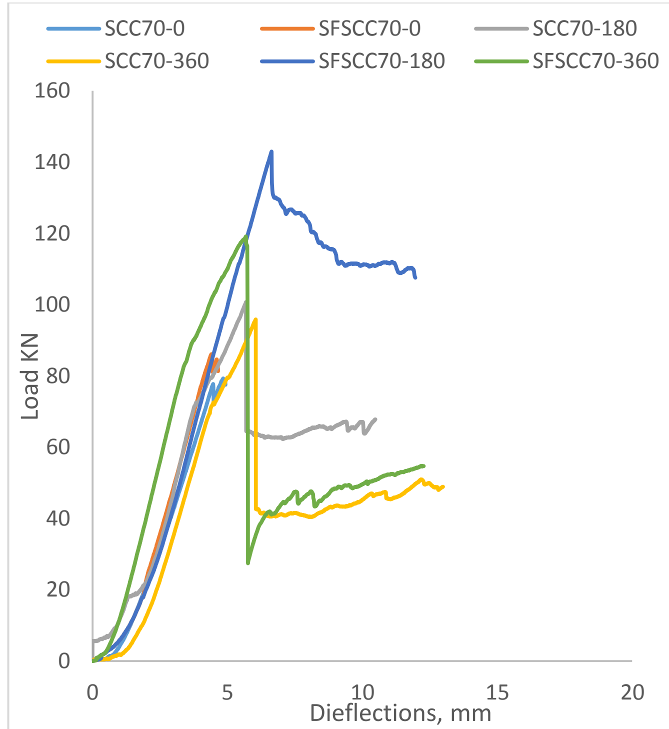


Figure: 6.16 Load vs Deflection for RASCC70 a/d=2

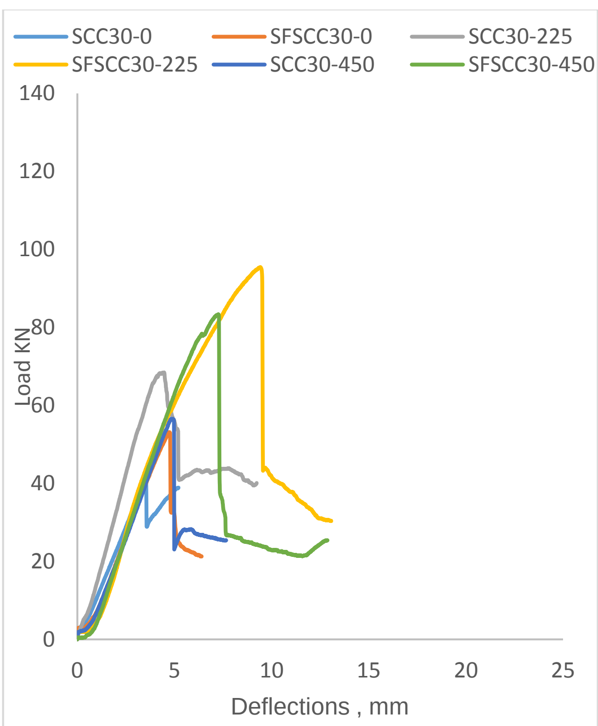


Figure:6.17 Load vs Deflection for RASCC30 a/d=2.5

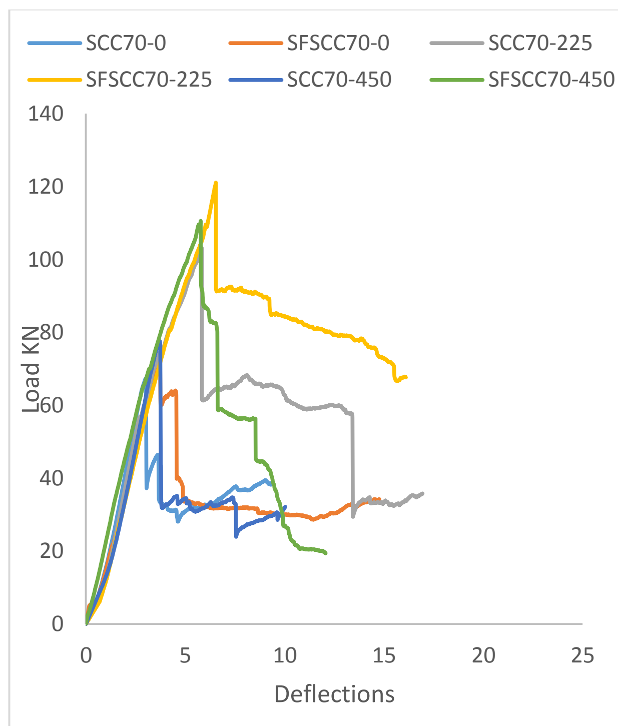


Figure:6.18 Load vs Deflection for RASCC70 a/d=2.5

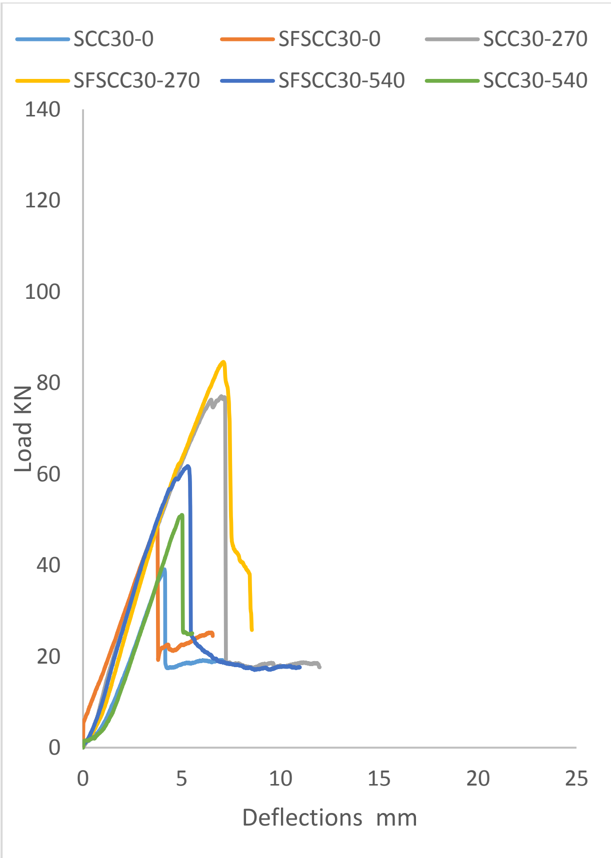


Figure: 6.19 Load vs Deflection for RASCC30 a/d=3

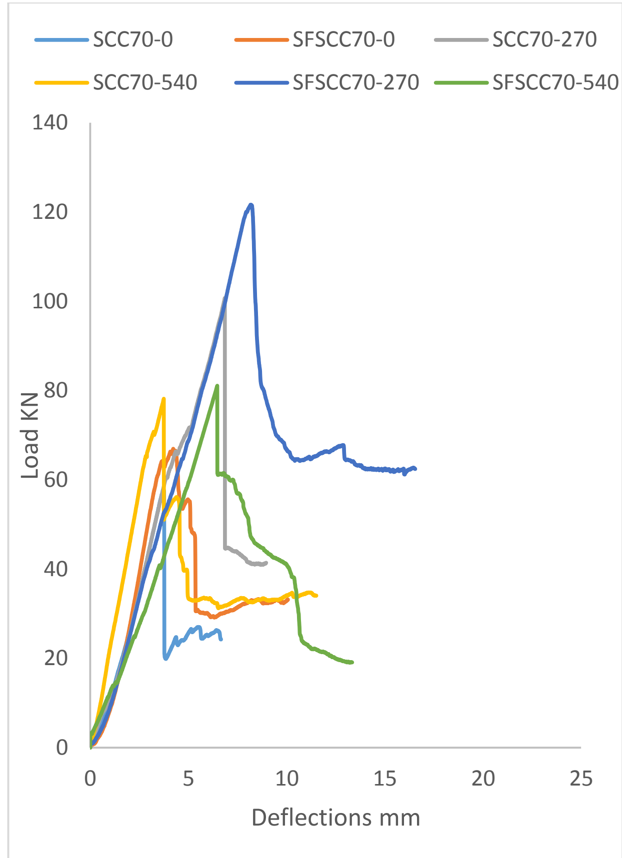


Figure: 6.20 Load vs Deflection for RASCC70 a/d=3

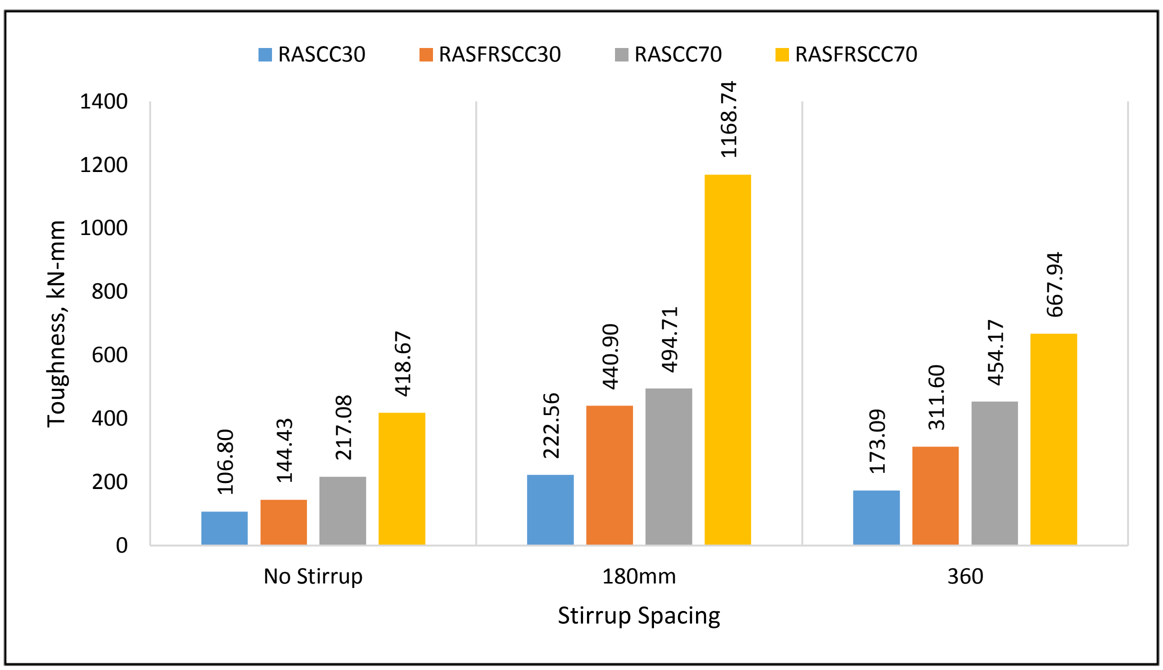


Figure: 6.21 Toughness vs stirrup spacing (a/d=2)

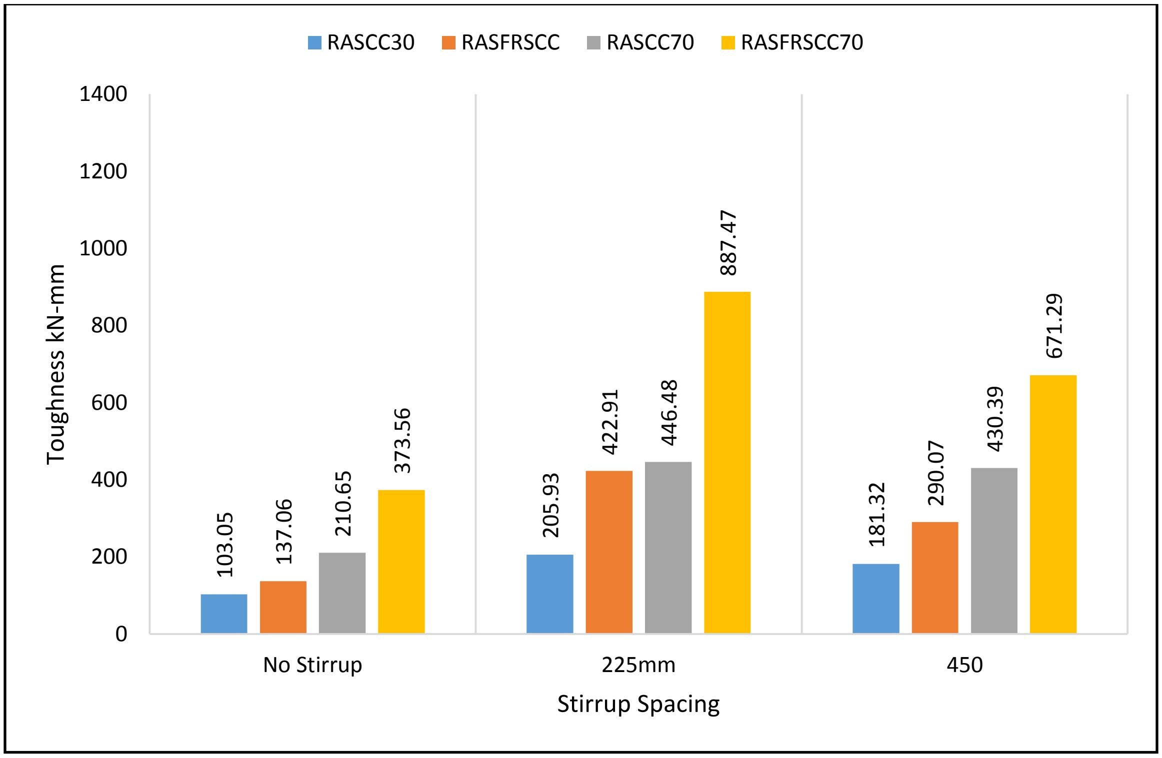


Figure: 6.22 Toughness vs stirrups spacing (a/d=2.5)

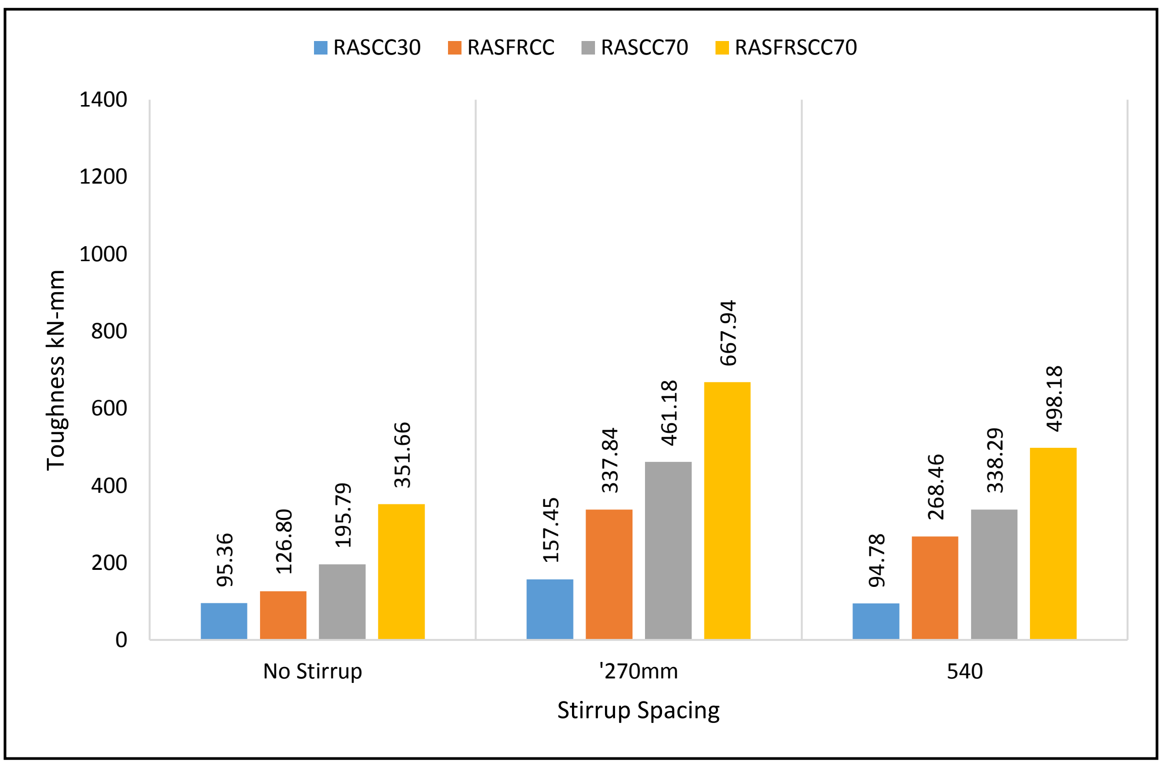


Figure: 6.23 Toughness vs stirrups spacing (a/d=3)

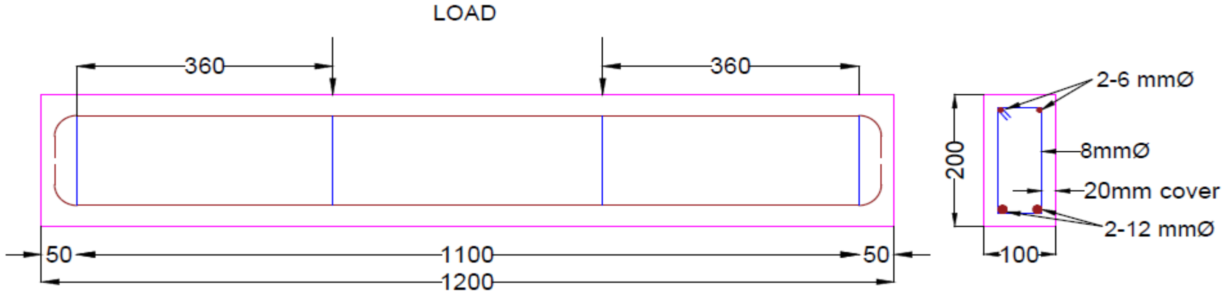


Figure: 6.24(a)

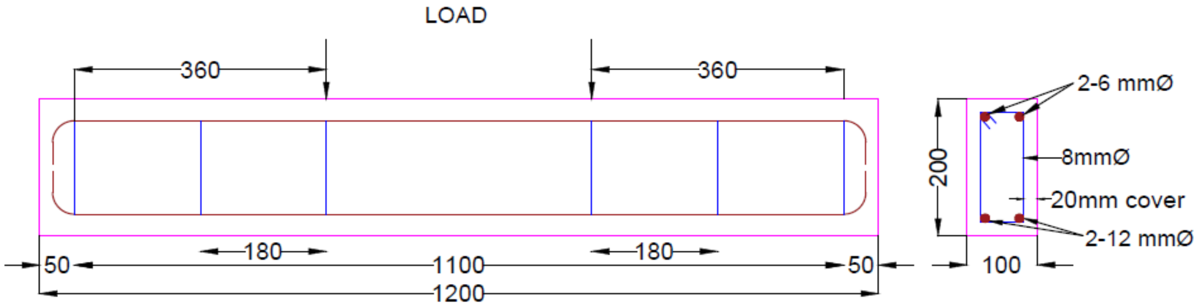


Figure: 6.24(b)

Figure: 6.24 Details of reinforcement for M30 mix with a/d=2 for 8mm Ø stirrup

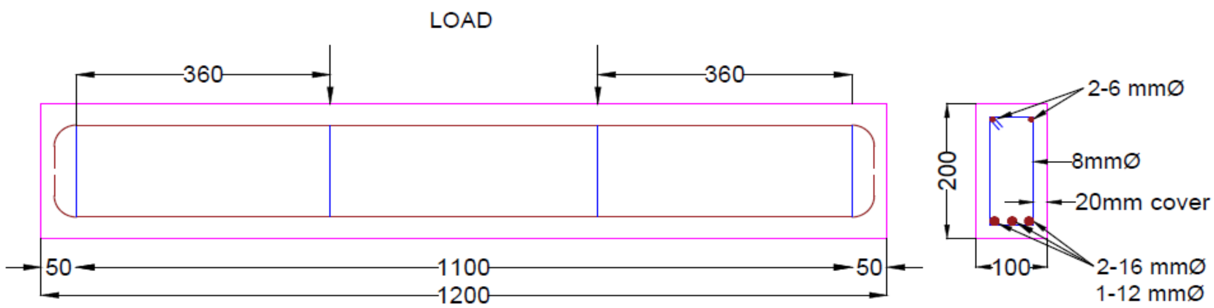


Figure: 6.25(a)

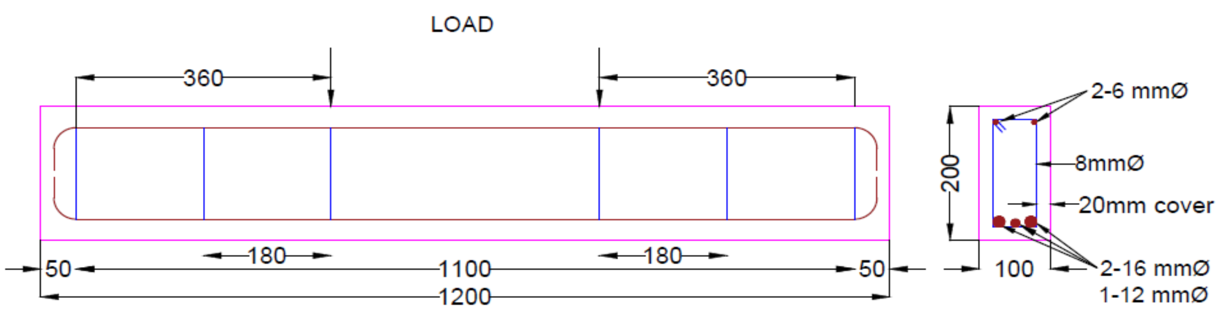
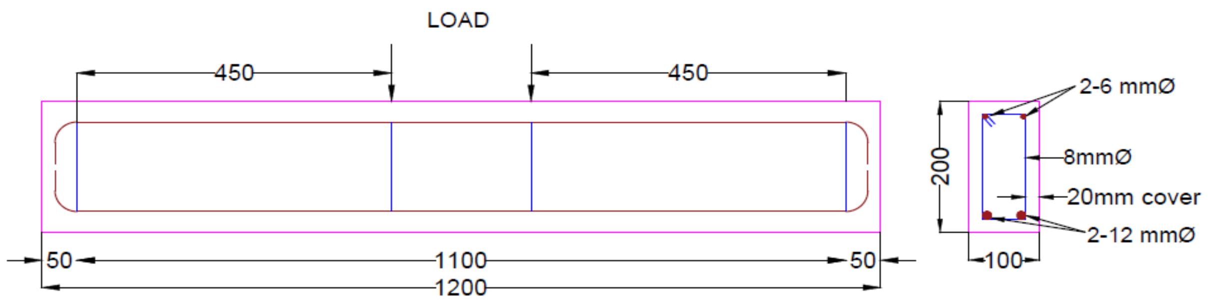


Figure: 6.25(b)

Figure: 6.25 Details of reinforcement for M70 mix with a/d=2 for 8mm Ø stirrup



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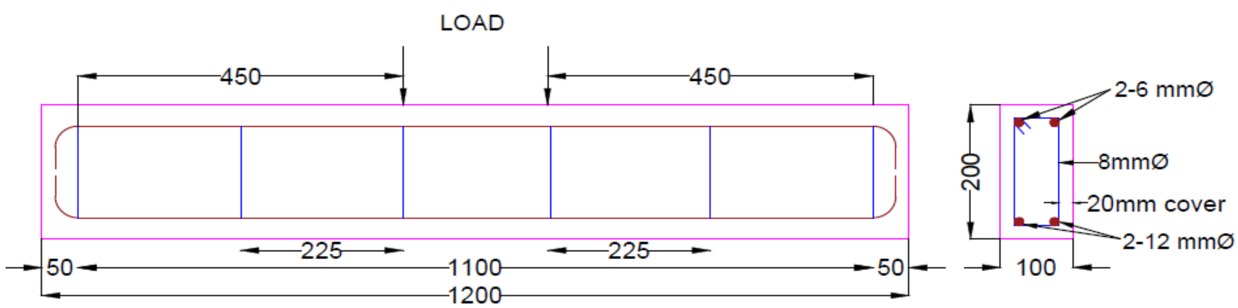

Figure: 6.26(b)

Figure: 6.26 Details of reinforcement for M30 mix with a/d=2.5 for 8mm Ø stirrup

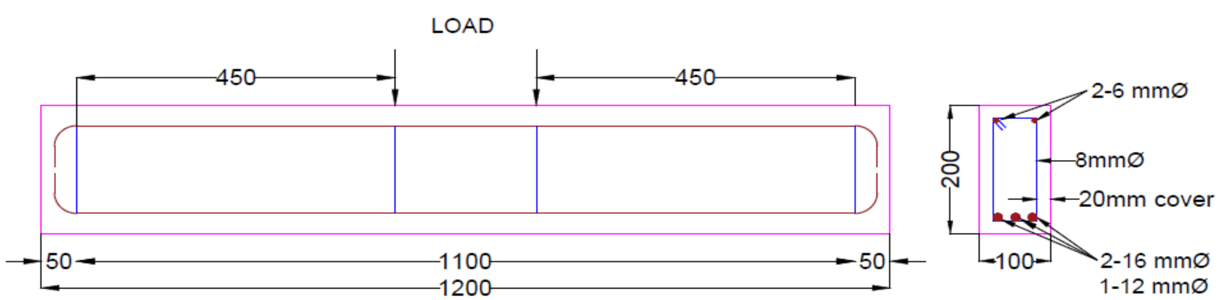

Figure: 6.27(a)

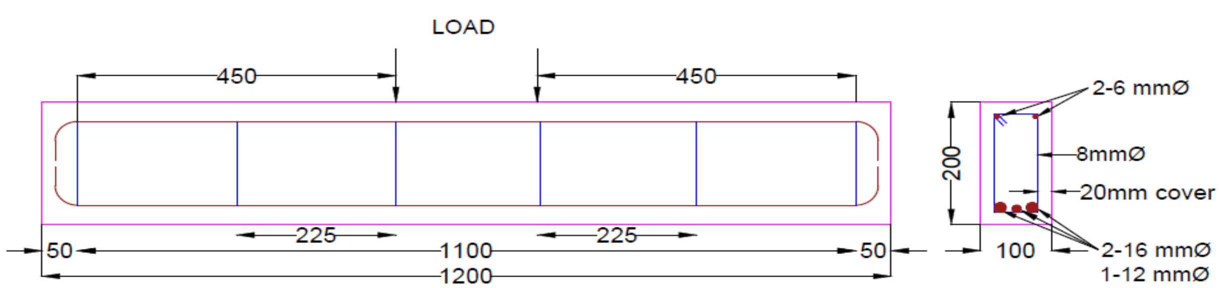

Figure: 6.27(b)

Figure: 6.27 Details of reinforcement for M70 mix with a/d=2.5 for 8mm Ø stirrup

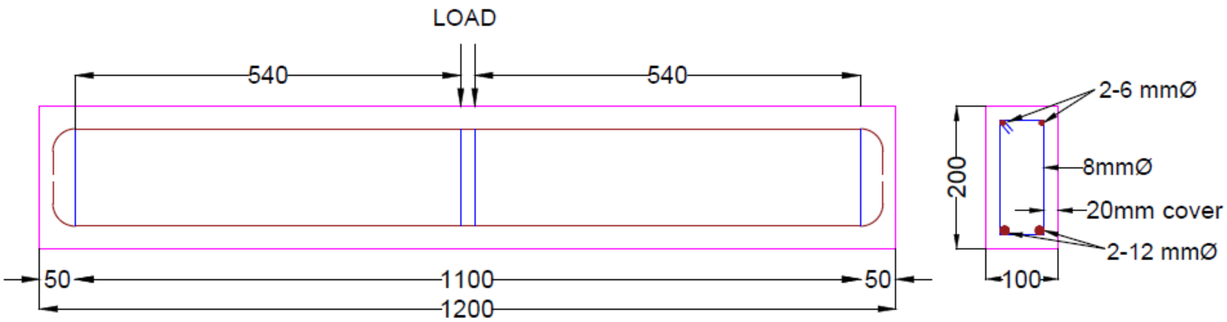

Figure: 6.28(a)

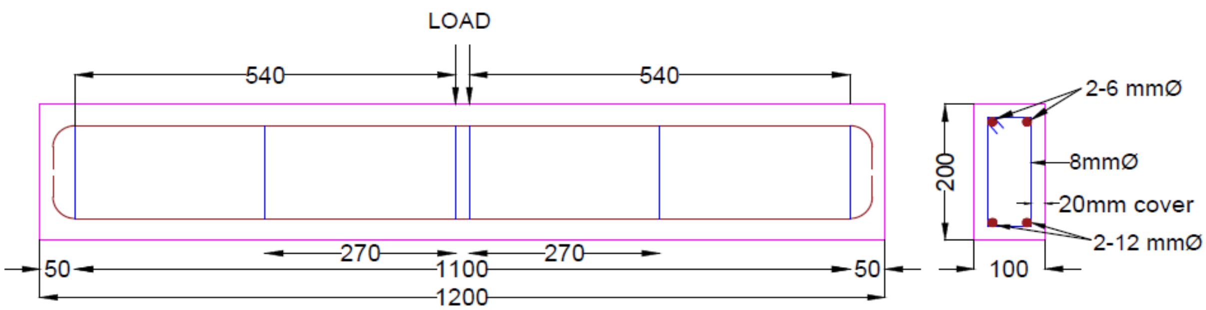

Figure: 6.28(b)

Figure: 6.28 Details of reinforcement for M30 mix with a/d=3 for 8mm Ø stirrup

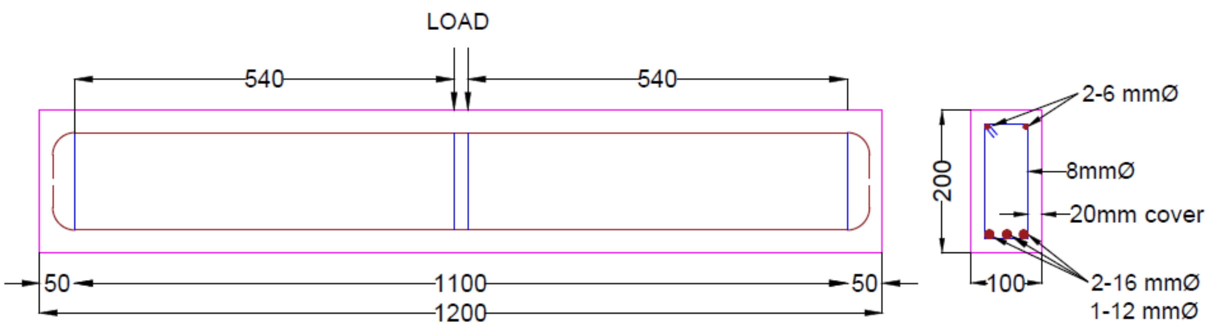

Figure: 6.29(a)

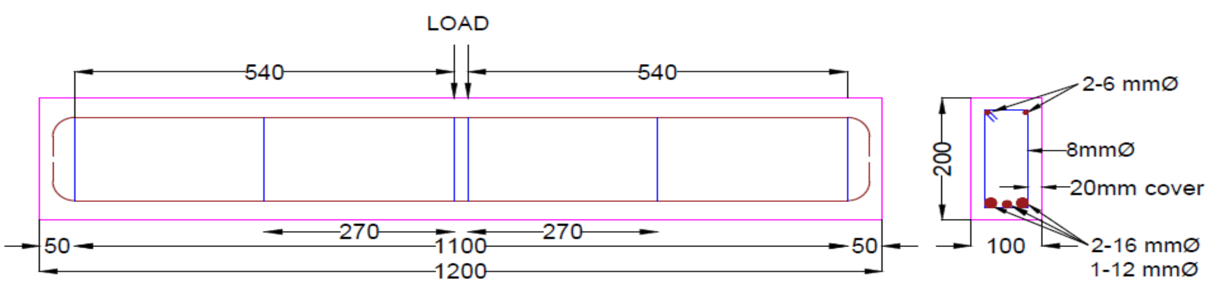

Figure: 6.29(b)

Figure: 6.29 Details of reinforcement for M70 mix with a/d=3 for 8mm Ø stirrup

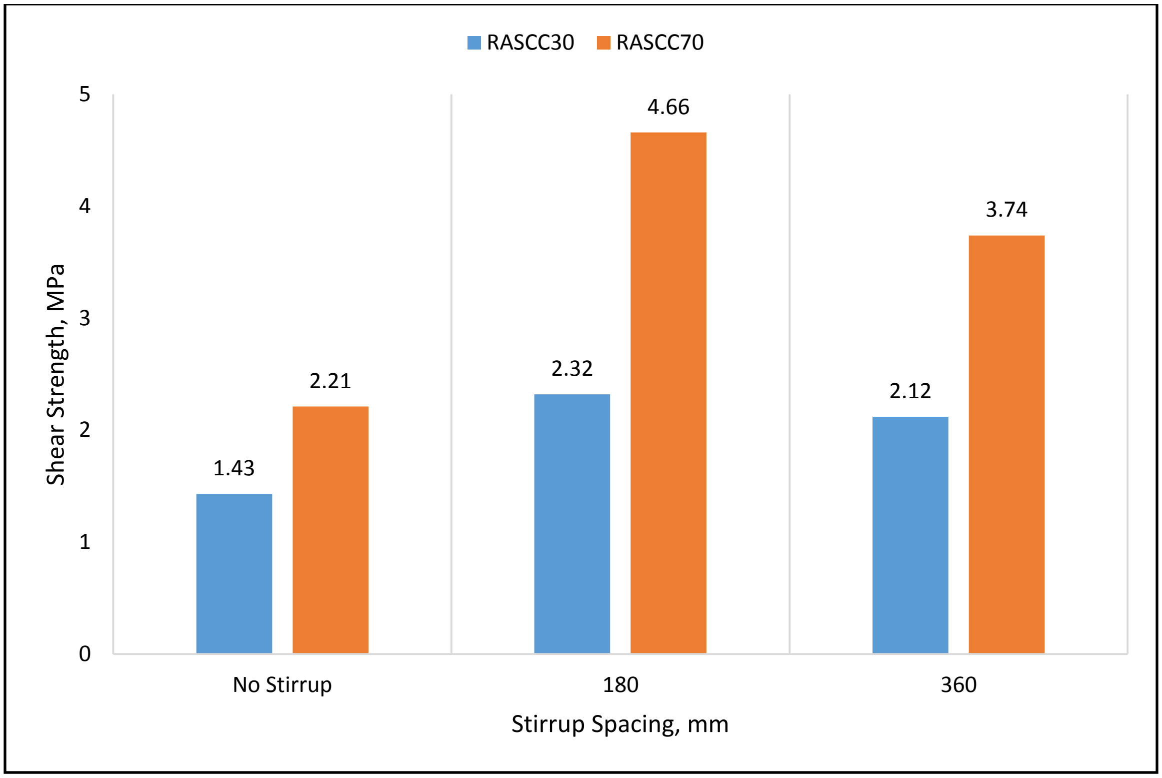

Figure: 6.30 Shear Strength vs Stirrup Spacing for a/d=2

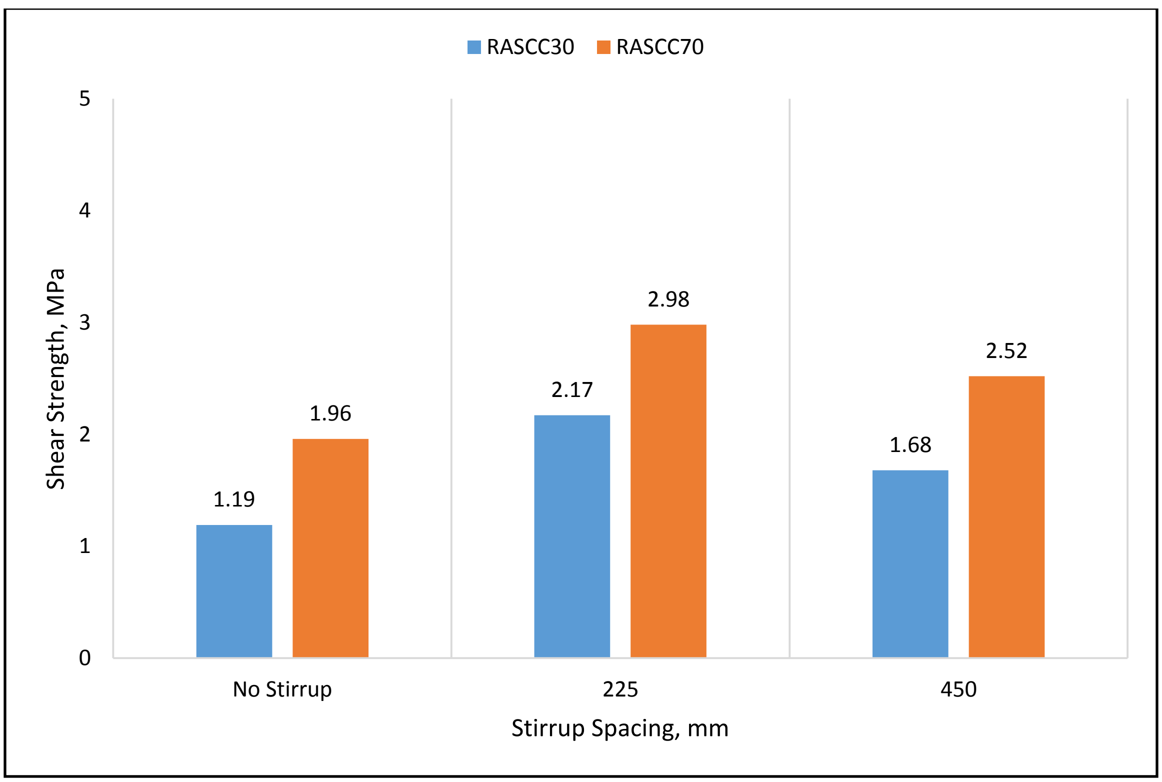

Figure: 6.31 Shear Strength vs Stirrup Spacing for a/d=2.5

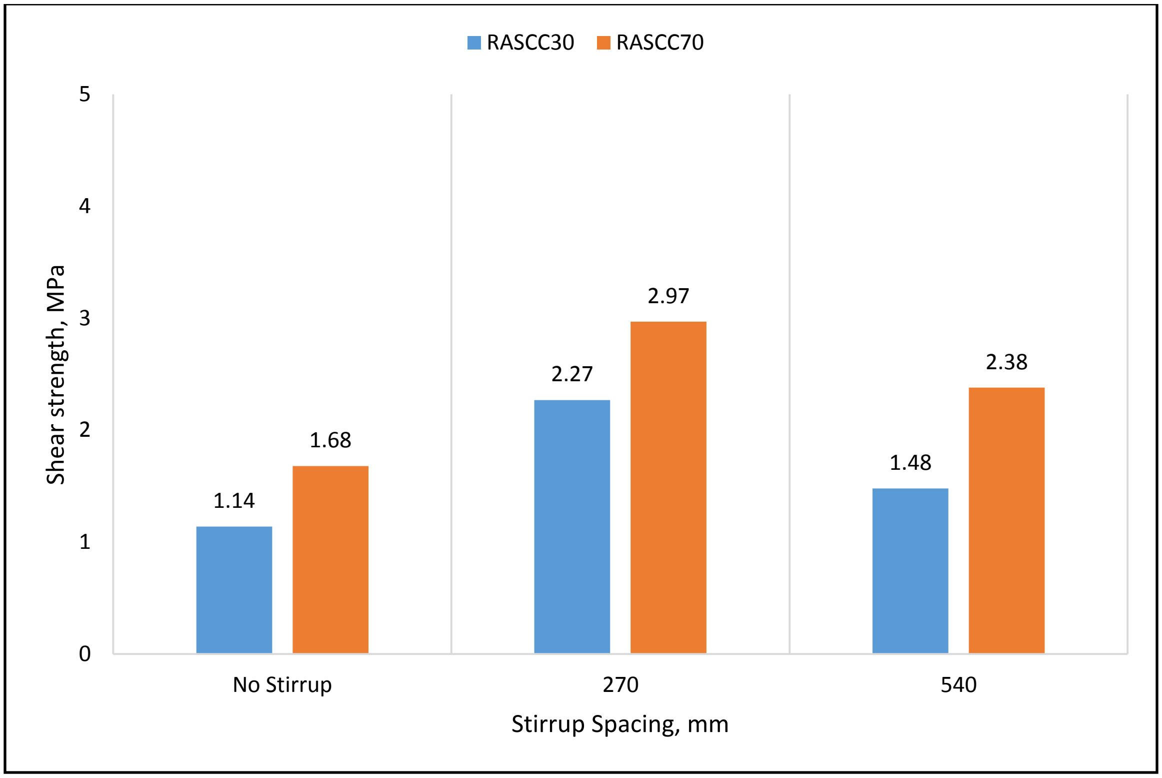

Figure: 6.32 Shear Strength vs Stirrup Spacing for a/d=3

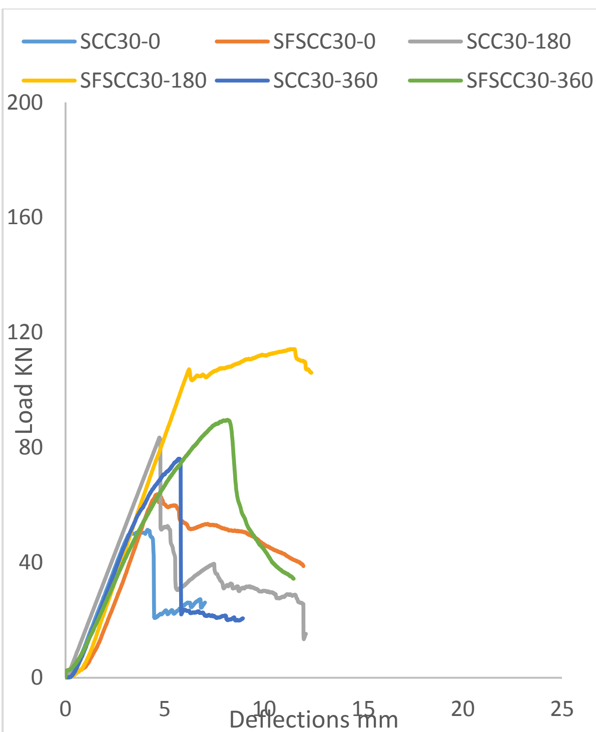

Figure: 6.33 Load vs Deflection for RASCC30 a/d=2 for 8mm Ø Stirrup

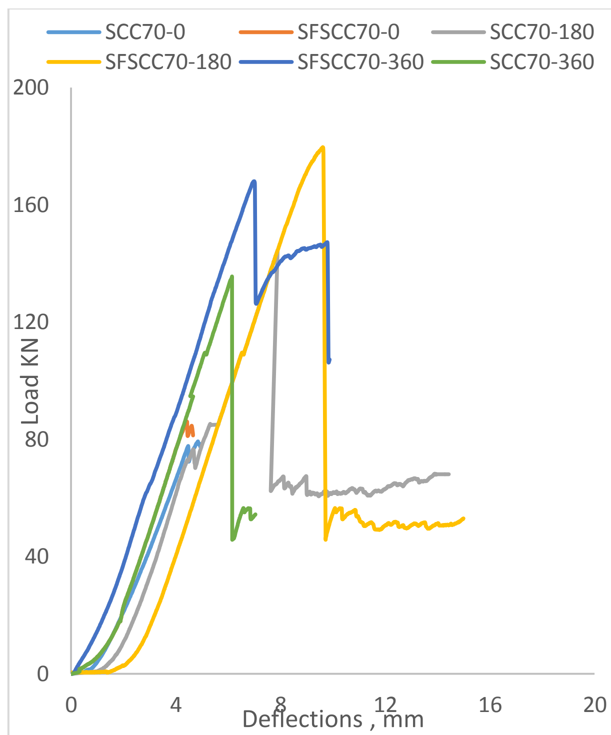

Figure: 6.34 Load vs Deflection for RASCC70 a/d=2 for 8mmØ Stirrup

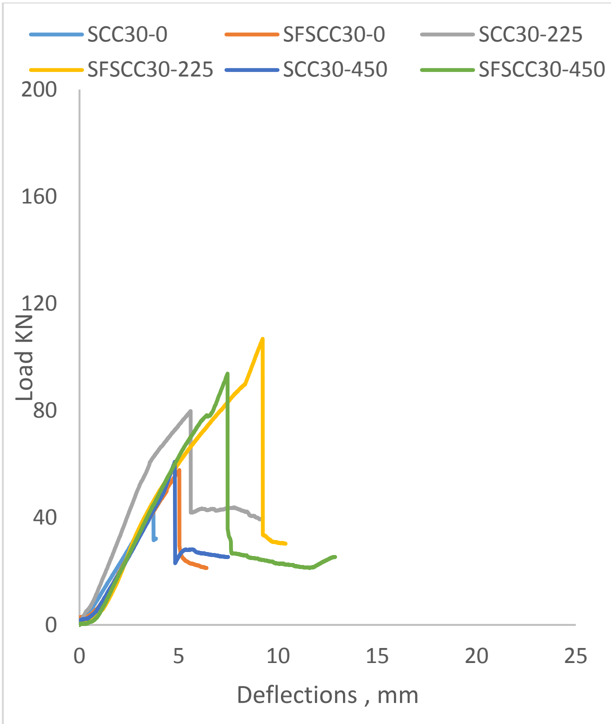

Figure:6.35 Load vs Deflection for RASCC30 a/d=2.5 for 8mm Ø Stirrup

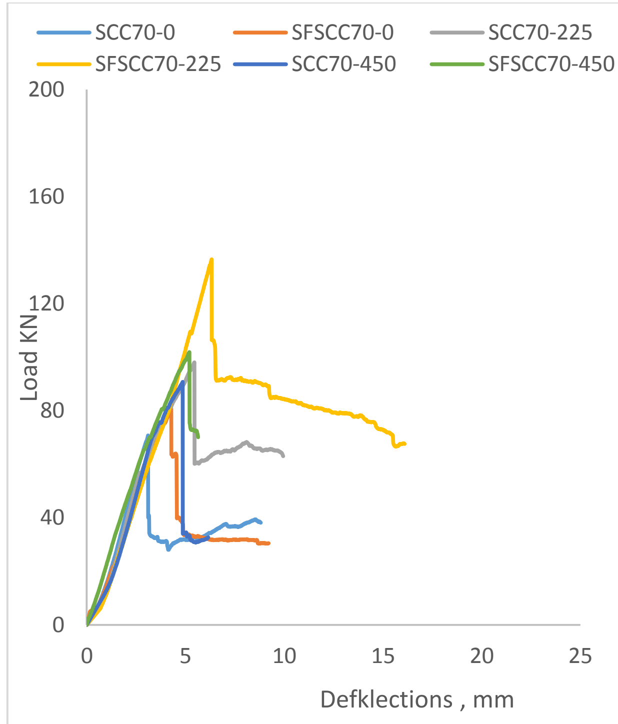

Figure: 6.36 Load vs Deflection for RASCC70 a/d=2.5 for 8mmØ Stirrup

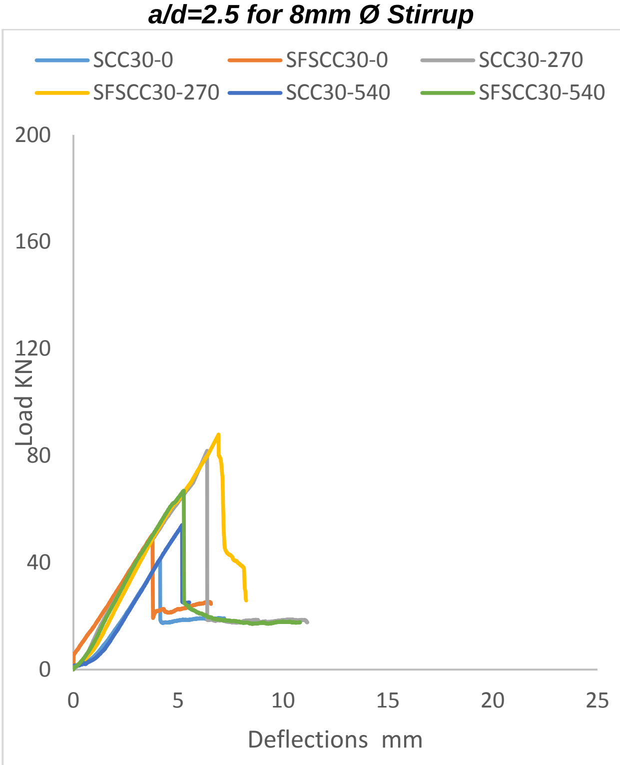

Figure: 6.37 Load vs Deflection for RASCC30 a/d=3;8mm Ø Stirrup

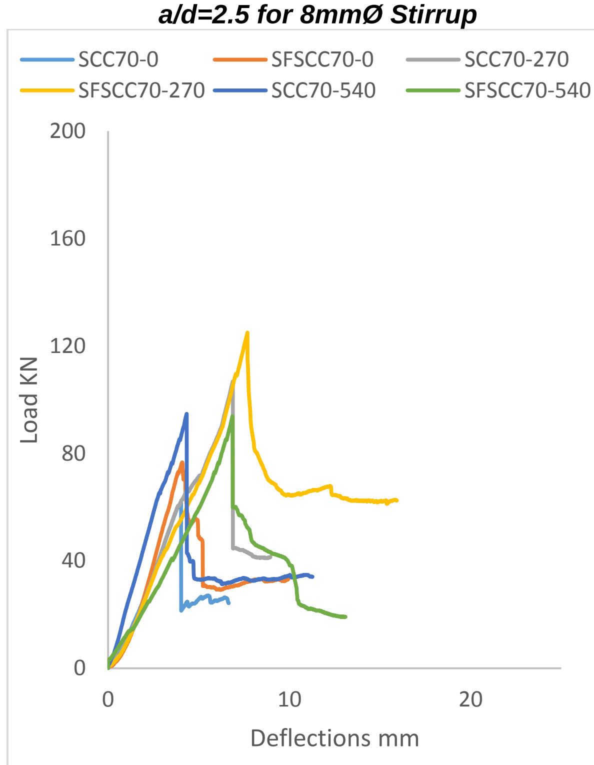

Figure: 6.38 Load vs Deflection for RASCC70 a/d=3;8mm Ø Stirrup

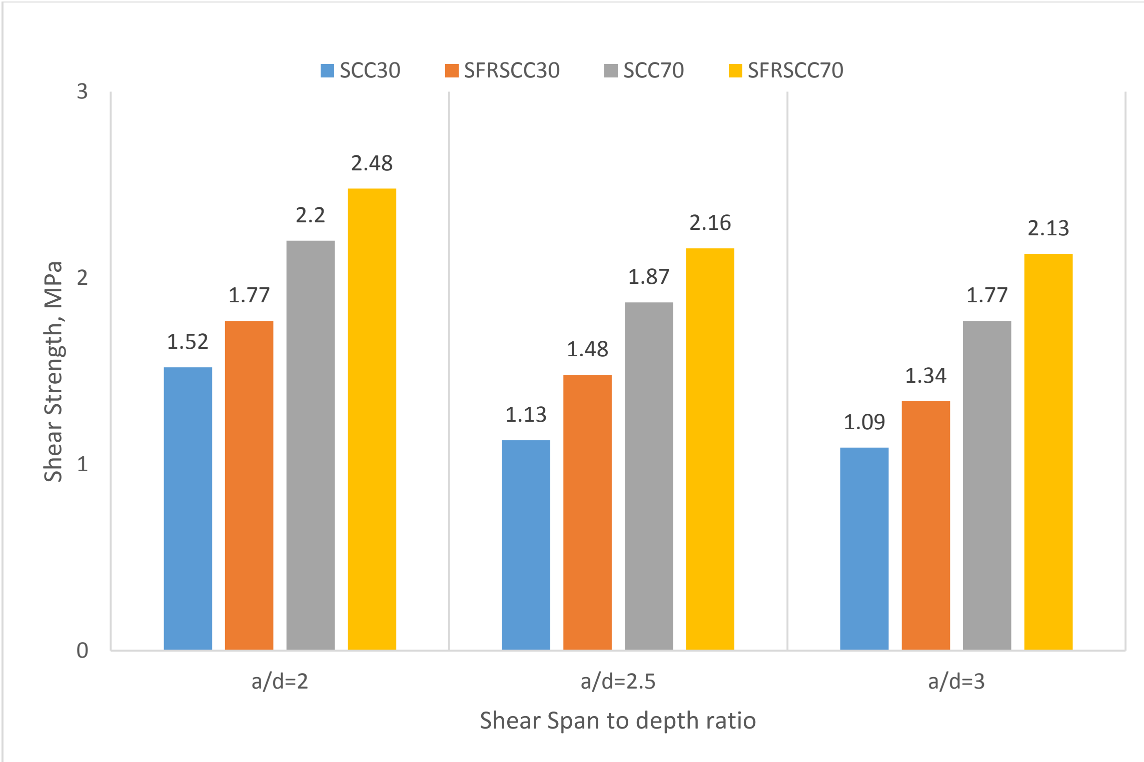

Figure: 6.39 Shear strength vs shear span to depth ratio for plain RASCC beams

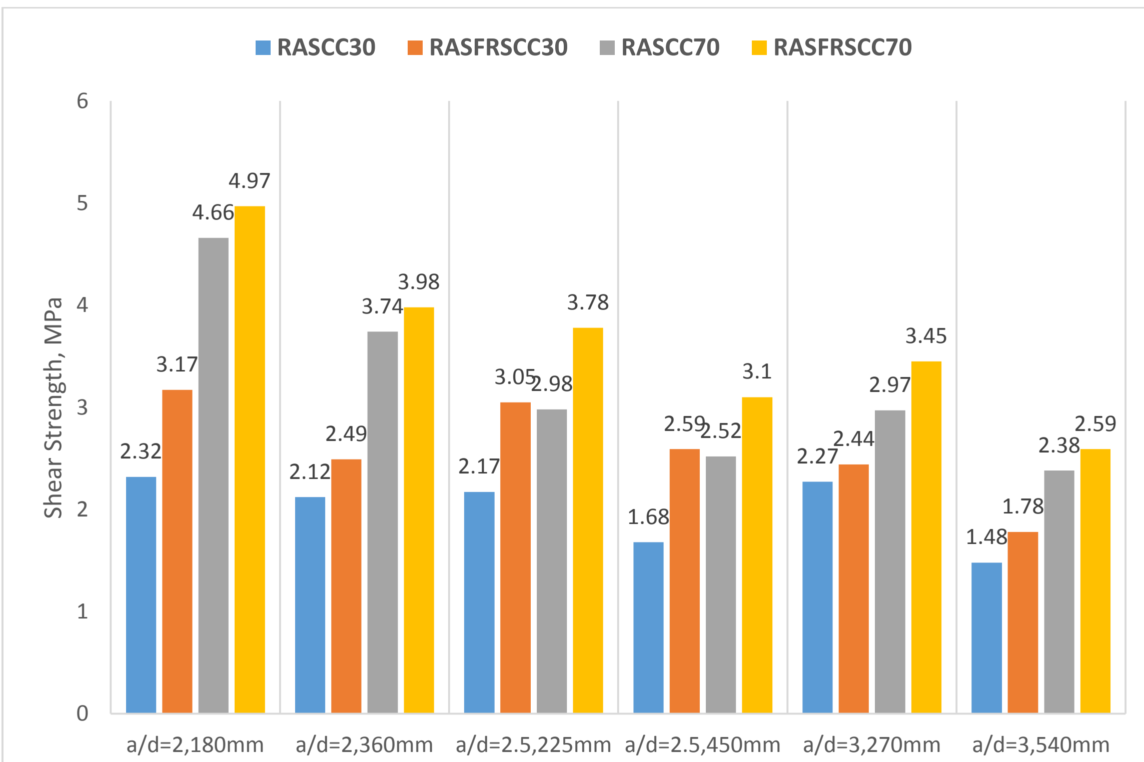

Figure: 6.40 Shear strength vs shear span to depth ratio using 8mm Ø stirrup.

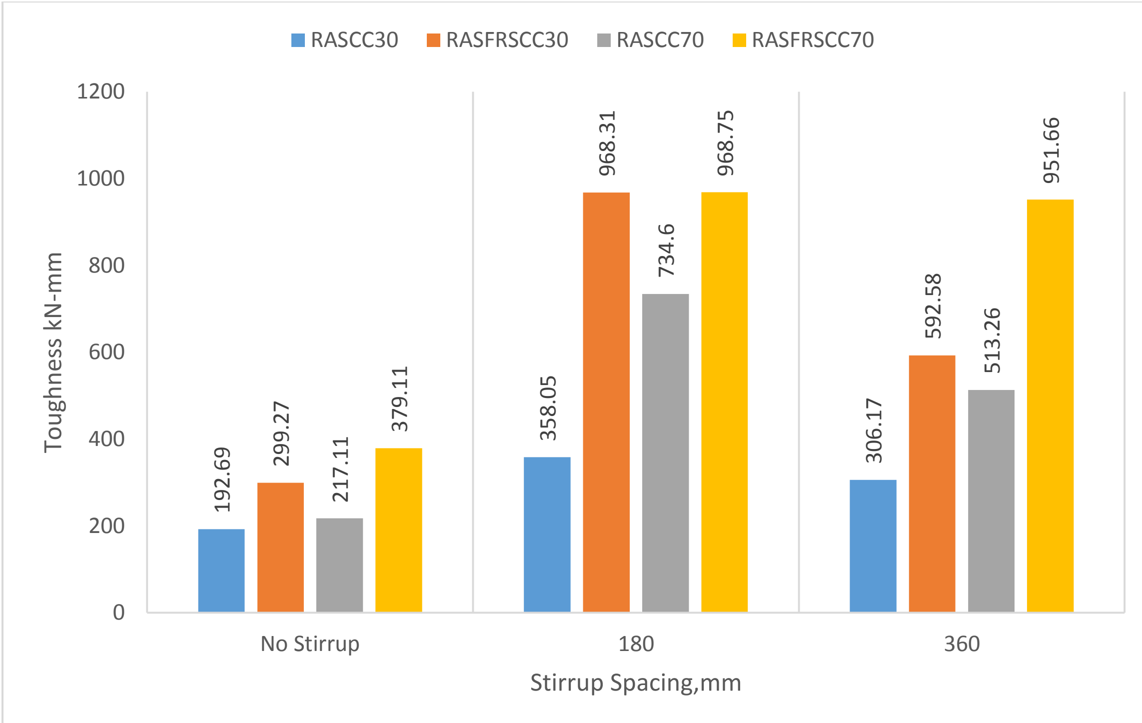

Figure: 6.41 Toughness vs Stirrups spacing for a/d=2

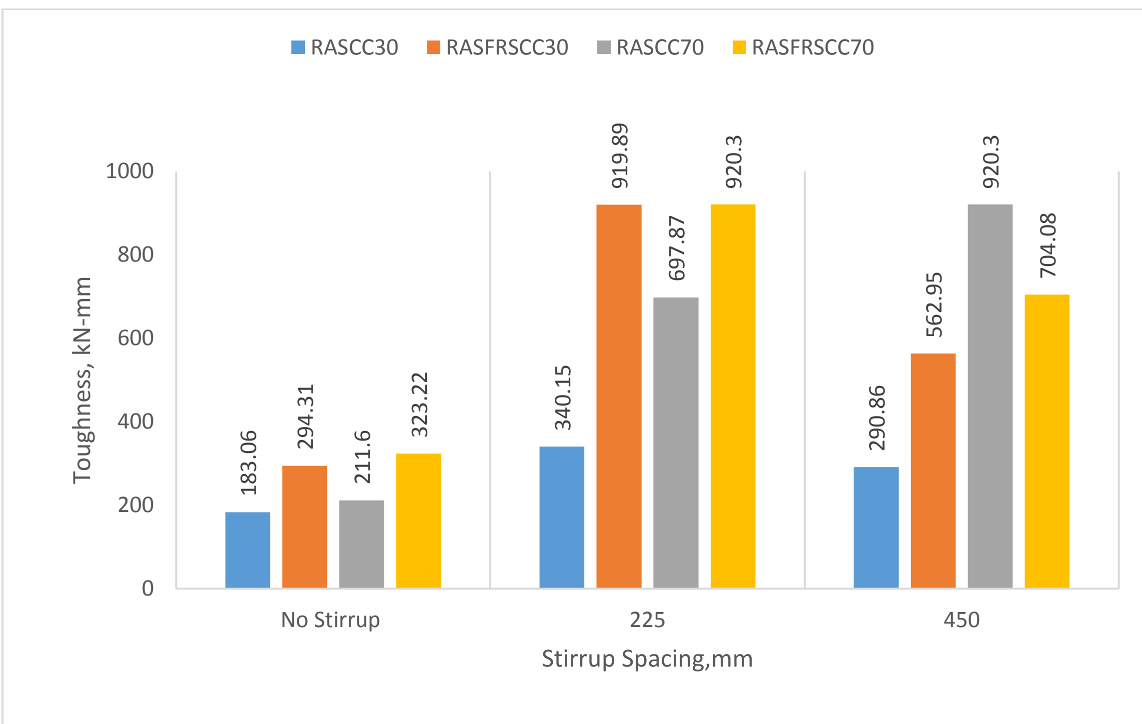

Figure: 6.42 Toughness vs Stirrups spacing for a/d=2.5

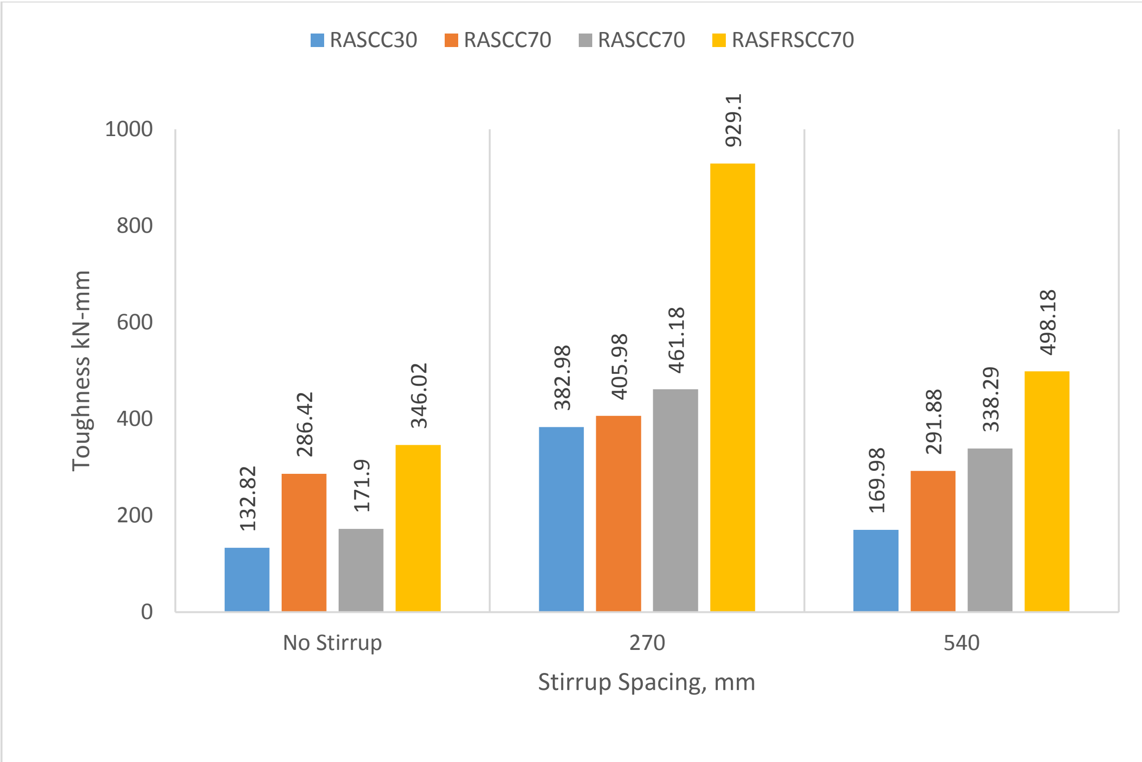

Figure: 6.43 Toughness vs Stirrups spacing for a/d=3

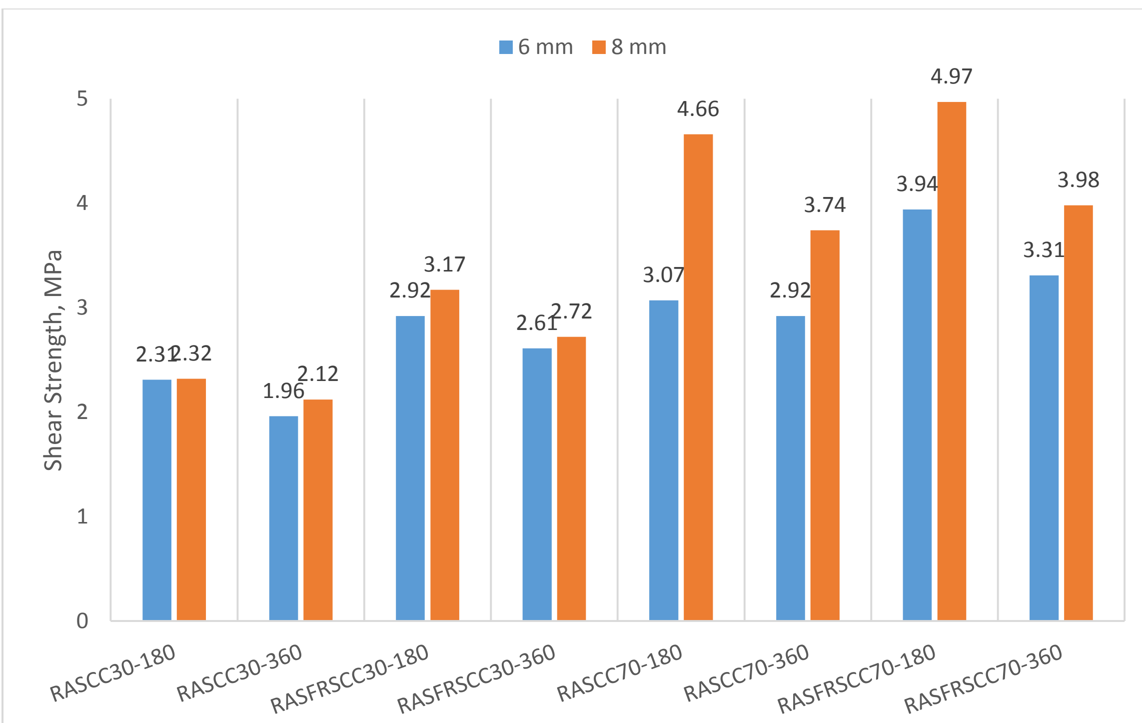

Figure: 6.44 Comparison of Shear Strength for 6mm and 8mm Ø for a/d=2

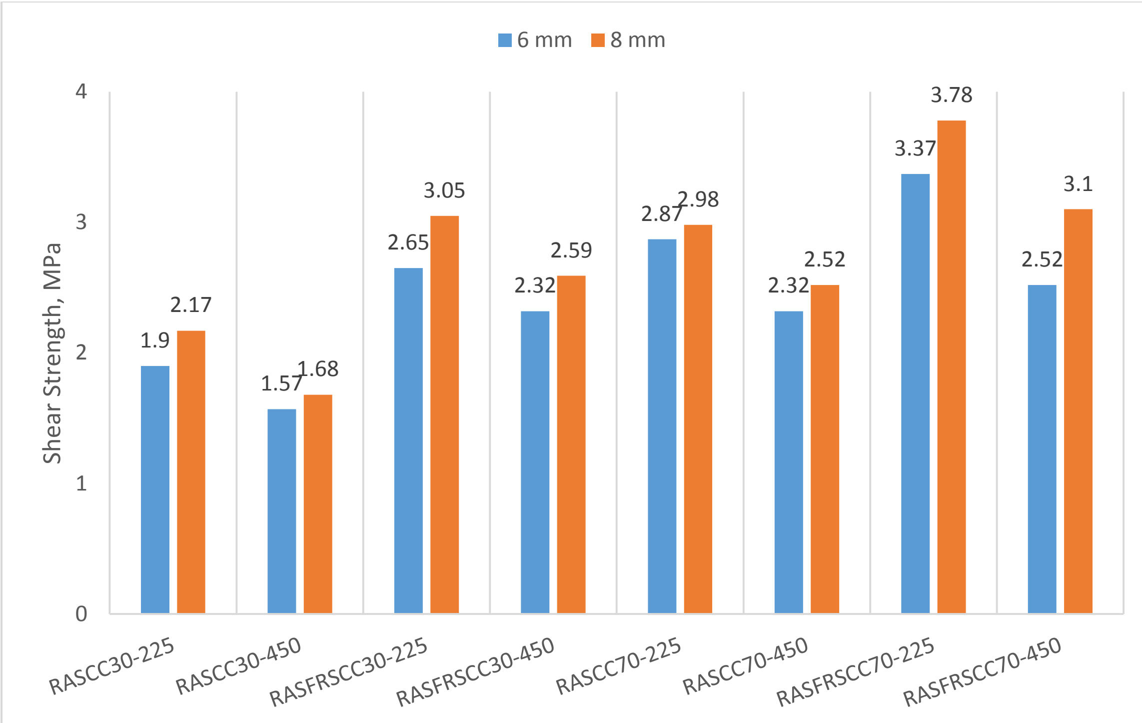

Figure: 6.45 Comparison of Shear Strength for 6mm and 8mm Ø for a/d=2.5

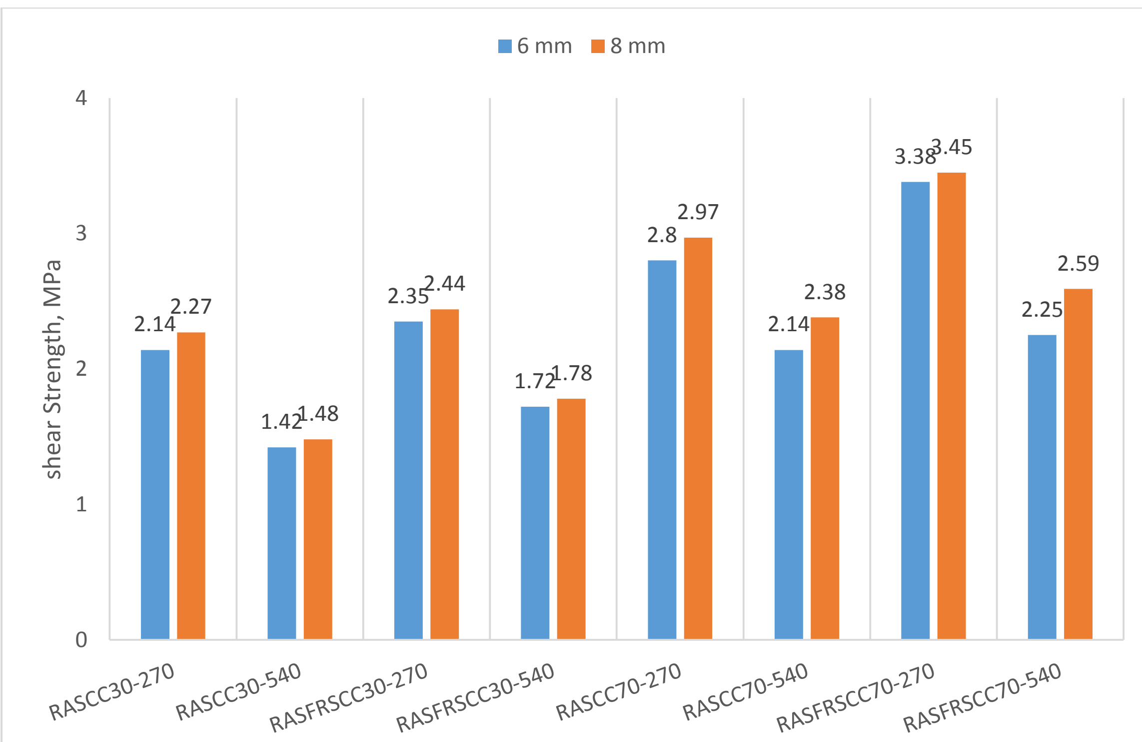

Figure: 6.46 Comparison of Shear Strength for 6mm and 8mm Ø for a/d=3

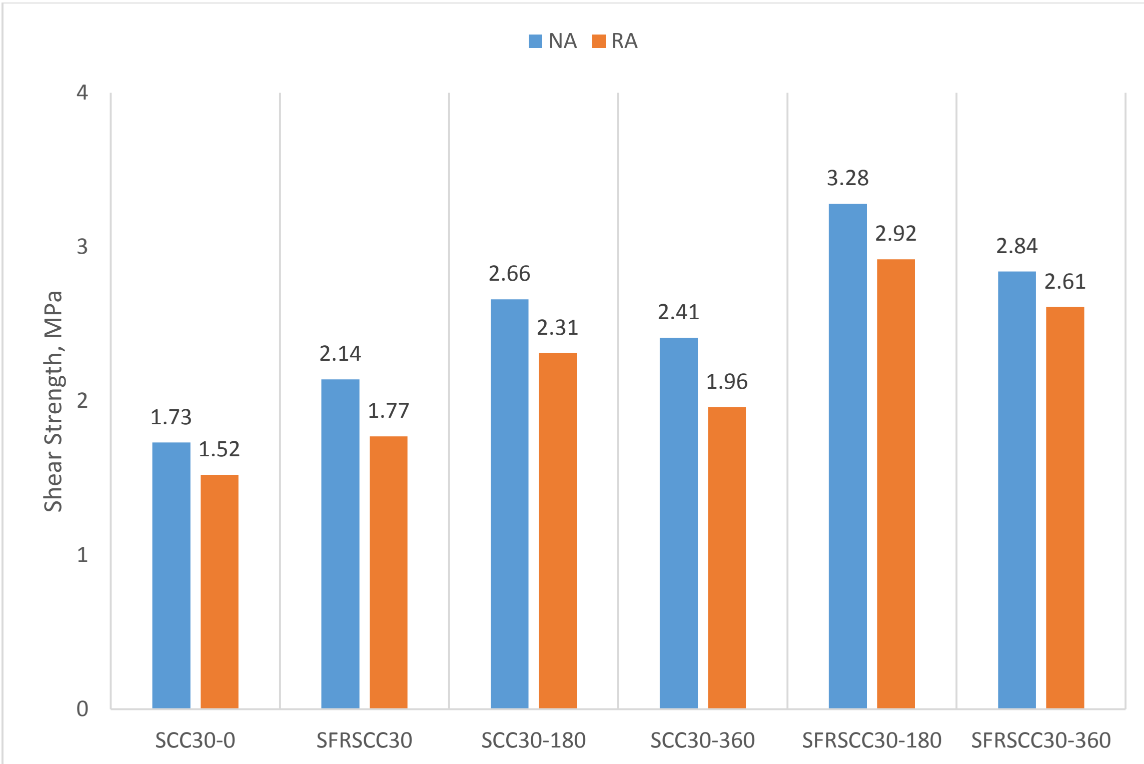

Figure: 6.47 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=2, for 30 MPa concrete

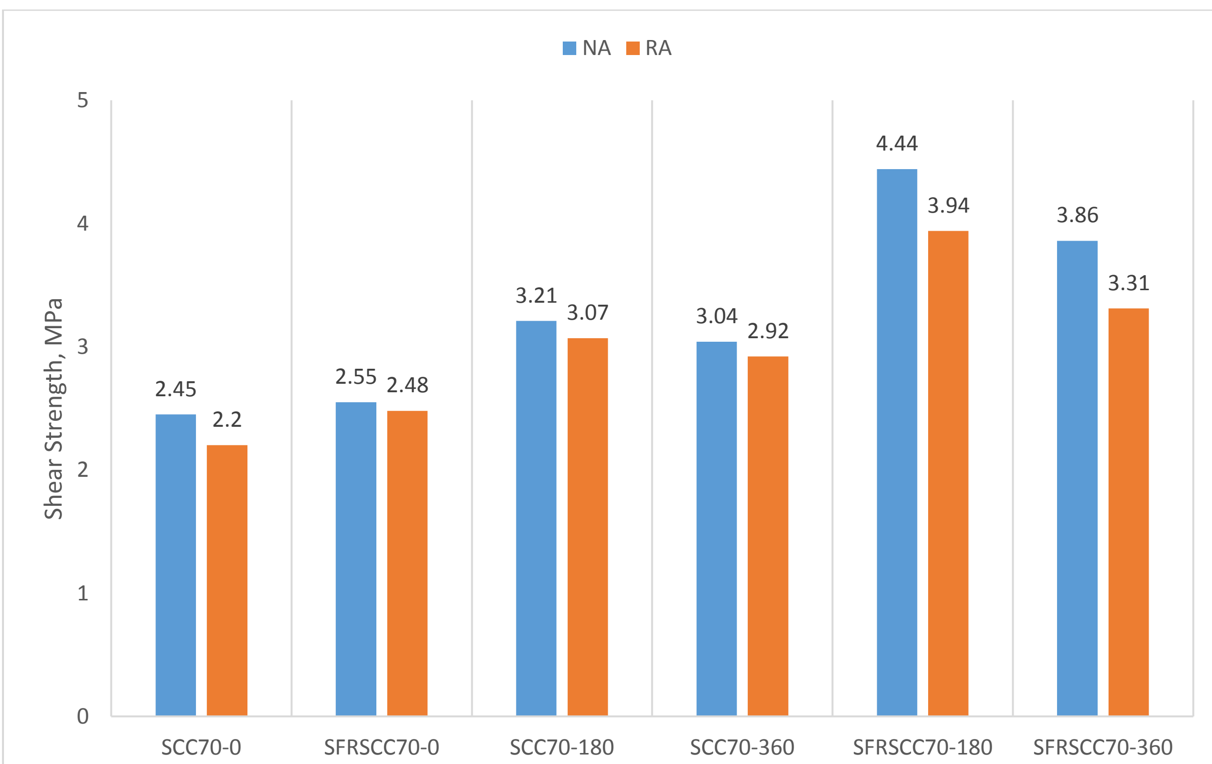

Figure: 6.48 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=2, for 70 MPa concrete

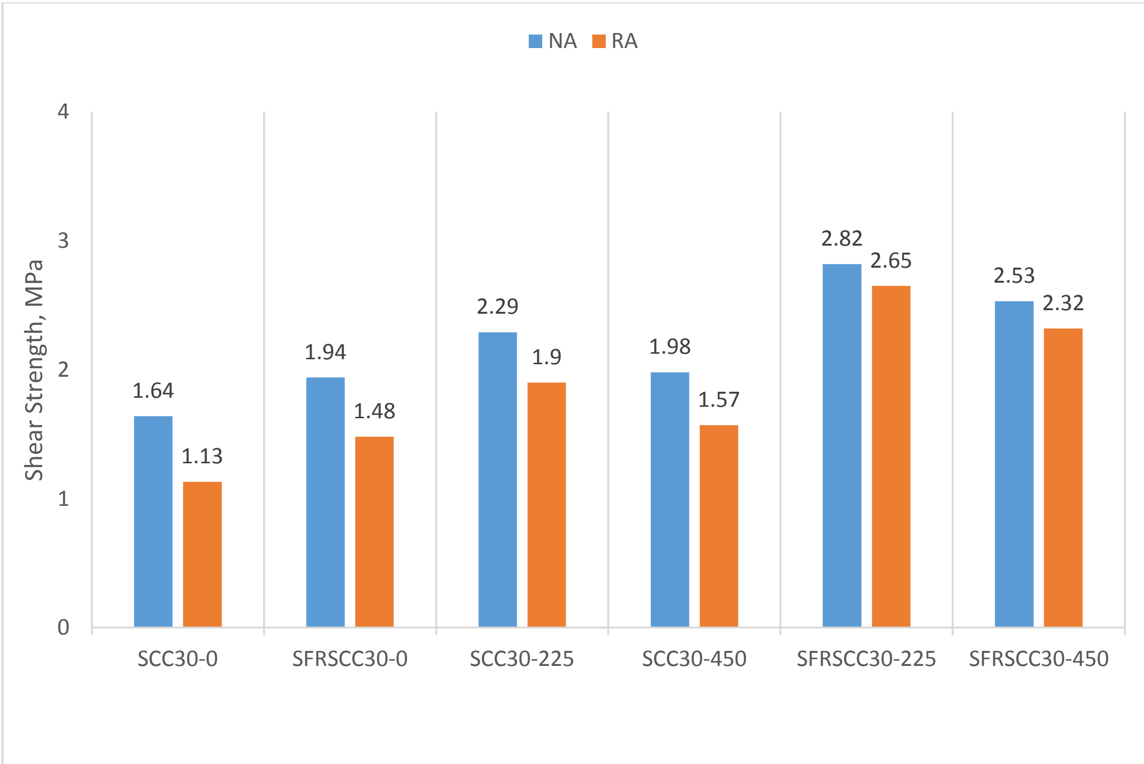

Figure: 6.49 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=2.5, for 30 MPa concrete

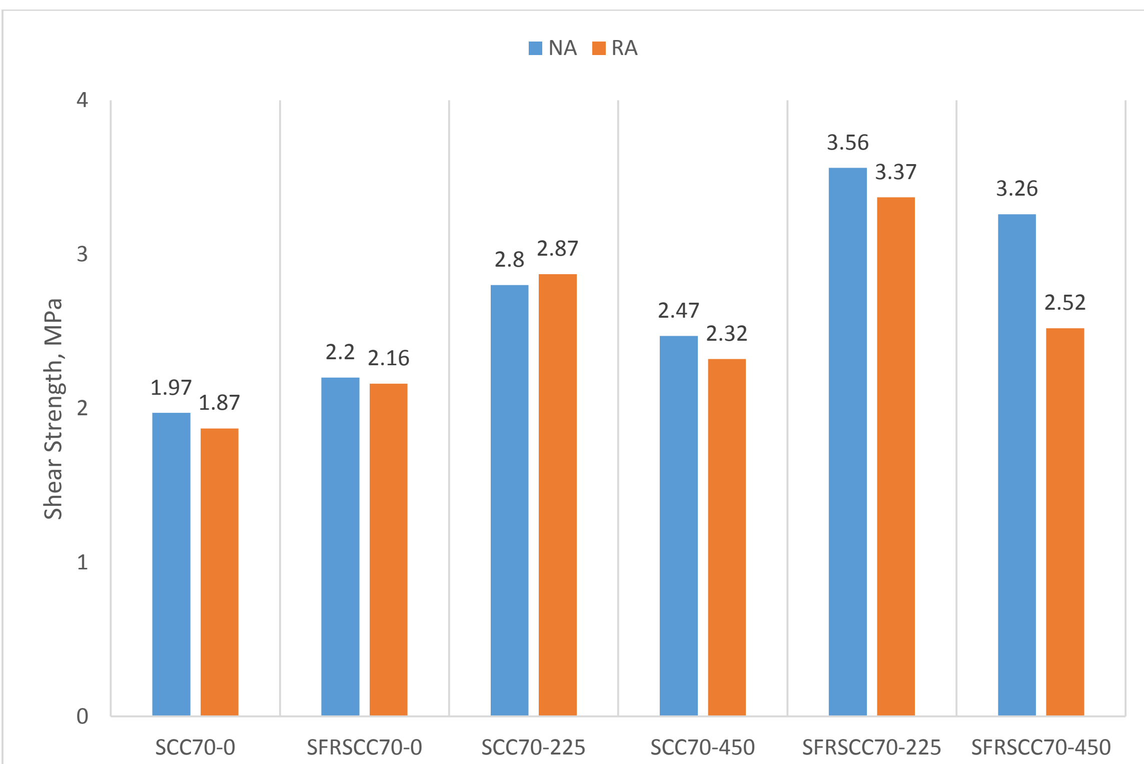

Figure: 6.50 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=2.5, for 70 MPa concrete

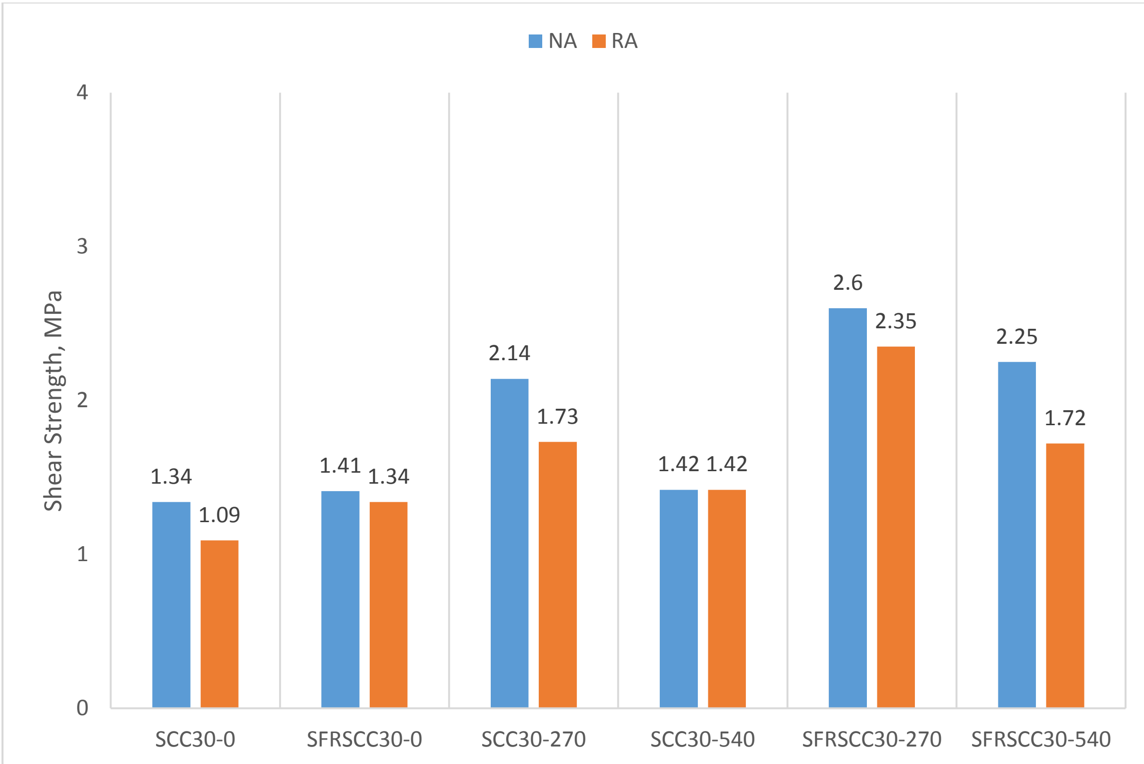

Figure: 6.51 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=3, for 30 MPa concrete

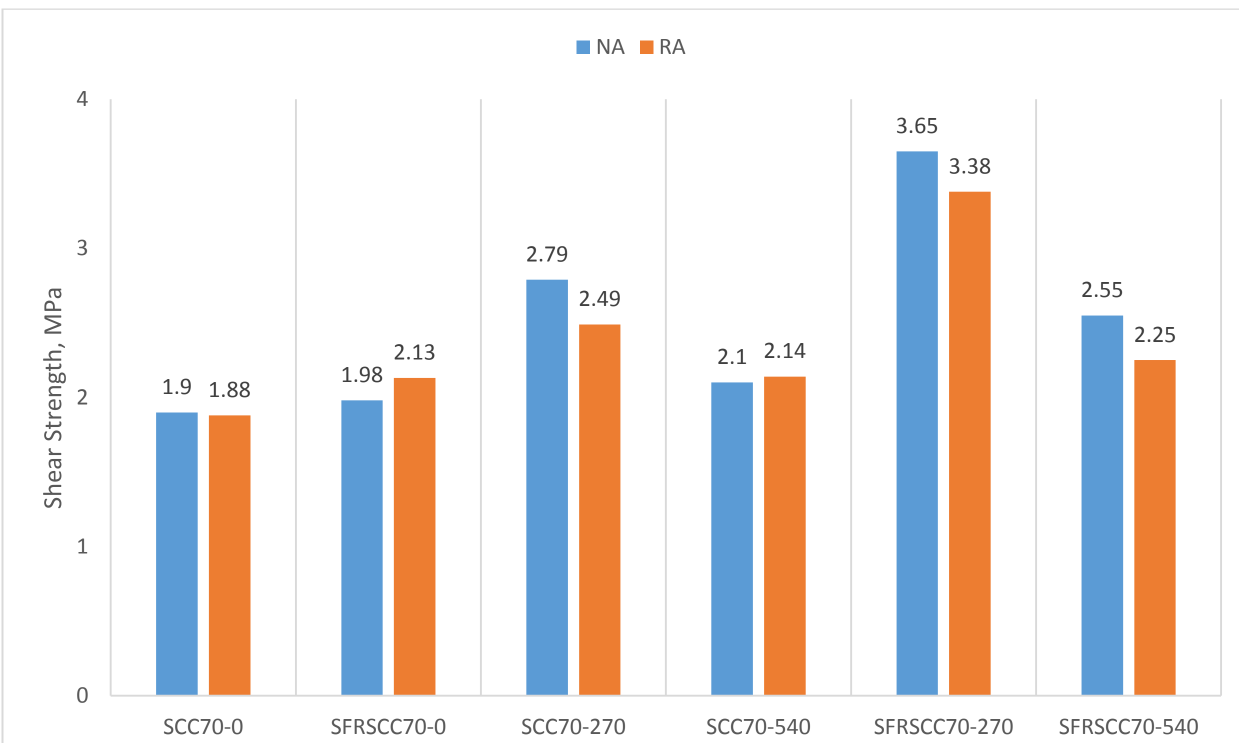

Figure: 6.52 Comparison of shear strength of NASCC and RASCC using 6mm diameter stirrup for a/d=3, for 70 MPa concrete

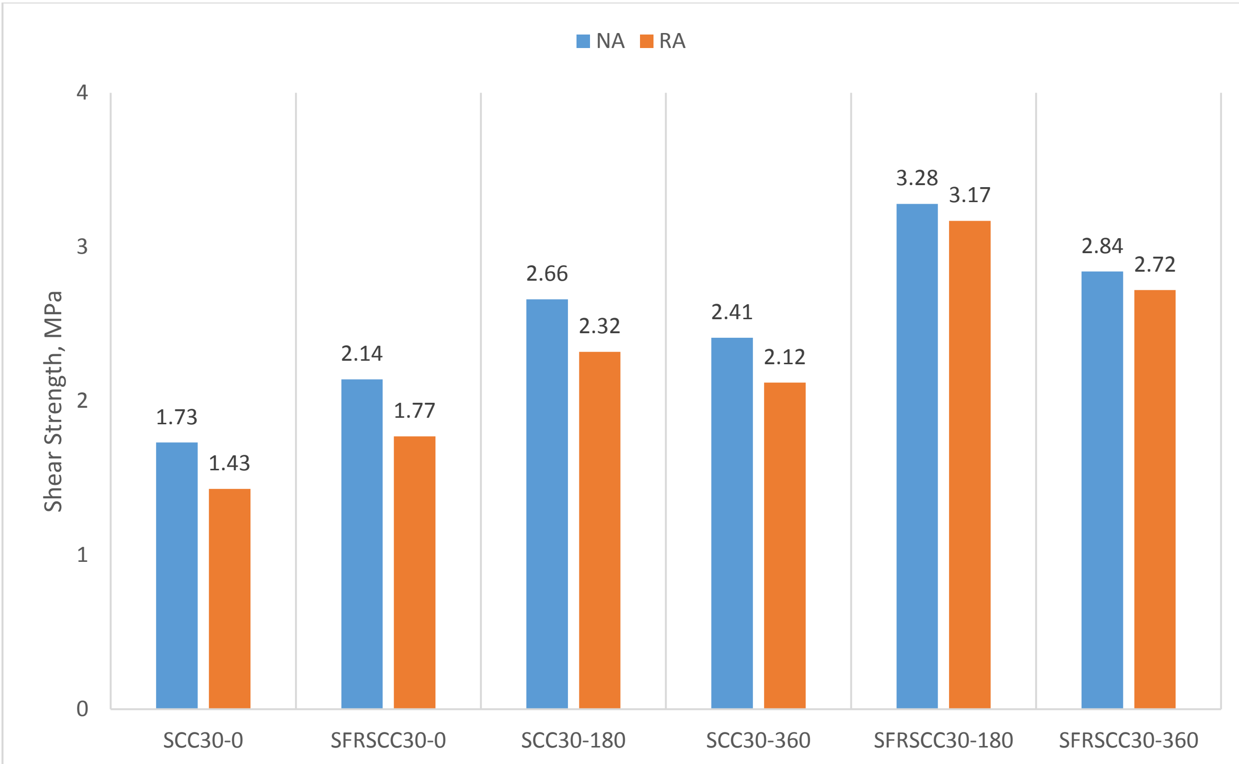

Figure: 6.53 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=2, for 30 MPa concrete

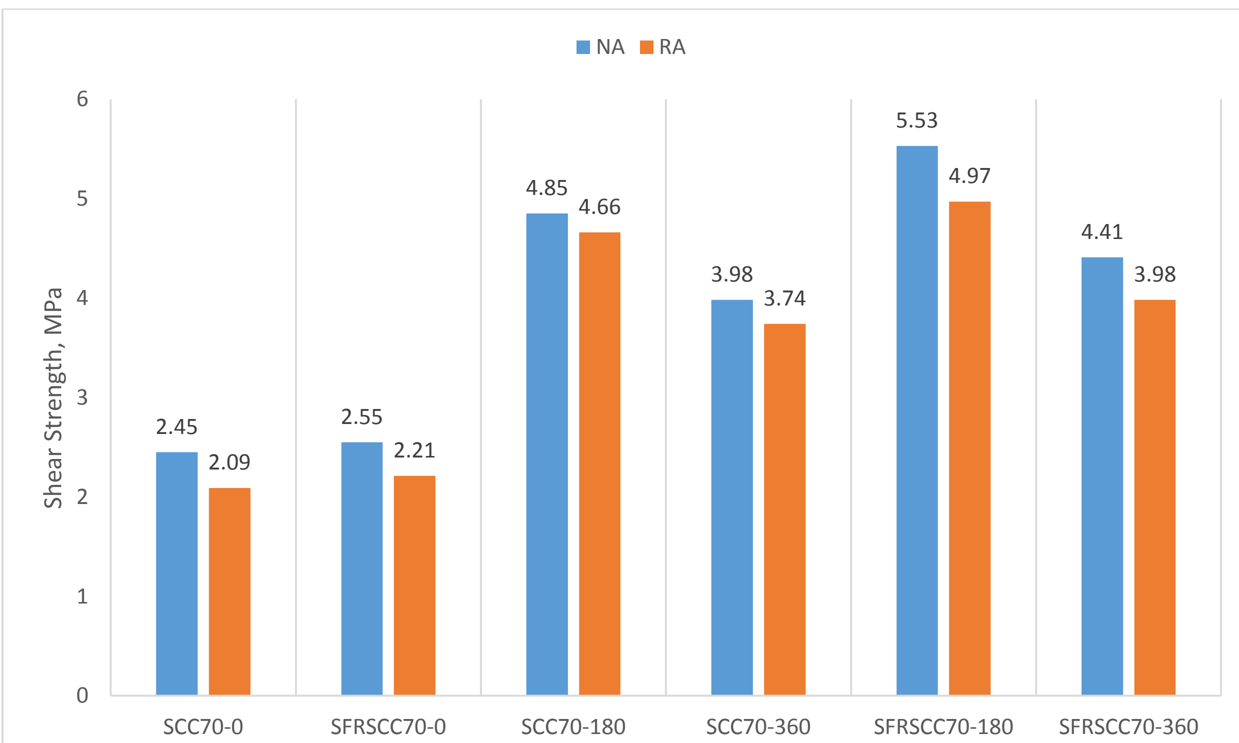

Figure: 6.54 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=2, for 70 MPa concrete

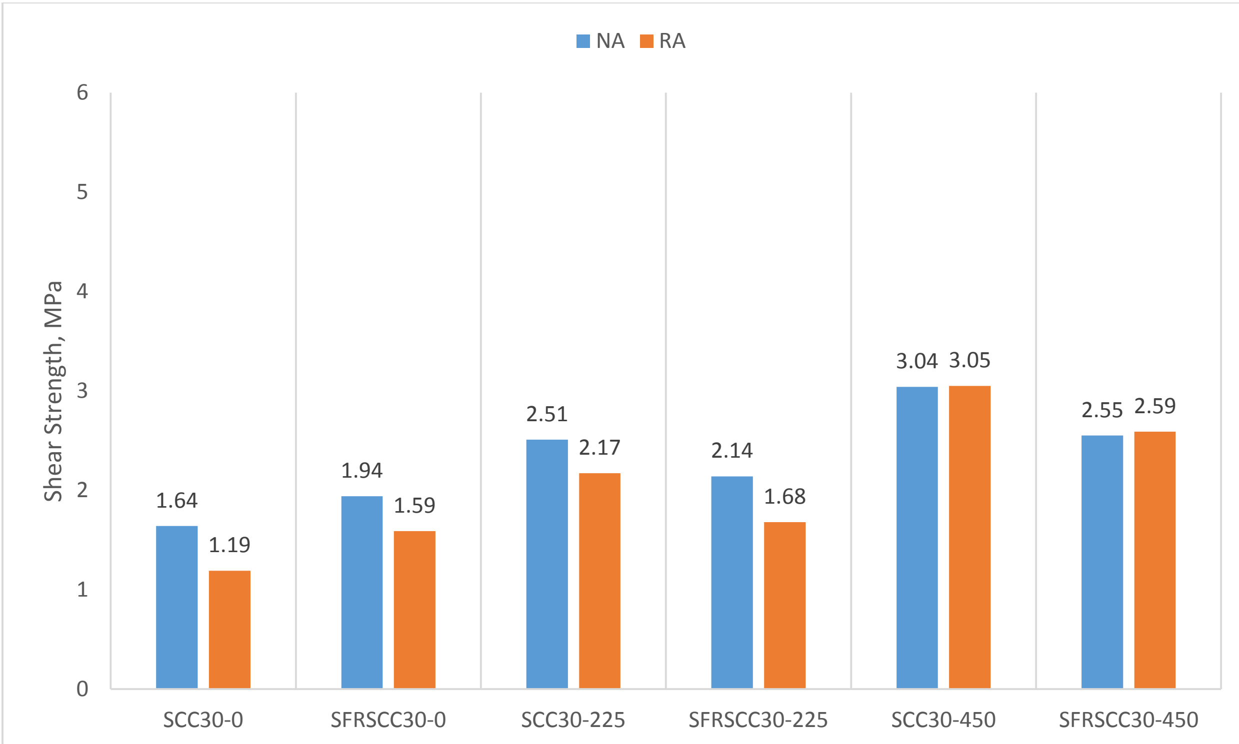

Figure: 6.55 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=2.5, for 30 MPa concrete

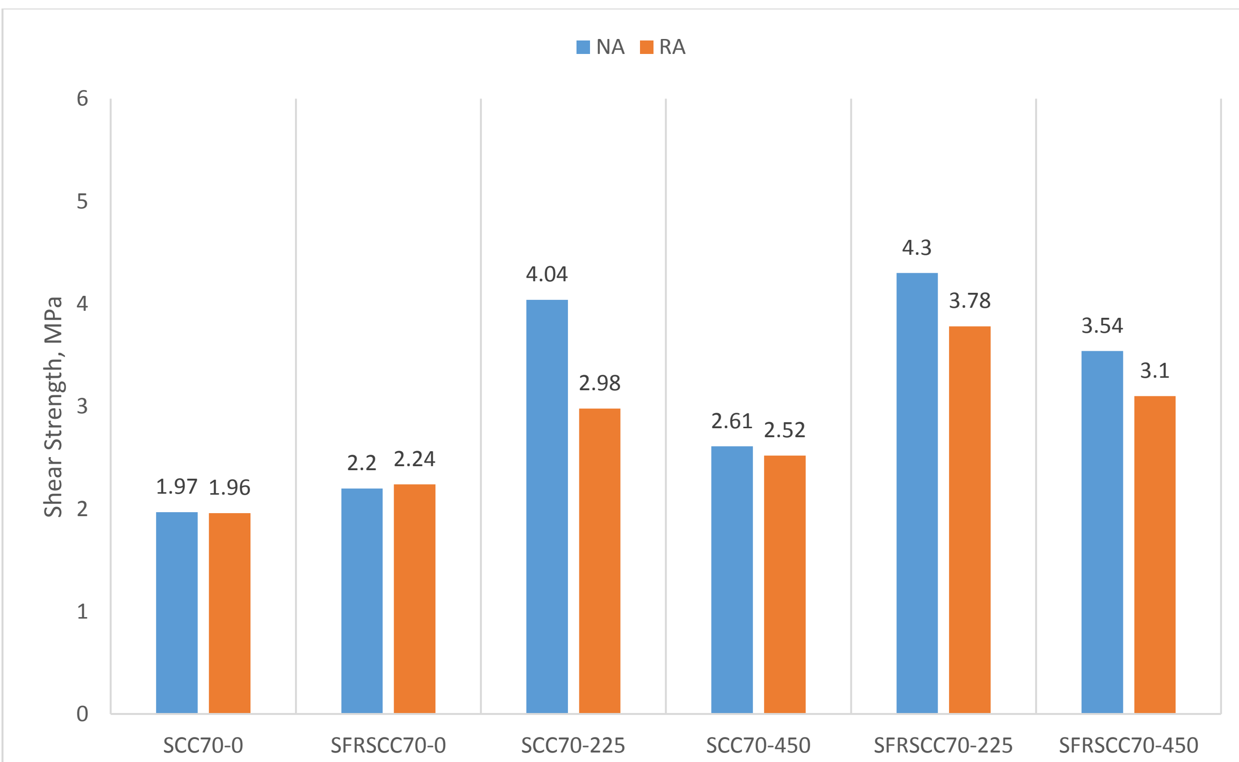

Figure: 6.56 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=2.5, for 70 MPa concrete

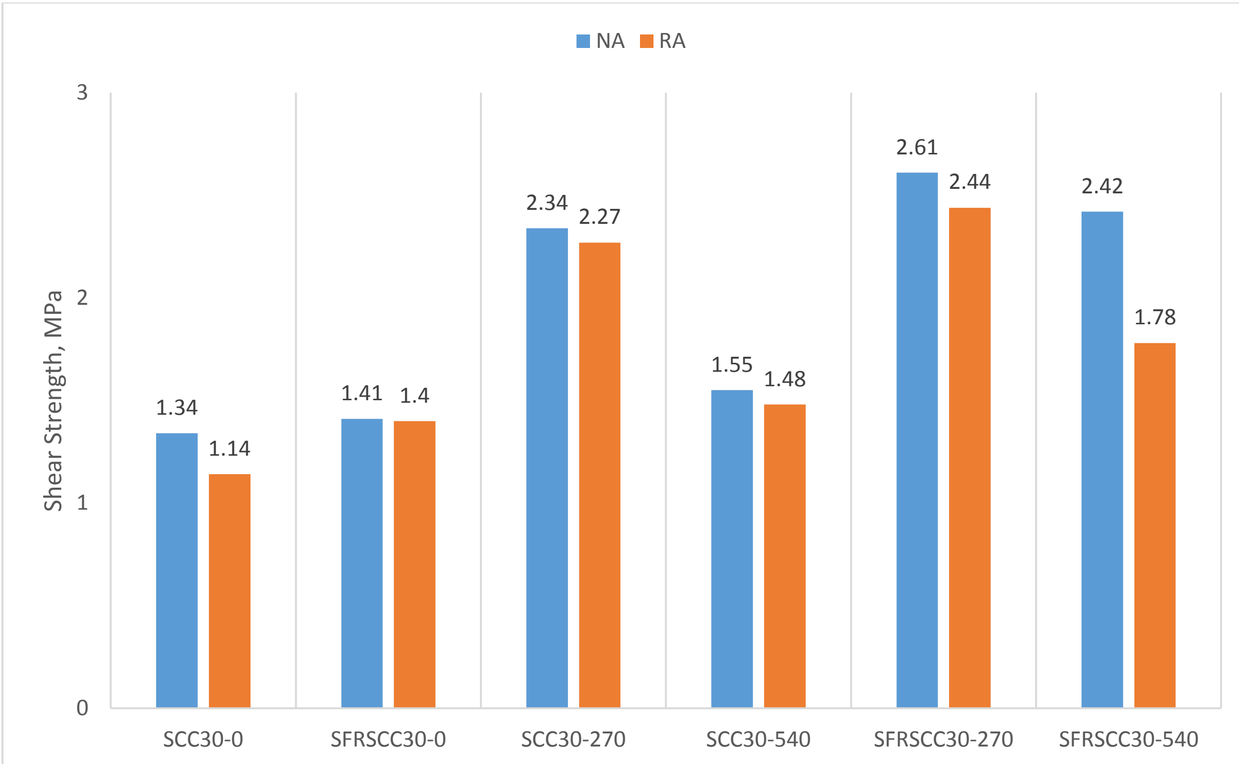

Figure: 6.57 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=3, for 30 MPa concrete

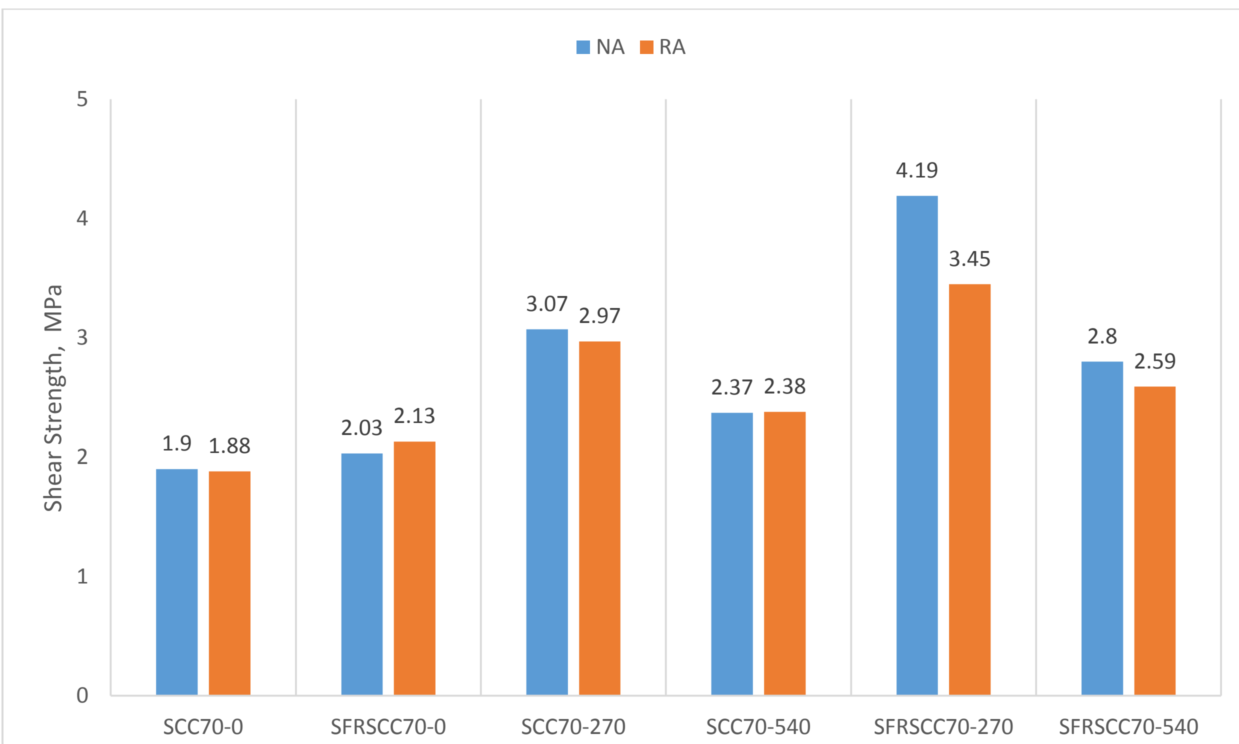

Figure: 6.58 Comparison of shear strength of NASCC and RASCC using 8mm diameter stirrup for a/d=3, for 70 MPa concrete

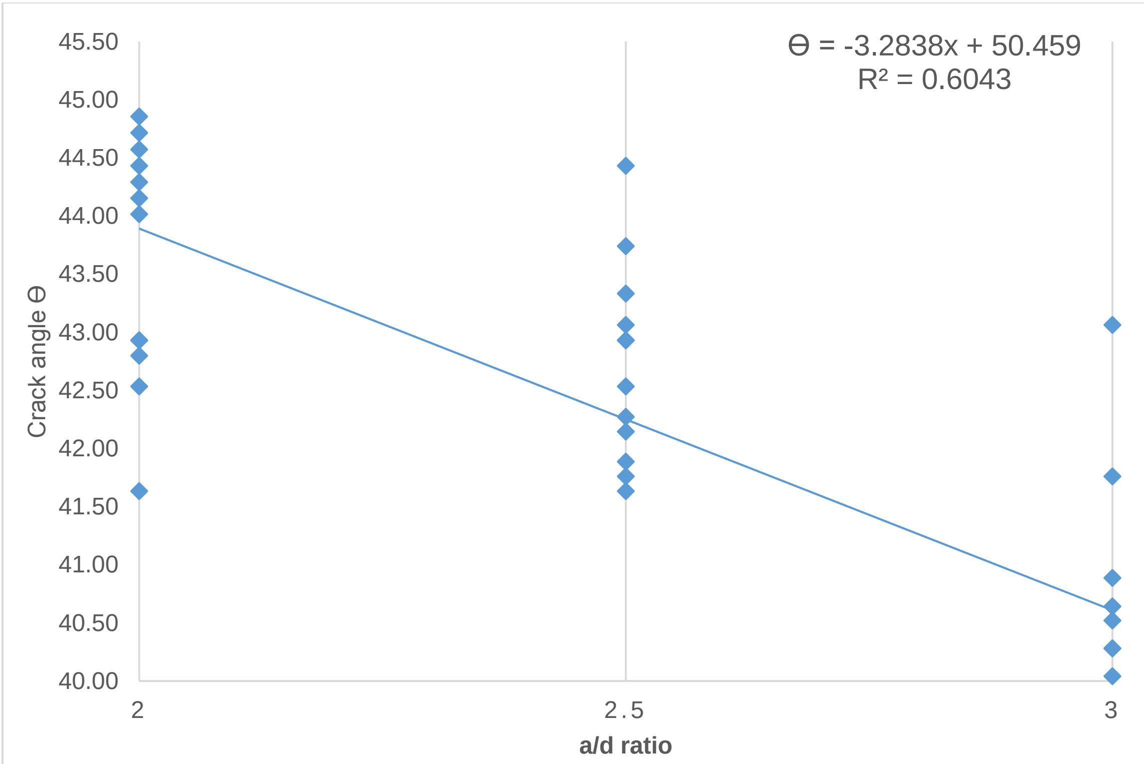

Figure: 6.59(a) Crack angle vs a/d ratio for RASCC

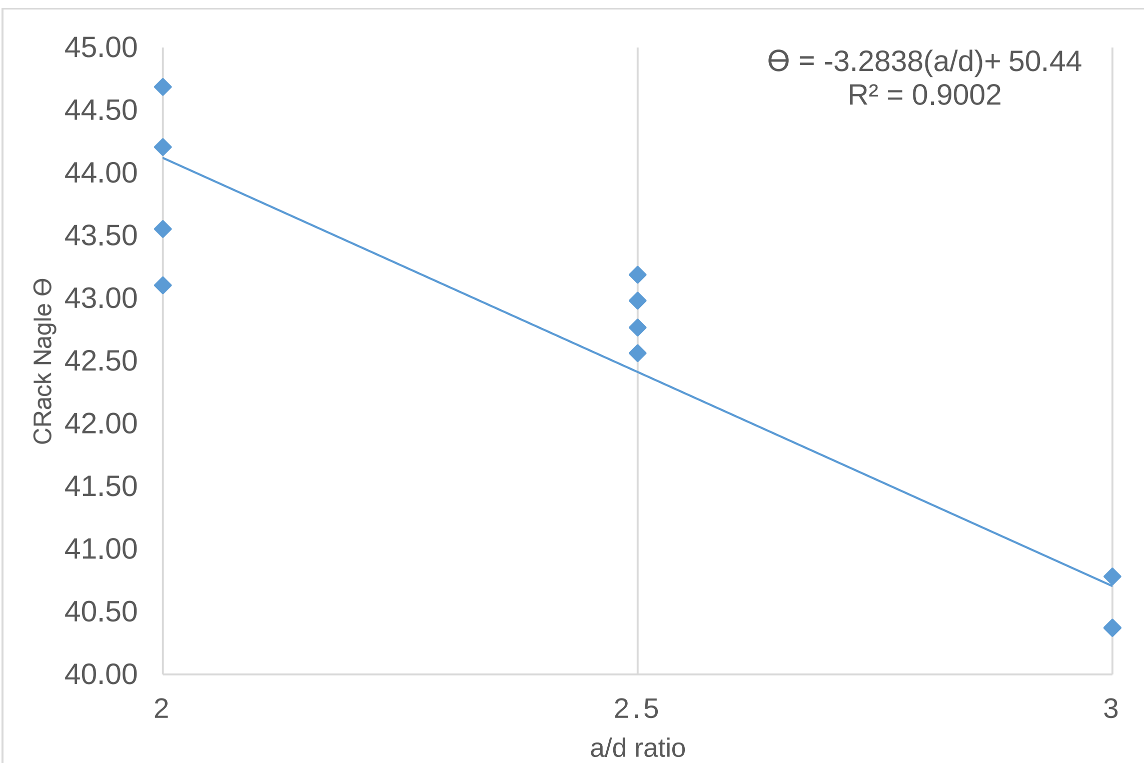

Figure: 6.59(b) Average Crack angle vs a/d ratio for RASCC

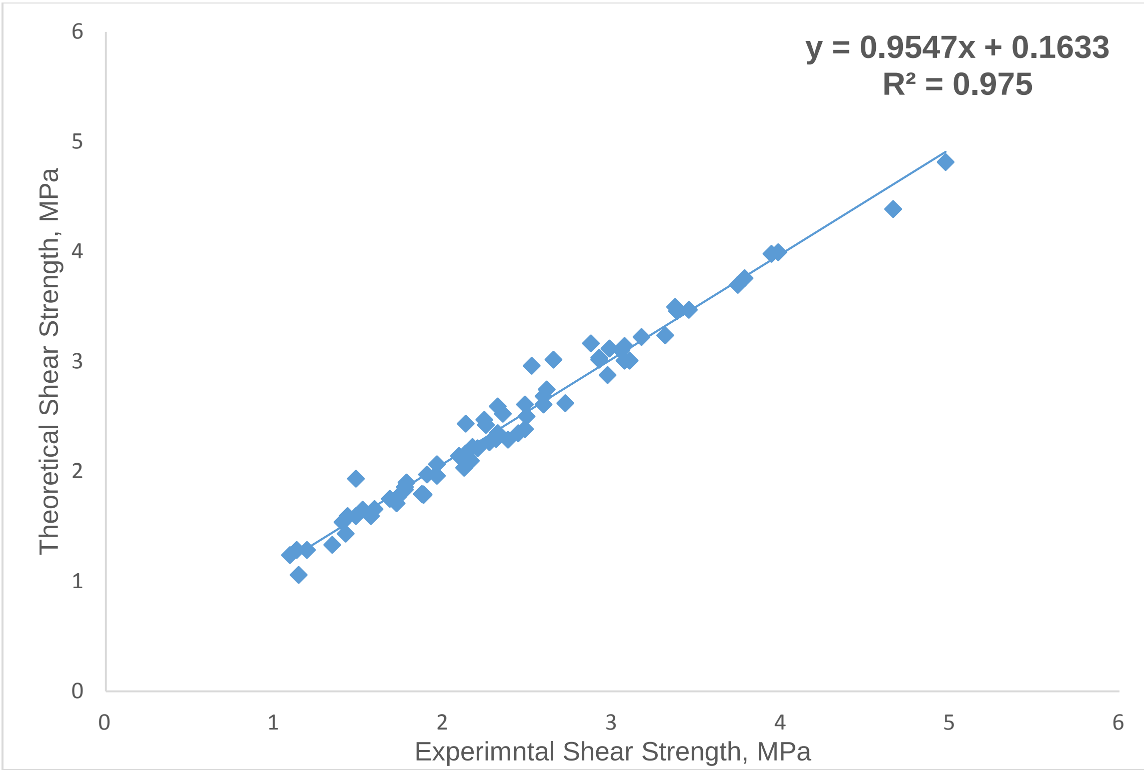

Figure 6.60: Experimental vs Theoretical Shear Strength for SCC30 and SCC70

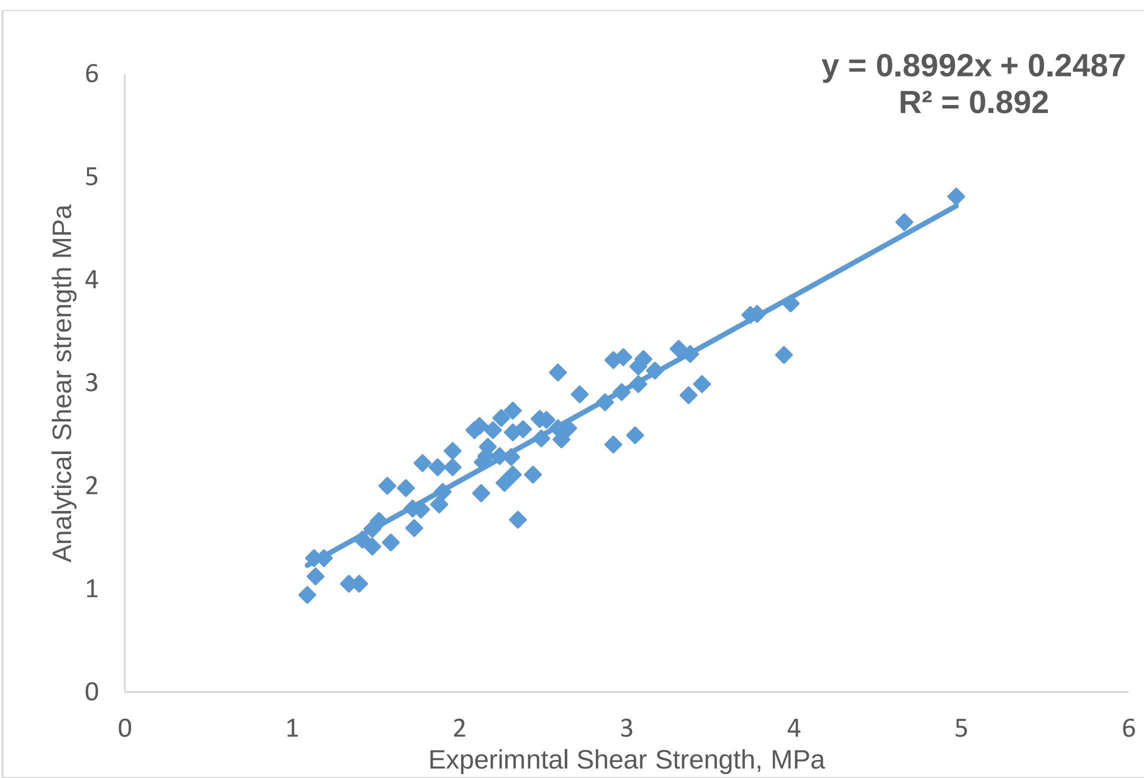

Figure 6.61: Experimental vs Analytical Shear Strength for SCC30 and SCC70

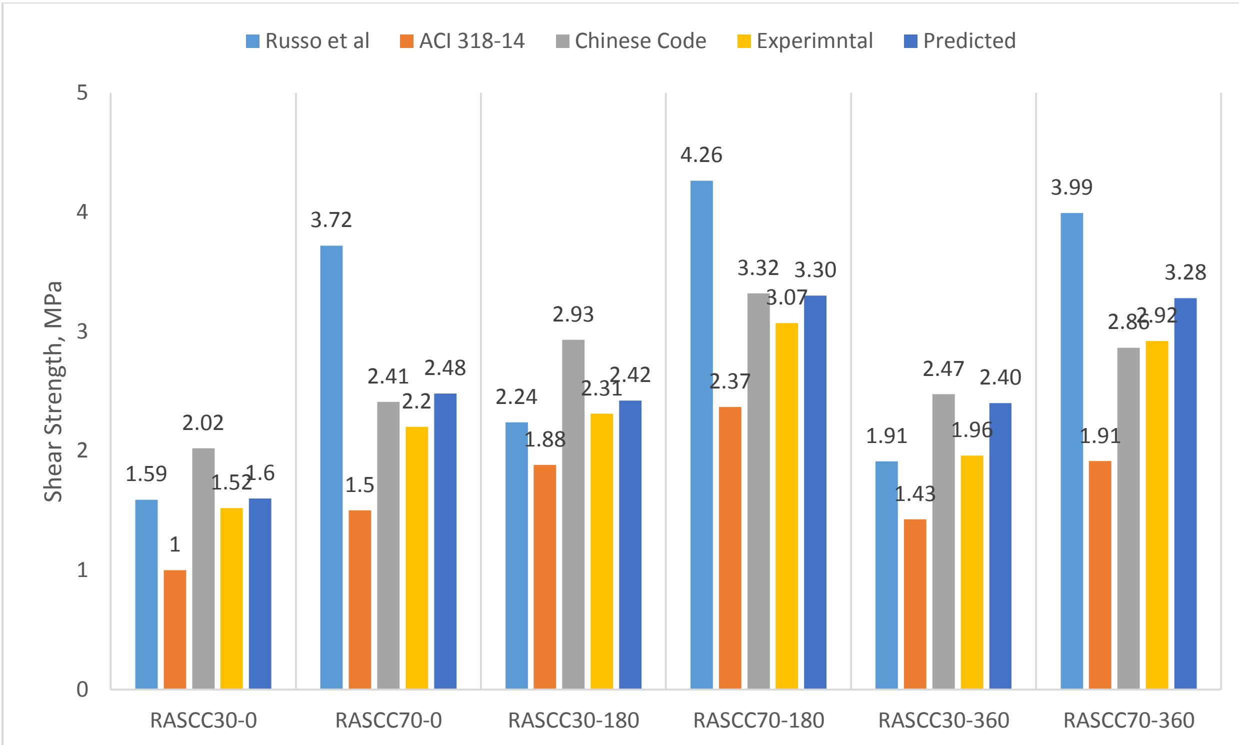

Figure: 6.62 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.

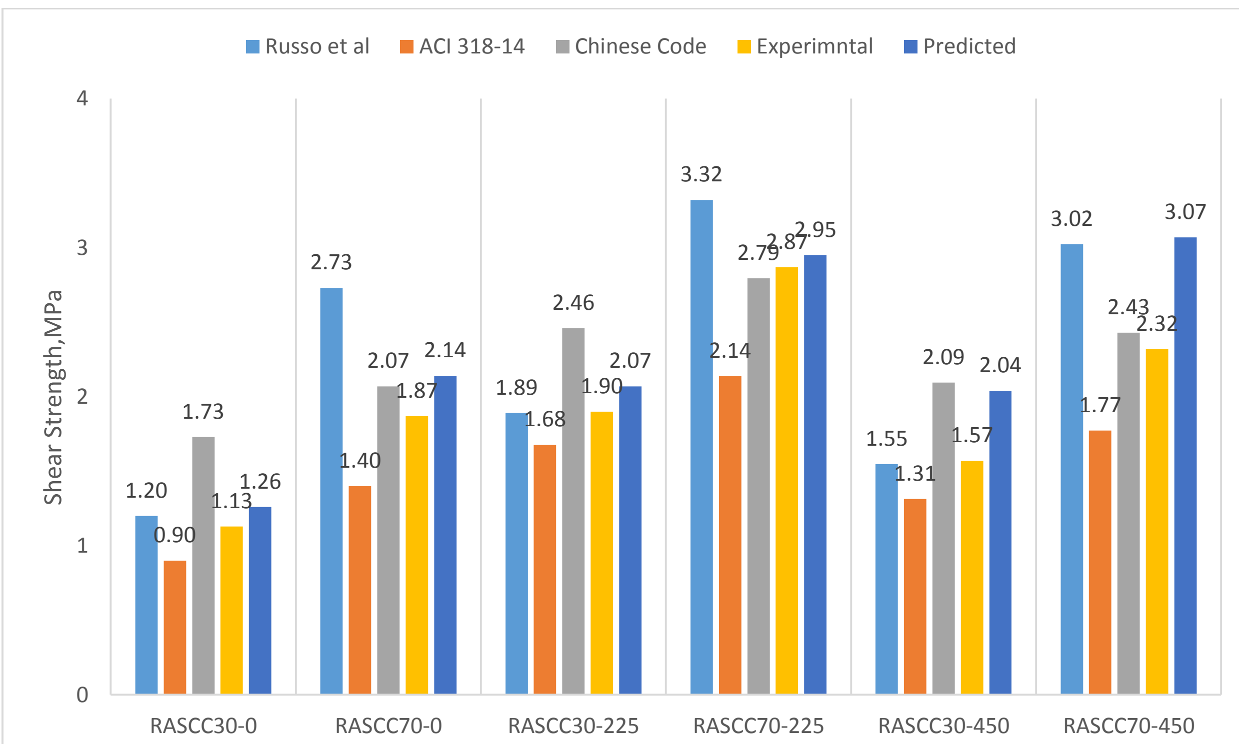

Figure: 6.63 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.5.

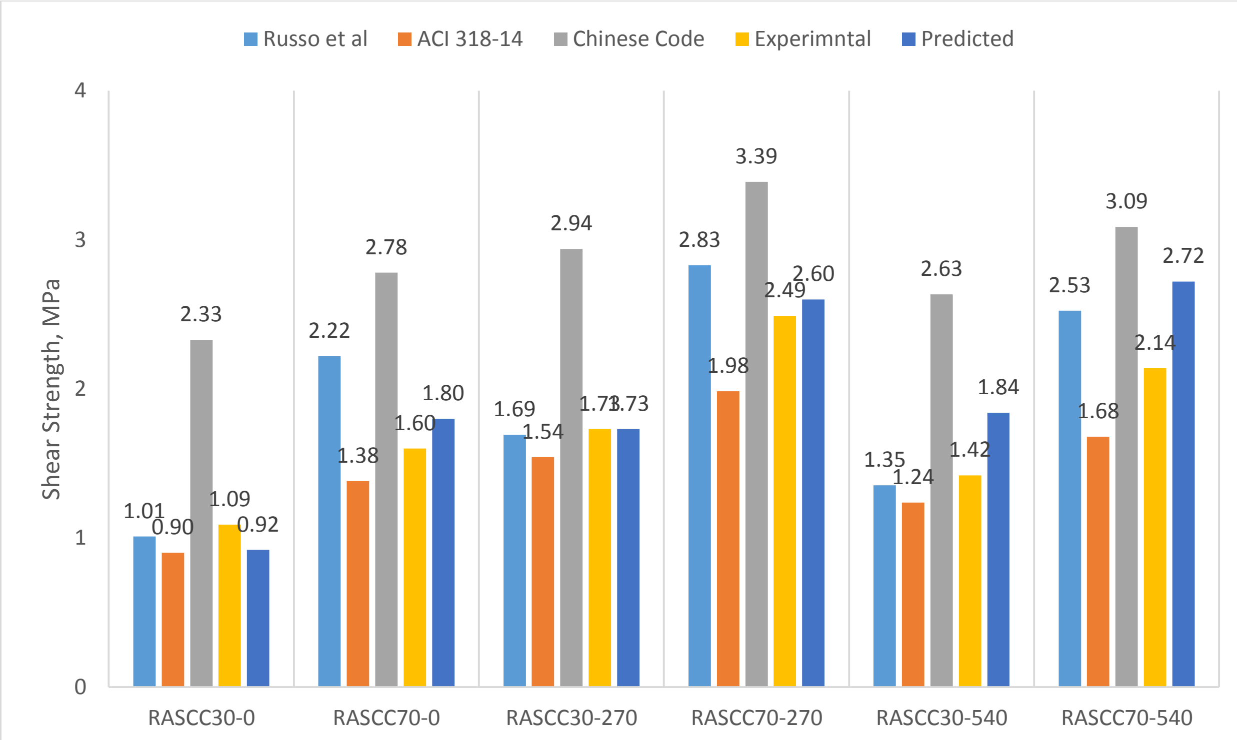

Figure: 6.64 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=3.

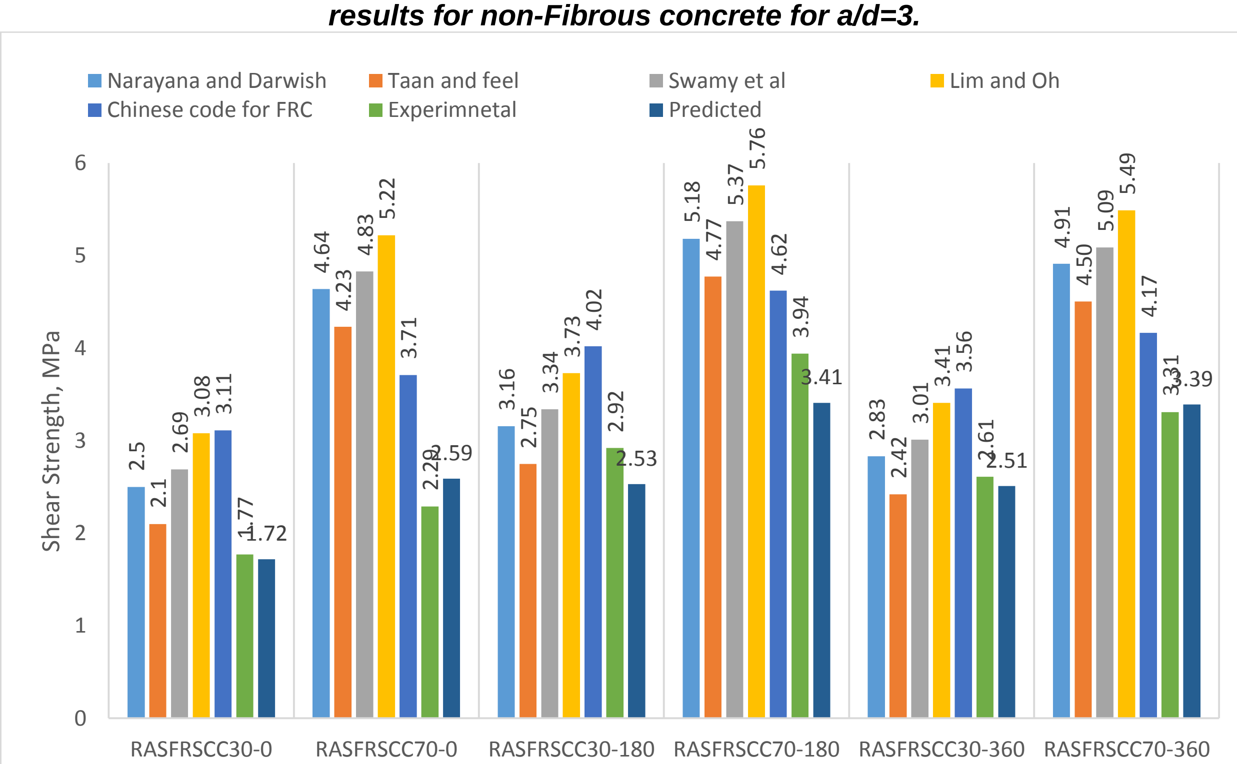

Figure: 6.65 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2).

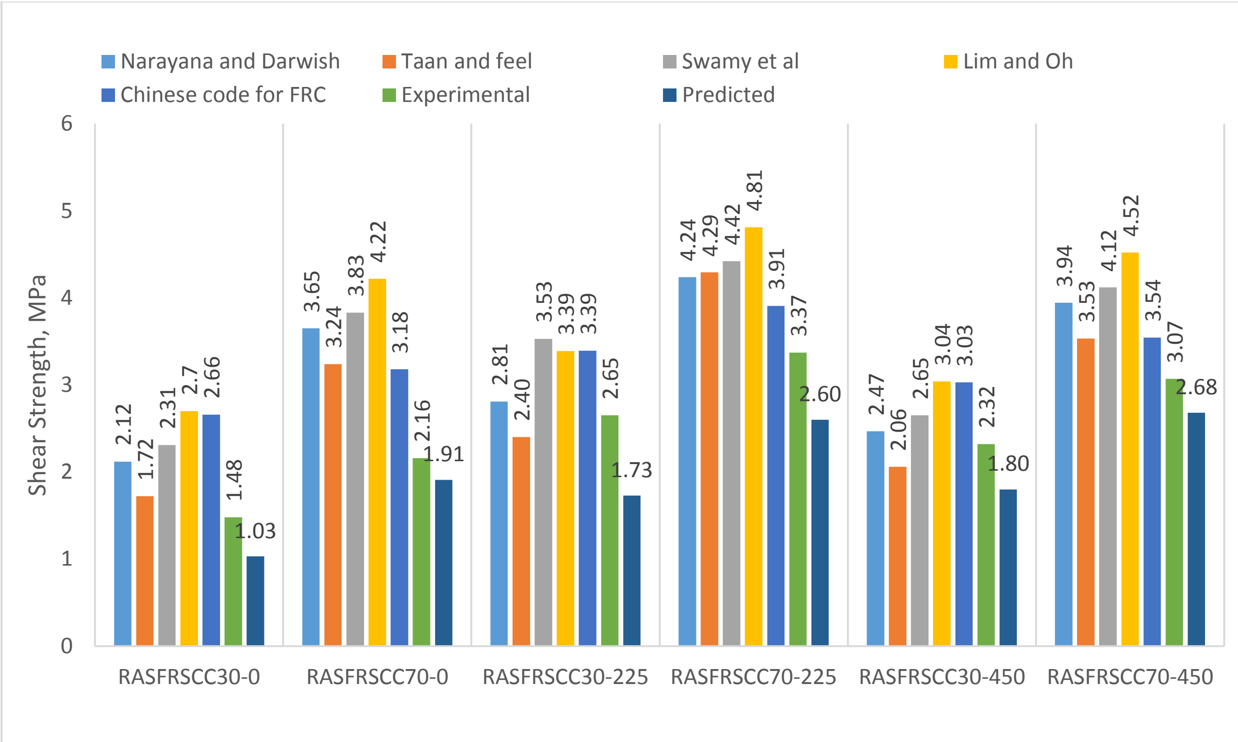

Figure: 6.66 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=2.5).

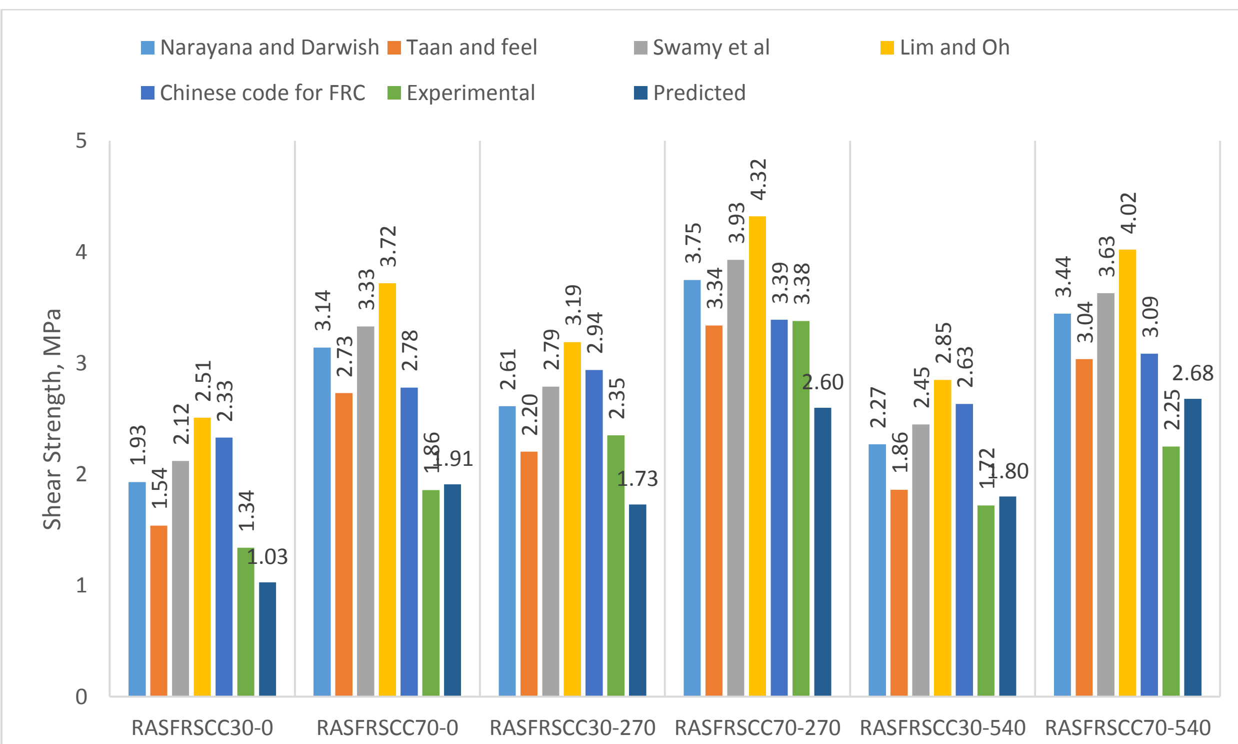

Figure: 6.67 Comparison of Shear Strength Values with various models and Experimental results for Fibrous concrete (a/d=3).

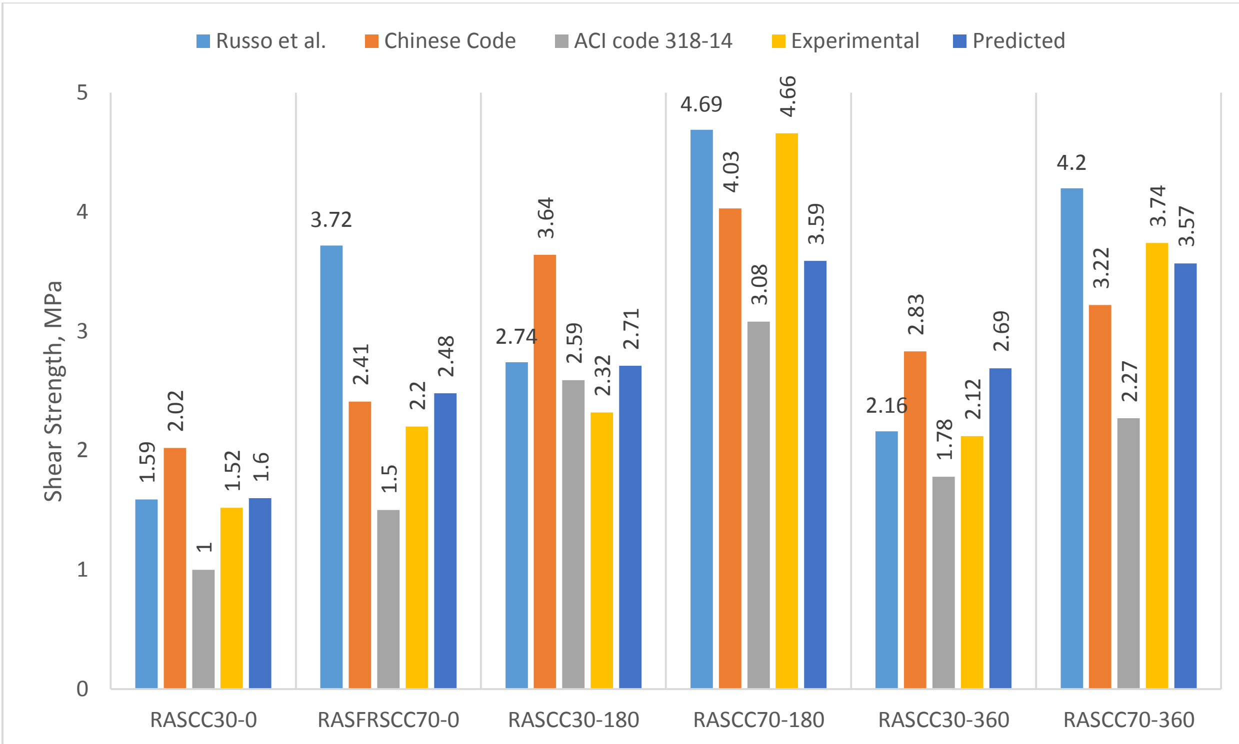

Figure: 6.68 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.

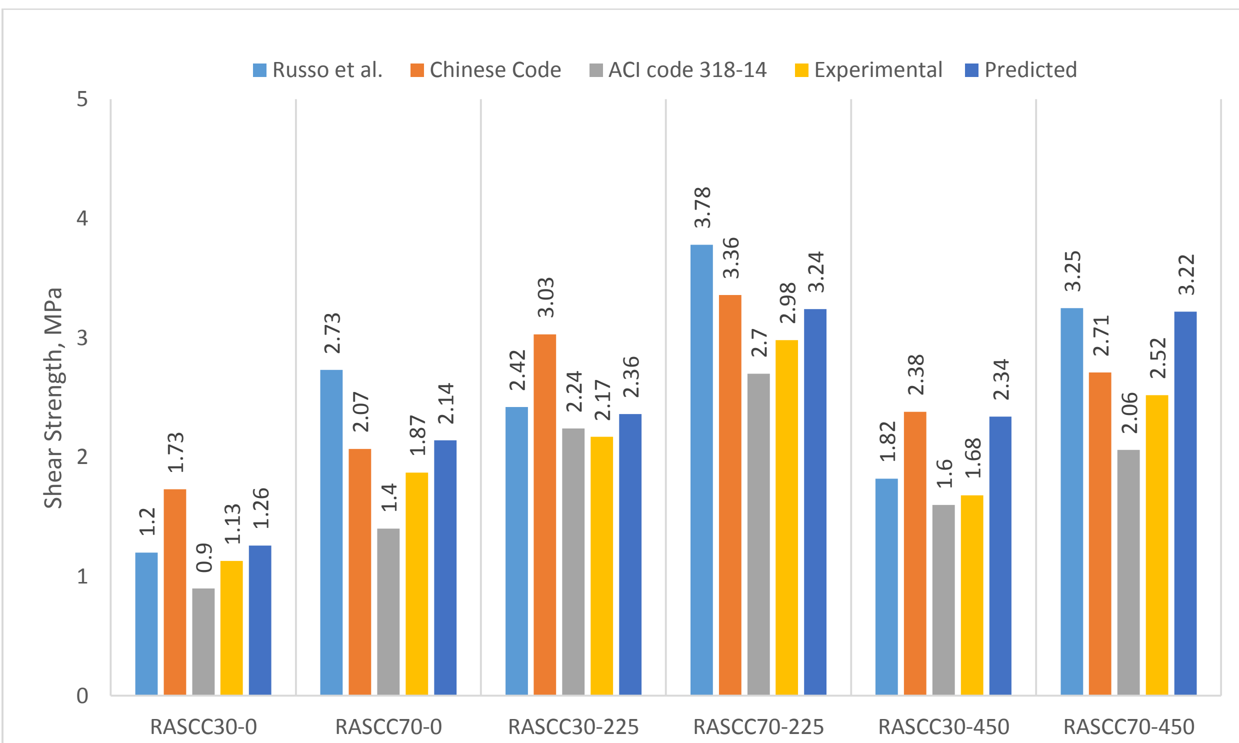

Figure: 6.69 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.5

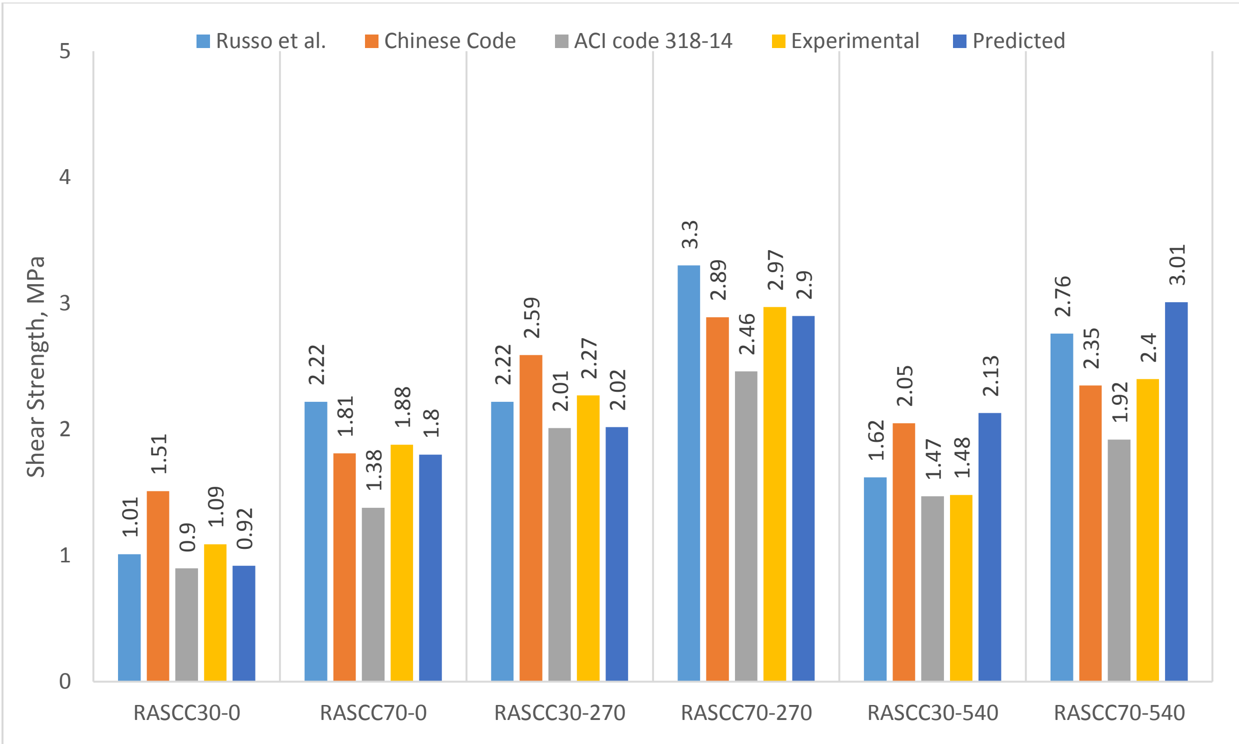

Figure: 6.70 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=3

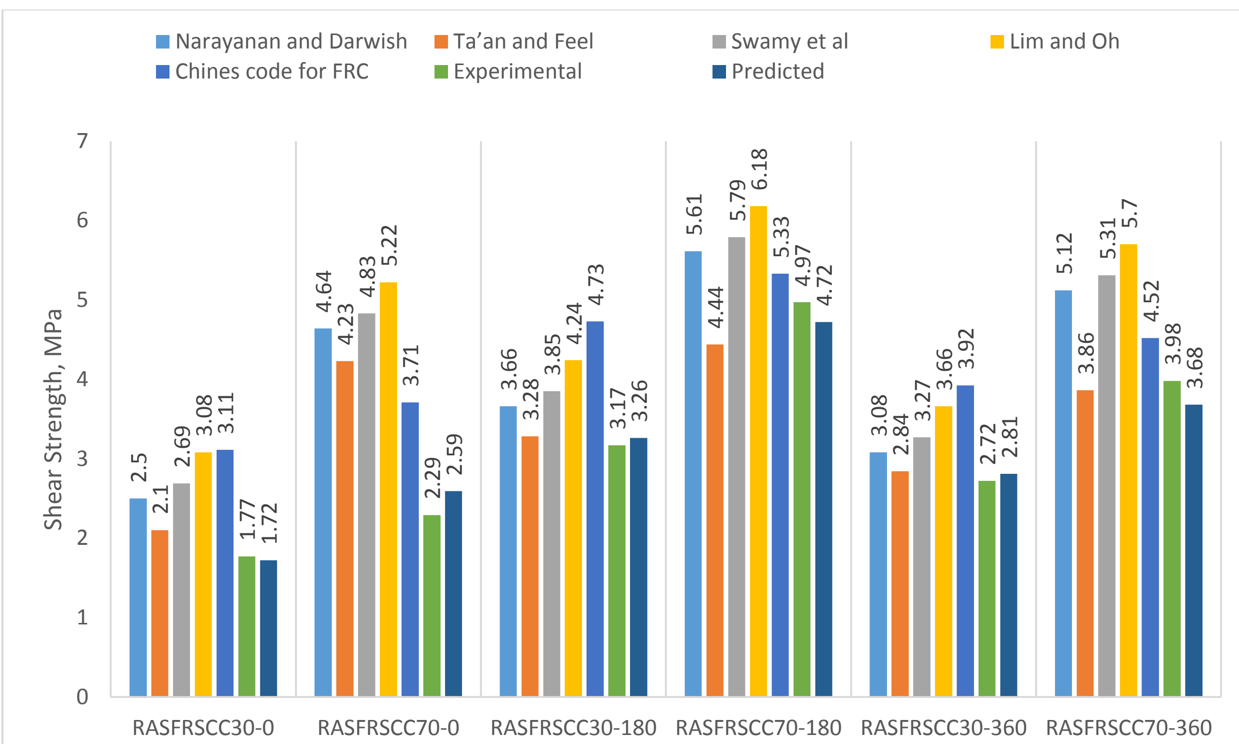

Figure: 6.71 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.

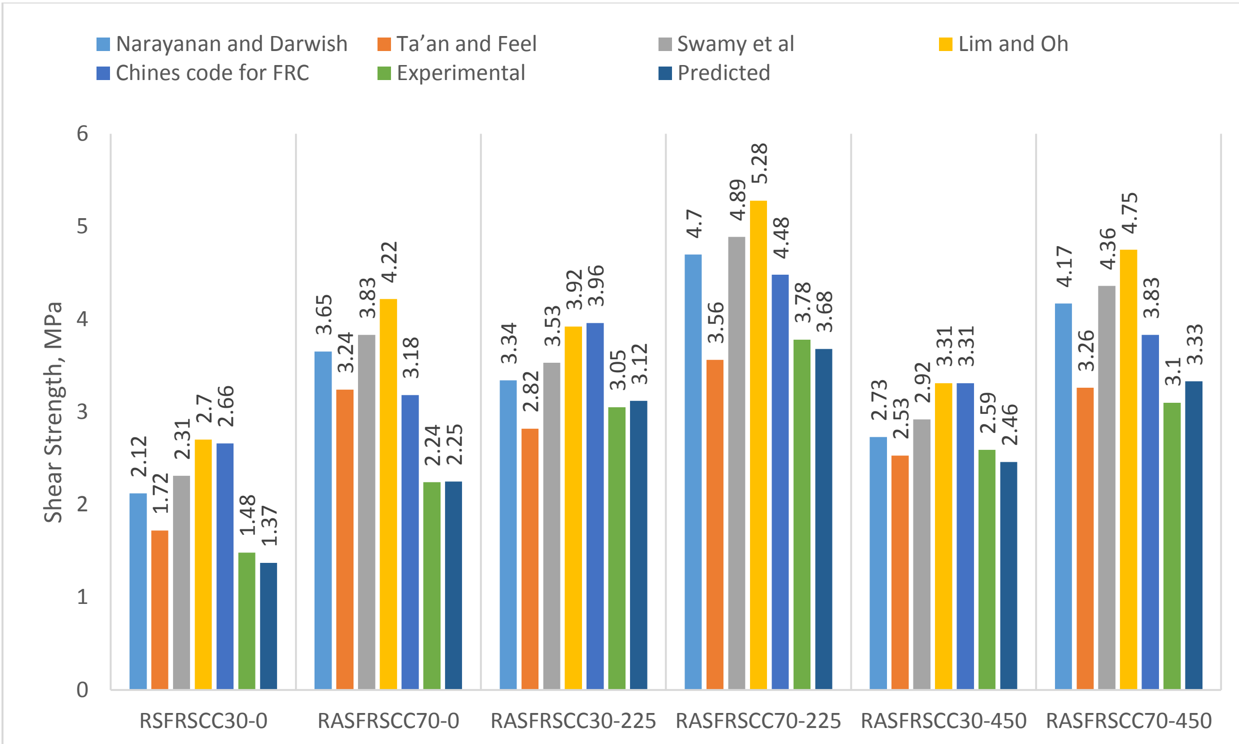

Figure: 6.72 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=2.5

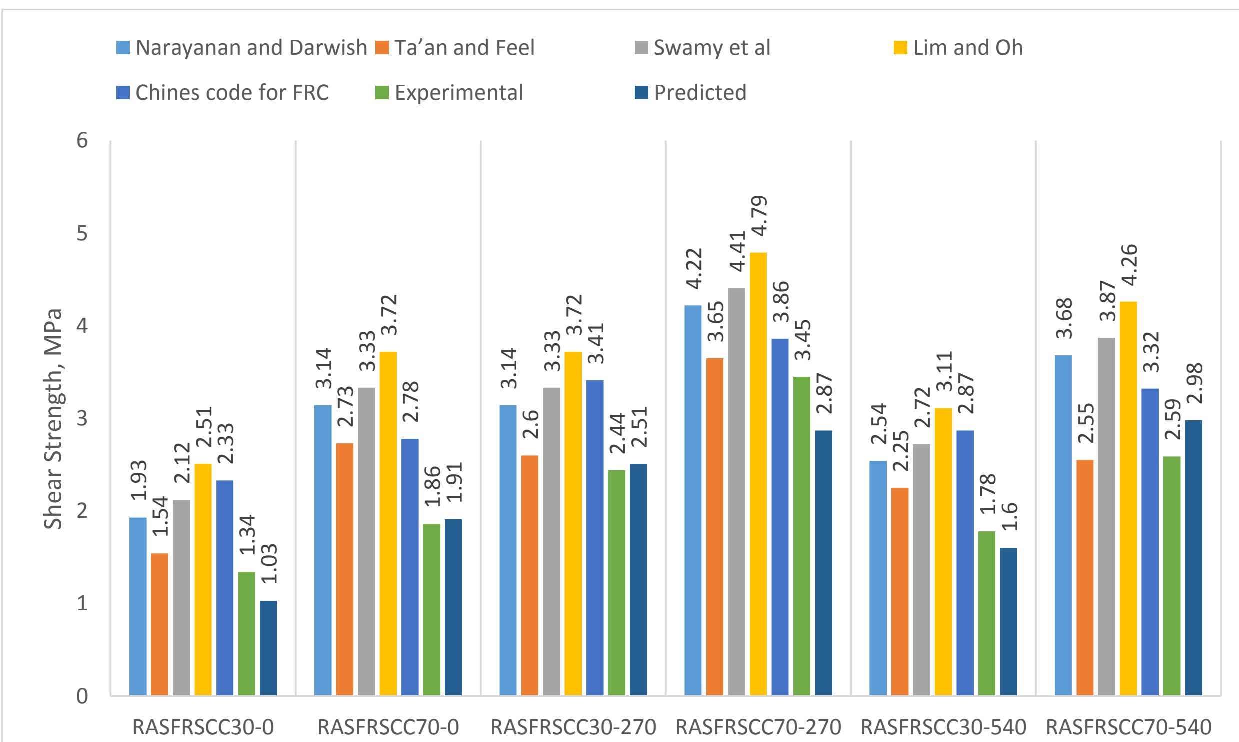

Figure: 6.73 Comparison of Shear Strength Values with various models and Experimental results for non-Fibrous concrete for a/d=3

CHAPTER 7

ANALYTICAL BEHAVIOUR OF STEEL FIBER REINFORCED NASCC AND RASCC USING FINITE ELEMENT SOFTWARE ATENA-GID UNDER SHEAR

7.0 General

The chapters 5 and 6 have dealt with studies on the shear behaviour of self-compacting concrete using natural and recycled aggregates for both without and with steel fibers and different shear span to depth ratios for 30 MPa and 70 MPa concrete. From the experimental results it is found that use of steel fibers can greatly enhance the shear performance and increase the load carrying capacity of self-compacting concrete. It was also found that with use of steel fibers, we can partially replace the traditional shear reinforcement (stirrups) and it helps the reducing the cost of construction. The toughness of the steel fiber reinforced SCC beams increased tremendously when compared with plain SCC beams. The combination of stirrups and steel fibers have shown a positive hybrid effect on shear behaviour of self-compacting concrete for both natural and recycled aggregates. It was also noticed that with use of recycled aggregates as the replacement of natural aggregates, has decreased the compressive strength of concrete by 8-10% for 30 MPa and 70 MPa SCC. This defect in RASCC can be overcome by using steel fibers. It was also observed that with the use of recycled aggregates the shear strength of both 30 MPa and 70 MPa is reduced when compared with natural aggregate based SCC.

The present chapter is aimed at studying the shear behaviour of fiber reinforced self-compacting concrete using a finite element software ATENA GID for both NASCC and RASCC beams for 30 MPa and 70 MPa compressive strengths for both without and with steel fibers. The experimental results were compared with the values obtained from a finite element model developed using Atena software.

7.1 Introduction on ATENA GID Software:

ATENA is a finite element based software used for nonlinear analysis of reinforced concrete members. By using Atena software actual behaviour of reinforced concrete structures, such has concrete crushing, cracking and yielding of reinforcing 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 and reinforcement details is created in Atena software and non- linear analysis is performed for both fibrous and non-fibrous 30 MPa and 70 MPa SCC for both using natural aggregates and recycled aggregates. The input details regarding type of materials used, material properties and boundary conditions for finite element model are explained in appendix-C.

7.2 Shear Behaviour of SFRSCC Beams using FEM:

The experimental results of steel fibrous self-compacting concrete are used to validate the finite element model. A nonlinear analysis is performed by creating an identical beam model of same cross sectional dimensions and reinforcement details as that of a similar beams used in experiential study for both SCC30 and SCC70 for three shear span to depth ratios (a/d) 2, 2.5 and 3 and for both 6mm and 8mm diameter stirrup. The detailed discussion is presented in the following sections.

7.2.1 Shear behaviour of SFRSCC beams for 6mm diameter stirrup.

In this section results obtained from the finite element modelling on the SFRSCC beams are presented. Tables 7.1-7.3 shows the ultimate load and shear strength values of fibrous and non-fibrous SCC beams for 6mm Ø stirrup for shear span to depth ratios (a/d) 2, 2.5 and 3.

a) Effect of Steel fibers on Shear Performance of SCC:

From the Tables 7.1-7.3 it is observed that due to the addition of steel fibers the ultimate load carrying capacity has improved and also failure of SCC beams was delayed as steel fibers helps in bridging the cracks faces and delaying the crack propagation. Figures 7.1-7.6 shows the load vs deflection curves of SCC30 and SCC70 beams for three shear span to depth ratios (a/d) 2, 2.5 and 3. For the beams with shear span to depth ratio (a/d) 2, in the presence of steel fibers the ultimate load carrying capacity of the beam

SFRSCC30-0 with no stirrups is increased by 42.84% when compared with SCC30-0 beam with no stirrups and without steel fibers and due to the combination of stirrups and steel fibers, the shear performance of SCC beams has increased by 113.3% and 76.67% for SFRSCC30-180 and SFRSCC30-360 beam compared to SCC30-0 plain beam without stirrups and steel fibers respectively. Similarly, for higher strength concrete mix due to the addition of steel fibers, ultimate load carrying capacity of the beam SFRSCC70-0 with steel fibers and no stirrups is increased by 30.54% and due to the combined effect of stirrups and steel fibers, the ultimate shear strength is increased by 90.76% and 58.96% for SFRSCC70-180 and SFRSCC70-360 beams when compared with SCC70-0 beam with no stirrups and steel fibers. Similar type of behaviour was observed for beams modelled for shear span to depth ratio 2.5 and 3.

b) Effect of Stirrup Spacing on Shear Performance of SCC Beams using 6 mm Ø stirrup:

Spacing of stirrups is one of the important parameter that effects the shear performance of SCC beams. To study the effect on spacing of stirrups on shear performance of SCC beams, two stirrup spacing are considered for each shear span to depth ratio (a/d) and plan beam with no stirrups is used as companion specimen. In the shear span to depth ratio (a/d) 2 with the provision of stirrups, the ultimate shear strength is increased by 34.35% and 52.76% respectively for SCC30-360 and SCC30-180 beams when compared to plain beam with no stirrups SCC30-0. Similarly, for higher strength concrete beams due to the presence of stirrups, ultimate shear strength is increased by 6.18% and 34.25% for SCC70-360 and SCC70-180 beams when compared to plain beam SCC70-0 with no stirrups. This shows that provision of stirrups at closer spacing enhances the shear performance of SCC. Similar type of behaviour was absorbed for beams tested for shear span to depth ratio 2.5 and 3 respectively. Figures 7.7-7.9 shows the variation of shear strength for different spacing of stirrups.

c) Effect of Shear Span to depth ratio (a/d) on Shear Performance of SCC beams:

Shear span to depth ratio (a/d) is the major parameter that effect the shear performance of SCC beams. To study the effect of a/d ratio on shear performance, three shear span to depth ratios were considered (2, 2.5 and 3). From the Tables 7.1-7.3 it is observed that as the shear span to depth ratio increased from 2 to 3, ultimate shear strength decreased by 2.65% and 27.11% respectively for SCC30 and similarly for higher strength concrete SCC70 as the shear span increased from 2 to 3 , ultimate shear strength decreased by 18.07% and 23.09% respectively. Figure 7.10 shows the variation of shear strength with respect to shear span to depth ratio for plain SCC30 and SCC70 beams.

7.2.2 Shear behaviour of SFRSCC beams for 8mm diameter stirrup.

Area of stirrup is considered as one of the important parameter that effects the shear strength of concrete. To study this effect two stirrups diameters are considered (6mm and 8mm) and beams are modelled used finite element software. In the previous section results obtained for beams of 6mm Ø stirrups are discussed and in this section analytical results obtained through finite element model for beam using 8mm Ø stirrup are discussed in the following sections. Tables 7.4-7.6 shows the ultimate load and shear strength values of fibrous and non-fibrous SCC for 8mm Ø stirrup for shear span to depth ratios (a/d) 2, 2.5 and 3.

a) Effect of steel fibers on Shear behaviour of SCC Beams using 8 mm Ø stirrup:

Due to the addition of steel fibers there is an increase in the load carrying capacity and also delayed the failure of SCC beams. From the results presented in tables 7.4-7.6 it is observed same. For instance, for the beams tested for shear span to depth ratio (a/d) 2 due to addition of steel fibers the ultimate load carrying capacity of the beam SFRSCC30-0 is increased by 42.84% when compared with plain beam SCC30-0 with no stirrups and without steel fibers. Due to the combination of stirrups and steel fibers, the ultimate load carrying capacity of the SFRSCC30-360 and SFRSCC30-180 is increased by 104.3% and 113.4% respectively compared with SCC30-0 plain beam with no stirrups and without steel fibers. Similarly, due to the addition of steel fibers the ultimate shear strength of the beams SFRSCC30-360 and SFRSCC30-180 is increased by 43.01% and 12.56% respectively when compared with identical beams SCC30-360 and SCC30-180 i.e. without steel fibers but with stirrups proved at 360 mm and 180 mm spacing. It can observed that with stirrups proved at larger spacing the steel fiber effect is more significant than for the beam with stirrup spacing proved at closer spacing. Similarly, for higher strength concrete beams SCC70, due to the addition of steel fibers the ultimate load carrying capacity of the beam (SFRSCC70-0) is increased by 15.33% when compared with plain beam (SCC70-0) with no stirrups and without steel fibers. Due to the combination of stirrups and steel fibers the ultimate shear strength of the beams SFRSCC70-360 and SFRSCC70-180 is increased by 72.2% and 126.8% respectively when compared with plain beam (SCC70-0) with no stirrups and without steel fibers. Similarly, due to addition of steel fibers, ultimate shear strength of the beams SFRSCC70-360 and SFRSCC70-180 is increased by 7% and 5.4% respectively when compared with identical beams (SCC70-360 and SCC70-180) with stirrups spaced at 360 mm and 180 mm and without steel fibers. It was observed that for the beams with stirrups provided at larger spacing, steel fibers addition is more significant than for the beam with stirrups proved at closer spacing. Similar type of behaviour was observed for the beams tested for shear span to depth ratio 2.5 and 3 for both lower and higher strength concrete. Figures 7.11-7.16 show the load vs deflection graphs for both SCC30 and SCC70 beams without and with steel fibers for three shear span to depth ratios (a/d) (2, 2.5 and 3).

b) Effect of stirrup spacing on shear behaviour of SCC beams:

To study the effect of spacing of stirrups, two stirrups are considered for each shear span to depth ratio. Tables 7.4-7.6 show the ultimate load and shear strength values of SCC30 and SCC70 beams for both without and with steel fibers for three shear span to depth ratios. From the analytical results presented in the above tables it can be observed that, as the stirrups spacing is decreased ultimate shear strength is increased and it is true for both SCC30 and SCC70 and for three shear span to depth ratios (a/d) 2, 2.5 and 3. For instance the ultimate shear strength of the beams SCC30-360 and SCC30-180 tested for shear span to depth (a/d) ratio 2, is increased by 32.6% and 89.64% respectively when compared with plain beam with no stirrup SCC30-0 and also ultimate shear strength is increased by 13.3% as the spacing of stirrup is decreased from 360 mm to 180mm. Similarly in case of higher strength concrete beams, the ultimate shear strength of the beams SCC70-360 and SCC70-180 is increased by 61.2% and 115.2% when compared with plain beam with no stirrups SCC70-0 and also as the spacing of stirrups is decreased from 360mm to 180 mm, the ultimate shear strength is increased by 33.6%. Similarly for the beams tested for shear span to depth ratio 2.5, the ultimate shear strength of the beams SCC30-450 and SCC30-225 is increased by 35.3% and 48% respectively when compared with plain beam with no stirrups SCC30-0 and also for as the spacing of stirrup is decreased from 450mm to 225mm, the ultimate shear strength is increased by 9.3%. Similarly in case of higher strength concrete, the ultimate shear strength is increased by 30.4% and 86.6% respectively when compared with plain beams with no stirrup (SCC70-0) and also as the spacing of stirrup is decreased from 450mm to 225mm, the ultimate shear strength is increased by 43.07%. Similar type of behaviour is observed in case of beams tested for shear span to depth ratio 3 for both SCC30 and SCC70 beams. Finally it can be concluded that as the spacing of stirrups is reduced the ultimate shear strength is enhanced and it is true for both SCC30 and SCC70beams this can be attributed to confining effect of stirrups with concrete at closer spacing results in increased load carrying capacity of the concrete and increases the shear strength. Figures 7.27-7.29 shows the variation of shear strength to spacing of stirrups for a/d 2, 2.5 and 3.

c) Effect of shear span to depth ratio on shear behaviour of SCC beams:

From the analytical results presented in the Tables 7.4-7.6 it is noticed that as the shear span to depth ratio increased from 2 to 3, the ultimate shear strength is decreased by 2.65% and 27.11% respectively for SCC30 and similarly for higher strength concrete SCC70 as the shear span increased from 2 to 3, ultimate shear strength decreased by 18.07% and 23.09% respectively. Figure 7.20 shows the variation of shear strength with respect to shear span to depth ratio for plain SCC30 and SCC70 beams.

d) Effect of stirrup diameter on shear behaviour of SFRSCC beams:

To study the effect of stirrup diameter on shear behaviour of SFRSCC beams, two stirrup (6mm and 8 mm) dimeters are considered in the present study. From the analytical results present in the above tables it is clearly understood that as the area of shear reinforcement is increased, there is an increase in the ultimate shear strength for both SCC30 and SCC70 beams. Figures 7.21-7.26 shows the variation of shear strength with respect to stirrup diameter (6mmand 8mm) for SCC30 and SCC70 for both without and with steel fibers and for three shear span to depth ratios (a/d) 2, 2.5 and 3.

7.2.3 Comparison between Experimental and ATENA results:

A comparison of experimental test results with the result obtained through analytical model are done and the results are presented in Tables 7.7 and 7.8 for both 6mm and 8 mm diameter stirrup. The comparison of experimental results with that of analytical results are compared and average percentage error in all cases is less than 15%.

7.3 Comparison of Theoretical and Numerical Shear Strength of NASCC:

A comparison is made among the numerical shear strength obtained through Atena modelling and predicted theoretical shear strength (proposed in chapter-5) for NASCC30 and NASCC70 and for both 6mm and 8 mm diameter stirrup. Tables 7.9-7.10 shows the comparison of numerical and theoretical shear strength for NASCC30 and NASCC70 for 6 mm and 8 mm diameter stirrup. The correlation of numerical and theoretical shear strength was satisfactory with average ratio of numerical to theoretical shear strength as 0.96. Figure: 7.27 shows the comparison numerical shear strength vs theoretical shear strength for NASCC30 and NASCC70

7.4 Comparison of Numerical Shear strength with Analytical Shear strength:

To validate the numerical results obtained through finite element modelling, a correlation is made among, numerical shear strength and analytical shear strength (proposed in chapter 5). It was observed that numerical shear strength are close to analytical shear strength. Figure: 7.28 shows the comparison of Numerical shear strength and analytical shear strength for NASCC30 and NASCC70

7.5 Shear Behaviour of RASFRSCC beams using FEM:

To validate the experimental results of recycled aggregate based steel fibrous self-compacting concrete beams, 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 reinforcement details as that of a similar beams used in experiential study for both RASCC30 and RASCC70 and for three shear span to depth ratios (a/d) 2, 2.5 and 3 and for both 6mm and 8mm diameter stirrup. The detailed discussion is presented in the following sections.

7.5.1 Shear behaviour of RASFSRCC beams using 6mm diameter stirrup.

In this section results obtained from the finite element modelling on the recycled aggregate based steel fibrous self-compacting concrete (RASFRSCC) beams are presented in Tables 7.13-7.15 for 6mm Ø stirrup and for shear span to depth ratios (a/d) 2, 2.5 and 3.

a) Effect of Steel fiber on shear Behaviour of RASCC beams:

As observed in the case of beams made with normal aggregate and with the addition of steel fibers, the ultimate load carrying capacity of the beams is increased and also steel fibres has bridged the crack faces and delayed the failure of the beams. Similarly in case of beams made with recycled aggregates as both fine and coarse aggregates has shown similar type of behaviour. This is true for the beams analyzed for shear span to depth ratio (a/d) 2. Due to addition of steel fibers the ultimate load carrying capacity of the beam RASFRSCC30-0 is increased by 24.4% when compared with plain beam RASCC30-0 with no stirrups and without steel fibers. In the combination of stirrups and steel fibers, the ultimate shear strength of the beams RASFRSCC30-360 and RASFRSCC30-180 is increased by 75.3% and 112.32% respectively when compared with plain beam RSFRSCC30-0 with no stirrups and without steel fibers. Similarly, with addition of steel fibers the ultimate load carrying capacity of the beam RASFRSCC30-360 and RASFRSCC30-180 is increased by 33.30% and 37.04% respectively compared to beams with stirrups spaced at 360mm and 180mm i.e. RASCC30-360 and RASCC30-180. Similarly, in case of beams of higher strength (RASCC70) due to the addition of steel fibers, the ultimate load carrying capacity of the beam RASFRSCC70-0 increased by 15.24% compared to plain beam with no stirrups and steel fibers RASCC70-0 and due to the combination of steel fiber and stirrups the ultimate shear strength of the beams RASFRSCC70-360 and RASFRSCC70-180 is increased by 62.73% and 97.56% respectively compared to plain beam with no stirrups and without steel fibers RASCC70-0 and the ultimate load carrying capacity is increased by 23.11% and 32.35% respectively compared to identical beam with stirrups spaced at 360mm and 180mm and without steel fibers i.e. RASCC70-360 and RASCC70-180. Similar type of behaviour was observed for beams tested and analyzed for shear span to depth ratio (a/d) 2.5 and 3 respectively. Figures 7.29-7.34 Shows the load vs deflection graphs for RASCC30 and RASCC70 for both without and with steel fibers for three shear span to depth ratios (a/d) 2, 2.5 and 3 based on ATENA.

b) Effect of Stirrup Spacing on Shear Behaviour of RASCC beams:

To study the effect of stirrups on shear behaviour of recycled aggregate based self-compacting concrete beams, two stirrup spacing are considered for each shear span and the nonlinear analysis is performed for both RASCC30 and RASCC70 beams. As it is observed as in the case of normal aggregates beams with provision of stirrups at closer spacing have higher shear strength, a similar type of behaviour was observed in the case of beams with recycled aggregate as both fine and coarse aggregate. For instance, due to provision of stirrups at 360mm and 180mm spacing, the ultimate shear strength of the beams RASCC30-360 and RASCC30-180 is increased by 31.5% and 54.9% respectively when compared with plain with no stirrups and steel fibers and also in case of fibrous beams the ultimate shear strength of RASFRSCC30-360 and RASFRSCC30-180 is increased by 40.9% and 70.67% respectively when compared with plain beam RASFRSCC30-0 with steel fibers and with no stirrups. Similarly, for higher strength concrete beams with provision of stirrups at 360mm and 180 mm spacing, the ultimate shear strength of the beams RASCC70-360 and RASCC70-180 is increased by 32.17% and 47.03% respectively and also in case of fibrous beams with provision of stirrups at 360mm and 180mm for the beams RASFRSCC70-360 and RASFRSCC70-180 the ultimate shear strength is increased by 41.20% and 68.83% when compared with plain fibrous beam RASFRSCC70-0 with no stirrups and with steel fibers. Similar type of behaviour was observed in case of beams tested for shear span 2.5 and 3 for both RASCC30 and RASCC70 for both fibrous and non-fibrous concrete beams. Form this discussion it can concluded that with provision of stirrups at closer spacing will have higher shear strength when compared with beams with stirrups provided at larger spacing and also with inclusion of steel fiber, the percentage increase in the ultimate shear strength is higher than in case of beams with steel fibers when compared with beams without steel fibers. The combination of stirrups and steel fibers have hybrid effect on shear behaviour of fibrous beams and also with addition of steel fibers, stirrups can be provided at larger spacing with similar shear strength as in case of beams with stirrups provided at closer spacing but without steel fibers. Figures 7.35-7.37 shows the variation of shear strength for RASCC30 and RASCC70 for different stirrup spacing for three shear span to depth ration and for both without and with steel fibers.

c) ***Effect of shear span to depth ratio on shear behaviour of RASFRSCC beams:***

To study the effect of shear span to depth ration on shear behaviour of recycled aggregate based self-compacting concrete (RASFRSCC) for both 30 MPa and &70 MPa strengths, three shear span to depth ratios(a/d) are considered 2, 2.5 and 3 and are numerically modelled in ATENA software. As observed in case of normal aggregates based SFRSCC, the shear span increased from 2 to 3 there is decrease in the ultimate shear strength, a similar type of behaviour was observed in case of beams tested with recycled aggregates a complete replacement of natural aggregates. For instance for RASCC30 beams as shear span increased from 2 to 2.5 and 3 , the ultimate shear strength is decreased by 12.25% and 16.25% respectively. In case of fibrous beams as the shear span increased from 2 to 2.5 and 3 the ultimate shear strength is decreased by 8.85% and 7.9% respectively. This show that with use of steel fibers, percentage increase in shear strength is higher when compared with that of plain beams. Similarly in case of higher strength concrete as the shear span increased from 2 to 2.5 and 3, ultimate shear strength is decreased by 1.65% and 6.74% respectively, where as in case of fibrous beams with increase in shear span, the ultimate shear strength is decreased by 1.5% and 5.26% respectively. So, it can be concluded that with use of steel fibers, percentage decrease in shear strength is reduced. Figure 7.38 shows the variation of shear strength with respect to shear span to depth ratio for plain beams RASCC30 and RASCC70 for both without and with steel fibers.

d) ***Comparison of shear behaviour of NASCC and RASCC beams for 6mm Ø stirrup:***

As observed in the case of experimental study due to use of recycled aggregate as complete replacement of both fine and coarse aggregates, the ultimate shear strength was reduced by 17.2% and 10.2% for 30 MPa and 70 MPa concrete respectively. In this section a comparison is among shear strengths obtained through analytical modeling for NASCC and RASCC beams for 30 MPa and 70 MPa strengths. Figures 7.39-7.44 shows the comparison of shear strengths of NASCC and RASCC beams of compressive strengths 30 MPa and 70 MPa for shear span to depth ratios 2, 2.5 and 3. It was observed that due to use of recycled aggregates as complete replacement of both natural fine and coarse aggregates, the shear strength is reduced by 12.8% and 15.5% respectively for 30 MPa and 70 MPa strength concrete for beams tested for shear span to depth ratio 2 and also similar type of behaviour was observed in case of beams tested for shear span to depth ratios 2.5 and 3 for 30 MPa and 70 MPa strength concrete.

7.5.2 Shear behaviour of RASFRSCC beams using 8mm diameter stirrup.

In this section, analytical results obtained for shear behaviour of fiber reinforced SCC beams for 8mm diameter stirrup modelled using ATENA software with recycled aggregate as complete replacement of both fine and coarse aggregates are presented. Tables 7.16-7.18 shows the ultimate load and shear strength values of fibrous and non-fibrous RASCC beams for 8mm Ø stirrup for shear span to depth ratios (a/d) 2, 2.5 and 3.

a) Effect of Steel fibers on Shear behaviour of RASFRSCC beams with 8 mm Ø stirrup:

As observed in the case of beams with 6mm diameter stirrups, a similar type of behaviour was observed. Due to addition of steel fibers, ultimate load carrying capacity of the beams is increased and also steel fibres has bridged the crack faces and delayed the failure of the beams. Similarly type of behaviour was noticed in case of beams with 8mm Ø stirrups. Due to addition of steel fibers, the ultimate load carrying capacity of the beams RASFRSCC30-360 and RASFRSCC30-180 is increased by 38.46% and 26.21% respectively when compared with identical beams with stirrups and without steel fibers and also for higher strength concrete i.e. RASFRSCC70-360 and RASFRSCC70-180, due to addition of steel fibers, the ultimate load carrying capacity of the beams is increased by 21.19% and 25.34% respectively when compared with identical beams with stirrups and without steel fibers. Due to the combined effect of stirrups and steel fibers, the ultimate load carrying capacity of the beams RASFRSCC30-360 and RASFSRCC30-180 is increased by 119.18% and 130.39% respectively when compared with plain beams with no stirrups and without steel fibers and in case of higher strength concrete beams due to addition of stirrups and steel fibers, the ultimate load carrying capacity of the beams RASFRSCC70-360 and RASFRSCC70-180 is increased by 112.13% and 171.51% respectively. Similar type of behaviour was observed in case of beams tested for beams with shear span to depth ratio 2.5 and 3. Figures 7.45-7.50 shows the load vs deflections graphs for RASFRSCC30 and RASFRSCC70 beams for shear span to depth ratio 2, 2.5 and 3.

b) Effect of Stirrup spacing on shear behaviour of RASFRSCC beams:

To study the effect of stirrups on shear behaviour of recycled aggregate based self-compacting concrete beams, two stirrup spacing are considered for each shear span and the nonlinear analysis is performed for both RASCC30 and RASCC70 beams. As it is observed as in the case of normal aggregates beams with provision of stirrups at closer spacing have higher shear strength, a similar type of behaviour was observed in the case of beams with recycled aggregate as both fine and coarse aggregate. For instance for the shear strength of the beams RASCC30-360 and RASCC30-180 is increased by 35.21% and 70.42% respectively when compared with plain beam without stirrups, similarly for beams with stirrups , with decrease in stirrup spacing from 360 to 180 mm, ultimate shear strength is increased by 26.04%. Similar behaviour was observed in case of higher strength concrete beams RASCC70. Figures 7.51-7.53 shows the variation of shear strength with respect to spacing of stirrups for RASCC30 and RASCC70 and for shear span to depth ratio (a/d) 2, 2.5 and 3.

c) Effect of stirrup diameter on shear behaviour of RASFRSCC beams:

As observed in case of beams modelled for Normal aggregate beams with 6mm and 8mm diameter stirrups, that with increase in the area of shear reinforcement the ultimate shear strength is increased, this is due to confining effect of stirrup which increase the ultimate load carrying capacity of the beam there by increase the ultimate shear resistance of the beam. From the analytical results present in the above tables it is clearly understood that as the area of shear reinforcement is increased, there is an increase in the ultimate shear strength for both RASCC30 and RASCC70 beams. Figures 7.54-7.59 shows the variation of shear strength with respect to stirrup diameter (6mm and 8mm) for RASCC30 and RASCC70 for both without and with steel fibers and for three shear span to depth ratios (a/d) 2, 2.5 and 3.

d) Comparison of shear behaviour of NASCC and RASCC beams for 8mm Ø stirrup:

As observed in the case of experimental study due to use of recycled aggregate as complete replacement of both fine and coarse aggregates, the ultimate shear strength was reduced by 17.2% and 10.2% for 30 MPa and 70 MPa concrete respectively. In this section a detailed comparison among shear strengths obtained through analytical modeling for NASCC and RASCC beams for 30 MPa and 70 MPa strengths is done. Figures 7.60-7.65 show the compression of shear strength of NASCC and RASCC beams for 30 MPa and 70 MPa strengths for beams modelled with 8 mm stirrup diameter. Due to use of recycled aggregates, the shear strength of RASCC beams is reduced by 21.68% and 29.6% for RASCC30-180 and RASCC30-360 beams when compared with similar type of beams with natural aggregates i.e. NASCC30-180 and NASCC30-180. Similarly, in case of higher strength of concrete beams due to use of recycled aggregates, the ultimate shear strength is reduced by 15.0% and 8.09% respectively, compared to similar type of beams with natural aggregates i.e. NASCC70-180 and NASCC70-360. Due to use of steel fibers, the percentage decrease in the ultimate shear strength is reduced. The ultimate shear strength of RASFRSCC30-180 and RASFRSCC30-360 is reduced by 5.7% and 6.3% respectively. Similarly, for higher strength concrete beams i.e. RASFRSCC70-180 and RASFRSCC70-360 with steel fibers, the percentage decrease in shear strength is reduced by 2.5% and 0.69% respectively compared to natural aggregates beams. Similar type of behaviour was observed in case of beams tested for shear span to depth ratios (a/d) 2.5 and 3.

7.5.3 Comparison of Shear Strength among Experimental and Atena results:

A comparison of experimental test results with the result obtained through analytical model are done and the results are presented in Tables 7.19 and 7.20 for both 6 mm and 8 mm diameter stirrup. 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%.

7.6 Comparison of Theoretical and Numerical Shear Strength of RASCC:

A comparison is made among the numerical shear strength obtained through Atena modelling and predicted theoretical shear strength (proposed in chapter-6) for NASCC30 and NASCC70 and for both 6mm and 8 mm diameter stirrup. Tables 7.21-7.22 shows a comparison of Numerical and Theoretical shear strength for NASCC30 and NASCC70 for 6 mm and 8 mm diameter stirrup. The correlation of numerical and theoretical shear strength was satisfactory with average ratio of numerical to theoretical shear strength as 1.01. Figure 7.66 shows Comparison Numerical Shear Strength vs Theoretical Shear strength for RASCC30 and RASCC70

7.7 Comparison of Numerical Shear strength with Analytical Shear strength:

To validate the numerical results obtained through finite element modelling, a correlation is made among, numerical shear strength and analytical shear strength (proposed in chapter 6). It was observed that numerical shear strength are close to analytical shear strength. Tables 7.23-7.24 shows the comparison of Numerical and Analytical shear strength for RASCC30 and RASCC70 for 6 mm and 8 mm diameter stirrup. Figure: 7.67 shows a comparison of Numerical Shear Strength and Analytical Shear strength for RASCC30 and RASCC70

7.8 Conclusion from the Phase-IV:

Based on the analytical studies using finite element software ATENA on Shear behaviour steel fiber reinforced of recycled aggregate based self-compacting concrete for both fibrous and non-fibrous concrete beams using 6mm and 8mm as stirrup diameter the following conclusions were made

1. The Numerical results obtained compared well those with experimental results and maximum values are within 85-90% level of confidence.
2. A correlation among experimental deflections and deflections obtained though ATENA modelling are close each other, the percentage error calculated in all the case is less than 15%.
3. Numerical shear strength obtained through finite element modelling using ATENA software is in good agreement with the proposed empirical formula to predict the ultimate shear strength.
4. Comparison of Numerical shear strength obtained through ATENA modelling with predicted Theoretical shear strength is satisfactory.

Table: 7.1 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=2 for 6mm Ø stirrup using ATENA

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
SCC30		
SCC30-0	58.74	1.63
SCC30-360	78.91	2.19
SCC30-180	89.77	2.49
SFRSCC30-0	83.91	2.33
SFRSCC30-360	103.78	2.88
SFRSCC30-180	125.3	3.48
SCC70		
SCC70-0	85.82	2.38
SCC70-360	91.13	2.53
SCC70-180	130.58	3.62
SFRSCC70-0	98.98	2.74
SFRSCC70-360	120.53	3.34
SFRSCC70-180	144.64	4.01

Table: 7.2 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=2.5 for 6mm Ø stirrup ATENA

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
SCC30		
SCC30-0	57.18	1.58
SCC30-450	64.58	1.79
SCC30-225	71.43	1.98
SFRSCC30-0	78.60	2.18
SFRSCC30-450	83.97	2.33
SFRSCC30-225	102.60	2.85
SCC70		
SCC70-0	78.31	2.17
SCC70-450	85.38	2.37
SCC70-225	102.87	2.85
SFRSCC70-0	89.76	2.49
SFRSCC70-450	109.27	3.03
SFRSCC70-225	120.48	3.34

Table: 7.3 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=3 for 6mm Ø stirrup ATENA

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
SCC30		
SCC30-0	46.81	1.30
SCC30-540	48.59	1.34

SCC30-270	67.33	1.87
SFRSCC30-0	57.56	1.59
SFRSCC30-540	75.10	2.08
SFRSCC30-270	95.66	2.65
SCC70		
SCC70-0	66.0	1.83
SCC70-540	73.95	2.05
SCC70-270	89.19	2.47
SFRSCC70-0	77.15	2.14
SFRSCC70-540	75.50	2.09
SFRSCC70-270	112.26	3.11

Table: 7.4 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=2 and 8mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
SCC30		
SCC30-0	58.74	1.63
SCC30-360	98.3	2.73
SCC30-180	111.4	3.09
SFRSCC30-0	83.91	2.32
SFRSCC30-360	120.0	3.33
SFRSCC30-180	125.4	3.48
SCC70		
SCC70-0	85.82	2.38
SCC70-360	138.2	3.83
SCC70-180	184.7	5.13
SFRSCC70-0	98.98	2.74
SFRSCC70-360	147.8	4.10
SFRSCC70-180	194.6	5.40

Table: 7.5 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=2.5 and 8mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
SCC30		
SCC30-0	57.18	1.58
SCC30-450	77.4	2.15
SCC30-225	84.60	2.35
SFRSCC30-0	78.60	2.18
SFRSCC30-450	88.2	2.45
SFRSCC30-225	102.6	2.85
SCC70		
SCC70-0	78.31	2.17
SCC70-450	91.7	2.54
SCC70-225	131.2	3.64

SFRSCC70-0	89.76	2.49
SFRSCC70-450	108.4	3.01
SFRSCC70-225	140.6	3.90

Table: 7.6 Ultimate load and shear strength of fibrous and non-fibrous SCC for a/d=3 and 8mm Ø stirrup

Designation	Ultimate Load (kN)	Ultimate Shear Strength (v_u) (MPa)
	SCC30	
SCC30-0	42.81	1.3
SCC30-540	52.5	1.45
SCC30-270	76.9	2.13
SFRSCC30-0	57.56	1.59
SFRSCC30-540	74.4	2.06
SFRSCC30-270	95.4	2.65
	SCC70	
SCC70-0	66.0	1.83
SCC70-540	74.7	2.07
SCC70-270	97.3	2.70
SFRSCC70-0	77.15	2.14
SFRSCC70-540	88.4	2.45
SFRSCC70-270	132.5	3.68

Table 7.7: Comparison of Experimental results with Analytical results for NASCC Beams using 6mm Ø stirrup

NASCC30							
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error
	Exp.	Atena			Exp.	Atena	
			a/d=2				
SCC30-0	62.3	58.74	5.71	**SFRSCC30-0**	85.81	83.91	2.26
SCC30-360	86.77	78.91	9.06	**SFSCC30-360**	102.34	103.78	1.41
SCC30-180	95.67	89.77	6.17	**SFSCC30-180**	117.92	125.3	6.26
			a/d=2.5				
SCC30-0	59.16	57.18	3.35	**SFRSCC30-0**	69.89	78.6	12.46
SCC30-450	71.2	64.58	9.30	**SFSCC30-450**	75.65	83.97	11.00
SCC30-225	82.3	71.43	13.21	**SFSCC30-225**	104.57	102.6	1.88
			a/d=3				
SCC30-0	48.42	46.81	3.43	**SFRSCC30-0**	50.84	57.56	13.22
SCC30-540	48.95	48.59	0.74	**SFRSCC30-540**	81.00	75.1	7.28
SCC30-270	62.3	67.33	7.47	**SFRSCC30-270**	93.45	95.66	2.36
			NASCC70				
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error

	Exp.	Atena			Exp.	Atena	
a/d=2							
SCC70-0	88.43	85.82	3.04	**SFRSCC70-0**	91.31	98.98	8.40
SCC70-360	91.22	91.13	0.10	**SFSCC70-360**	135.72	120.53	11.19
SCC70-180	121	130.58	7.92	**SFSCC70-180**	159.75	144.64	9.63
a/d=2.5							
SCC70-0	71.1	78.31	9.21	**SFRSCC70-0**	79.25	89.76	13.26
SCC70-450	80.1	85.38	6.18	**SFRSCC70-450**	117.48	109.27	7.51
SCC70-225	107.69	102.87	4.48	**SFRSCC70-225**	128.15	120.48	5.98
a/d=3							
SCC70-0	68.49	66	3.64	**SFRSCC70-0**	71.32	77.15	8.17
SCC70-540	80.1	73.95	7.68	**SFRSCC70-540**	84.55	75.5	10.70
SCC70-270	86.77	89.19	2.71	**SFRSCC70-270**	131.27	112.26	14.48

Table 7.8: Comparison of Experimental results with Analytical results for NASCC Beams using 8mm Ø stirrup

NASCC30							
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error
	Exp.	Atena			Exp.	Atena	
a/d=2							
SCC30-0	62.3	58.74	5.71	**SFRSCC30-0**	85.81	83.91	2.26
SCC30-360	100.65	98.3	2.33	**SFRSCC30-360**	122.57	120	2.10
SCC30-180	113.62	111.4	1.95	**SFRSCC30-180**	127.04	125.4	1.29
a/d=2.5							
SCC30-0	59.16	57.18	3.35	**SFRSCC30-0**	69.89	78.6	12.46
SCC30-450	76.94	77.4	0.60	**SFRSCC30-450**	91.7	88.2	3.82
SCC30-225	90.52	84.6	6.54	**SFRSCC30-225**	109.6	102.6	6.39
a/d=3							
SCC30-0	48.42	42.81	11.59	**SFRSCC30-0**	50.84	57.56	13.22
SCC30-540	55.92	52.5	6.12	**SFRSCC30-540**	87.39	74.4	14.86
SCC30-270	84.51	76.9	9.00	**SFRSCC30-270**	93.94	95.4	1.55
NASCC70							
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error
	Exp.	Atena			Exp.	Atena	
a/d=2							
SCC70-0	88.43	85.82	3.04	**SFRSCC70-0**	91.31	98.98	8.40
SCC70-360	143.15	138.2	3.46	**SFRSCC70-360**	158.8	147.2	7.30
SCC70-180	174.59	184.7	5.79	**SFRSCC70-180**	199.06	194.6	2.24
a/d=2.5							

SCC70-0	71.1	78.31	9.20	**SFRSCC70-0**	79.25	89.76	13.26
SCC70-450	93.94	91.7	2.38	**SFRSCC70-450**	154.78	140.6	9.16
SCC70-225	145.38	131.2	9.75	**SFRSCC70-225**	127.49	108.4	14.97
a/d=3							
SCC70-0	68.49	66	3.64	**SFRSCC70-0**	71.32	77.15	8.17
SCC70-540	75.57	74.7	1.15	**SFRSCC70-540**	95.65	88.4	7.58
SCC70-270	110.65	97.3	12.07	**SFRSCC70-270**	150.75	132.5	12.11

Table 7.9: Numerical and Theoretical shear strength for NASCC30 and NASCC70 for 6 mm dia. Stirrup.

Designation	Numerical	Theoretical	Num/The
SCC30-0	1.63	1.93	0.84
SFRSCC30-0	2.33	2.29	1.02
SCC30-180	2.49	2.72	0.92
SCC30-360	2.19	2.28	0.96
SFRSCC30-180	3.48	3.3	1.05
SFRSCC30-360	2.88	2.92	0.99
SCC30-0	1.58	1.58	1.00
SFRSCC30-0	2.18	1.97	1.11
SCC30-225	1.98	2.77	0.71
SCC30-450	1.79	2.06	0.87
SFRSCC30-225	2.85	2.83	1.01
SFRSCC30-450	2.33	2.41	0.97
SCC30-0	1.3	1.21	1.07
SFRSCC30-0	1.59	1.33	1.20
SCC30-270	1.87	2.17	0.86
SCC30-540	1.34	1.65	0.81
SFRSCC30-270	2.65	2.85	0.93
SFRSCC30-540	2.08	2.15	0.97
SCC70			
SCC70-0	2.38	2.56	0.93
SFRSCC70-0	2.74	2.95	0.93
SCC70-180	3.62	3.11	1.16
SCC70-360	2.53	2.89	0.88
SFRSCC70-180	4.01	4.52	0.89
SFRSCC70-360	3.34	4.12	0.81
SCC70-0	2.17	2.21	0.98
SFRSCC70-0	2.49	2.43	1.02
SCC70-225	2.85	2.71	1.05
SCC70-450	2.37	2.77	0.86
SFRSCC70-225	3.34	3.52	0.95
SFRSCC70-450	3.03	3.23	0.94
SCC70-0	1.83	1.91	0.96
SFRSCC70-0	2.14	2.24	0.96
SCC70-270	2.47	2.91	0.85

SCC70-540	2.05	2.19	0.94
SFRSCC70-270	3.11	3.59	0.87
SFRSCC70-540	2.09	2.56	0.82

Table 7.10: Showing the Numerical and Theoretical shear strength for NASCC30 and NASCC70 for 8 mm dia. Stirrup

Designation	Numerical	Theoretical	Num/The
SCC30-0	1.63	1.79	0.91
SFRSCC30-0	2.32	2.25	1.03
SCC30-180	3.09	3.15	0.98
SCC30-360	2.73	2.77	0.99
SFRSCC30-180	3.48	3.44	1.01
SFRSCC30-360	3.33	3.12	1.07
SCC30-0	1.58	1.61	0.98
SFRSCC30-0	2.35	2.23	1.05
SCC30-225	2.18	2.19	1.00
SCC30-450	2.15	2.03	1.06
SFSCC30-225	2.85	2.95	0.97
SFSCC30-450	2.45	2.63	0.93
SCC30-0	1.3	1.36	0.96
SFRSCC30-0	1.45	1.64	0.88
SCC30-270	2.13	2.13	1.00
SCC30-540	1.59	1.57	1.01
SFRSCC30-270	2.6	2.51	1.04
SFRSCC30-540	3.04	2.43	1.25
SCC70			
SCC70-0	2.38	2.51	0.95
SFRSCC70-0	2.74	2.7	1.01
SCC70-180	5.13	4.94	1.04
SCC70-360	3.83	3.7	1.04
SFRSCC70-180	5.4	5.32	1.02
SFRSCC70-360	4.1	4.05	1.01
SCC70-0	2.17	2.02	1.07
SFRSCC70-0	2.49	2.22	1.12
SCC70-225	3.64	4.09	0.89
SCC70-450	2.54	2.51	1.01
SFRSCC70-225	3.9	4.59	0.85
SFRSCC70-450	3.01	3.18	0.95
SCC70-0	1.83	2.09	0.88
SFRSCC70-0	2.14	2.37	0.90
SCC70-270	2.7	2.86	0.94
SCC70-540	2.07	2.31	0.90
SFRSCC70-270	3.68	4.26	0.86
SFRSCC70-540	2.45	3.33	0.74

Table 7.11: Showing the Numerical and Analytical shear strength for NASCC30 and NASCC70 for 6 mm dia. Stirrup.

Designation	Numerical	Analytical	Exp/Pre
SCC30-0	1.63	1.77	0.92
SFRSCC30-0	2.33	2.17	1.07
SCC30-180	2.49	2.49	1.00
SCC30-360	2.19	2.31	0.95
SFRSCC30-180	3.48	2.89	1.20
SFRSCC30-360	2.88	2.71	1.06
SCC30-0	1.58	1.42	1.11
SFRSCC30-0	2.18	1.82	1.20
SCC30-225	1.98	2.09	0.95
SCC30-450	1.79	1.86	0.96
SFRSCC30-225	2.85	2.49	1.14
SFRSCC30-450	2.33	2.26	1.03
SCC30-0	1.3	1.06	1.23
SFRSCC30-0	1.59	1.46	1.09
SCC30-270	1.87	1.69	1.11
SCC30-540	1.34	1.41	0.95
SFRSCC30-270	2.65	2.56	1.04
SFRSCC30-540	2.08	2.19	0.95
SCC70			
SCC70-0	2.38	2.6	0.92
SFRSCC70-0	2.74	3	0.91
SCC70-180	3.62	3.31	1.09
SCC70-360	2.53	3.13	0.81
SFRSCC70-180	4.01	3.71	1.08
SFRSCC70-360	3.34	3.53	0.95
SCC70-0	2.17	2.24	0.97
SFRSCC70-0	2.49	2.64	0.94
SCC70-225	2.85	2.91	0.98
SCC70-450	2.37	2.68	0.88
SFRSCC70-225	3.34	3.31	1.01
SFRSCC70-450	3.03	3.08	0.98
SCC70-0	1.83	1.88	0.97
SFRSCC70-0	2.14	2.28	0.94
SCC70-270	2.47	2.51	0.98
SCC70-540	2.05	2.24	0.92
SFRSCC70-270	3.11	3.36	0.93
SFRSCC70-540	2.09	2.63	0.79

Table 7.12: Showing the Numerical and Analytical shear strength for NASCC30 and NASCC70 for 8 mm dia. Stirrup.

Designation	Numerical	Predicted	Exp/Pre
SCC30-0	1.63	1.77	0.92
SFRSCC30-0	2.32	2.17	1.07
SCC30-180	3.09	3.19	0.97
SCC30-360	2.73	3.01	0.91
SFRSCC30-180	3.48	3.59	0.97
SFRSCC30-360	3.33	3.4	0.98
SCC30-0	1.58	1.42	1.11
SFRSCC30-0	2.35	1.82	1.29
SCC30-225	2.18	2.79	0.78
SCC30-450	2.15	2.56	0.84
SFRSCC30-225	2.85	3.19	0.89
SFRSCC30-450	2.45	2.96	0.83
SCC30-0	1.3	1.06	1.23
SFRSCC30-0	1.45	1.46	0.99
SCC30-270	2.13	2.39	0.89
SCC30-540	1.59	2.11	0.75
SFRSCC30-270	2.6	2.78	0.94
SFRSCC30-540	3.04	2.51	1.21
SCC70			
SCC70-0	2.38	2.6	0.92
SFRSCC70-0	2.74	3	0.91
SCC70-180	5.13	4.78	1.07
SCC70-360	3.83	3.83	1.00
SFRSCC70-180	5.4	4.41	1.22
SFRSCC70-360	4.1	4.23	0.97
SCC70-0	2.17	2.24	0.97
SFRSCC70-0	2.49	2.64	0.94
SCC70-225	3.64	3.61	1.01
SCC70-450	2.54	3.38	0.75
SFRSCC70-225	3.9	4.01	0.97
SFRSCC70-450	3.01	3.78	0.80
SCC70-0	1.83	1.88	0.97
SFRSCC70-0	2.14	2.28	0.94
SCC70-270	2.7	3.21	0.84
SCC70-540	2.07	2.93	0.71
SFRSCC70-270	3.68	3.61	1.02
SFRSCC70-540	2.45	3.33	0.74

Table: 7.13 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=2 and 6mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
RASCC30		
SCC30-0	51.26	1.42
SCC30-360	67.43	1.87
SCC30-180	79.42	2.21
SFRSCC30-0	63.77	1.77
SFRSCC30-360	89.89	2.5
SFRSCC30-180	108.84	3.02
RASCC70		
SCC70-0	72.5	2.01
SCC70-360	95.83	2.66
SCC70-180	113.76	3.16
SFRSCC70-0	83.55	2.32
SFRSCC70-360	117.98	3.27
SFRSCC70-180	141.06	3.91

Table: 7.14 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=2.5 and 6mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
RASCC30		
SCC30-0	44.98	1.24
SCC30-450	53.64	1.49
SCC30-225	62.43	1.73
SFRSCC30-0	58.12	1.61
SFRSCC30-450	77.58	2.15
SFRSCC30-225	93.86	2.60
RASCC70		
SCC70-0	71.3	1.98
SCC70-450	83.71	2.32
SCC70-225	98.25	2.79
SFRSCC70-0	82.29	2.28
SFRSCC70-450	96.45	2.67
SFRSCC70-225	117.8	3.27

Table: 7.15 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=3 and 6mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
RASCC30		
SCC30-0	42.93	1.19
SCC30-540	46.17	1.28

SCC30-270	60.11	1.67
SFRSCC30-0	58.73	1.63
SFRSCC30-540	63.73	1.77
SFRSCC30-270	87.13	2.42
RASCC70		
SCC70-0	67.6	1.88
SCC70-540	76.67	2.13
SCC70-270	94.12	2.61
SFRSCC70-0	79.15	2.19
SFRSCC70-540	84.51	2.34
SFRSCC70-270	109.69	3.05

Table: 7.16 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=2 8mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
RASCC30		
SCC30-0	51.26	1.42
SCC30-360	69.30	1.92
SCC30-180	87.3	2.42
SFRSCC30-0	63.77	1.77
SFRSCC30-360	112.3	3.12
SFRSCC30-180	118.1	3.28
RASCC70		
SCC70-0	72.5	2.01
SCC70-360	126.9	3.52
SCC70-180	157.10	4.36
SFRSCC70-0	83.55	2.32
SFRSCC70-360	153.8	4.27
SFRSCC70-180	196.9	5.46

Table: 7.17 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=2.5, 8mm Ø stirrup

Designation	Ultimate Load(kN)	Ultimate Shear Strength (v_u) (MPa)
RASCC30		
SCC30-0	44.98	1.24
SCC30-450	58.60	1.62
SCC30-225	62.10	1.72
SFRSCC30-0	58.12	1.61
SFRSCC30-450	88.2	2.45
SFRSCC30-225	99.6	2.76
RASCC70		
SCC70-0	71.3	1.98
SCC70-450	92.90	2.58
SCC70-225	104.70	2.90

SFRSCC70-0	82.29	2.28
SFRSCC70-450	109.5	3.04
SFRSCC70-225	137.40	3.81

Table: 7.18 Ultimate load and shear strength of fibrous and non-fibrous RASCC for a/d=3, 8mm Ø stirrup

Designation	**Ultimate Load(kN)**	**Ultimate Shear Strength (v_u) (MPa)**
	RASCC30	
SCC30-0	42.93	1.19
SCC30-540	56.20	1.56
SCC30-270	81.60	2.26
SFRSCC30-0	58.73	1.63
SFRSCC30-540	64.2	1.78
SFRSCC30-270	92.10	2.55
	RASCC70	
SCC70-0	67.6	1.88
SCC70-540	77.4	2.15
SCC70-270	99.5	2.76
SFRSCC70-0	79.15	2.19
SFRSCC70-540	93.7	2.60
SFRSCC70-270	109.7	3.04

Table: 7.19 Comparison of Experimental results with Atena Software for RASCC Beams for 6mm Ø stirrup

RASCC30							
	Ultimate Load (KN)				**Ultimate Load (KN)**		
Designation	Exp.	Atena	% error	**Designation**	Exp.	Atena	% error
			a/d=2				
RASCC30-0	54.68	51.26	6.25	**RASFRSCC30-0**	60.99	63.77	4.35
RASCC30-360	70.64	66.25	6.21	**RASFRSCC30-360**	94.16	89.89	4.53
RASCC30-180	83.36	79.42	4.73	**RASFRSCC30-180**	105.12	108.84	3.41
			a/d=2.5				
RASCC30-0	40.6	44.98	10.79	**RASFRSCC30-0**	53.13	58.12	9.39
RASCC30-450	56.56	53.64	5.16	**RASFRSCC30-450**	83.36	77.58	6.93
RASCC30-225	68.42	62.43	8.75	**RASFRSCC30-225**	95.4	93.86	1.61
			a/d=3				
RASCC30-0	39.13	42.93	9.71	**RASFRSCC30-0**	57.8	58.3	0.85
RASCC30-540	48.34	54.11	11.94	**RASFRSCC30-540**	65.3	63.73	2.40
RASCC30-270	51.05	54.86	7.46	**RASFRSCC30-270**	84.6	87.13	2.99
			RASCC70				
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error

	Exp.	Atena			Exp.	Atena	
a/d=2							
RASCC70-0	72.33	72.5	0.24	**RASFRSCC70-0**	79.6	83.55	4.96
RASCC70-360	105.17	95.83	8.88	**RASFRSCC70-360**	119.18	117.98	1.01
RASCC70-180	110.61	113.76	2.76	**RASFRSCC70-180**	142.02	141.06	0.67
a/d=2.5							
RASCC70-0	67.25	71.3	6.02	**RASFRSCC70-0**	77.64	82.29	5.99
RASCC70-450	83.36	83.71	0.41	**RASFRSCC70-450**	90.79	96.45	6.23
RASCC70-225	93.33	98.25	5.27	**RASFRSCC70-225**	109.13	117.8	7.35
a/d=3							
RASCC70-0	63.72	67.06	4.98	**RASFRSCC70-0**	76.13	79.15	3.94
RASCC70-540	77.10	76.67	5.32	**RASFRSCC70-540**	81.08	84.51	4.05
RASCC70-270	100.75	94.12	6.58	**RASFRSCC70-270**	121.65	109.69	9.83

Table: 7.20 Comparison of Experimental results with Atena Software for RASCC Beams for 8mm Ø stirrup

RASCC30							
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error
	Exp.	Atena			Exp.	Atena	
a/d=2							
RASCC30-0	54.68	51.26	6.25	**RASFRSCC30-0**	60.99	63.77	4.35
RASCC30-360	76.14	69.3	8.98	**RASFRSCC30-360**	98.06	112.32	14.54
RASCC30-180	83.5	87.3	4.55	**RASFRSCC30-180**	114.23	118.1	3.39
a/d=2.5							
RASCC30-0	40.6	44.98	10.79	**RASFRSCC30-0**	53.13	58.12	9.39
RASCC30-450	60.46	58.6	3.08	**RASFRSCC30-450**	93.36	88.2	5.53
RASCC30-225	78	72	7.69	**RASFRSCC30-225**	109.77	99.6	9.26
a/d=3							
RASCC30-0	39.13	42.93	9.71	**RASFRSCC30-0**	57.8	58.3	0.85
RASCC30-540	53.28	56.2	5.48	**RASFRSCC30-540**	64.21	64.2	0.02
RASCC30-270	81.75	81.6	0.18	**RASFRSCC30-270**	87.93	92.1	4.74
RASCC70							
Designation	**Ultimate Load (KN)**		% error	**Designation**	**Ultimate Load (KN)**		% error
	Exp.	Atena			Exp.	Atena	
a/d=2							
RASCC70-0	79.33	72.5	8.61	**RASFRSCC70-0**	79.6	83.55	4.96
RASCC70-360	134.09	126.9	5.36	**RASFRSCC70-360**	143.43	153.8	7.23
RASCC70-180	168.1	157.1	6.54	**RASFRSCC70-180**	179.1	196.9	9.94
a/d=2.5							
RASCC70-0	67.25	71.3	6.02	**RASFRSCC70-0**	77.64	82.29	5.99

RASCC70-450	90.75	92.9	2.31	**RASFRSCC70-450**	111.68	109.5	1.95
RASCC70-225	107.33	104.7	2.51	**RASFRSCC70-225**	136.16	137.4	0.90
a/d=3							
RASCC70-0	63.72	67.12	4.98	**RASFRSCC70-0**	76.53	79.15	3.94
RASCC70-540	85.58	77.4	9.56	**RASFRSCC70-540**	93.24	93.7	0.49
RASCC70-270	106.8	99.5	6.84	**RASFRSCC70-270**	124.08	109.7	11.59

Table: 7.21 Numerical and Theoretical shear strength for RASCC30 and RASCC70 for 6 mm dia. Stirrup.

Designation	**Numerical**	**Theoretical**	**Num/The**
RASCC30-0	1.42	1.65	0.86
RASFRSCC30-0	1.77	1.84	0.96
RASCC30-180	2.21	2.3	0.96
RASCC30-360	1.87	2.06	0.91
RASFRSCC30-180	3.02	3.02	1.00
RASFRSCC30-360	2.5	2.74	0.91
RASCC30-0	1.24	1.28	0.97
RASFRSCC30-0	1.61	1.6	1.01
RASCC30-225	1.73	1.97	0.88
RASCC30-450	1.49	1.6	0.93
RASFRSCC30-225	2.6	3.02	0.86
RASFRSCC30-450	2.15	2.35	0.91
RASCC30-0	1.19	1.24	0.96
RASFRSCC30-0	1.63	1.33	1.23
RASCC30-270	1.67	1.77	0.94
RASFRSCC30-270	2.58	2.68	0.96
RASCC30-540	2.44	2.41	1.01
RASFRSCC30-540	1.77	1.71	1.04
RASCC70			
RASCC70-0	2.01	2.21	0.91
RASFRSCC70-0	2.32	2.38	0.97
RASCC70-180	3.16	3.14	1.01
RASCC70-360	3.26	3.03	1.08
RASFRSCC70-180	3.91	3.98	0.98
RASFRSCC70-360	3.27	3.24	1.01
RASCC70-0	1.98	1.79	1.11
RASFRSCC70-0	2.28	2.1	1.09
RASCC70-225	3.12	3.17	0.98
RASFRSCC70-225	3.67	3.5	1.05
RASCC70-450	2.79	2.59	1.08
RASFRSCC70-450	3.27	3.01	1.09
RASCC70-0	1.88	1.79	1.05
RASFRSCC70-0	2.19	2.16	1.01

RASCC70-270	2.61	2.5	1.04
RASFRSCC70-270	3.56	3.46	1.03
RASCC70-540	3.05	2.09	1.46
RASFRSCC70-540	2.34	2.42	0.97

Table: 7.22 Numerical and Theoretical shear strength for RASCC30 and RASCC70 for 8 mm dia. Stirrup.

Designation	**Numerical**	**Theoretical**	**Num/The**
RASCC30-0	1.42	1.6	0.89
RASFRSCC30-0	1.77	1.86	0.95
RASCC30-180	2.42	2.35	1.03
RASCC30-360	1.92	2.03	0.95
RASFRSCC30-180	3.28	3.22	1.02
RASFRSCC30-360	3.12	2.62	1.19
RASCC30-0	1.24	1.28	0.97
RASFRSCC30-0	1.62	1.66	0.98
RASCC30-225	2.46	2.22	1.11
RASCC30-450	1.72	1.75	0.98
RASFRSCC30-225	3.27	3.1	1.05
RASFRSCC30-450	2.67	2.61	1.02
RASCC30-0	1.19	1.06	1.12
RASFRSCC30-0	1.63	1.54	1.06
RASCC30-270	1.78	2.27	0.78
RASFRSCC30-270	2.55	2.35	1.09
RASCC30-540	1.56	1.56	1.00
RASFRSCC30-540	2.26	1.9	1.19
RASCC70			
RASCC70-0	2.01	2.14	0.94
RASFRSCC70-0	2.32	2.61	0.89
RASCC70-180	4.36	4.39	0.99
RASCC70-360	3.52	3.7	0.95
RASFRSCC70-180	5.46	4.81	1.14
RASFRSCC70-360	4.27	4	1.07
RASCC70-0	1.98	1.96	1.01
RASFRSCC70-0	2.28	2.47	0.92
RASCC70-225	2.9	3.12	0.93
RASFRSCC70-225	3.58	3.76	0.95
RASCC70-450	3.81	2.96	1.29
RASFRSCC70-450	3.04	3.01	1.01
RASCC70-0	1.88	1.79	1.05
RASFRSCC70-0	2.19	2.43	0.90
RASCC70-270	2.76	2.88	0.96
RASFRSCC70-270	3.5	3.47	1.01
RASCC70-540	3.04	2.29	1.33
RASFRSCC70-540	2.6	2.68	0.97

Table: 7.23 Numerical and Analytical shear strength for RASCC30 and RASCC70 for 6 mm dia. Stirrup.

Designation	Numerical	Analytical	Experimental/analytical
RASCC30-0	1.42	1.66	0.86
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.21	2.28	0.97
RASCC30-360	1.87	2.34	0.80
RASFRSCC30-180	3.02	2.4	1.26
RASFRSCC30-360	2.5	2.45	1.02
RASCC30-0	1.24	1.3	0.95
RASFRSCC30-0	1.61	1.41	1.14
RASCC30-225	1.73	1.94	0.89
RASCC30-450	1.49	2	0.75
RASFRSCC30-225	2.6	2.56	1.02
RASFRSCC30-450	2.15	2.11	1.02
RASCC30-0	1.19	0.94	1.27
RASFRSCC30-0	1.63	1.05	1.55
RASCC30-270	1.67	1.59	1.05
RASCC30-540	1.77	1.67	1.06
RASFRSCC30-270	2.58	1.48	1.74
RASFRSCC30-540	2.44	1.78	1.37
RASCC70			
RASCC70-0	2.01	2.54	0.79
RASFRSCC70-0	2.32	2.65	0.88
RASCC70-180	3.16	3.16	1.00
RASCC70-360	3.26	3.22	1.01
RASFRSCC70-180	3.91	3.27	1.20
RASFRSCC70-360	3.27	3.33	0.98
RASCC70-0	1.98	2.18	0.91
RASFRSCC70-0	2.28	2.29	1.00
RASCC70-225	2.79	2.81	0.99
RASCC70-450	2.32	2.88	0.81
RASFRSCC70-225	3.27	2.52	1.30
RASFRSCC70-450	2.67	2.99	0.89
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.19	1.93	1.13
RASCC70-270	2.61	2.46	1.06
RASCC70-540	2.13	2.23	0.96
RASFRSCC70-270	3.05	3.28	0.93
RASFRSCC70-540	2.34	2.66	0.88

Table: 7.24 Numerical and Analytical shear strength for RASCC30 and RASCC70 for 8 mm dia. Stirrup

Designation	Numerical	Analytical	Experimental/analytical
RASCC30-0	1.42	1.66	0.86
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.42	2.73	0.89
RASCC30-360	1.92	2.58	0.74
RASFRSCC30-180	3.28	3.12	1.05
RASFRSCC30-360	3.12	2.89	1.08
RASCC30-0	1.24	1.3	0.95
RASFRSCC30-0	1.62	1.45	1.12
RASCC30-225	2.46	2.38	1.03
RASCC30-450	1.72	1.98	0.87
RASFRSCC30-225	3.27	2.49	1.31
RASFRSCC30-450	2.67	2.56	1.04
RASCC30-0	1.19	1.12	1.06
RASFRSCC30-0	1.63	1.05	1.55
RASCC30-270	1.78	2.03	0.88
RASCC30-540	1.56	2.11	0.74
RASFRSCC30-270	2.55	1.58	1.61
RASFRSCC30-540	2.26	2.22	1.02
RASCC70			
RASCC70-0	2.01	2.54	0.79
RASFRSCC70-0	2.32	2.65	0.88
RASCC70-180	4.36	4.56	0.96
RASCC70-360	3.52	3.66	0.96
RASFRSCC70-180	5.46	4.81	1.14
RASFRSCC70-360	4.27	3.77	1.13
RASCC70-0	1.98	2.18	0.91
RASFRSCC70-0	2.28	2.29	1.00
RASCC70-225	2.9	3.25	0.89
RASCC70-450	3.58	3.67	0.98
RASFRSCC70-225	3.81	2.64	1.44
RASFRSCC70-450	3.04	3.23	0.94
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.19	1.93	1.13
RASCC70-270	2.76	2.91	0.95
RASCC70-540	2.15	2.99	0.72
RASFRSCC70-270	3.04	3.38	0.90
RASFRSCC70-540	2.6	3.1	0.84

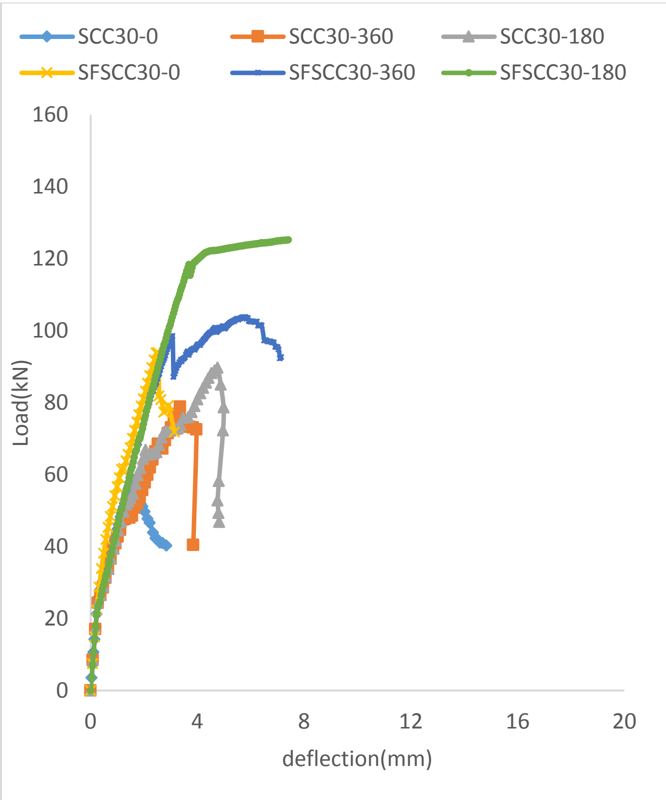

Figure 7.1: Load Vs Deflection for SCC30;a/d=2

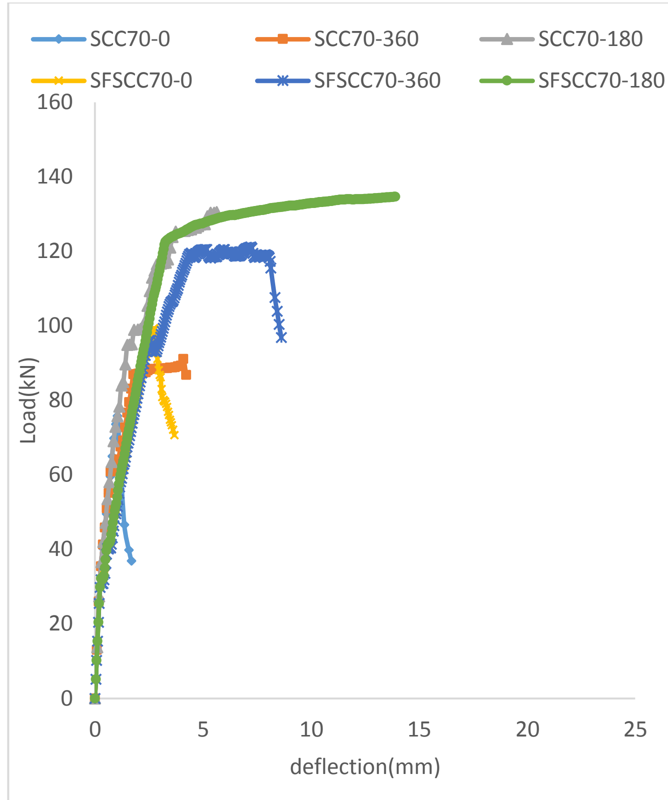

Figure 7.2: Load Vs Deflection for SCC70;a/d=2

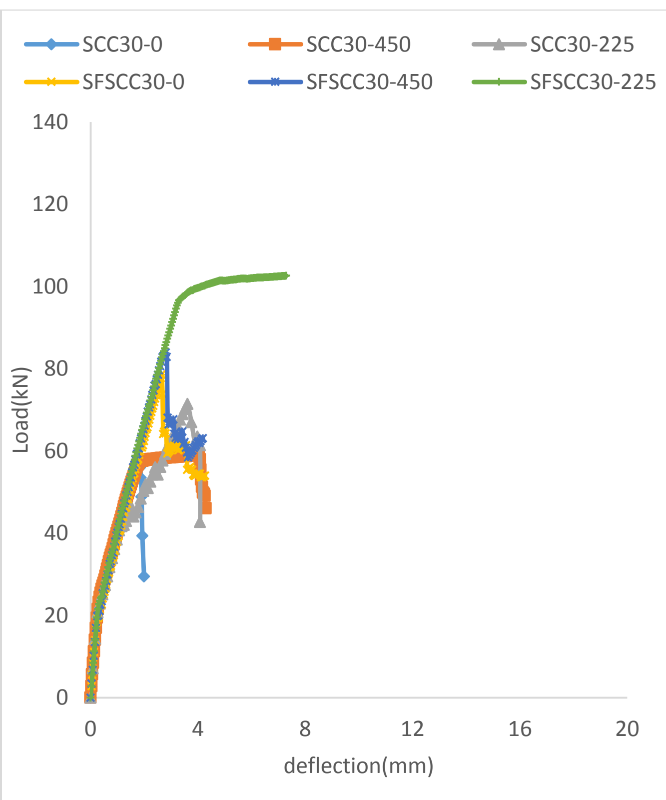

Figure 7.3: Load Vs Deflection for SCC70;a/d=2

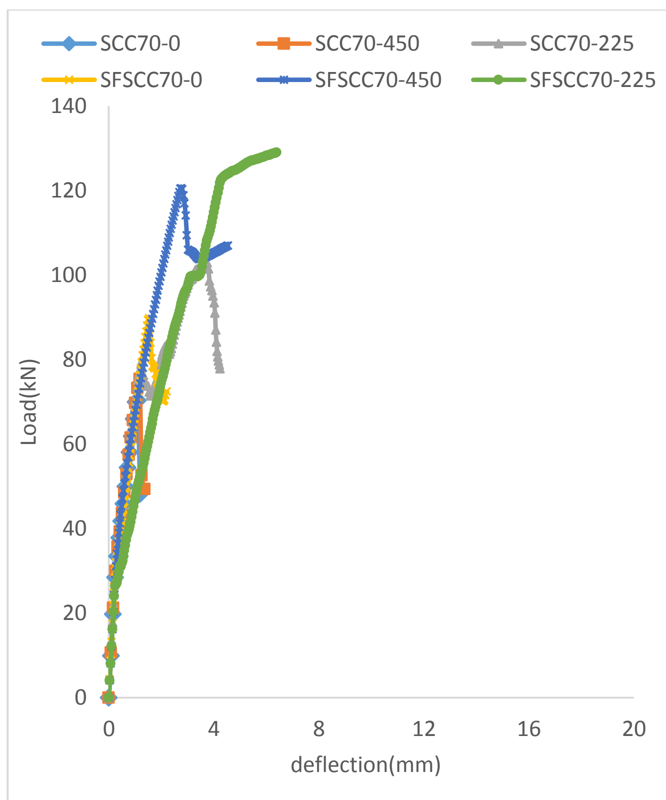

Figure 7.4: Load Vs Deflection for SCC70;a/d=2.5

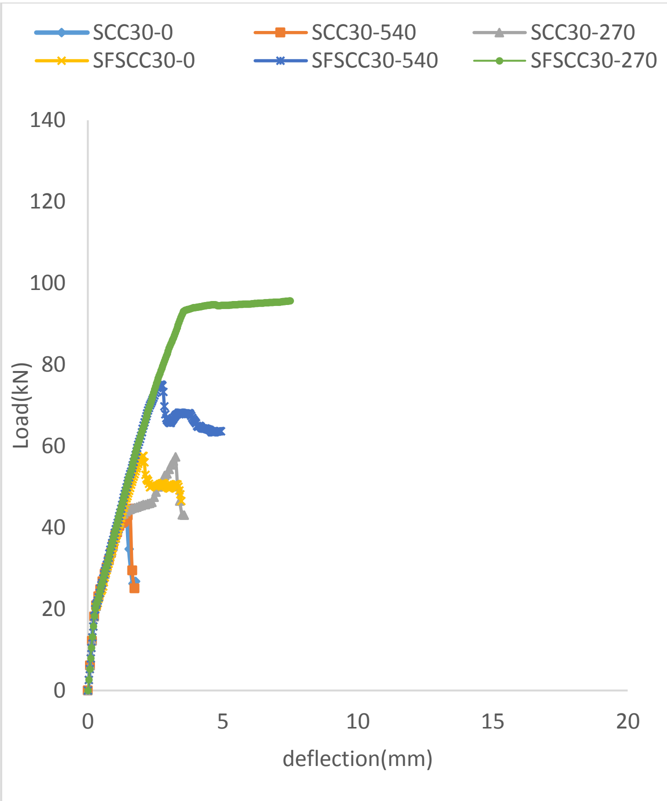

Figure 7.5: Load Vs Deflection for SCC30;a/d=3

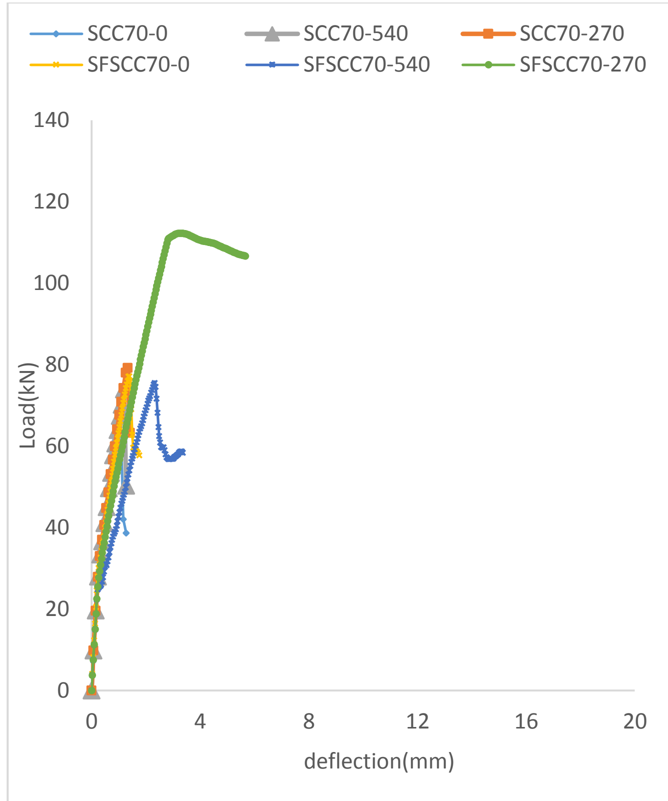

Figure 7.6: Load Vs Deflection for SCC70;a/d=3

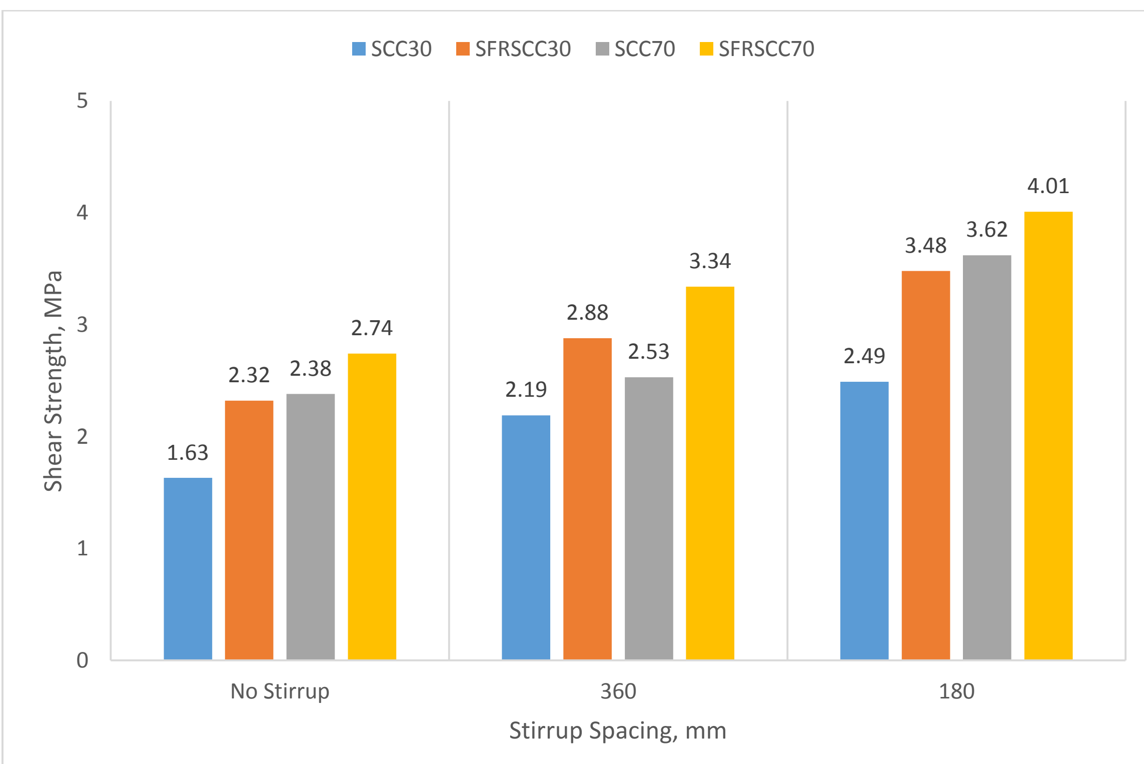

Figure: 7.7 Shear Strength vs Spacing of stirrups for shear span to depth ratio (a/d) 2

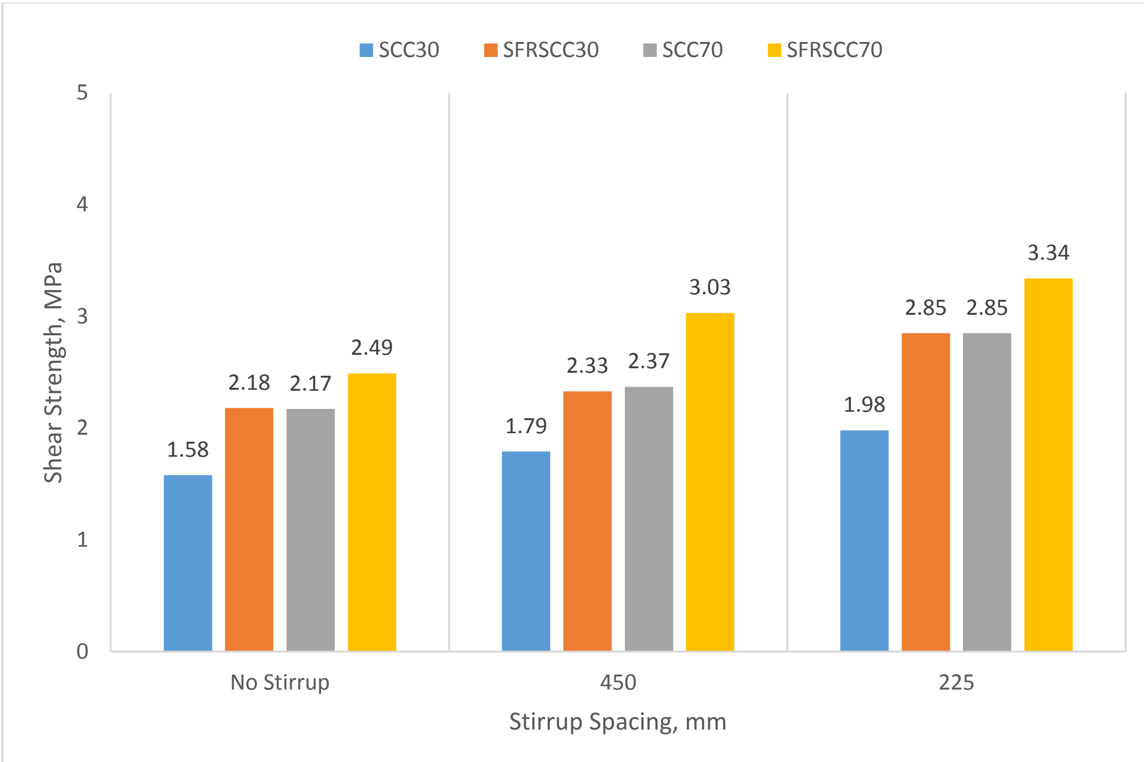

Figure: 7.8 Shear Strength vs Spacing of stirrups for shear span to depth ratio (a/d) 2.5

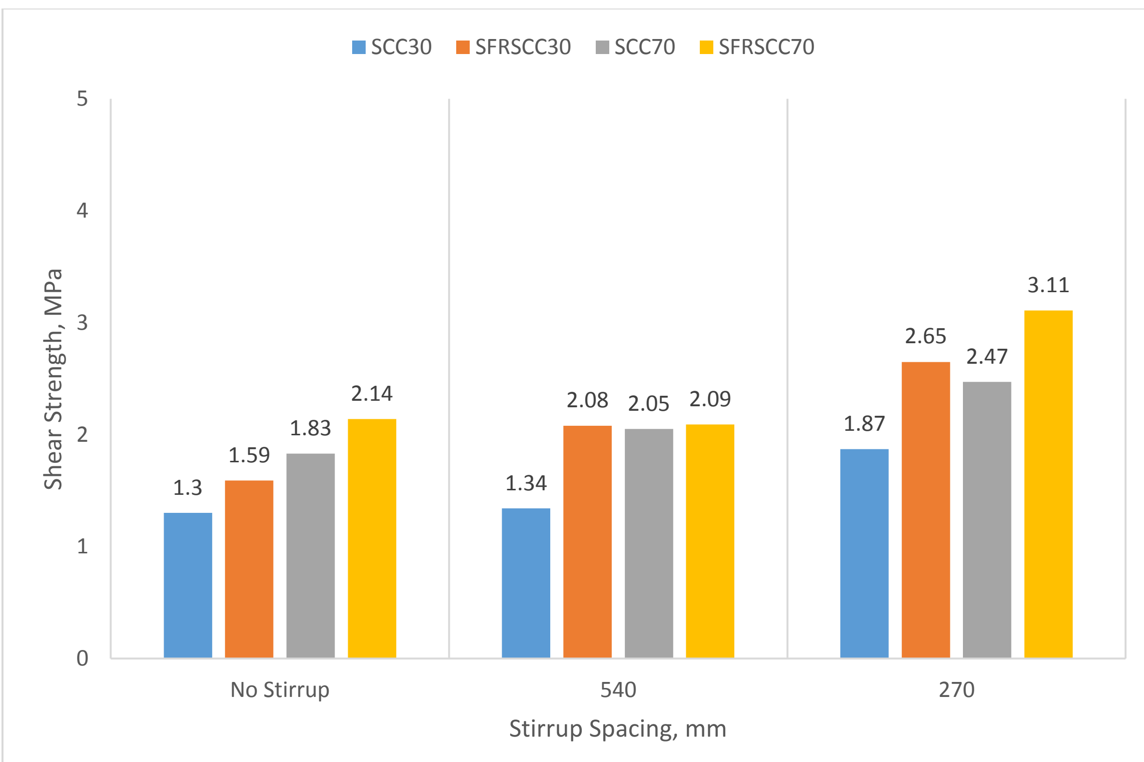

Figure: 7.9 Shear Strength vs Spacing of stirrups for shear span to depth ratio (a/d) 3

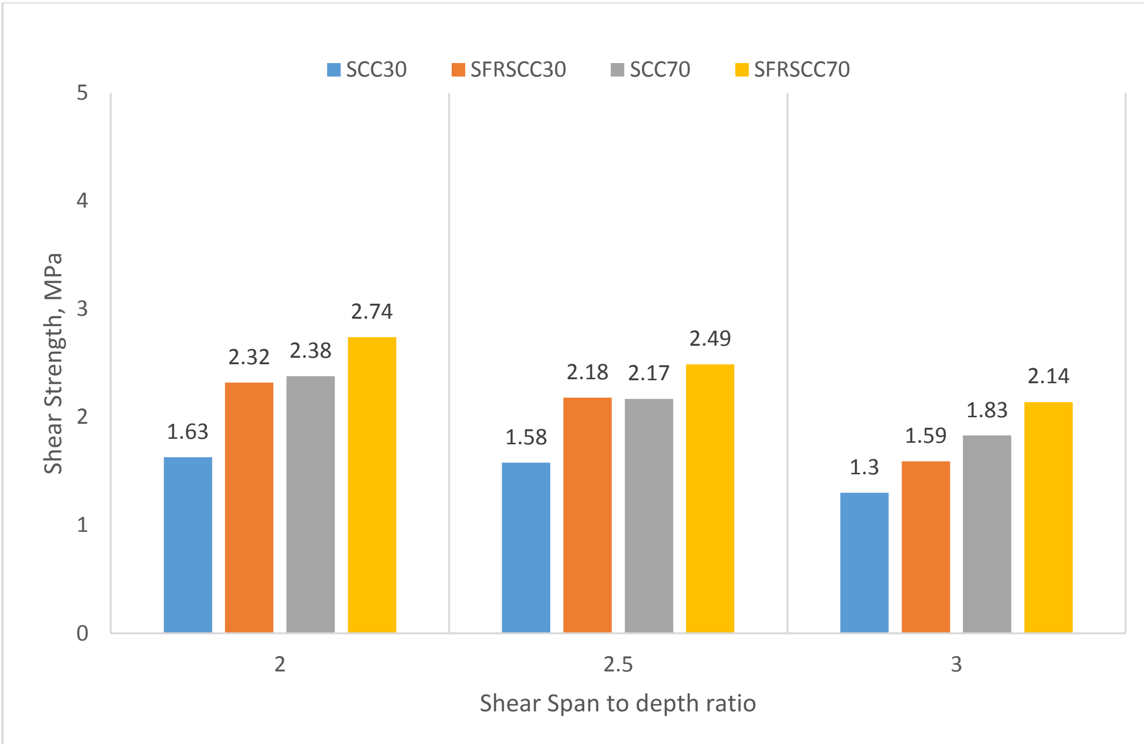

Figure: 7.10 Shear Strength vs Shear span to depth ratio (a/d) for plain beams

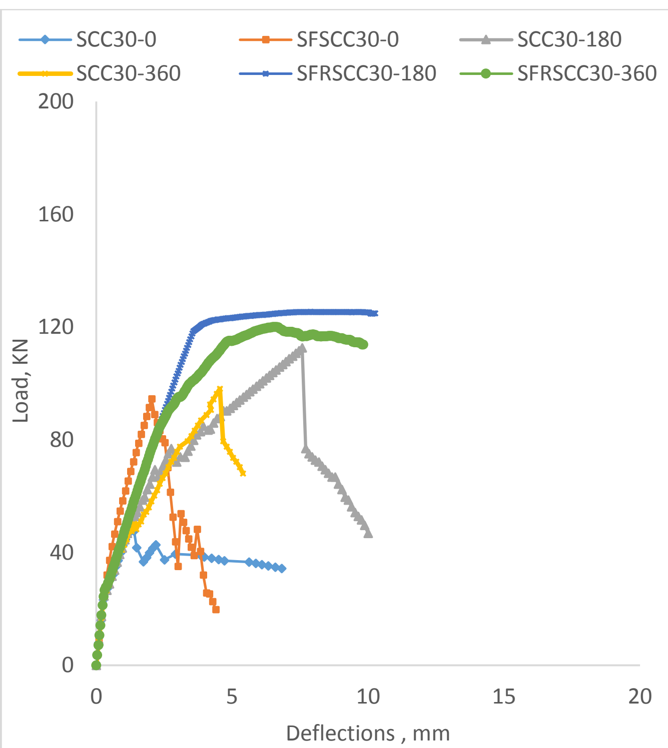

Figure 7.11: Load Vs Deflection for SCC30 a/d=2 ;8mm

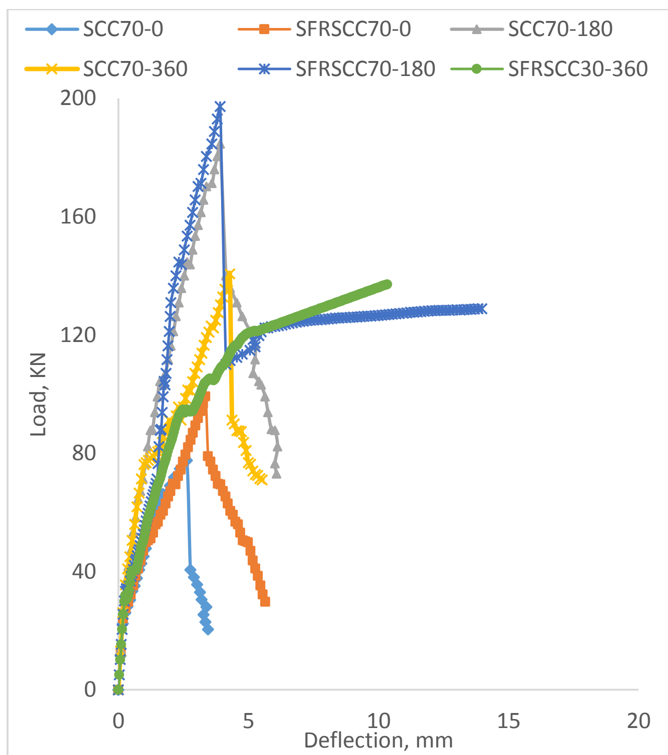

Figure 7.12: Load Vs Deflection for SCC70 a/d=2;8mm

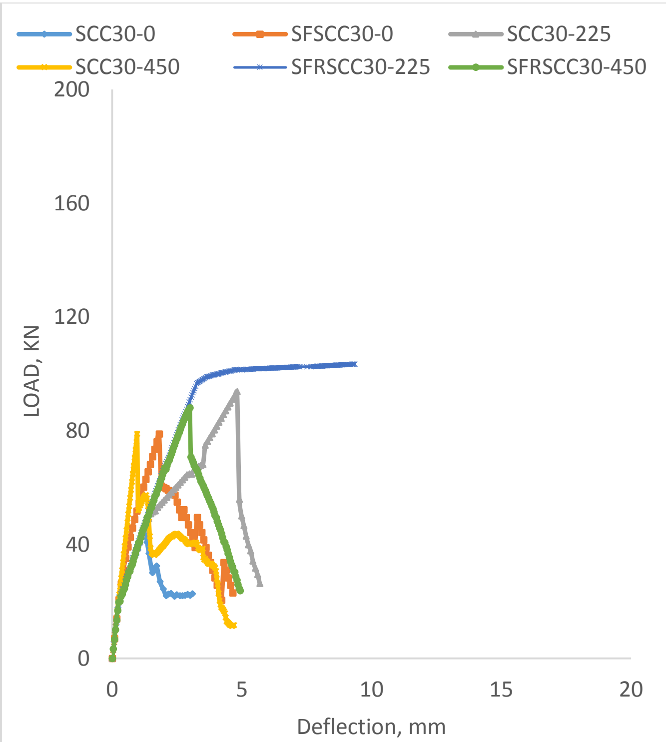

Figure 7.13: Load Vs Deflection for SCC30 a/d=2.5;8mm

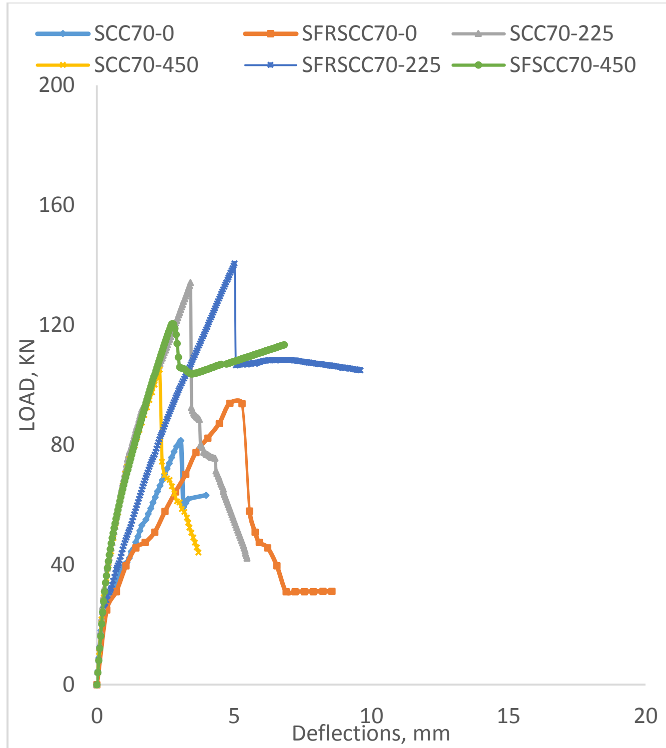

Figure 7.14: Load Vs Deflection for SCC70 a/d=2.5;8mm

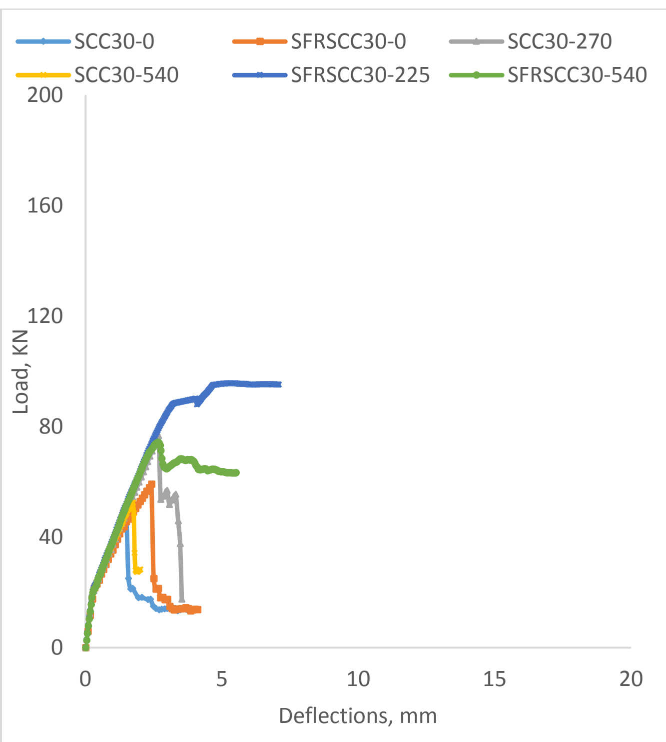

Figure 7.15: Load Vs Deflection for SCC30; a/d=3; 8mm

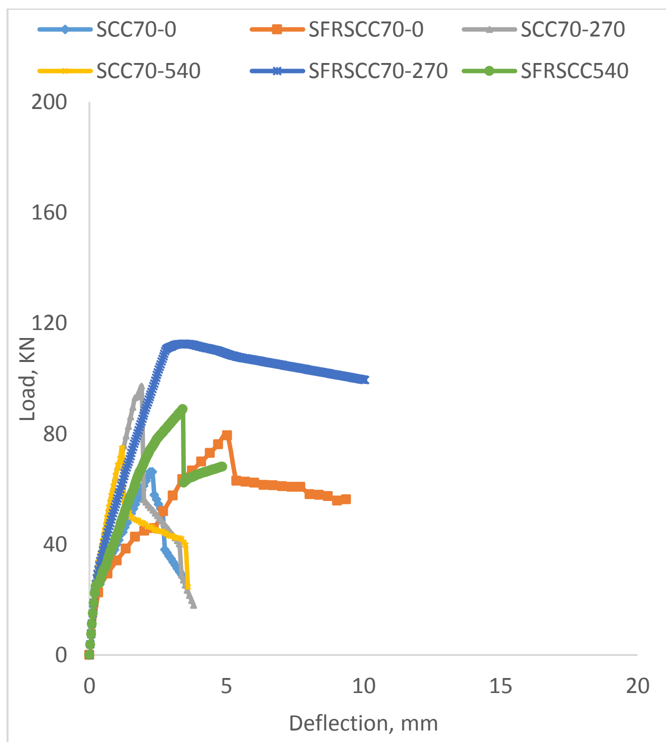

Figure 7.16: Load Vs Deflection for SCC70 a/d=3;8mm

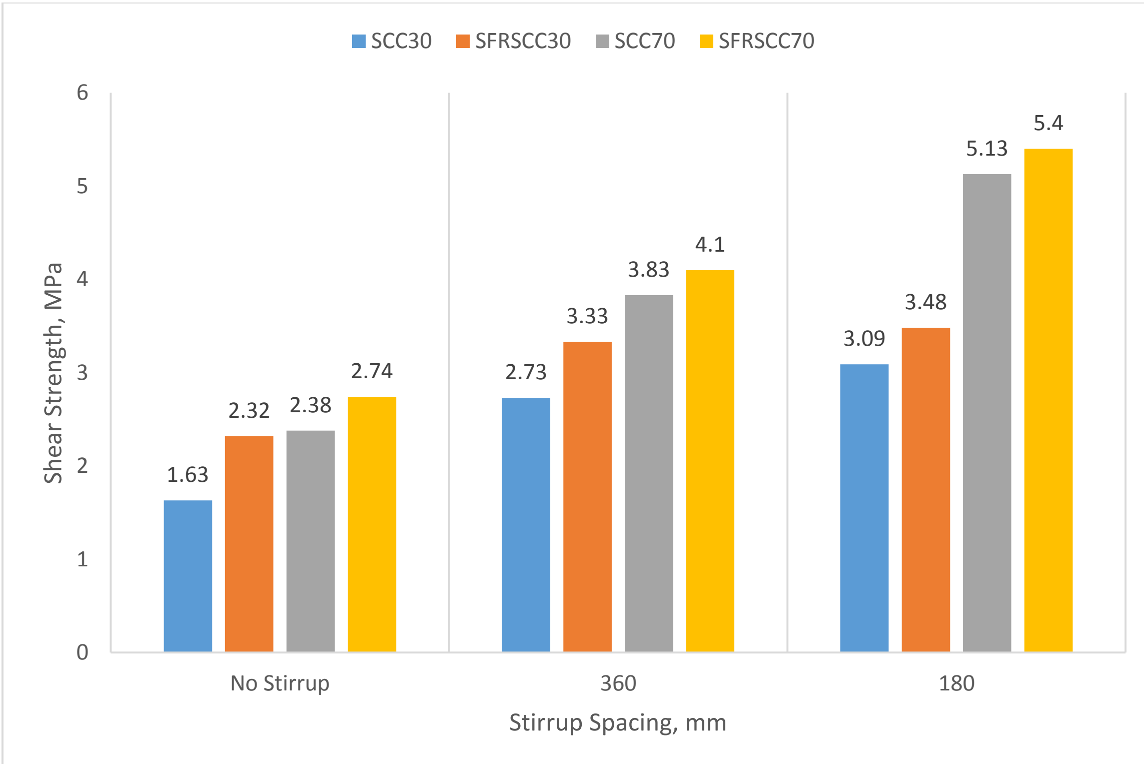

Figure: 7.17 Shear Strength vs Spacing of Stirrup for a/d=2

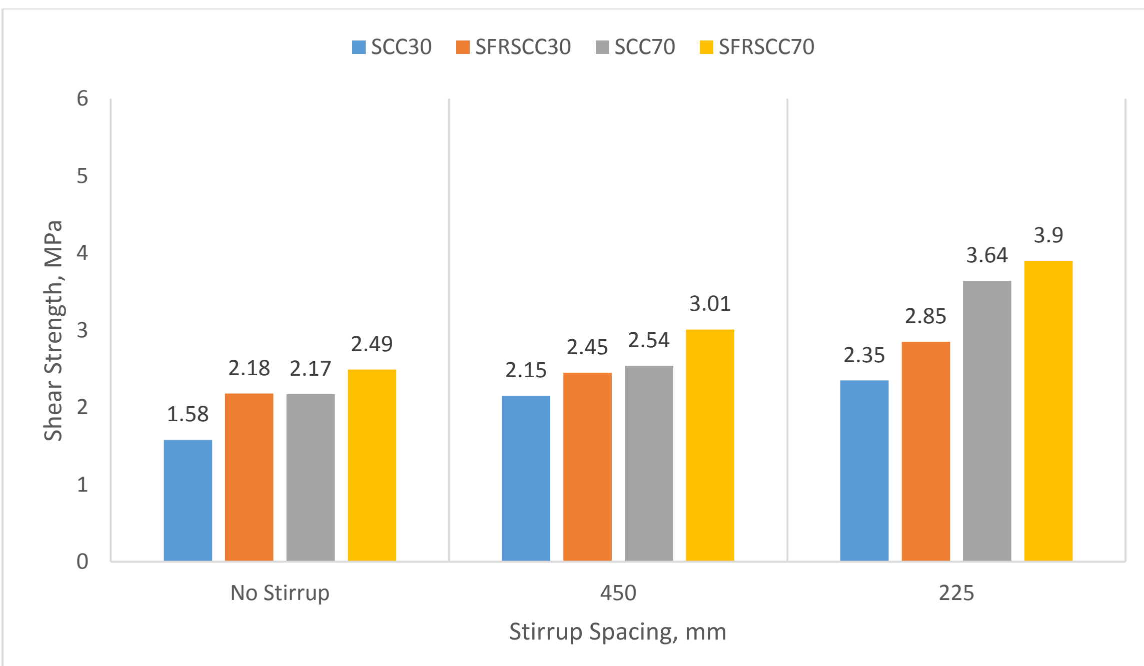

Figure: 7.18 Shear Strength vs Spacing of Stirrup for a/d=2.5

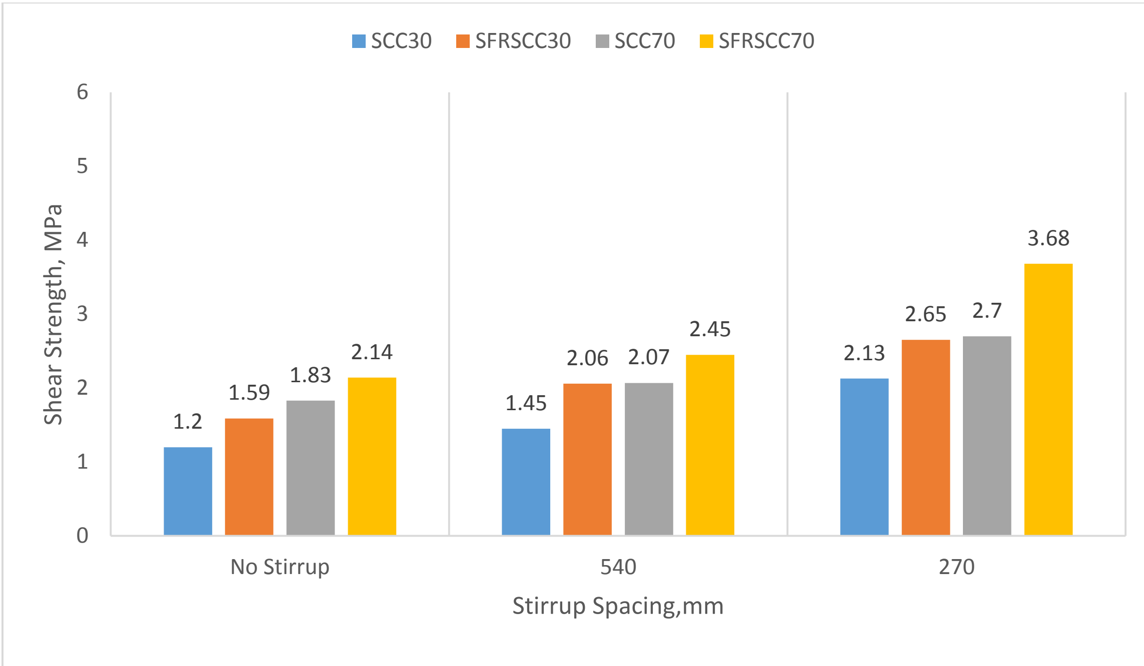

Figure: 7.19 Shear Strength vs Spacing of Stirrup for a/d=3

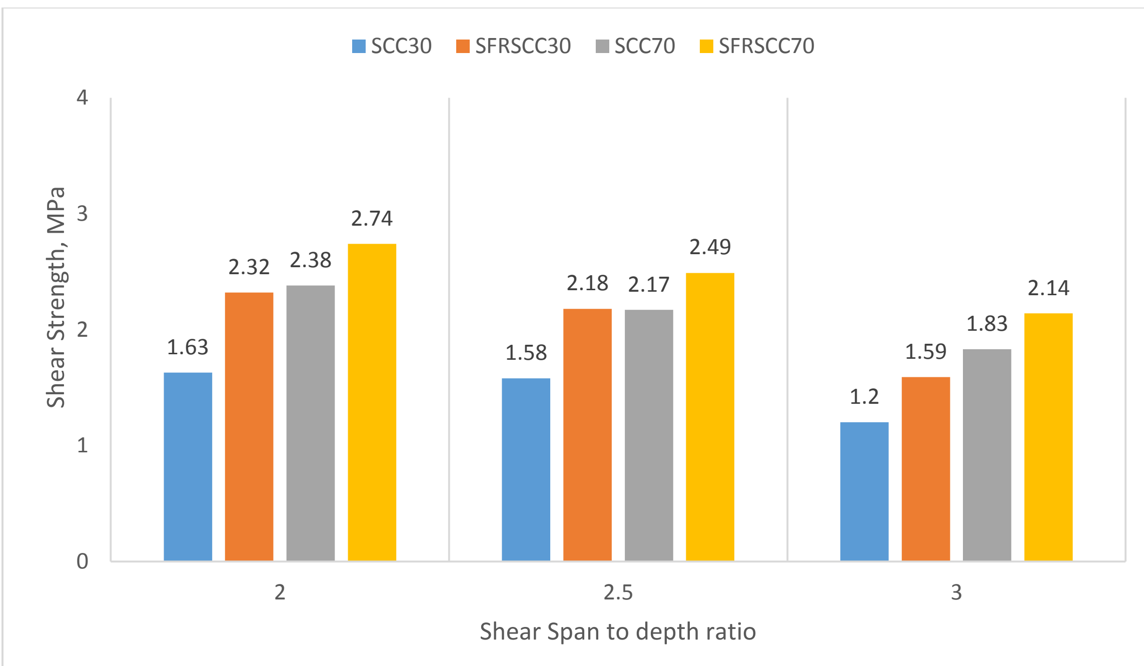

Figure: 7.20 Shear Strength vs Shear Span to depth ratio (a/d)

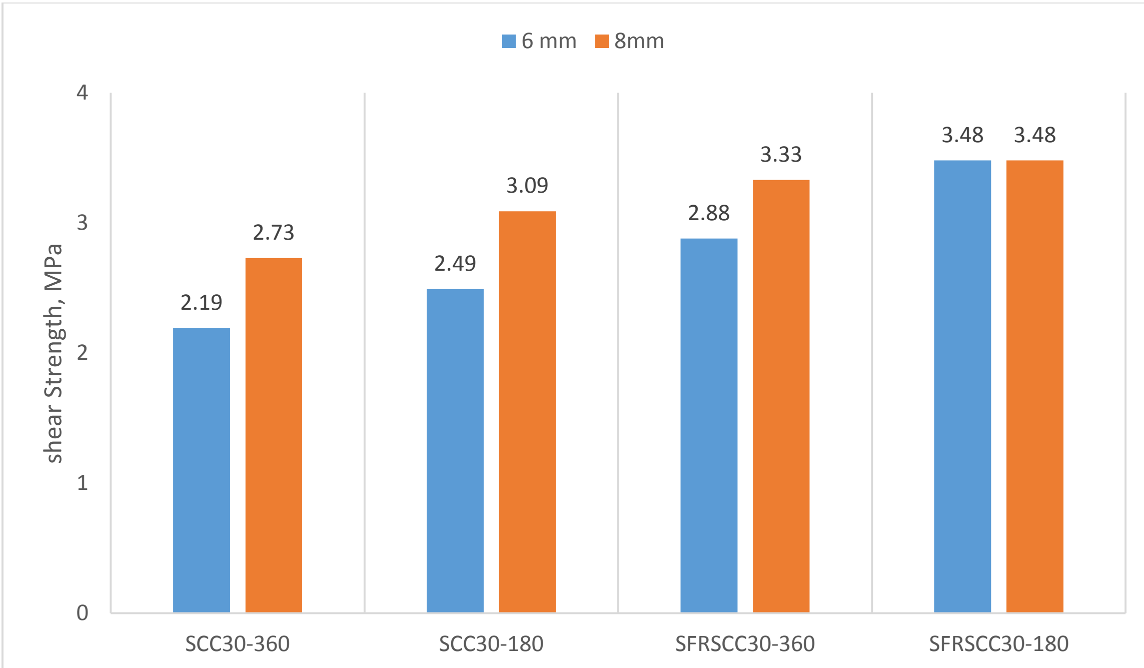

Figure: 7.21 Comparison of Shear Strength vs Stirrup diameter for SCC30 (a/d=2)

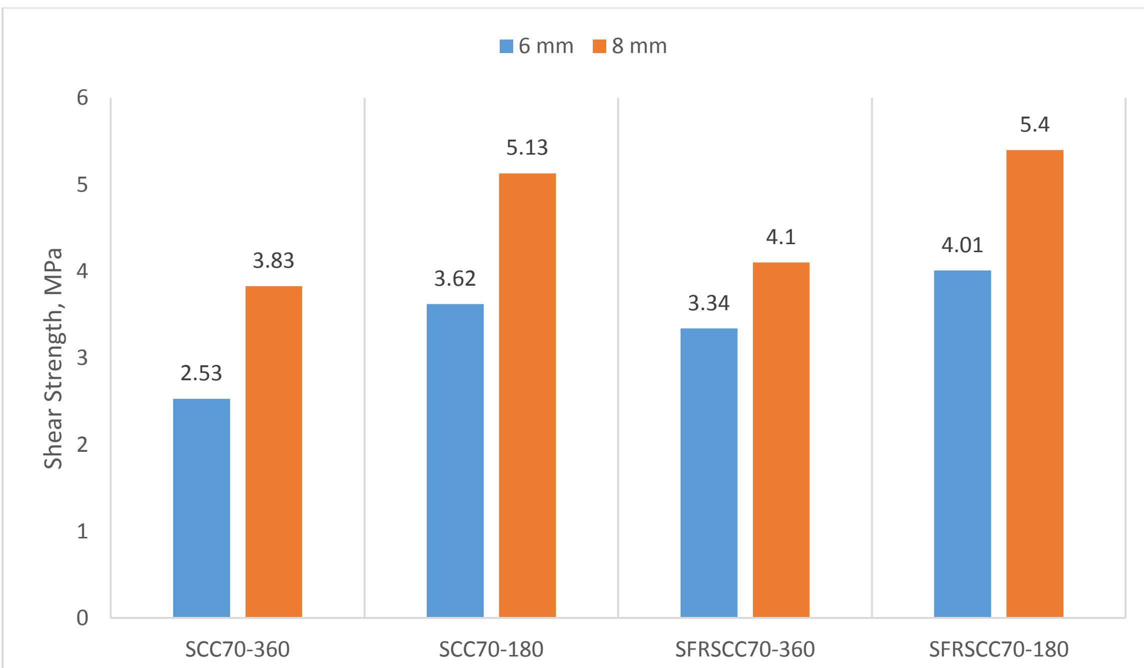

Figure: 7.22 Comparison of Shear Strength vs Stirrup diameter for SCC70 (a/d=2)

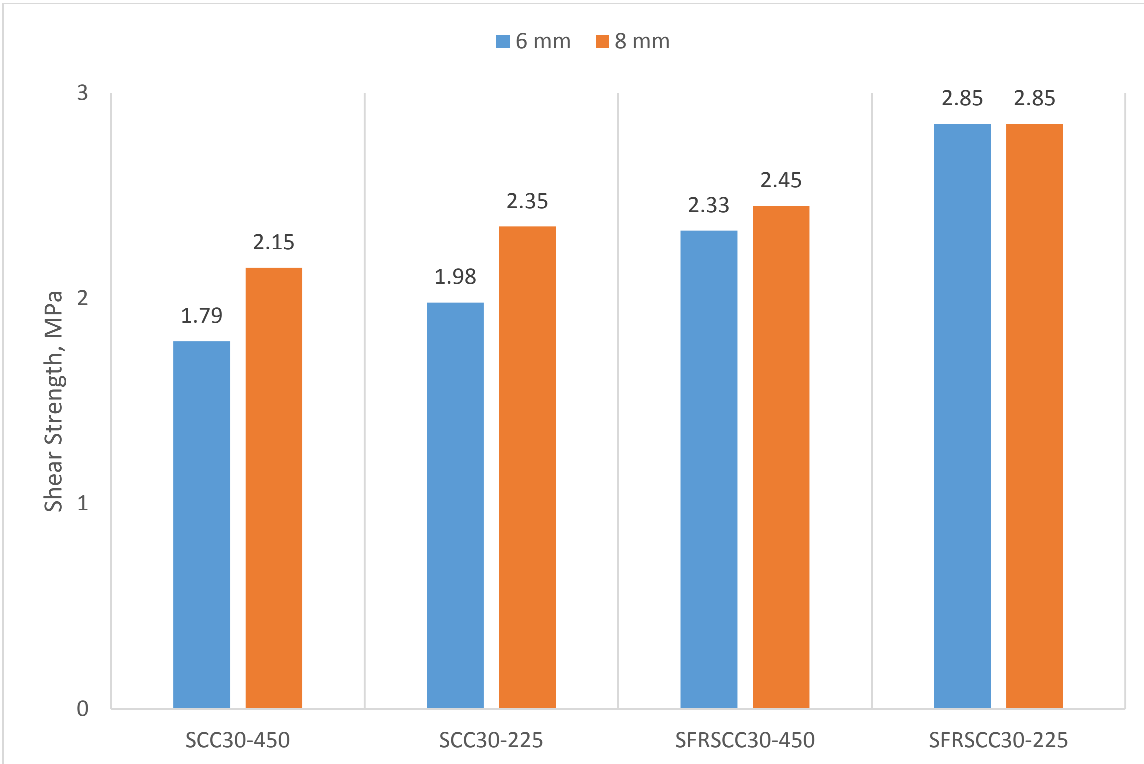

Figure: 7.23 Comparison Shear Strength vs Stirrup diameter for SCC30 (a/d=2.5)

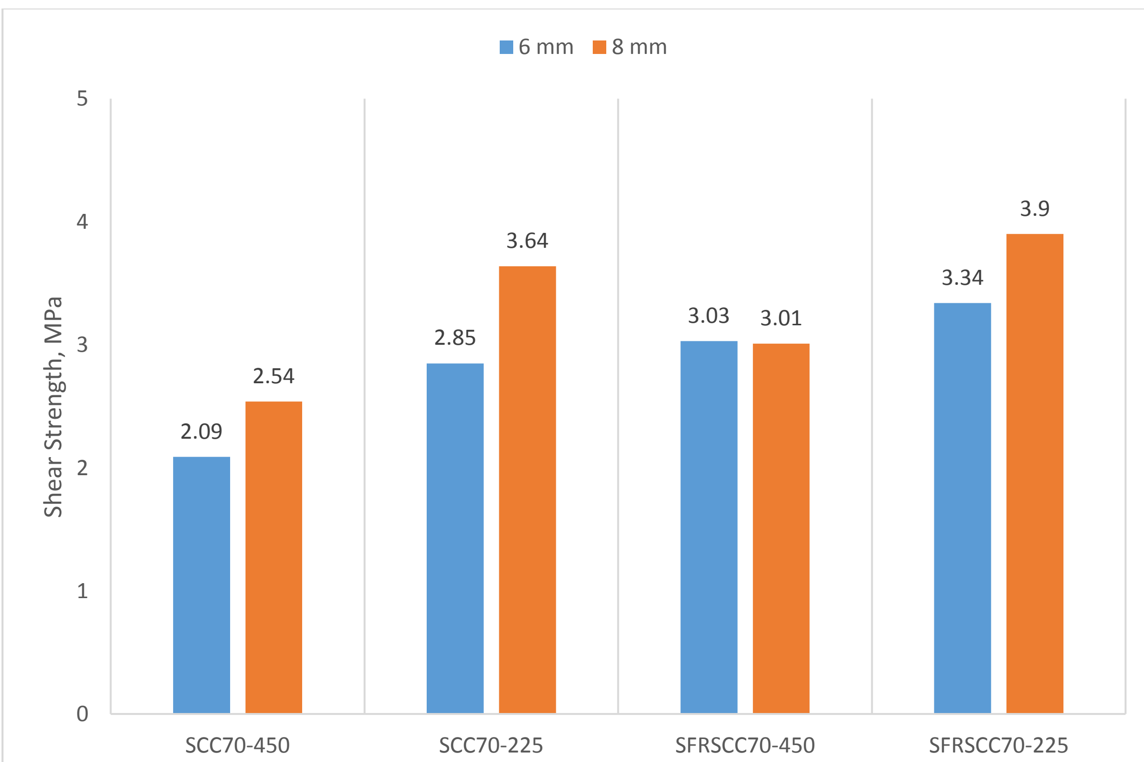

Figure: 7.24 Comparison Shear Strength vs Stirrup diameter for SCC70 (a/d=2.5)

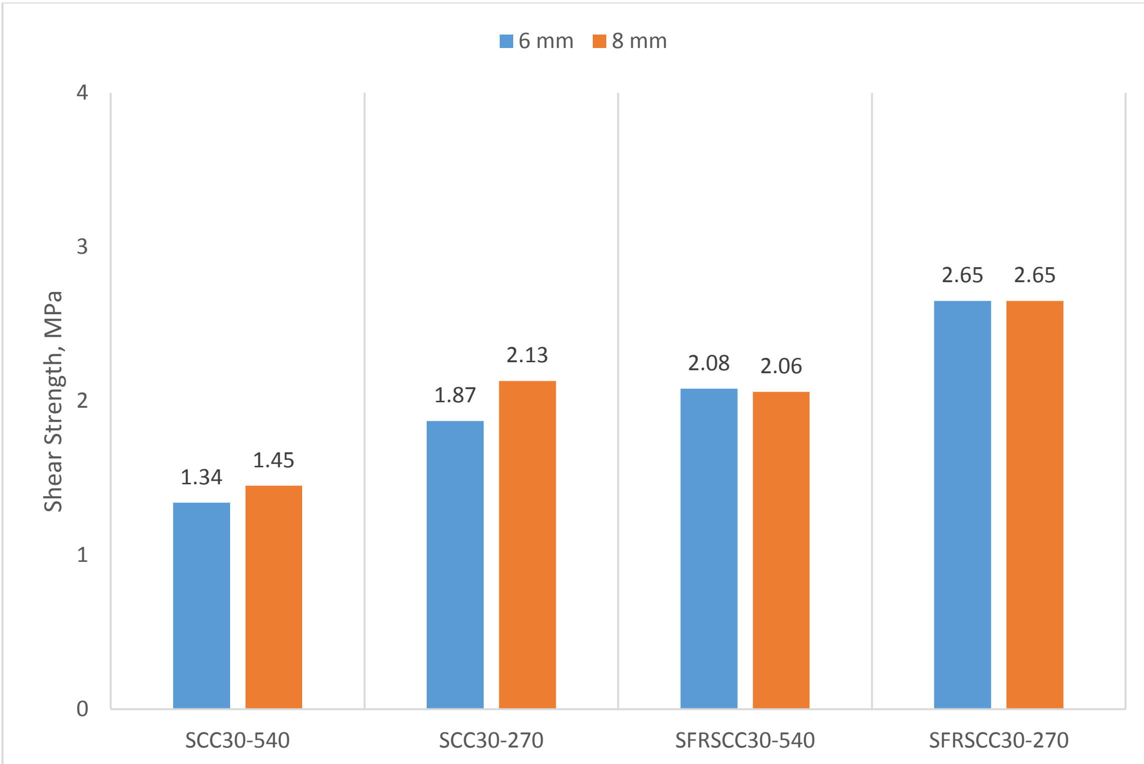

Figure: 7.25 Comparison Shear Strength vs Stirrup diameter for SCC30 (a/d=3)

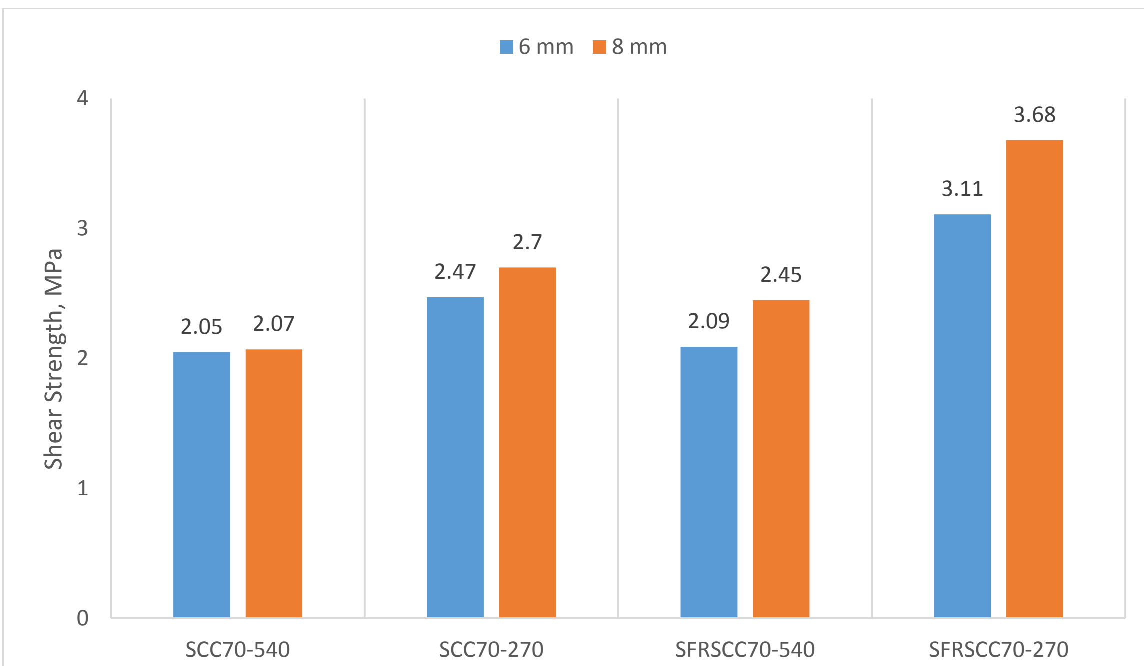

Figure: 7.26 Comparison Shear Strength vs Stirrup diameter for SCC70 (a/d=3)

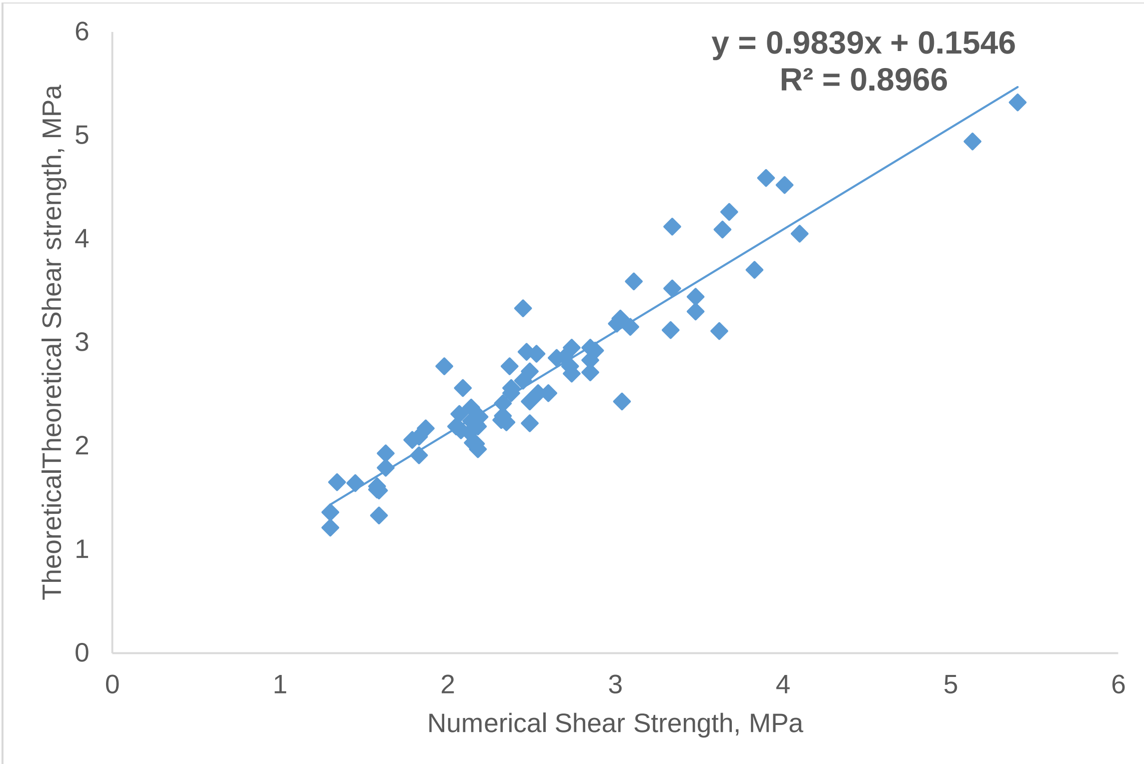

Figure: 7.27 Comparison Numerical Shear Strength vs Theoretical Shear strength for NASCC30 and NASCC70

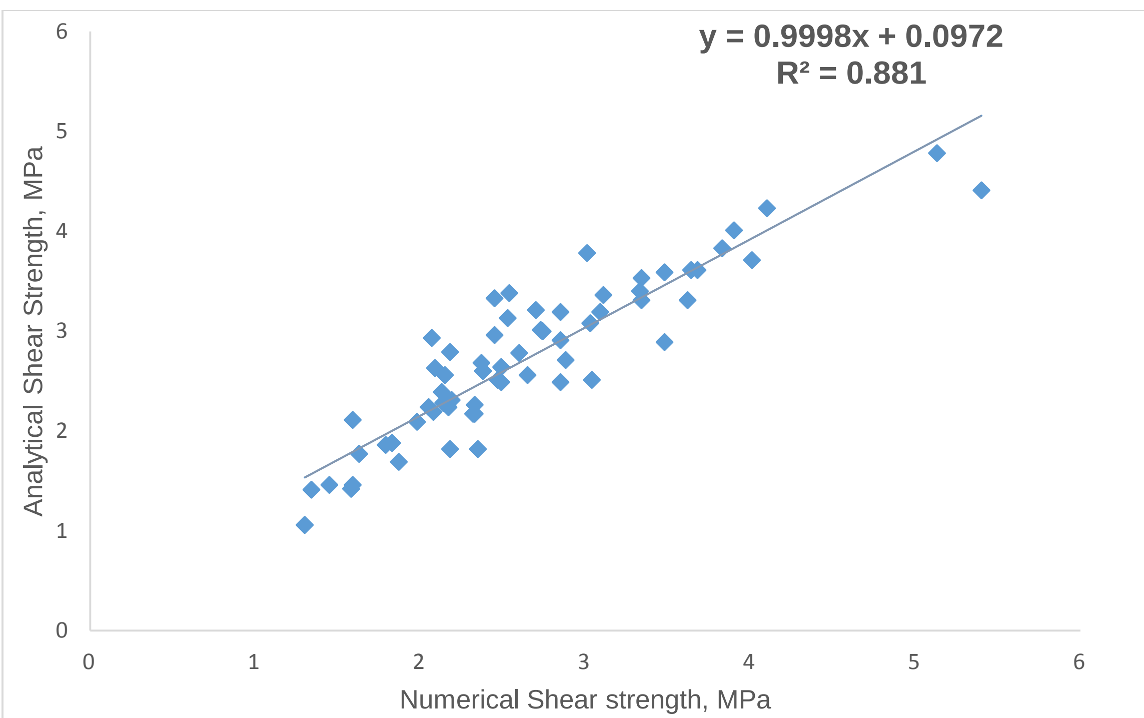

Figure: 7.28 Comparison Numerical Shear Strength vs Analytical Shear strength for NASCC30 and NASCC70

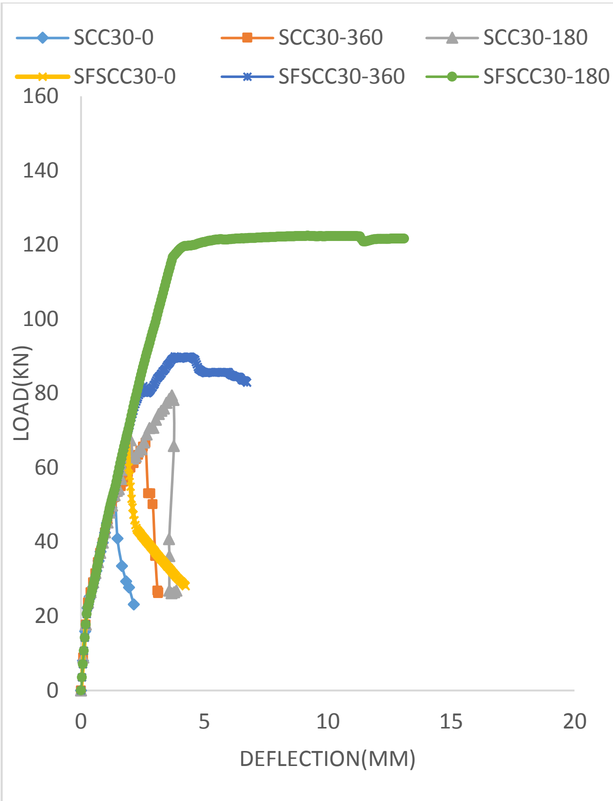

Figure 7.29: Load Vs Deflection for RASCC30; a/d=2

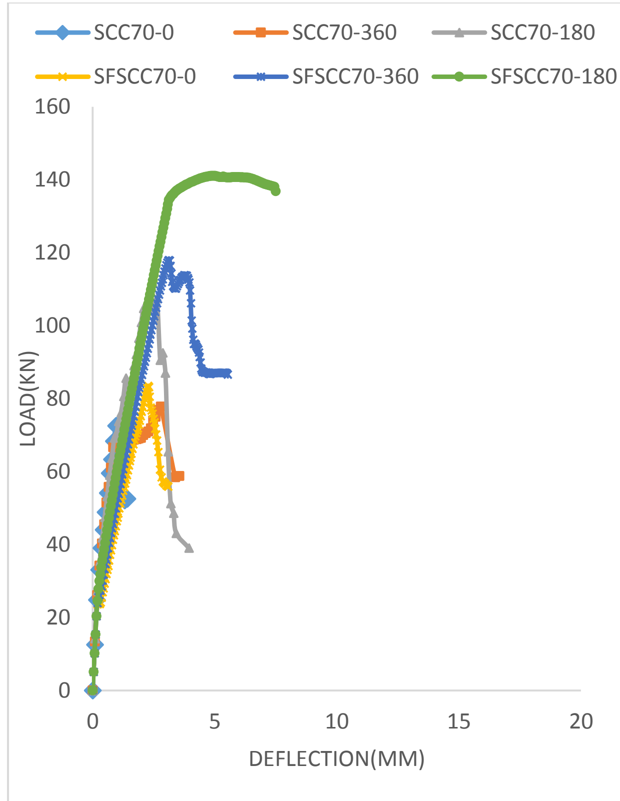

Figure 7.30: Load Vs Deflection for RASCC70; a/d=2

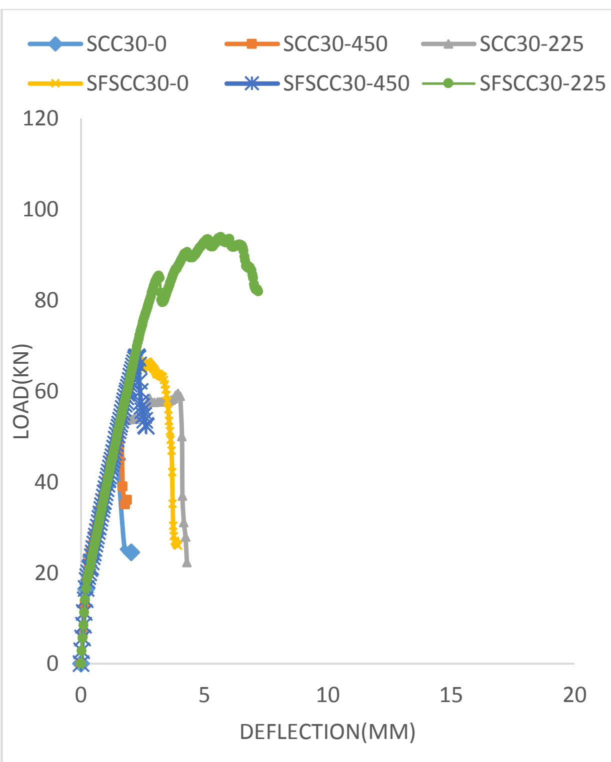

Figure 7.31: Load Vs Deflection for RASCC30; a/d=2.5

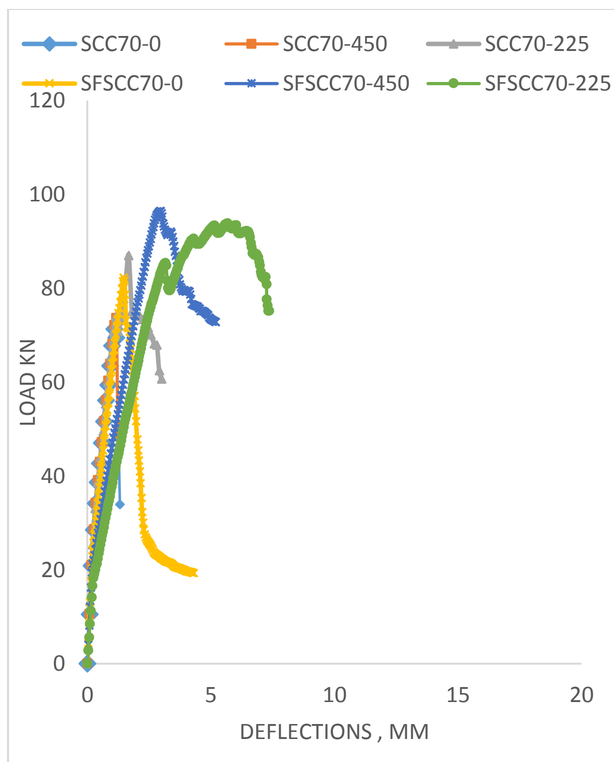

Figure 7.32: Load Vs Deflection for RASCC70;a/d=2.5

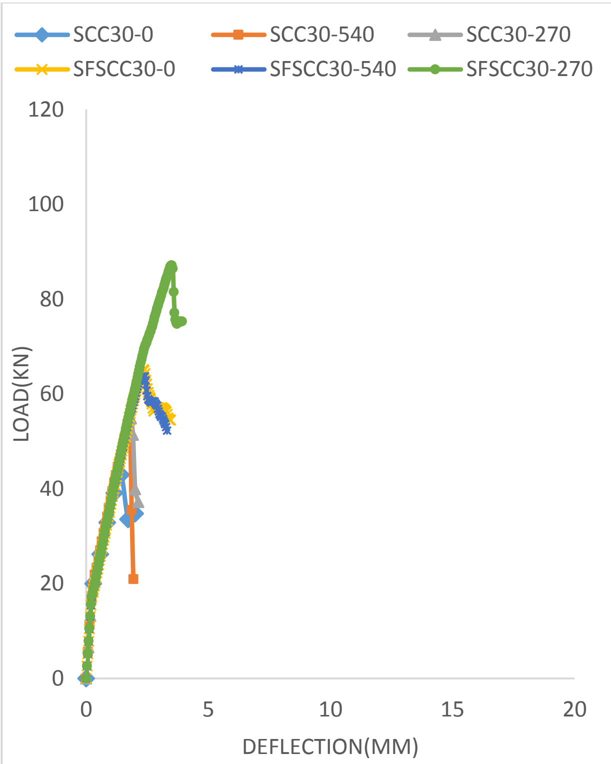

Figure 7.33: Load Vs Deflection for RASCC30 ; a/d=3

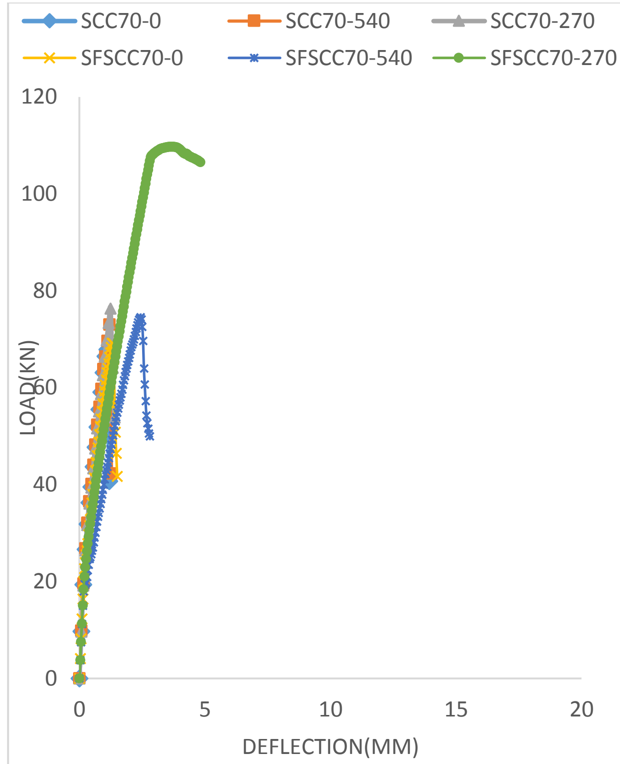

Figure 7.34: Load Vs Deflection for RASCC70; a/d=3

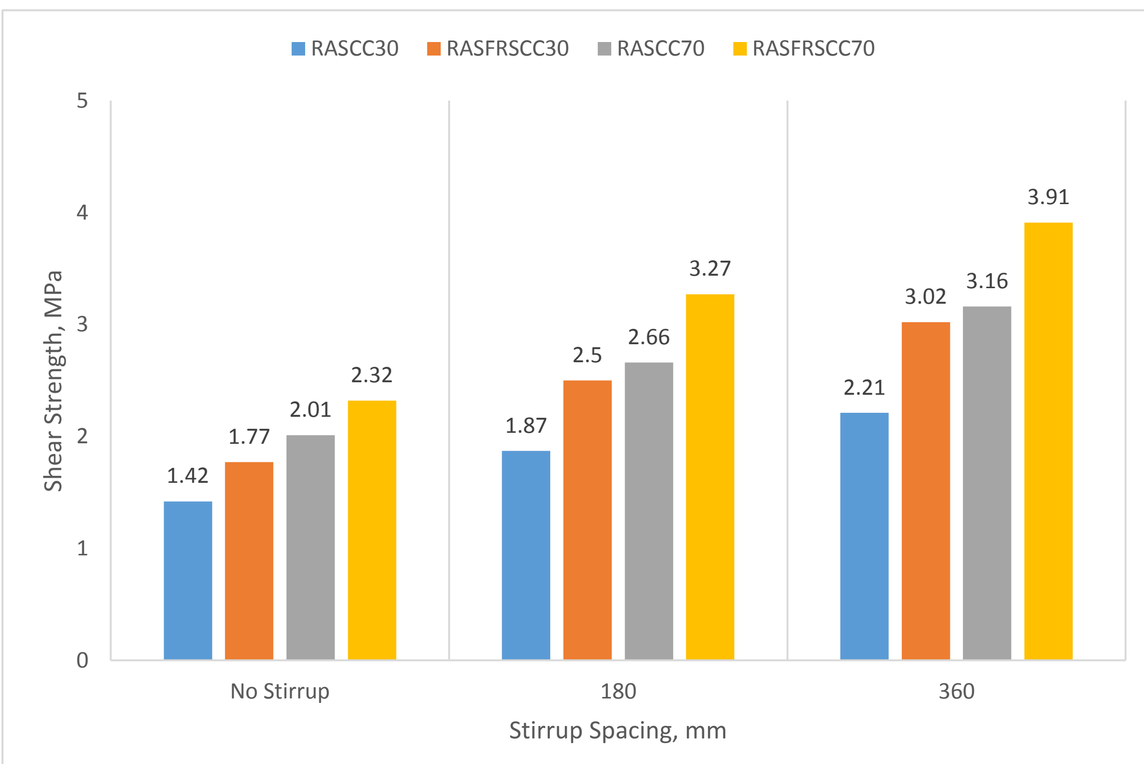

Figure: 7.35 Shear strength vs stirrup spacing for a/d=2

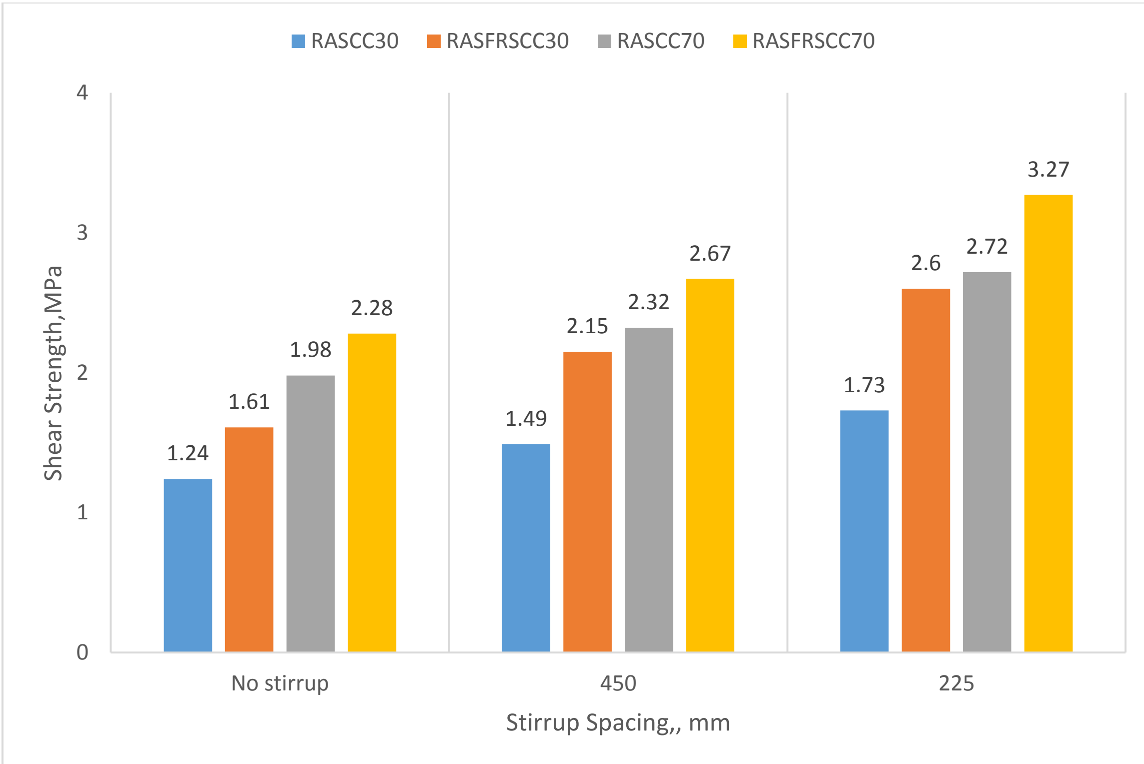

Figure: 7.36 Shear strength vs stirrup spacing for a/d=2.5

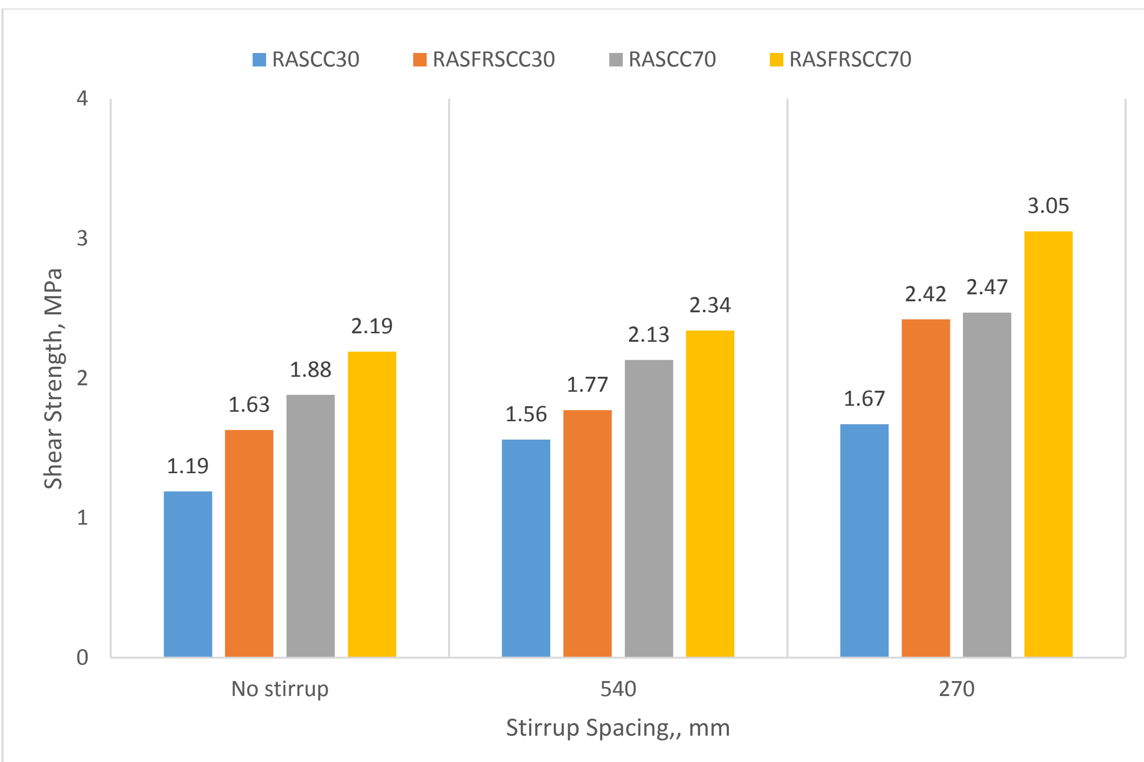

Figure: 7.37 Shear strength vs stirrup spacing for a/d=3

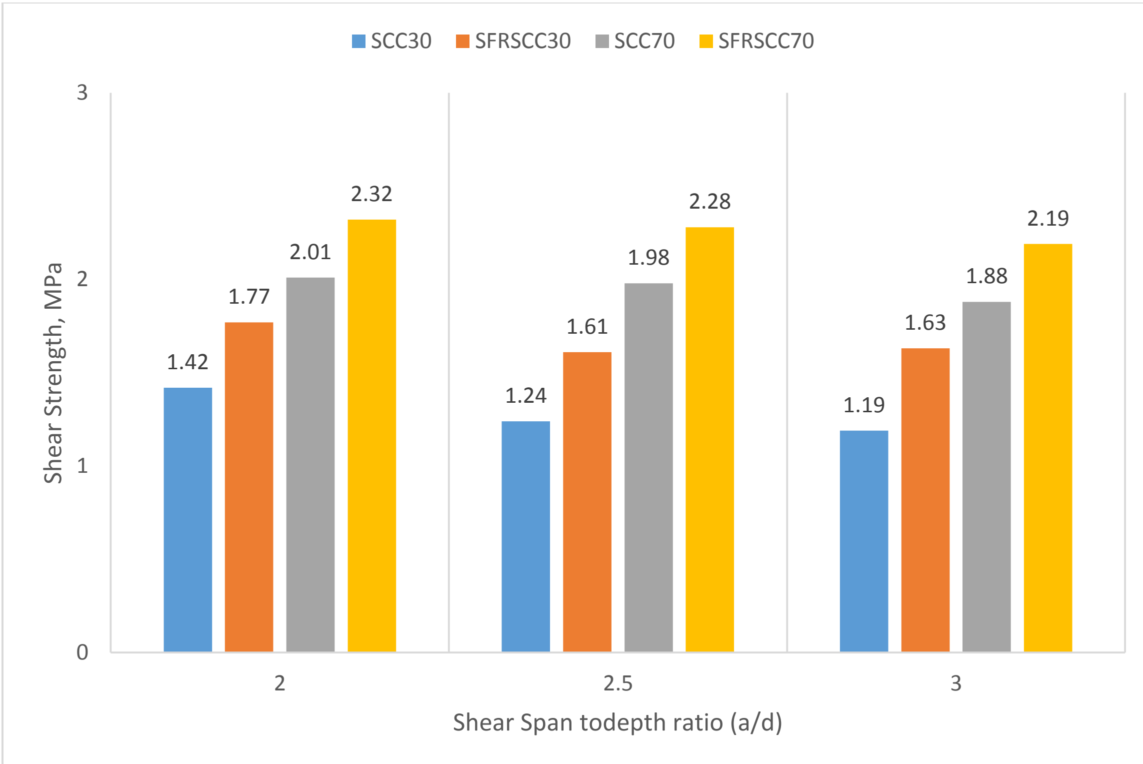

Figure: 7.38 Shear Strength vs shear span to depth ratio (a/d) for plain beams

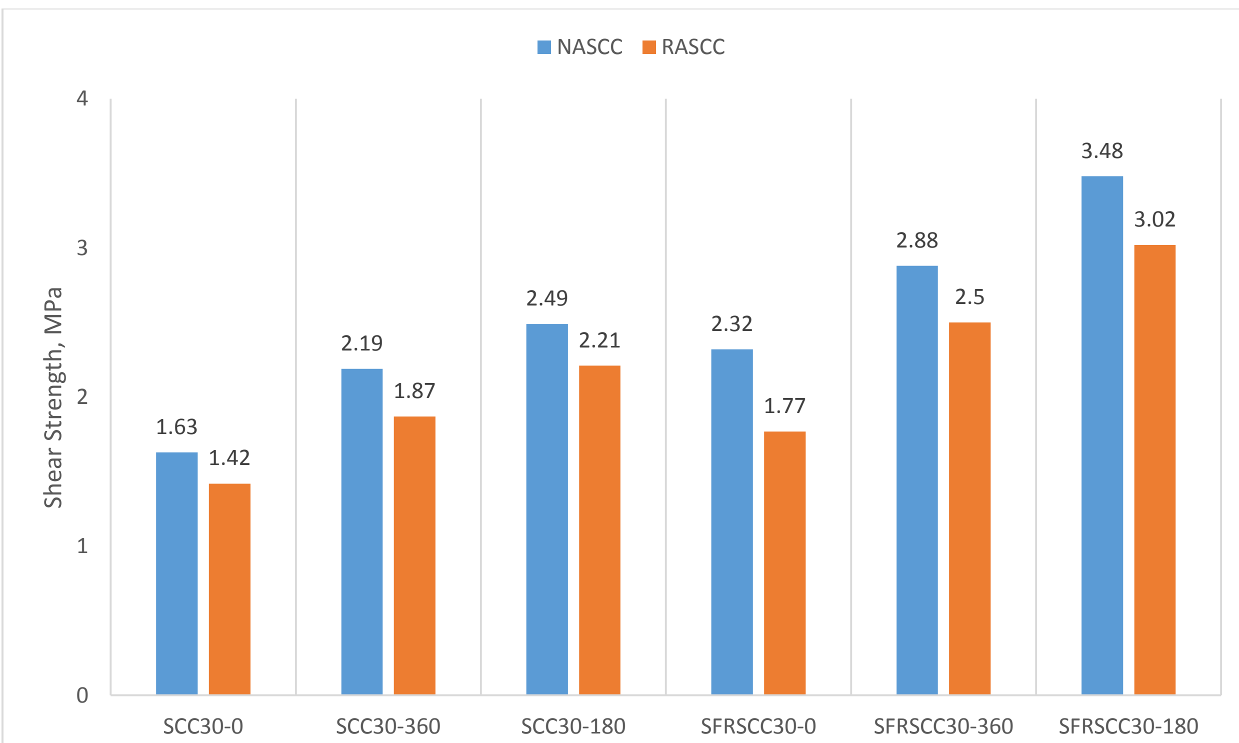

Figure: 7.39 Comparison of shear strength of NASCC30 and RASCC30 for a/d=2

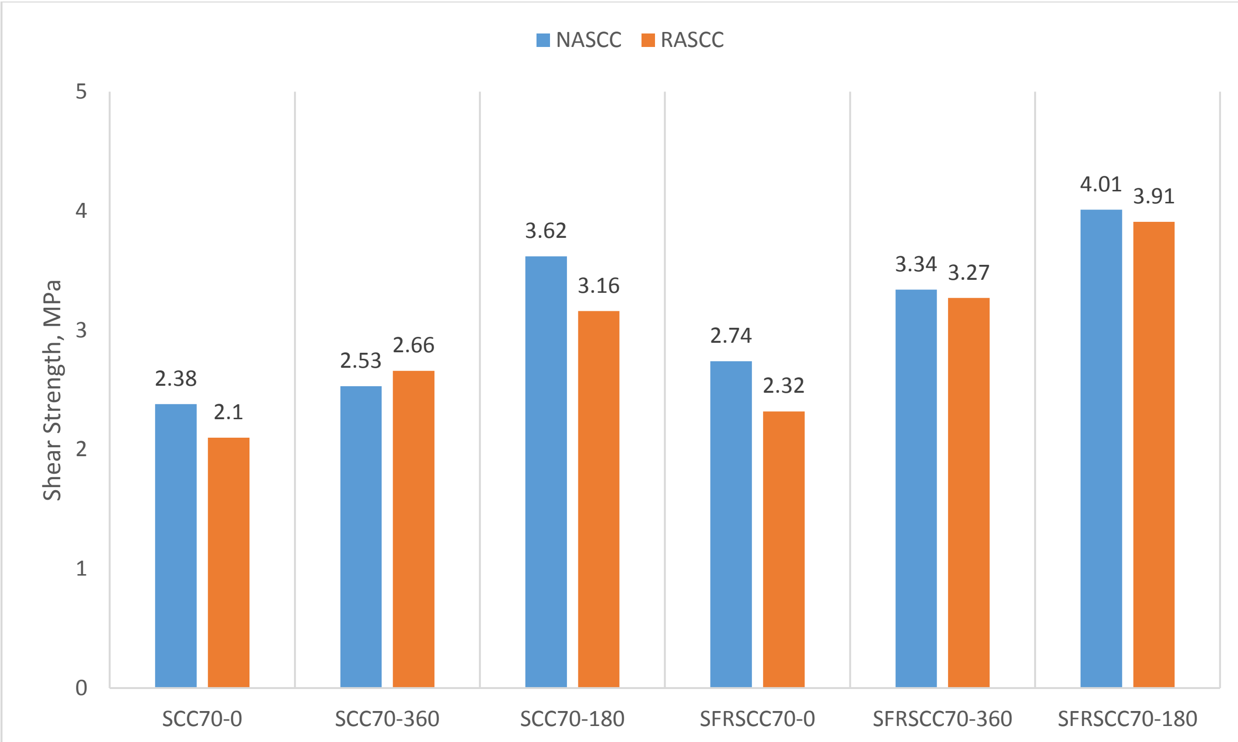

Figure: 7.40 Comparison of shear strength of NASCC70 and RASCC70, for a/d=2

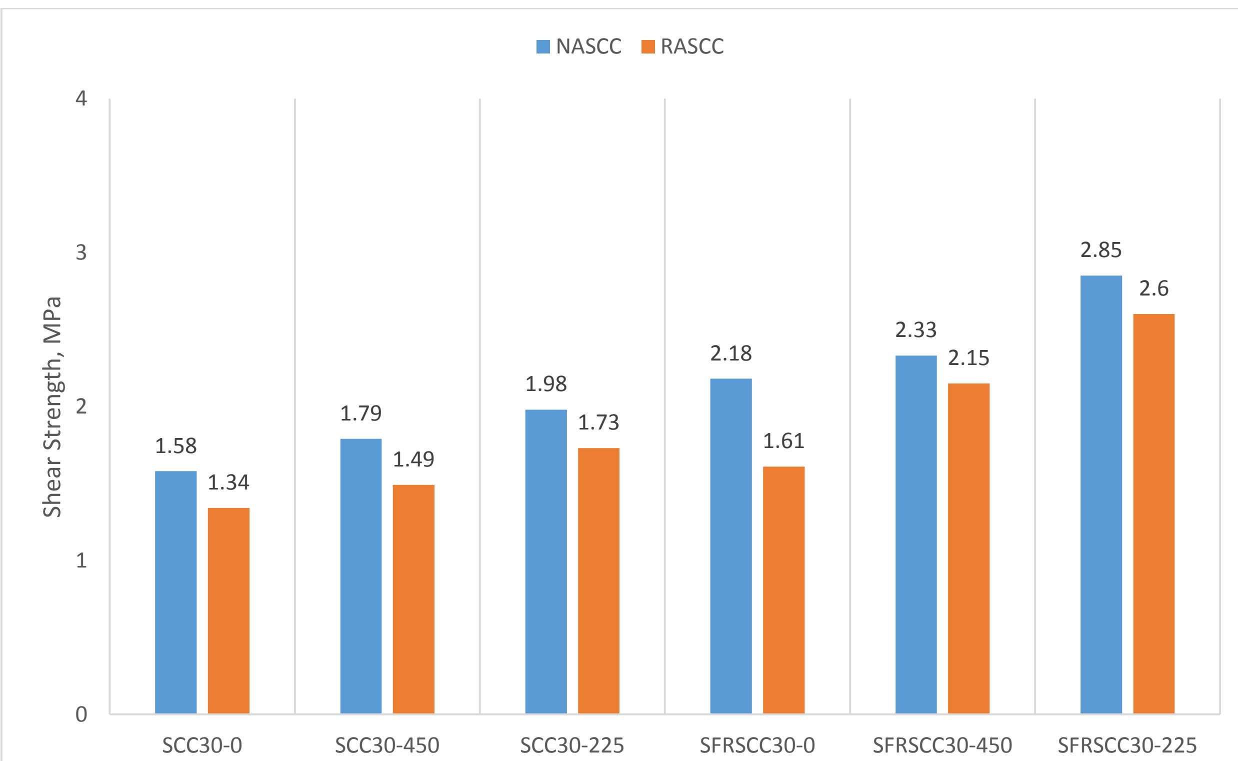

Figure: 7.41 Comparison of shear strength of NASCC30 and RASCC30, for a/d=2.5

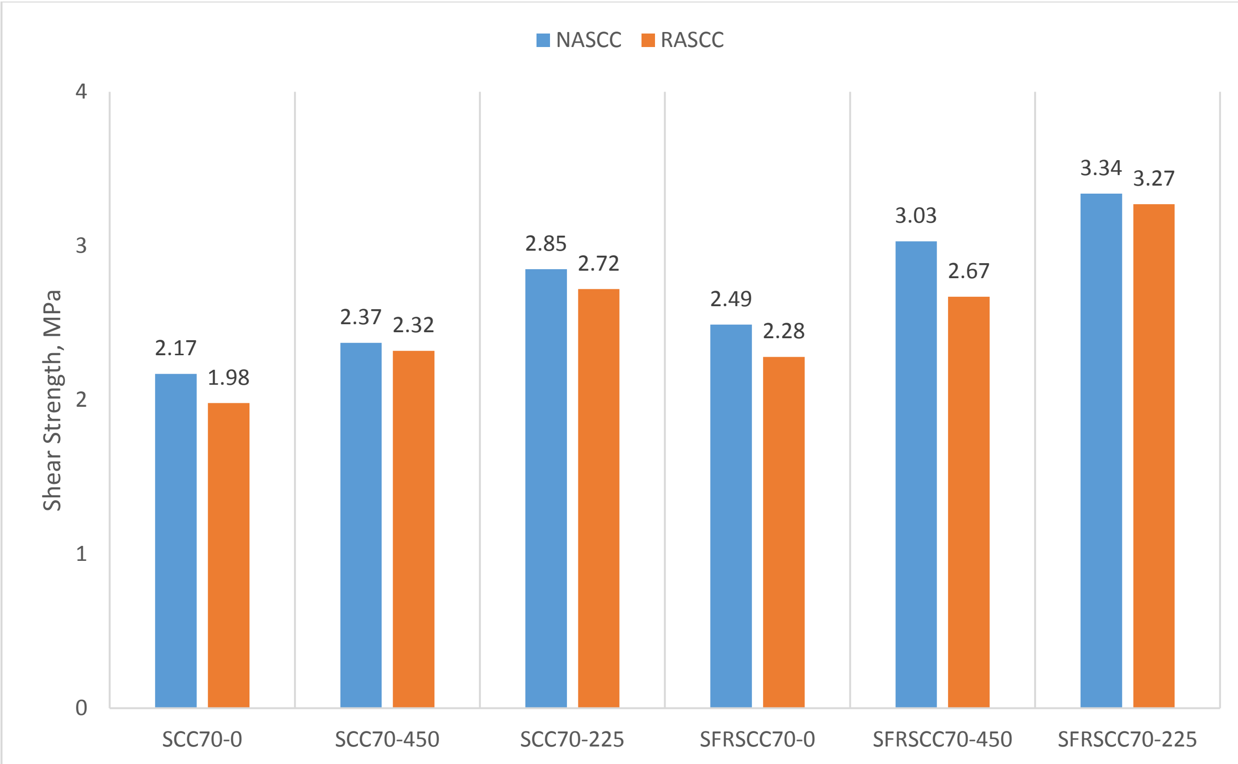

Figure: 7.42 Comparison of shear strength of NASCC70 and RASCC70, for a/d=2.5

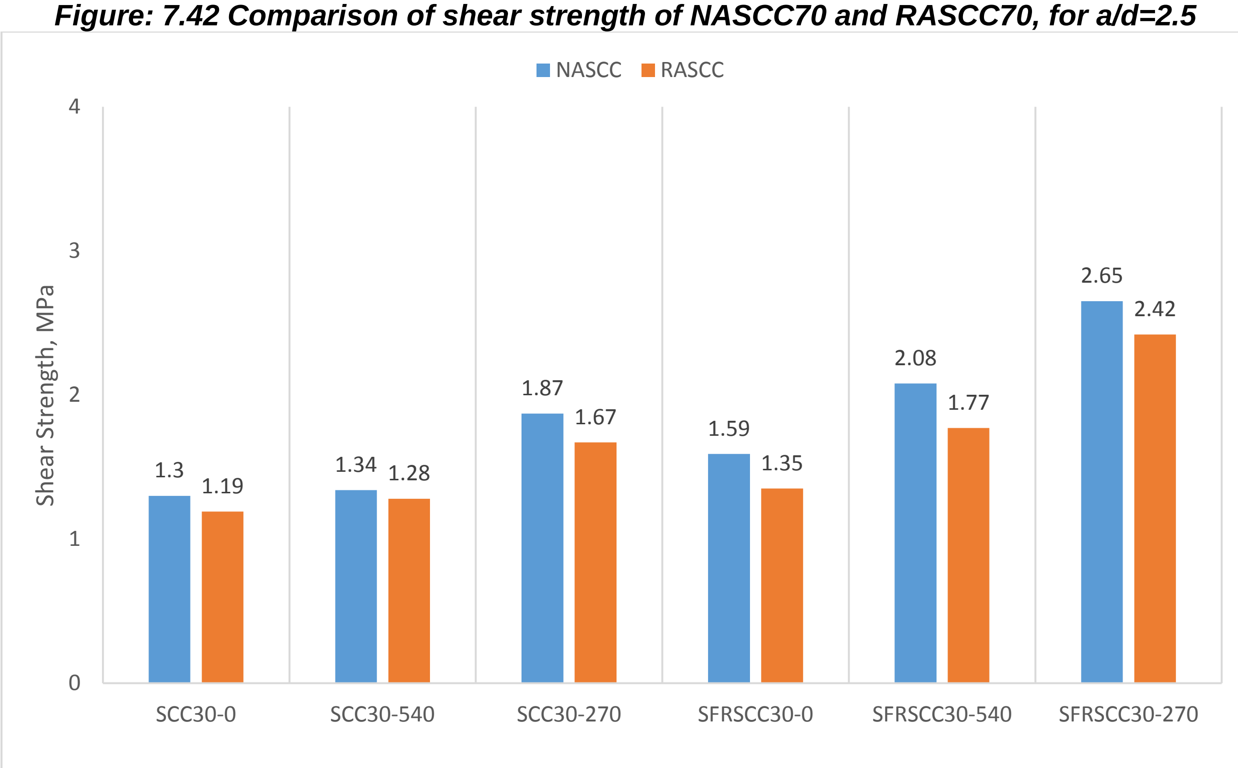

Figure: 7.43 Comparison of shear strength of NASCC30 and RASCC30, for a/d=3

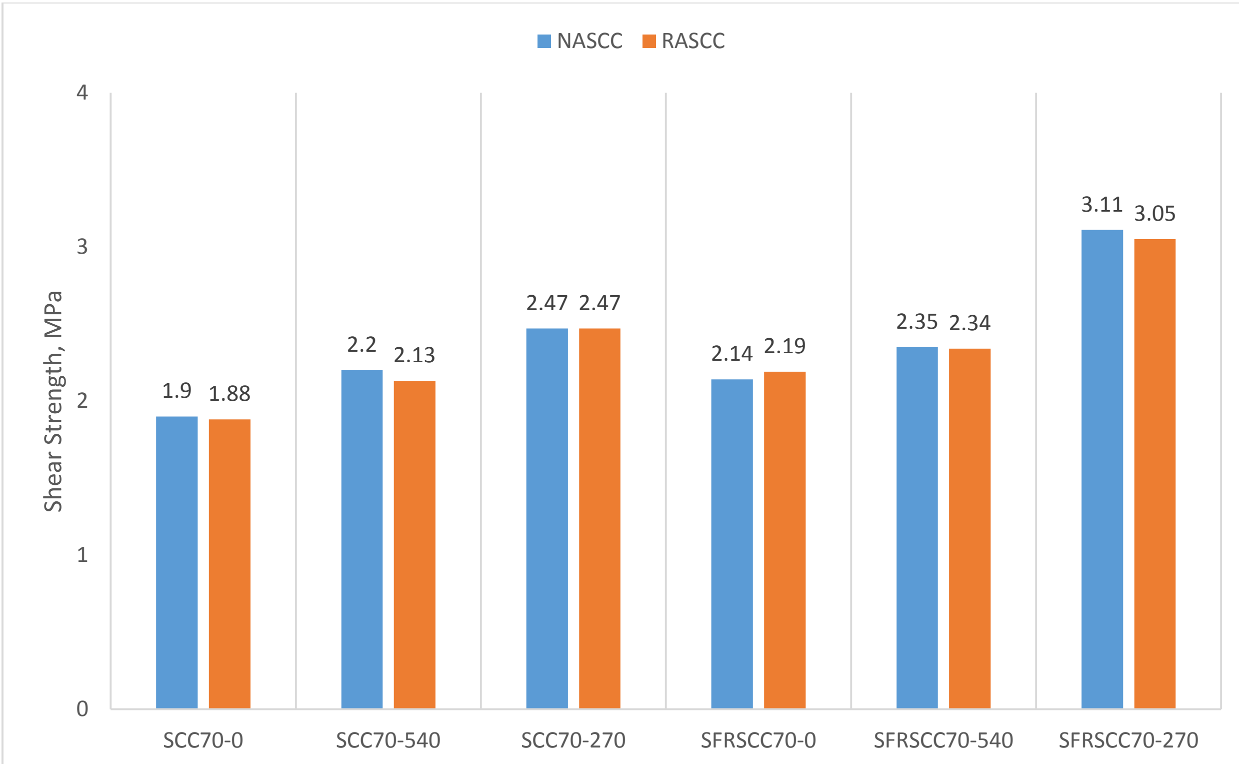

Figure: 7.44 Comparison of shear strength of NASCC70 and RASCC70, for a/d=3

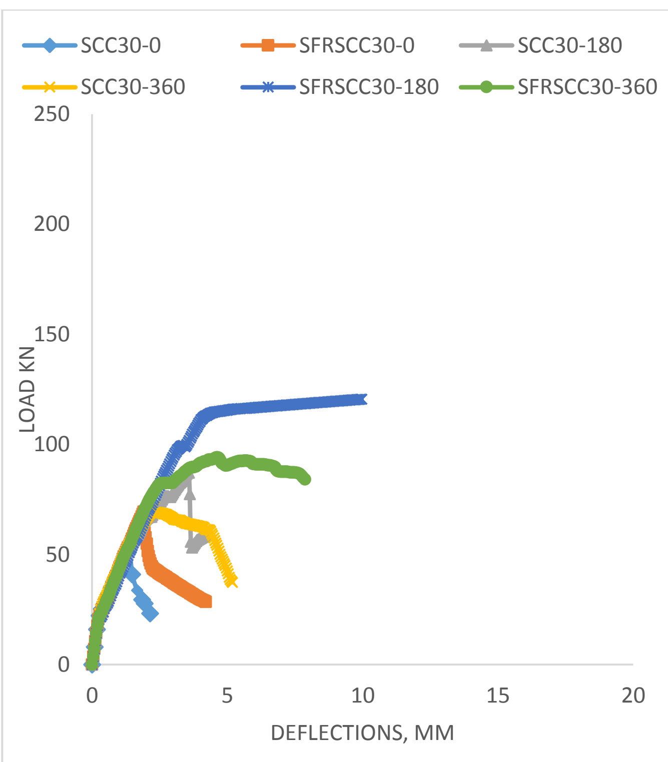

Figure 7.45: Load Vs Deflection for RASCC30; a/d=2

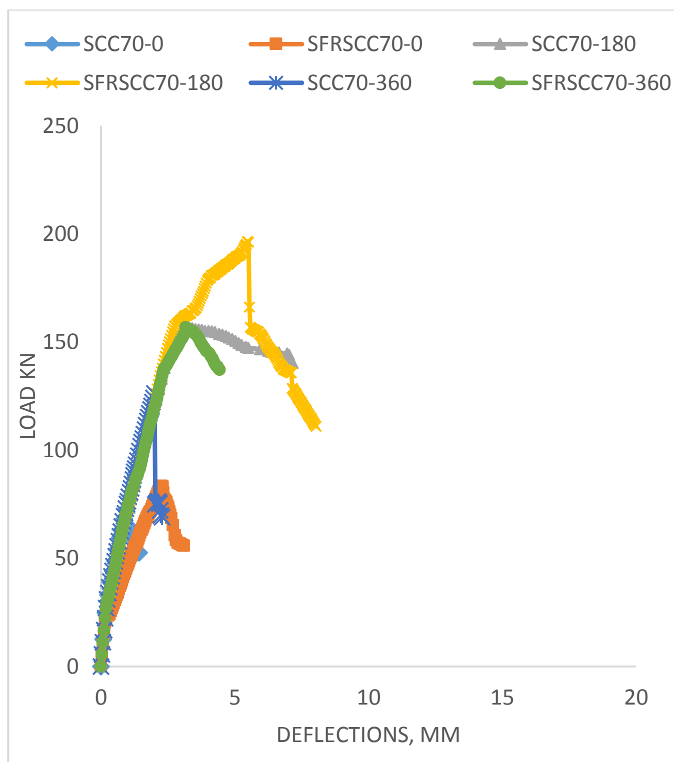

Figure 7.46: Load Vs Deflection for RASCC70; a/d=2

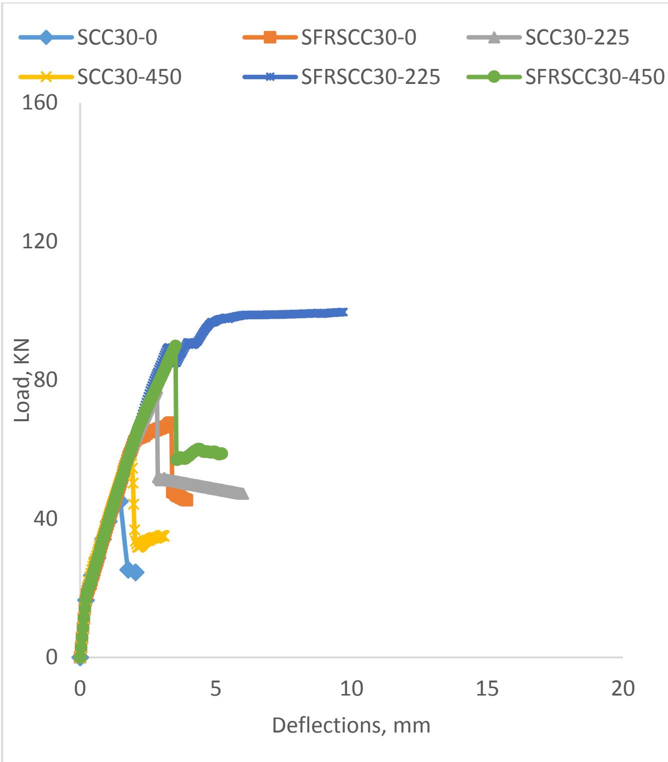

Figure 7.47: Load Vs Deflection for RASCC30; a/d=2.5

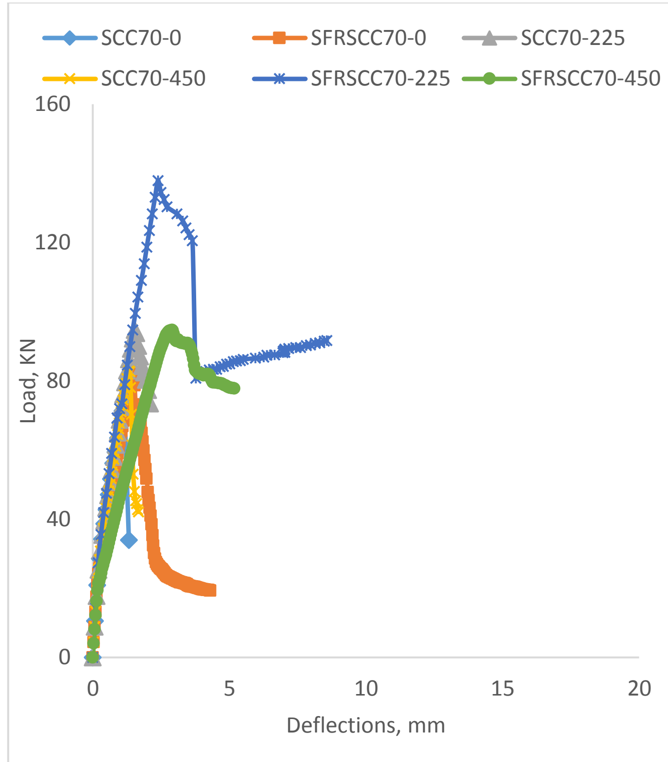

Figure 7.48: Load Vs Deflection for RASCC70; a/d=2.5

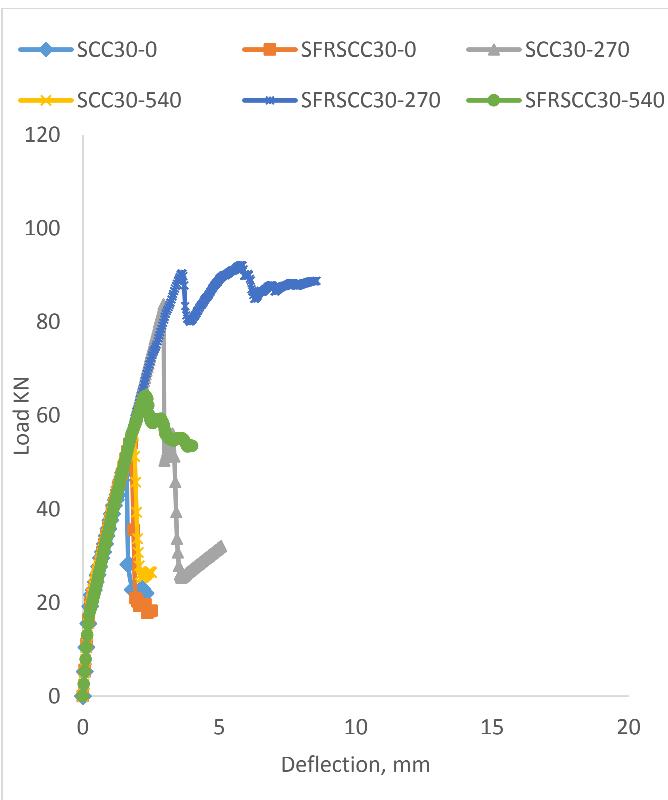

Figure 7.49: Load Vs Deflection for RASCC30; a/d=3

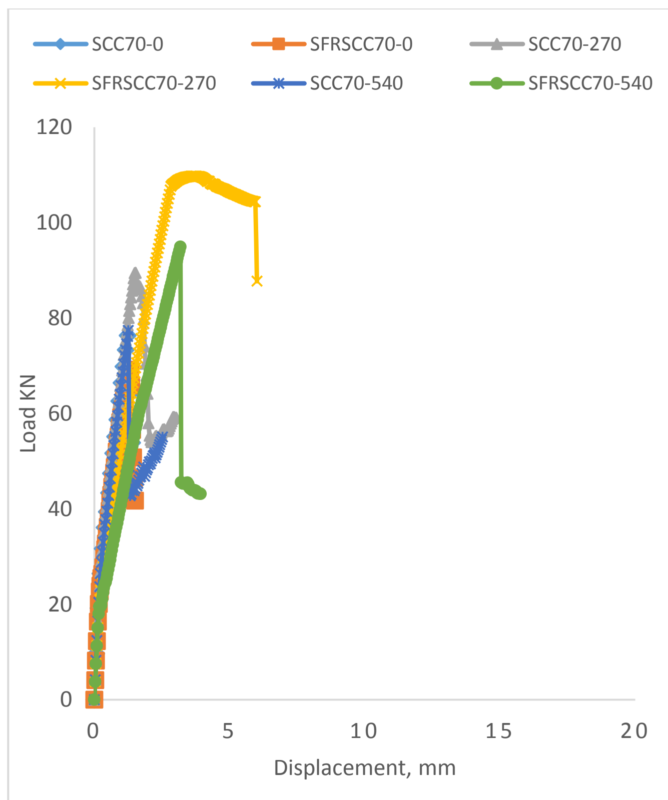

Figure 7.50: Load Vs Deflection for RASCC70; a/d=3

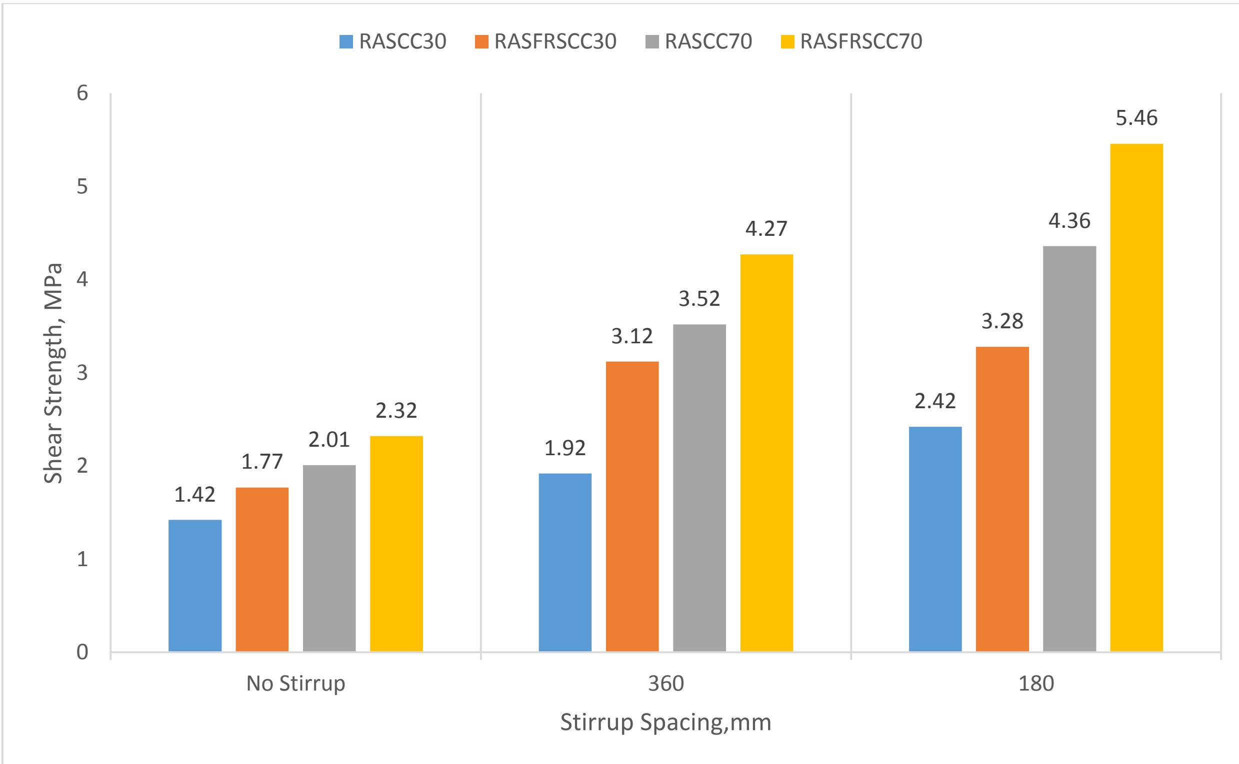

Figure 7.51: Shear strength vs Stirrups Spacing, for a/d=2

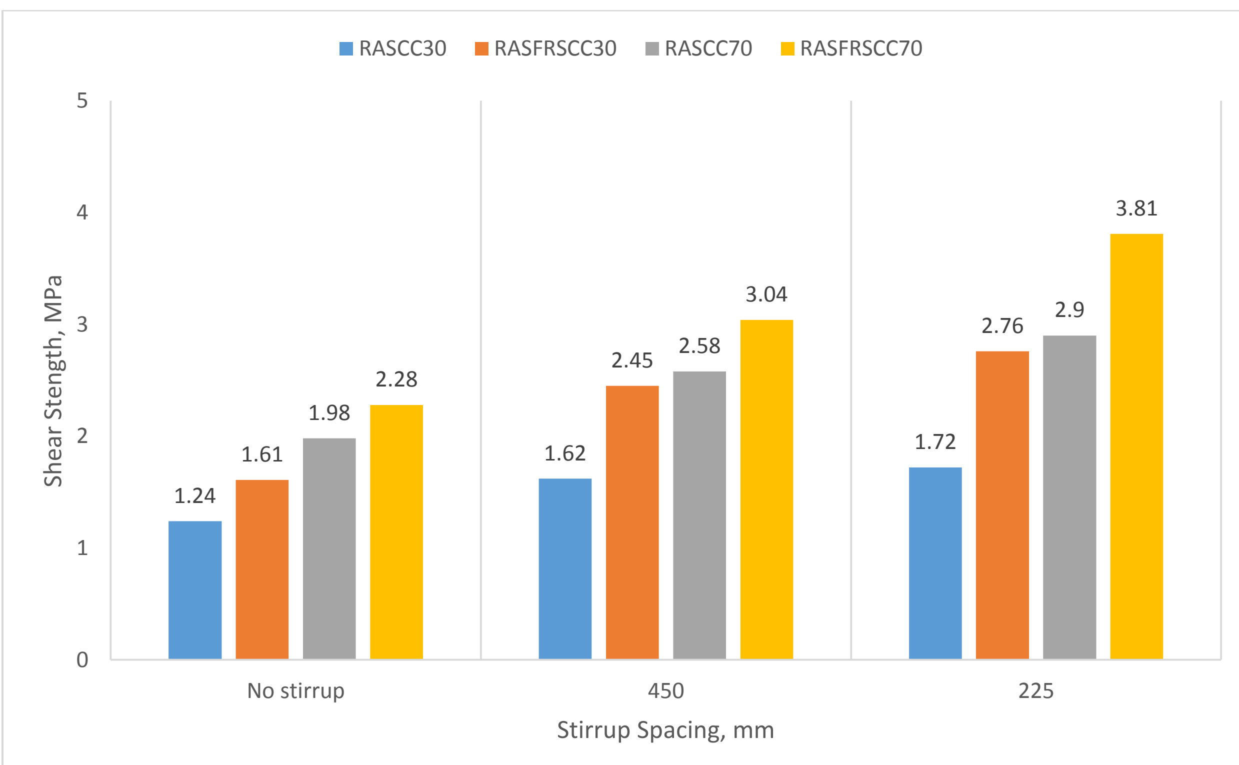

Figure 7.52: Shear strength vs Stirrups Spacing, for a/d=2.5

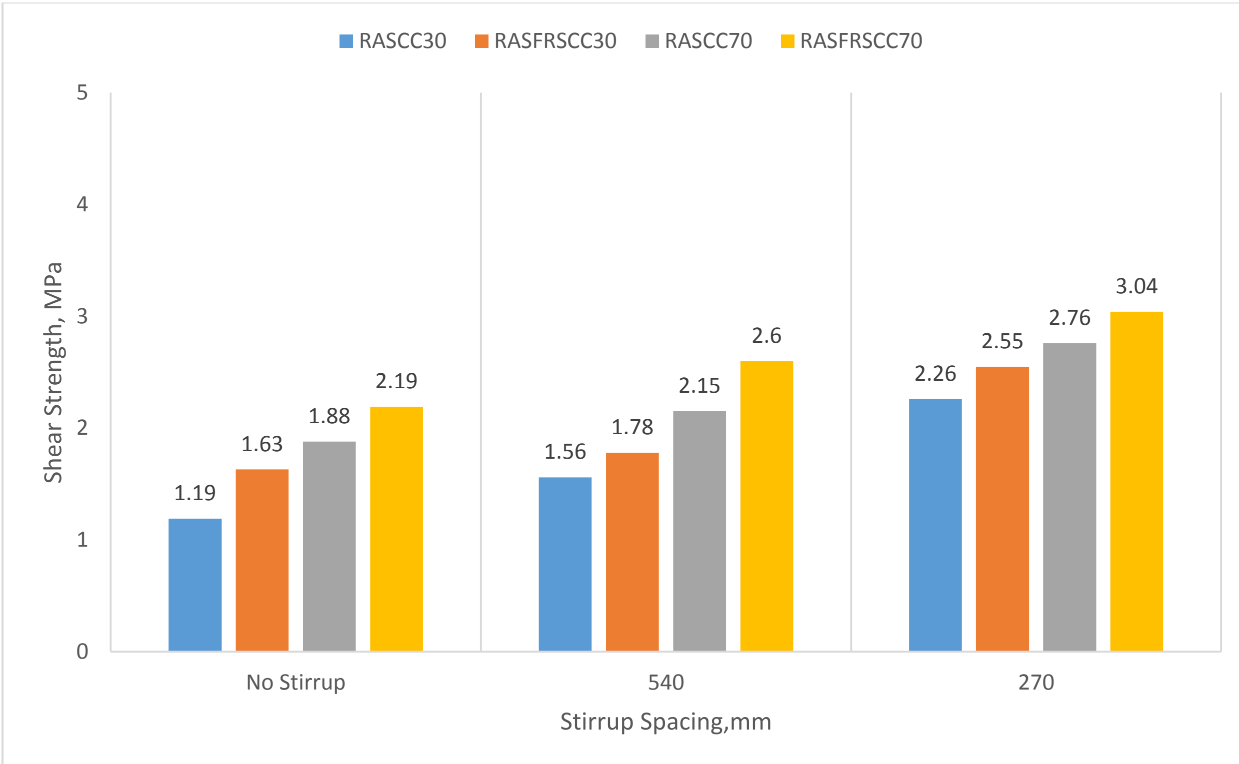

Figure 7.53: Shear strength vs Stirrups Spacing, for a/d=3

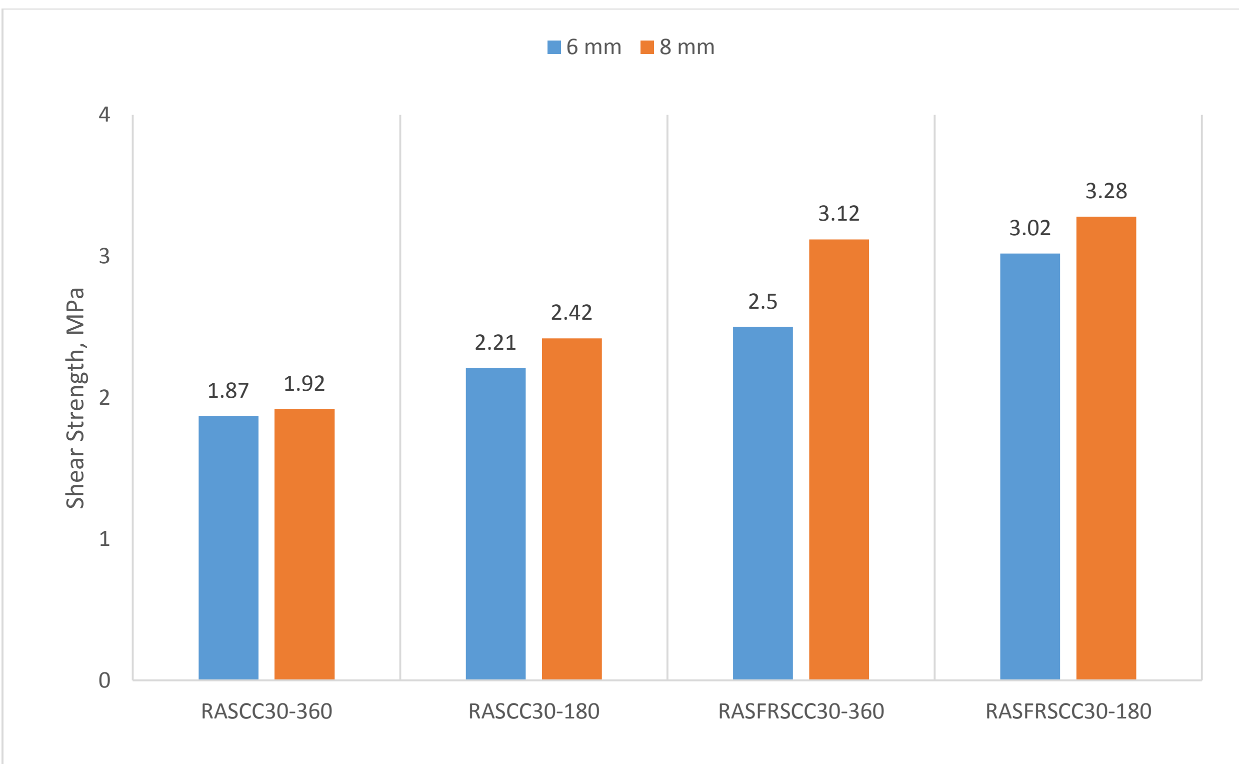

Figure 7.54 Stirrup Diameter vs Shear Strength for RASCC30, a/d=2

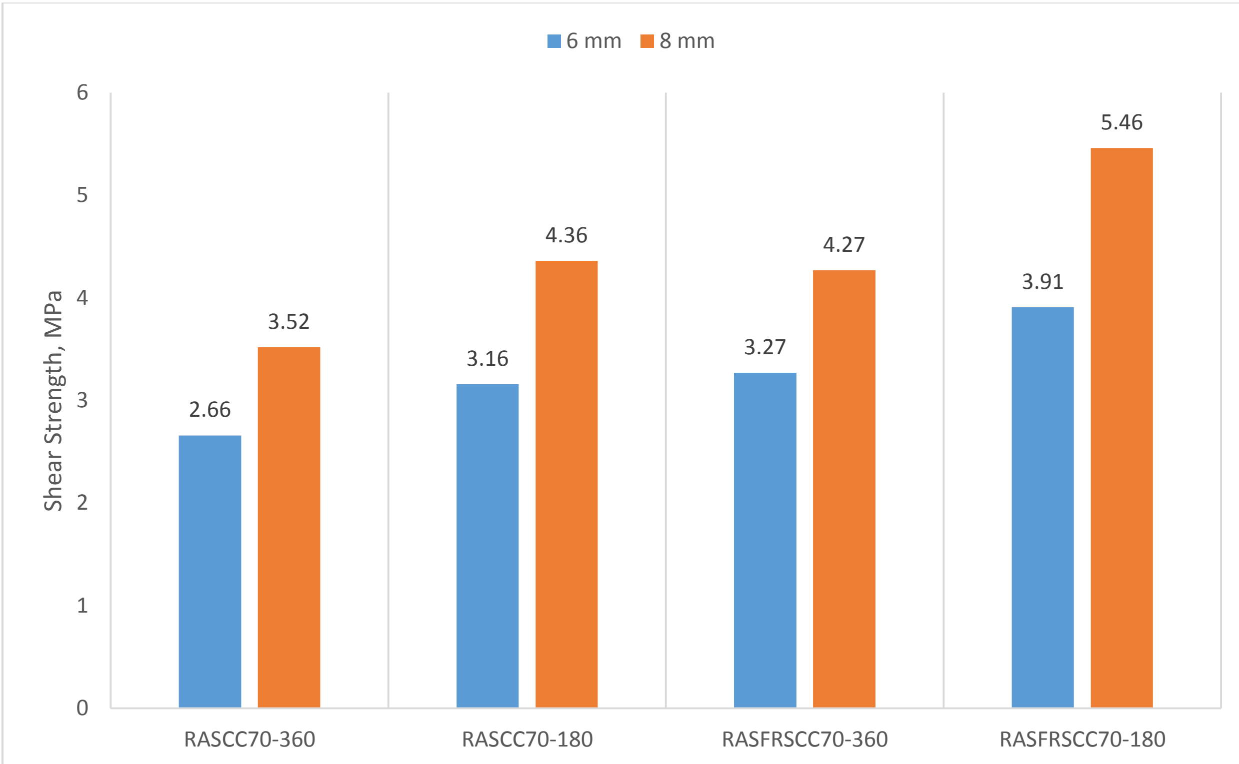

Figure 7.55 Stirrup Diameter vs Shear Strength for RASCC70, a/d=2

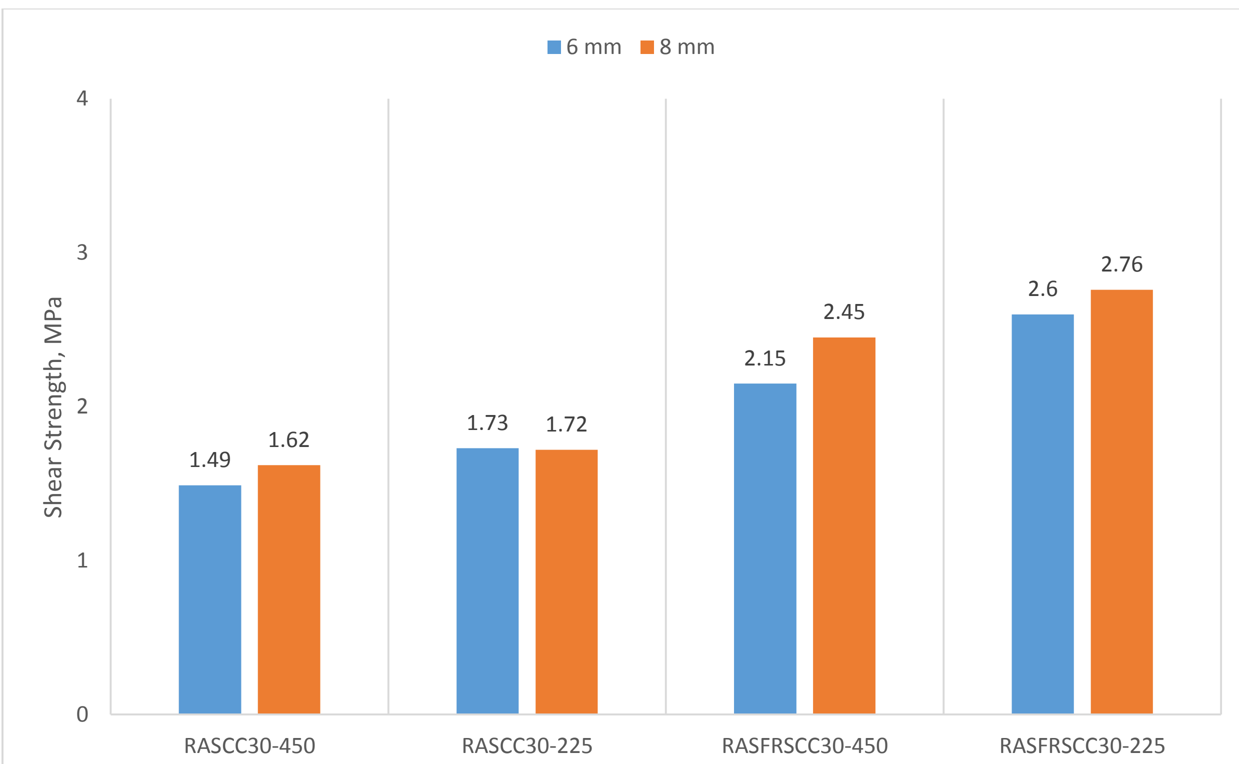

Figure 7.56 Stirrup Diameter vs Shear Strength for RASCC30, a/d=2.5

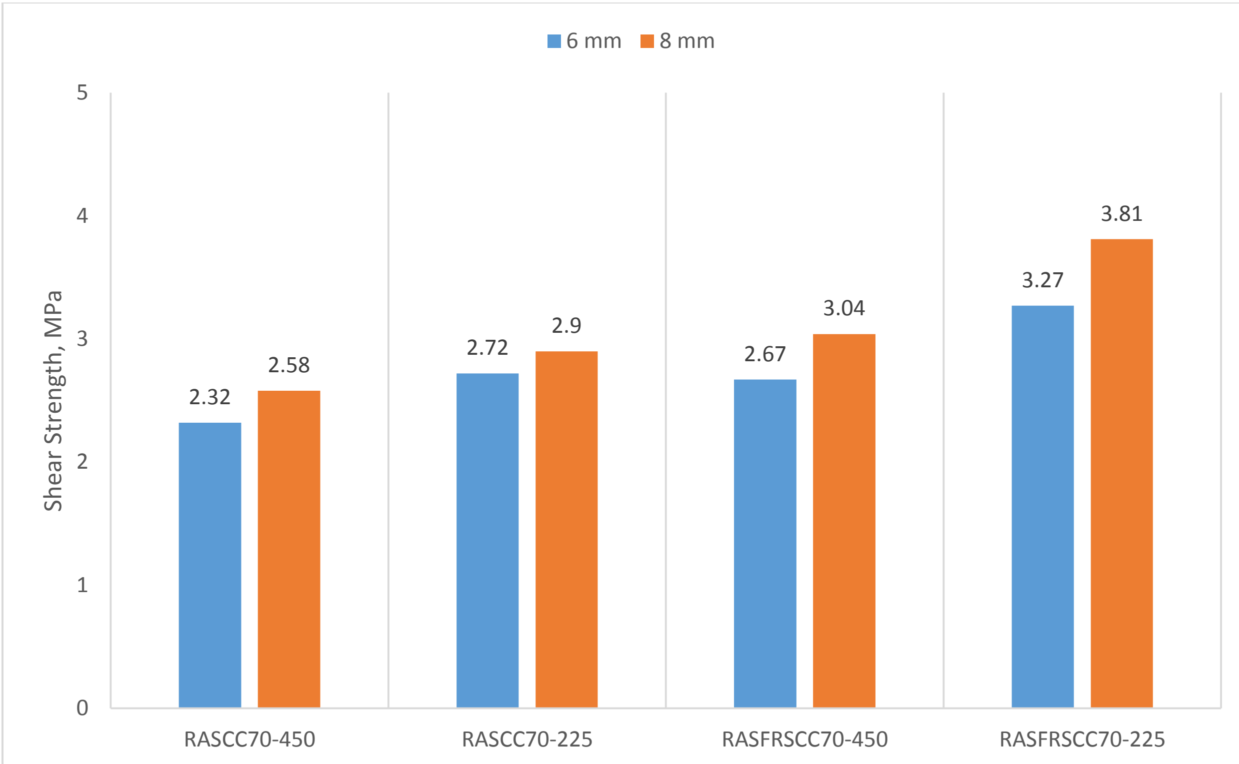

Figure 7.57 Stirrup Diameter vs Shear Strength for RASCC70, a/d=2.5

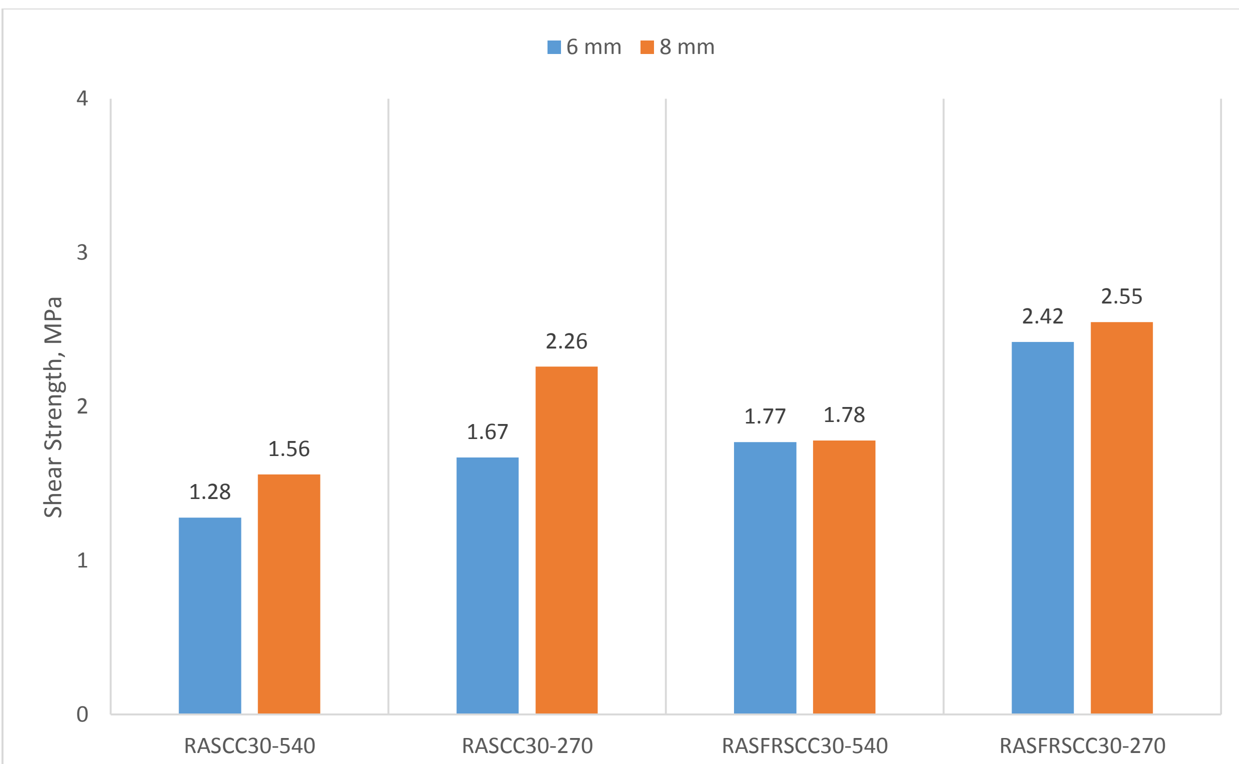

Figure 7.58 Stirrup Diameter vs Shear Strength for RASCC70, a/d=3

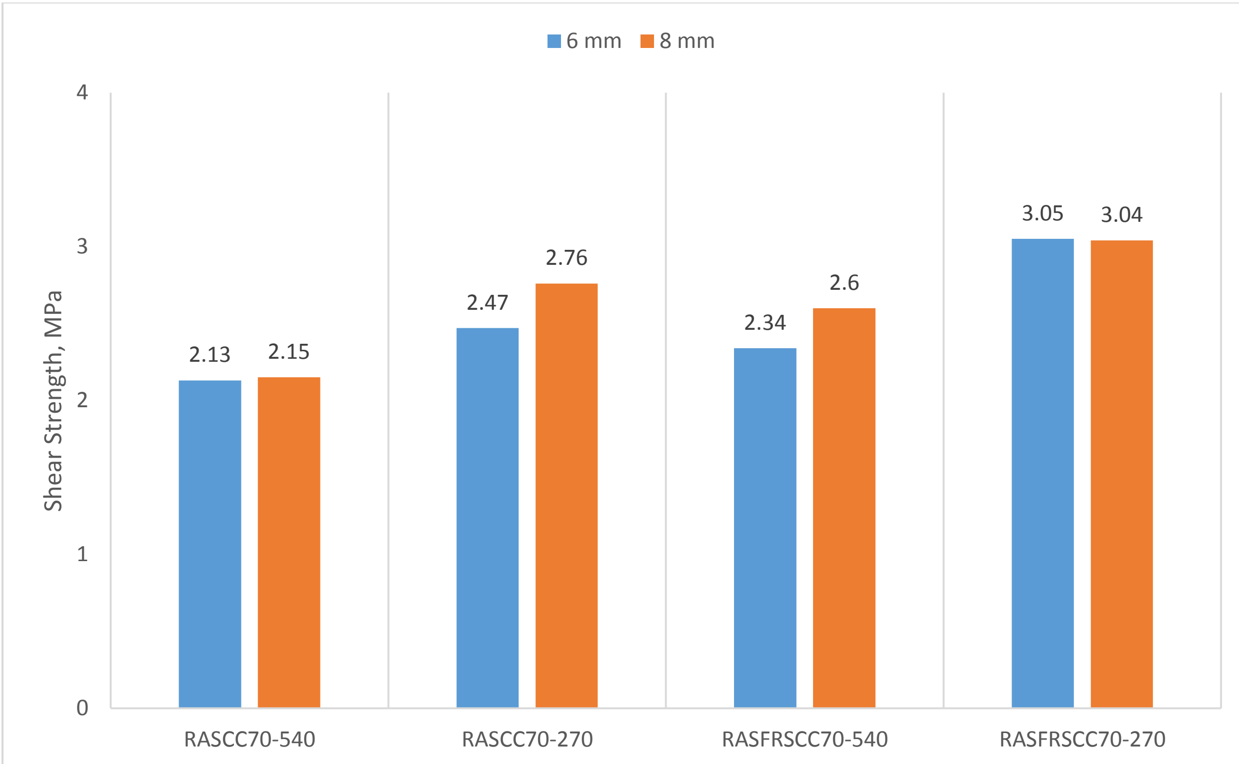

Figure 7.59 Stirrup Diameter vs Shear Strength for RASCC70, a/d=3

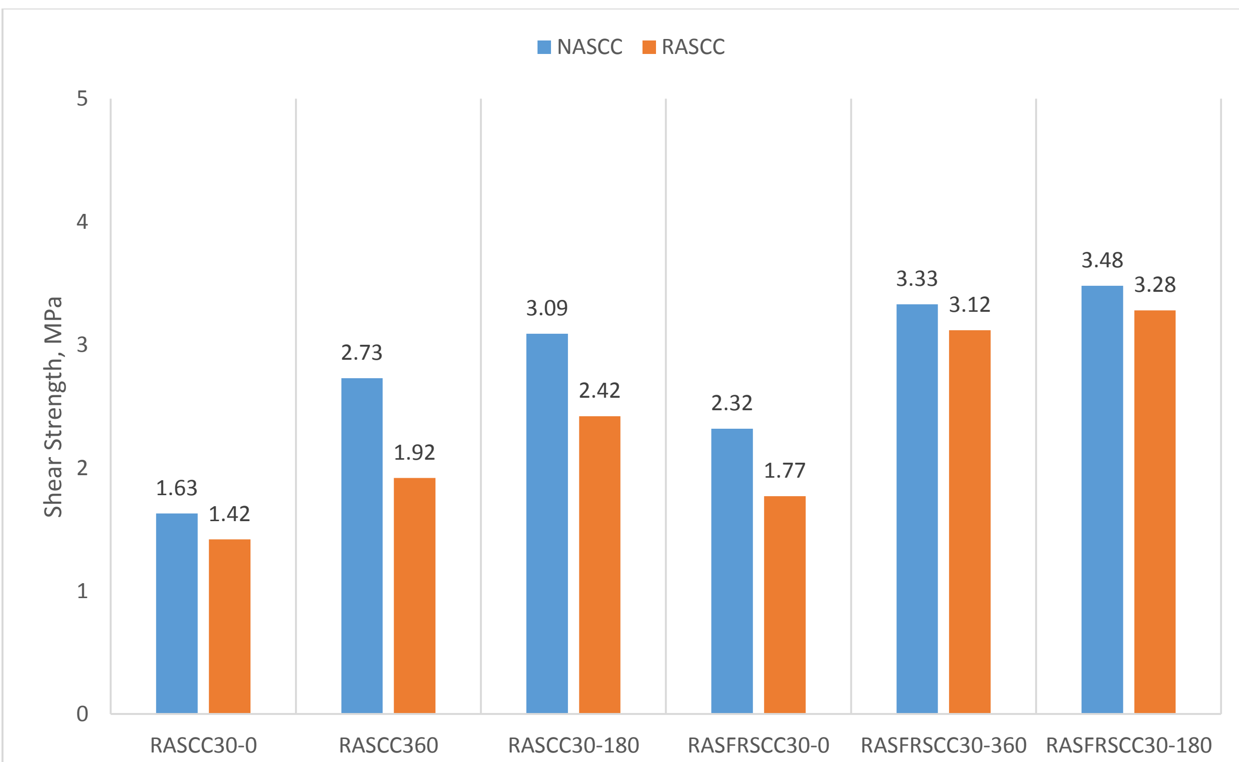

Figure: 7.60 Comparison of shear strength of NASCC30 and RASCC30, for a/d=2 and 8mm Ø stirrup

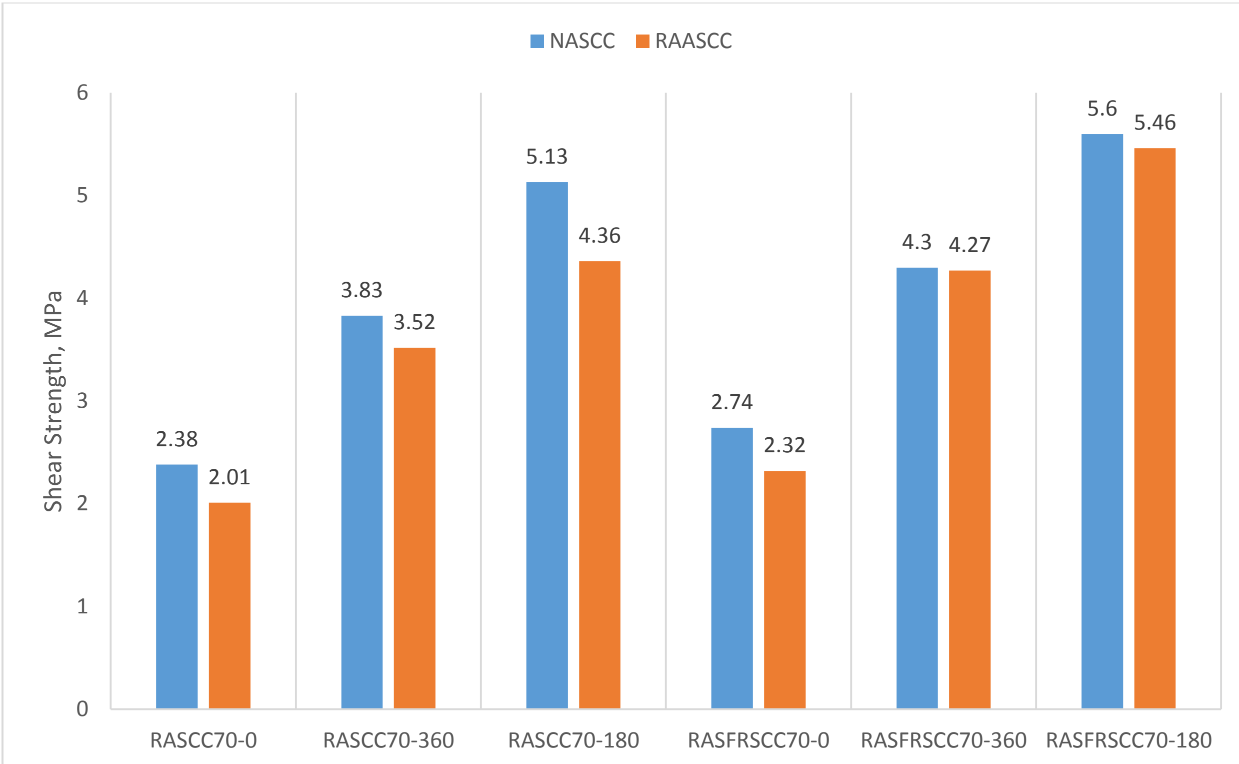

Figure: 7.61 Comparison of shear strength of NASCC70 and RASCC70, for a/d=2 and 8mm Ø stirrup

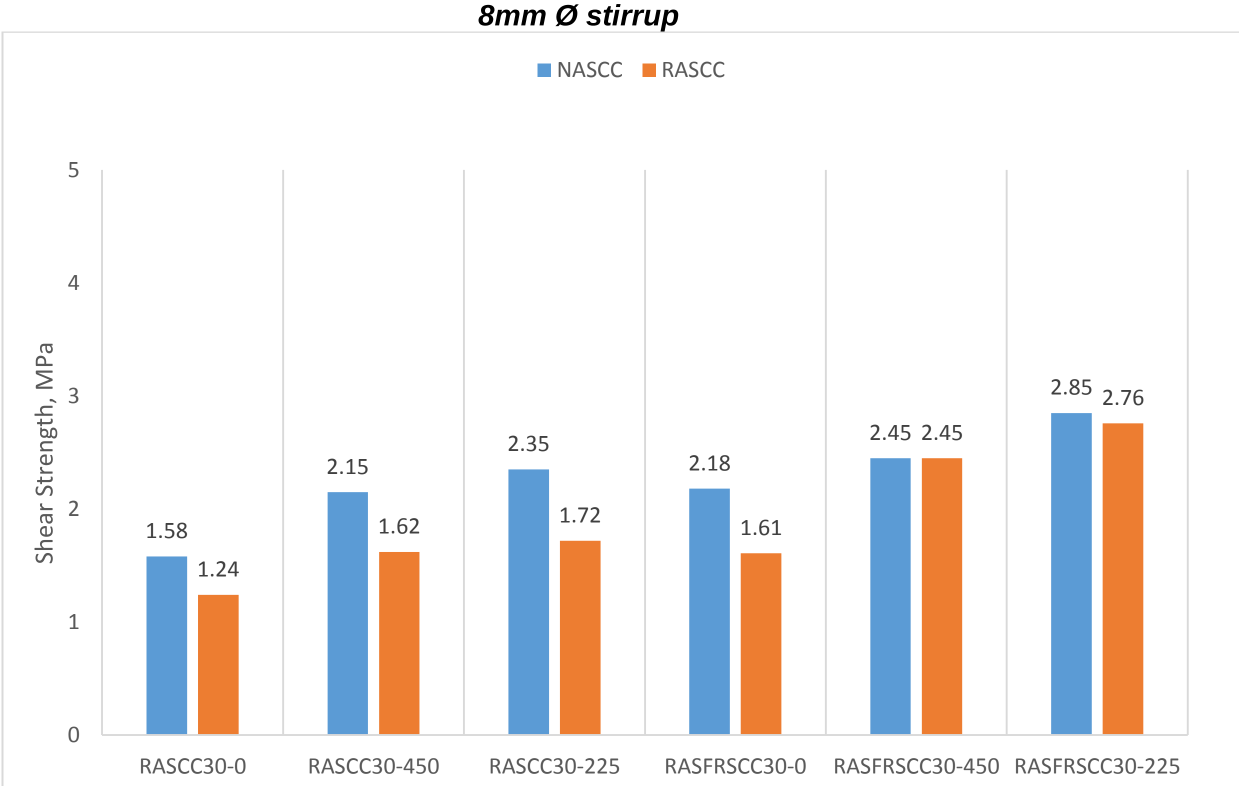

Figure: 7.62 Comparison of shear strength of NASCC30 and RASCC30, for a/d=2.5 and 8mm Ø stirrup

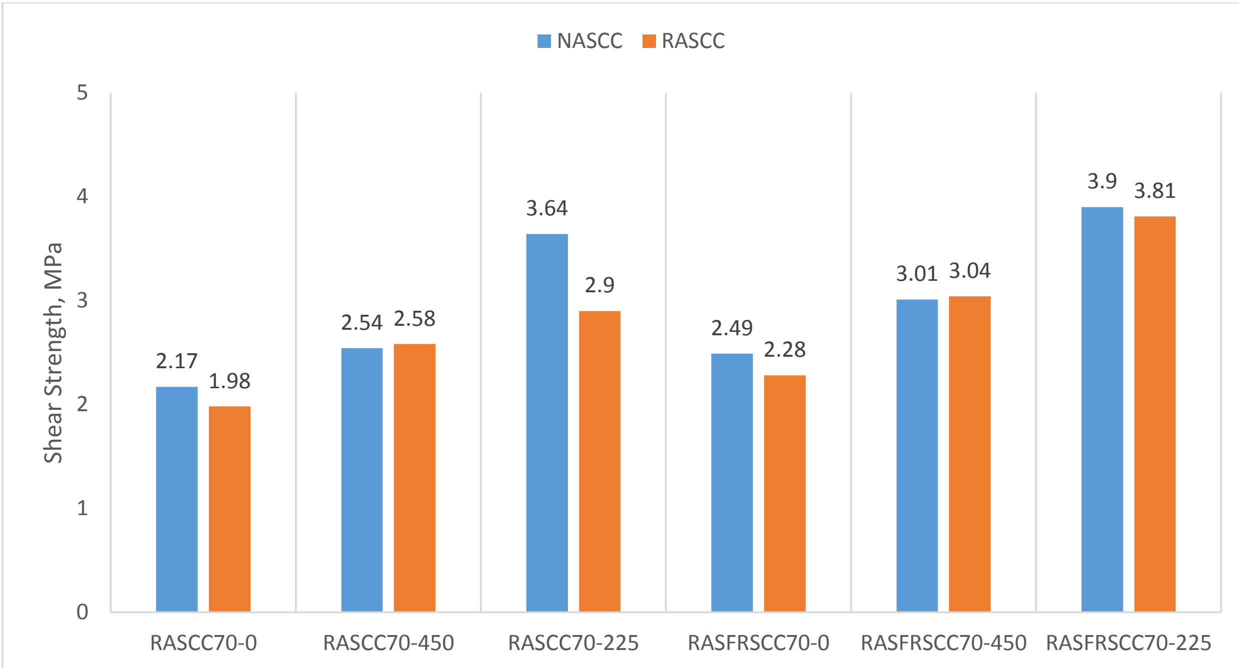

Figure: 7.63 Comparison of shear strength of NASCC70 and RASCC70, for a/d=2.5 and 8mm Ø stirrup

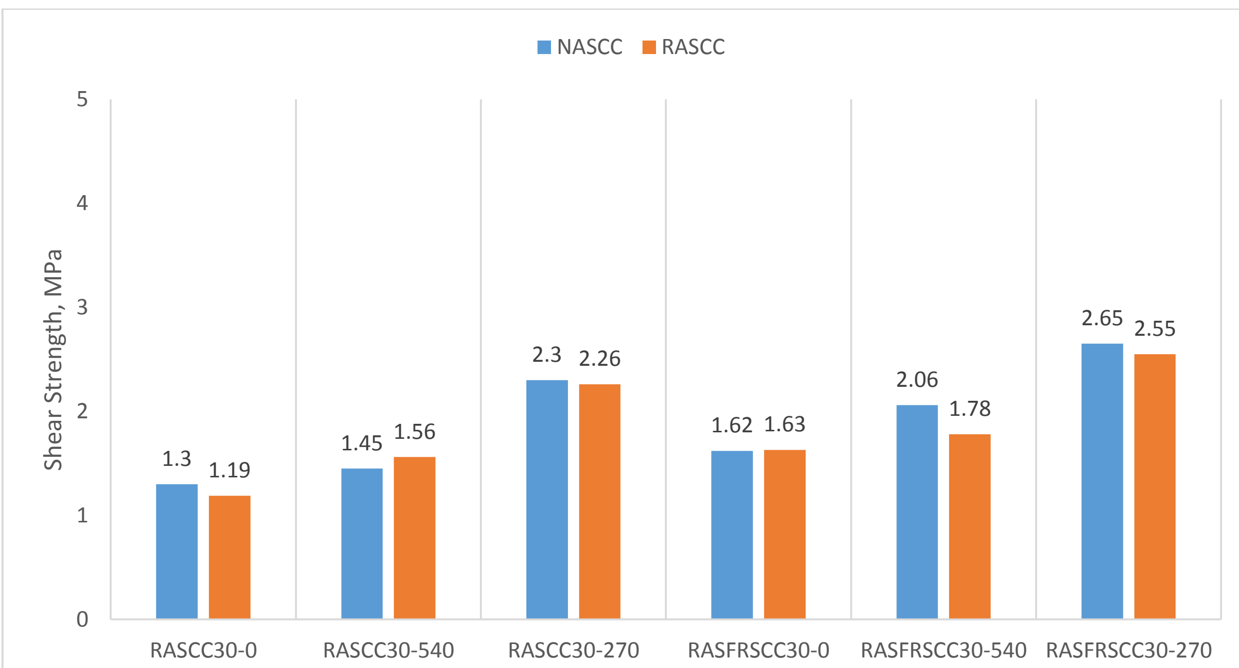

Figure: 7.64 Comparison of shear strength of NASCC30 and RASCC30, for a/d=3 and 8mm Ø stirrup

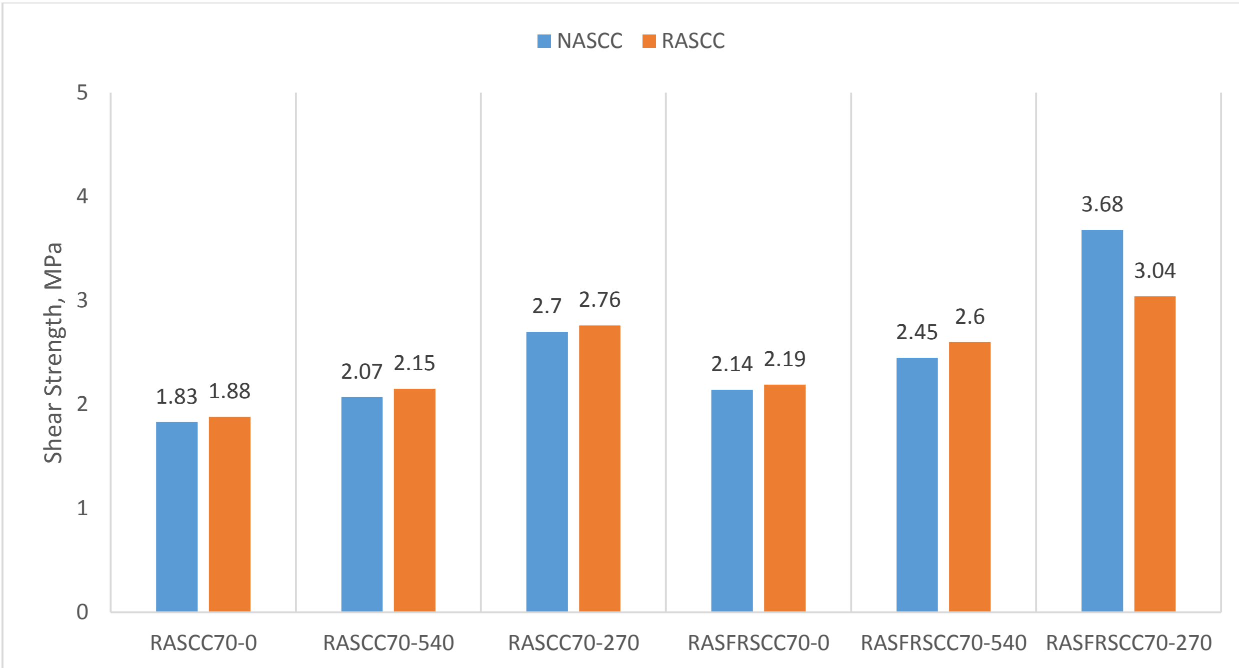

Figure: 7.65 Comparison of shear strength of NASCC70 and RASCC70, for a/d=3 and 8mm Ø stirrup

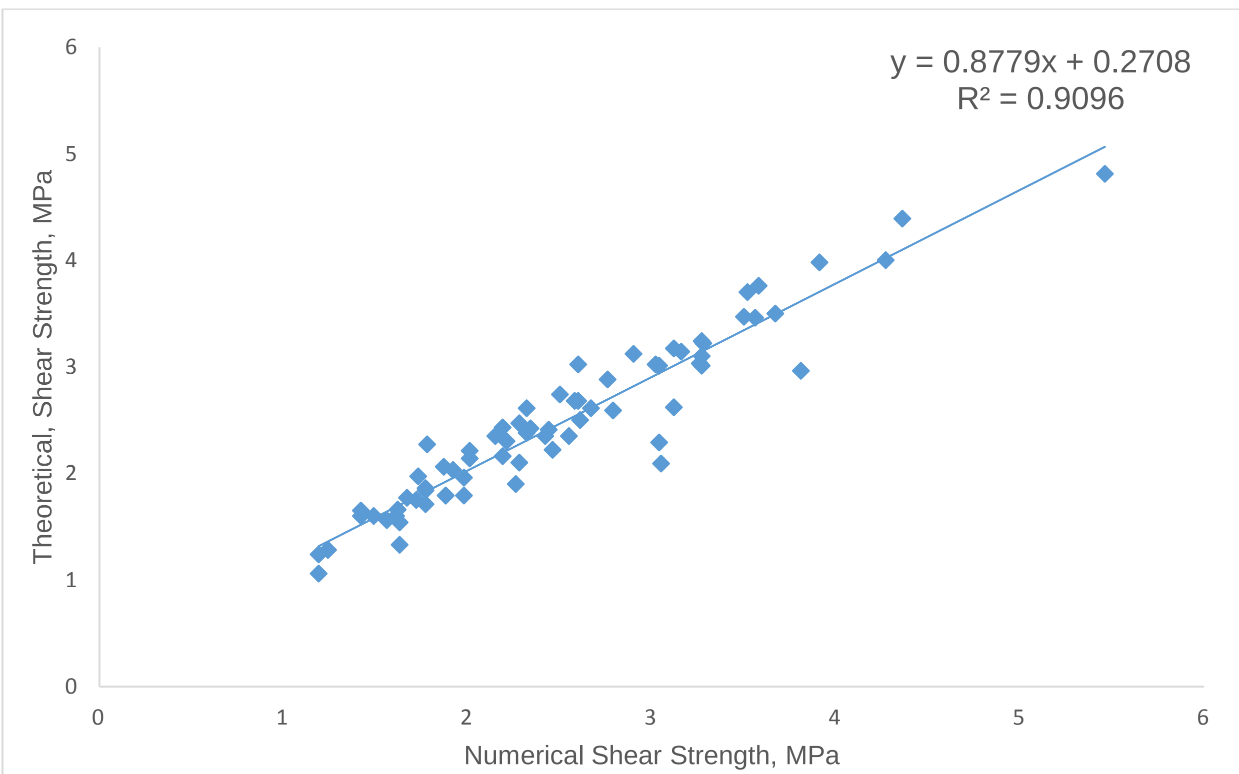

Figure: 7.66 Comparison Numerical Shear Strength vs Theoretical Shear strength for RASCC30 and RASCC70

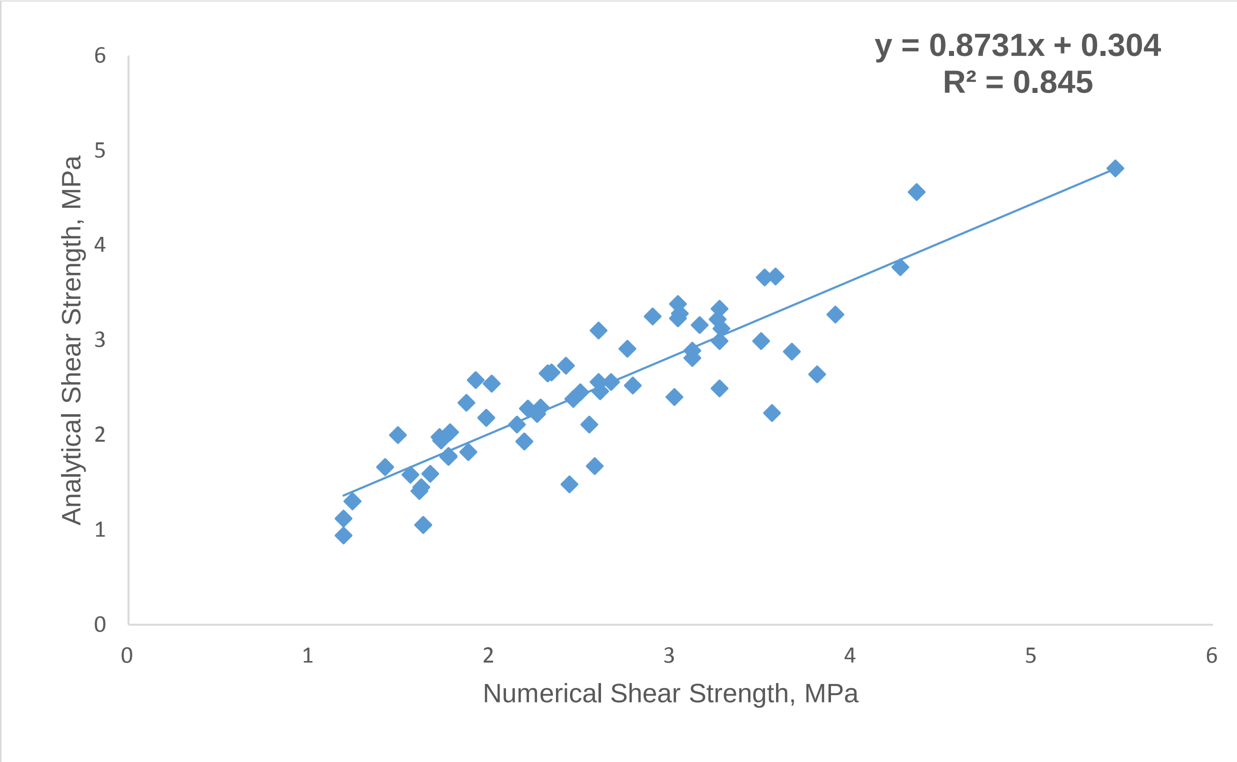

Figure: 7.67 Comparison Numerical Shear Strength vs Analytical Shear strength for RASCC30 and RASCC70

CHAPTER 8

CONCLUSIONS AND SCOPE FOR FURTHER WORK

8.0 Conclusions:

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

Phase-I Mechanical properties of steel fiber reinforced self-compacting concrete:

1. Based on Fresh and hardened properties it can be confirmed that 0.5 % dosage of steel fibers by volume of concrete is maximum for self-compacting concrete in all the three grades (30MPa, 50MPa and 70 MPa). There is a good increase in the split and flexural strengths due to the fibres bridging the crack propagation resulting in increased ultimate load carrying capacity of the specimens.
2. The compressive strength increased by 4.9% whereas, split tensile by 15.44% and flexural strength by 22.3% for normal strength concrete (30 MPa) with the use of maximum dosage of steel fibers (i.e. 0.5% by volume of concrete).
3. In case of standard grade SCC (50 MPa) due to addition of maximum dosage of steel fibers(0.5% volume of concrete), the compressive strength increased by 2.63%, split tensile strength by 20.8% and flexural strength by 14.5%.
4. Similarly, in case of high strength SCC (70 MPa) due to addition of steel fibers, the compressive strength increased by 6.51%,split tensile strength increased by 12% and flexural strength by 21.67% with 0.5% dosage of steel fibers.
5. From the pilot studies conducted on Vibrated Concrete (VC) and SCC beams, it was found that shear strength of VC and SCC are comparable. The shear span to depth ratios (a/d) 2, 2.5 and 3 were considered for detailed study. The crack pattern of VC and SCC were quite similar.

Phase-II Shear behaviour of steel fiber reinforced self-compacting concrete using natural aggregates:

1. Due to addition of steel fibers, the ultimate shear strength increased by 36.8% and 15% in SCC30 and SCC70 respectively compared to plain beams. The failure mode

changed from a sudden brittle failure to a ductile flexural type failure. This is true for both the stirrup diameters (6mm and 8mm).

2. Due to the combined effect of stirrups and steel fibers, the ultimate shear strength increased by 89.34% and 80.65% in SCC30 and SCC70 respectively compared to plain beams for beam with a/d=2 at 180 mm spacing.
3. With increase in the shear span to depth (a/d) ratio, the ultimate shear strength reduced by 5.2% and 22.54% for SCC30 for a/d =2.5 and 3 when compared with a/d=2. Similarly, in case of SCC70, it is reduced by 19.59% and 22.44% respectively. This behaviour was true in case of both fibrous and non-fibrous concrete beams with 8mm stirrup.
4. With increase in the area of shear reinforcement, the ultimate shear strength increased by 18.7% and 51.09% for SCC30-180 and SCC70-180. Similarly, the shear strength decreased with increase in the spacing of stirrups. It was also noticed that with the use of steel fiber reduction in area of stirrup was possible. Similar behaviour was observed in case of beams tested for shear span to depth ratio 2.5 and 3 also.
5. As the shear span to depth (a/d) ratio increased, crack angle (θ) has reduced and this is true for both grades SCC30 and SCC70. The Theoretical Shear Strength for NASCC is given by:

   - $\mathbf{V_u = V_{uc} + V_{us}}$
   - $\mathbf{V_u = \left\{\frac{d}{Sin\theta} * b * F_t * Cos\theta\right\} + \left\{\frac{0.87 * f_y * A_{sv}}{Cos\theta}\right\} * k_1}$; Where F_t = Split tensile strength of NASCC or NASFRSCC and θ = 50.459 - 3.2802(a/d).

   $k_1 = 0$, when crack does not cross the stirrup and $k_1 = 1$ **,** when crack crosses the stirrup
6. The Analytical shear strength predicted based on Non-linear Regression analysis for NASCC is given by:

   - **Vu = (0.3*f_{ck})+(0.016*A_{sv})-(0.001*S_v)-(0.038*A_{st})-(0.712*a/d) + (0.8*V_f)**

     Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5)

7. A comparison was made between experimental and predicted shear strength values with various models available on vibrated concrete. It was noticed that the ultimate shear strength predicted by Russo model [Russo et al, (2004)] for plain SCC beams and Narayana and Darwish model [Narayanan and Darwish, (1987)] for SFRSCC are relatively close to experimental values for beams with 6mm and 8 diameter stirrup.

Phase - III Shear Behaviour of Steel fiber reinforced Self-Compacting Concrete using Recycled concrete aggregates:

1. With the use of recycled aggregates, the compressive strength decreased by 7.8% and 8% respectively for 30MPa and 70 MPa concrete.
2. The ultimate shear strength decreased by 12% and 10.2% in case of plain SCC beams with use of recycled aggregates. Similarly, in case of fibrous SCC beams the ultimate shear strength reduced by 2.36% and 6.98% respectively for standard (30 MPa) and high strength (70 MPa) SCC with respect to plain NA beams.
3. With the presence of stirrups, the ultimate shear strength of RASCC beams decreased by 13.15% and 14.36% for 30 MPa and 70 MPa concrete. Due to combination of stirrups and steel fibers, the ultimate shear strength reduced by 10.36% and 11.26% respectively for shear span to depth ratio (a/d) 2, compared to natural aggregate SCC beams. Similar type of behaviour was observed in case of beams tested for shear span to depth ratio 2.5 and 3 also.
4. Due to addition of steel fibers in RASCC beams, the shear strength increased by 2.3% for 30 MPa and 1.2% for 70 MPa concrete, compared to plain NASCC beams.
5. The predicted theoretical shear strength for RASCC is given by:

❖ $\mathbf{V_u = V_{uc} + V_{us}}$ **;**

❖ $\mathbf{V_u = \left\{\frac{d}{Sin\theta} * b * F_t * Cos\theta\right\} + \left\{\frac{0.87 * f_y * A_{sv}}{Cos\theta}\right\} * k_2}$; Where F_t = Split tensile strength of RASCC or RASFRSCC and θ = 50.459 - 3.2838(a/d).

$k_2 = 0$, when crack does not cross the stirrup and $k_2 = 1$ **,** when crack crosses the stirrup

6. The analytical shear strength predicted based on Non-linear Regression analysis for RASCC is given by

❖ $\mathbf{V_u = (0.35*f_{ck}) + (0.014*A_{sv})-(0.001*S_v)-(0.04*A_{st})-(0.73*a/d) + (0.24*V_f)}$

Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of Shear reinforcement, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5).

7. A comparison was made between experimental and predicted shear strength values with various models available on vibrated concrete. It was noticed that the ultimate shear strength predicted by Russo model [Russo et al, (2004)] and ACI-318 code [ACI-318, (2014)] for plain SCC beams and Narayana and Darwish [Narayanan and Darwish, (1987)] for FRSCC are relatively close to experimental values for beams with 6mm and 8mm diameter stirrups.

Phase- IV Numerical behaviour of Steel fiber reinforced NASCC and RASCC Using Finite Element Software ATENA-GiD under shear:

1. The Numerical results obtained compared well with those of the experimental results and the values are within 85-90% limits.
2. A correlation among experimental deflections and the deflections obtained though ATENA modelling are close to each other, with a percentage variation less than 15%.
3. A comparison of Numerical shear strength obtained based on ATENA modelling with the predicted theoretical shear strength was found to be satisfactory.

The numerical shear strength obtained based on finite element modelling (ATENA) is in good agreement with the proposed empirical formula to predict the ultimate shear strength.

8.1 Significant Contribution from the Research Work:

1. The influence of steel fibers on different grades (30MPa, 50MPa and 70MPa) of self-compacting concrete was evaluated and Maximum dosage of steel fibers was found based on fresh and hardened properties.
2. A theoretical equation to predict the ultimate shear strength for NASFRSCC and RSFRSCC involving various parameters such as, shear span to depth ratio (a/d), angle of inclination (ϴ) and split tensile strength of concrete was proposed.
3. An analytical model was proposed to predict the ultimate shear strength for both NASFRSCC and RASFRSCC involving all the major parameters influencing the shear strength of an RC beam.

4. Numerical behaviour of Steel fiber reinforced NASCC and RASCC under shear was carried out using Finite element software ATENA and correlation of experimental and predicted results with numerical results was done and the correlation was satisfactory.

8.2 Scope for Further work:

1. To study the influence of dowel effect on shear behaviour of steel fiber reinforced self-compacting concrete for different shear span to depth ratios (a/d).
2. To study the effect of aggregate interlock mechanism on the shear behaviour of NASCC and RASCC for both without and with steel fibers.
3. Detailed studies on the torsional behaviour of NASCC and RASCC using steel fiber can be done.

PUBLICATIONS RELATED TO PRESENT WORK:

International Journals:

1. **K. Praveen**, S. Venkateswara Rao, P. R. Kumar, "A Study on the Influence of a/d ratio and Stirrup Spacing on Shear Behaviour of Steel Fiber Reinforced SCC"**.** International Journal of Cement Wapno Baton, Volume no.13 November-December, CWB-6/2016. pp 405-422. **(SCI Indexed, IF 0.52)**
2. **Praveen Kannam**, Venkateswara Rao Sarella and Rathish Kumar Pancharathi. "Hybrid Effects of Stirrup Ratio and Steel Fibers on Shear Behaviour of Self-Compacting Concrete" Archives of Civil Engineering, Volume 64, Issue 1, May 2018, Pages 145–169, ISSN 1230-2945. https://doi.org/10.2478/ace-2018-0010 **(Elsevier-Scopus).**
3. **Praveen Kannam**, Venkateswara Rao Sarella**, "**A study on validation of shear behaviour of steel fibrous SCC based on numerical modelling (ATENA)", Journal of Building Engineering, Volume 19, September 2018, Pages 69-79, ISSN 2352-7102, https://doi.org/10.1016/j.jobe.2018.05.003 **(Elsevier- Scopus and ESCI).**
4. **Praveen Kannam**, Venkateswara Rao Sarella and Rathish Kumar Pancharathi "Influence of Recycled Aggregate on Shear Behaviour of Steel Fibrous SCC". Journal of Materials and Engineering structures, Volume 5 No 2, May 2018, Pages 185–205, e-ISSN: 2170-127X **(ESCI Indexed).**
5. **Praveen K.** and S. Venkateswara Rao. "Steel Fibres as a Partial Shear Reinforcement in Self-compacting Concrete". Recent Advances in Structural Engineering, Volume 1. Springer, Singapore, 2019. 935-946. https://doi.org/10.1007/978-981-13-0362-3_74 (**Springer - Scopus)**

International Conference:

1. **K. Praveen**, S. Venkateswara Rao, "An Experimental Study on the shear Behaviour of Self-compacting Concrete beams with Varying Fiber Content**".** Ukeri Concrete Congress an International Conference organised by NIT Jalandhar. November, 2-5 2015
2. **K. Praveen**, S. Venkateswara Rao, "A Study on effect of steel fibers on Fresh and Hardened Properties of Self-Compacting Concrete**".** International Conference on

Advances in Concrete Technology Materials and Construction Practices organised by Goa College of Engineering, Goa. June 22-24 2016.

3. **K. Praveen**, S. Venkateswara Rao “A Study on Hybrid effect of Stirrup diameter and Steel Fibers on High Strength Self-Compacting Concrete”**.** International Conference on Advances in Concrete Technology Materials and Construction Practices organized by Goa College of Engineering, Goa. June 22-24 2016
4. **K. Praveen**, S. Venkateswara Rao “Effect of Steel Fiber and Shear Span to depth ratio (a/d) on Shear Behaviour of Self-Compacting Concrete”**.** International Conference on Trends and Recent Advances in Civil Engineering, organized by Amity University, Noida. Conference Proceedings, pp 517-527. August 11-12 2016.
5. **K Praveen**, S Venkateswara Rao “A Study On Composite Effect Of Shear Span to depth ratio (a/d) and Stirrup Spacing On Shear Behaviour of Steel Fiber Reinforced Self-Compacting Concrete”. Second International Conference on Advances in Concrete, Structural & Geotechnical Engineering (ACSGE - 2018) organized by, Birla Institute of Technology & Science, Pilani, Rajasthan India. February 26 – 28, 2018.

National Conference:

1. **K. Praveen**, S. Venkateswara Rao “Steel Fibers as a Partial Shear Reinforcement in Self Compacting Concrete” Structural Engineering Convention 2016 (SEC-2016) organized by CSIR-SERC, Chennai, INDIA. Conference Proceedings, pp 1572-1577. 21-23 December 2016
2. **K Praveen**, D Ashok Reddy, S Venkateswara Rao. **“**A Study on Effect of Steel Fibers on Self-Compacting Concrete”**.** National Conference on MODERN CONCRETES – DRIVING PROFIT AND SUSTAINABILITY (MCDPS-16) organized by VNRVJIET, Hyderabad. August, 26th-27th 2016.

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APPENDIX -A

Mix design for M30, M50 & M70 grade of SCC using rational mix design

Step 1: Determination of Target mean strength

Characteristic strength fck= 30 N/mm^2

Target mean strength = fck+1.65*S

Standard deviation S = 5 N/mm^2

fc = 38.25 N/mm^2 say 38 N/mm^2

Step 2: Determination of Coarse and Fine aggregate:

Packing factor = 1.17-(0.0008*fck)

= 1.17-(0.0008*38)

= 1.13

% of Air in SCC = 1.5%

S/a = 0.55 fine aggregate to total aggregate ratio

Amount of C.A = P.F* W_{gl}(1-(S/a))

= 1.13*1450(1-0.55)

= 738 kg/m^3

Amount of F.A =PF x W_{gl} (S/a)

= 1.13*1500*0.55

= 915.3 kg/m^3

Step 3: Determination of Cement content

Cement content = 10.23+9.535*fck

= 372.56 kg/m^3

Say 373 kg/m^3

Step 4: Determination of Water content

$fc = 22.456(w/c)^{-1.1743}$

$38/22.456 = (w/c)^{-1.1743}$

$1.69 = (w/c)^{-1.1743}$

0.22= -1.174 log(w/c)

w/c = 0.63

Water = 0.63*373 = 235 kg/m^3

Step 5: Determination of Fly ash content

$\%f_a = 68.43 – 0.535* fc$

$= 48.1\%$

Fly ash $f_a = 345.02$ kg/m^3

Powder content = 718.025 kg/m^3

Step 6: Dosage of Super plasticizer

Dosage of S.P = 1.2% of powder content

The Final mix proportion after some trials for M30 grade SCC

Mix proportions for M30 grade of SCC		
Materials	**Proportions(kg/m^3)**	**Ratio**
Cement	350	1
Fly ash	324	0.93
Coarse aggregate	746	2.13
Fine aggregate	945	2.7
Water	203	0.58
Super plasticizer	5.73	

Following the same procedure, the final mix proportions for M50 and M70 are obtained as

The Final mix proportion after some trials for M50 grade SCC

Mix proportions for M50 grade of SCC		
Materials	**Proportions(kg/m^3)**	**Ratio**
Cement	500	1
Fly ash	270	0.54
Coarse aggregate	775	2.87
Fine aggregate	868	1.73
Water	223	0.44
Super plasticizer	5.69	

The Final mix proportion after some trials for M30 grade SCC

Mix proportions for M70 grade of SCC		
Materials	**Proportions(kg/m^3)**	**Ratio**
Cement	600	1
Fly ash	226	0.37
Silica fume	48	0.08
Coarse aggregate	780	1.3
Fine aggregate	874	1.45
Water	245	0.40
Super plasticizer	6.03	

APPENDIX –B

Beam design for M30 and M70 grade

Step 1: Dimensions of the beam

Length = 1200 mm

Breadth = 100 mm

Depth = 200 mm

Step 2: Load calculations

Live load = 4.5 kN/m^2

Self-weight of the beam = 0.1*0.2*25 (Density of the concrete = 25 kN/m^3)

= 0.5 kN/m^2

Total load = 5 kN/m^2

Ultimate load = 5*1.5= 7.5 kN/m^2

Step 3: Bending moment calculations

Ultimate bending moment $M_u = W_u l^2/8$

$= 1.35$ kN-m $= 1.35*10^6$

$M_{u,\ lim.} = 0.138\ fckbd^2$

$= 0.138*70*0.1*0.2^2$

$= 31.298*10^6$ N-mm

$Mu < M_{u,\ lim.}$ (under reinforced beam)

(For FE-500, Xu = 0.46d, as per IS: 456-2000)

$Mu = 0.87\ f_y * A_{st} * (d-0.42Xu)$

$31.298*10^6 = 0.87*500*(180-(0.42*0.46*180))\ A_{st}$

$A_{st} = 496\ mm^2$

Providing 2-16mm and 1-12 mm dia bars as $A_{st} = 515mm^2 > 496\ mm^2$ (Hence O.K)

Step 4: Design of shear

Ultimate shear force $V_u = W_u l/2 = 4.5$ kN

Shear strength due to load = V_u/bd

= 4.5*1000/100*180

= 0.257 N/mm^2

Shear strength of concrete depends on its grade and percentage of its tension reinforcement

Grade of concrete = M70

% of tension reinforcement = $100A_{st}/bd$

= 100*515/(100*180) =2.86%

From the IS: 456-2000, Table no 19, Page no. 73,

The shear strength of concrete = 0.99 N/mm^2

From IS: 456-2000 table no 20, pg no 73 the value of max shear strength taken by the concrete= 4.0 N/mm^2

Shear strength due to load is lesser than the shear strength taken by the concrete.

Minimum amount of shear reinforcement must be provided (As per IS: 456- 2000)

Step 5: Design of minimum shear reinforcement

Providing min. shear reinforcement consists of 2 legged 6 mm stirrups

Minimum spacing of shear reinforcement is given by

$S_v = A_{sv}*0.87f_y/ 0.4b$

$A_{sv}= 2*\pi r^2=56.54mm^2$

S_v= 300 mm

Step 6: Spacing of shear reinforcement

As per IS: 456-2000 spacing is calculated from the min of the following

- 0.75d- for vertical stirrups = 0.75*180 =135 mm
- Min shear reinforcement spacing
- 300mm

Provided stirrup spacing for a/d= 2 is 360mm, 180mm,

a/d= 2.5 is 450mm, 225mm and for a/d=3 270 and 540mm

The beams were designed as shear deficient beams.

Following same procedure for M30 grade concrete, as per design the longitudinal tension reinforcement is provided as 2-12mm dia bars. Stirrup spacing is varied as 180mm, 360mm for a/d=2, for a/d 2.5 as 450mm, 225mm and for a/d=3 it is 270 and 540mm.

APPENDIX-C

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. 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.

Selection of Materials

a) Plain beam

Material used is Reinforced concrete (GID Name) also called 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 Ft, and the cube compressive strength Fc.

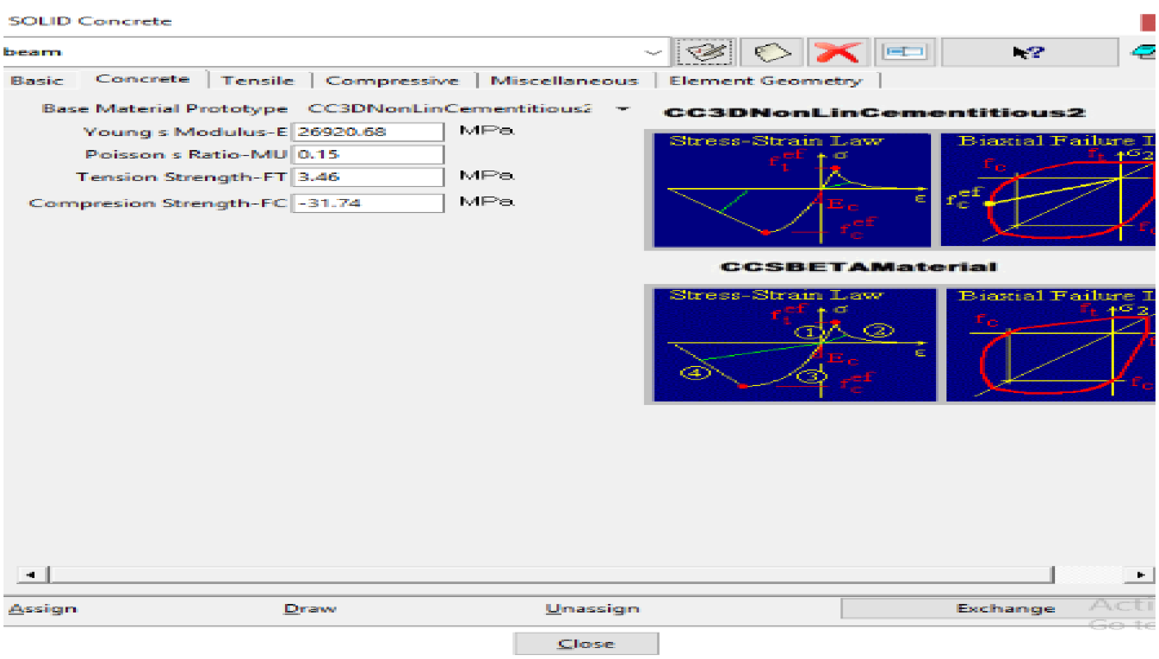

Figure: 1 showing the material properties of Plain beam

(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). The only difference from Reinforced Concrete is the Fibre Reinforcement tab.

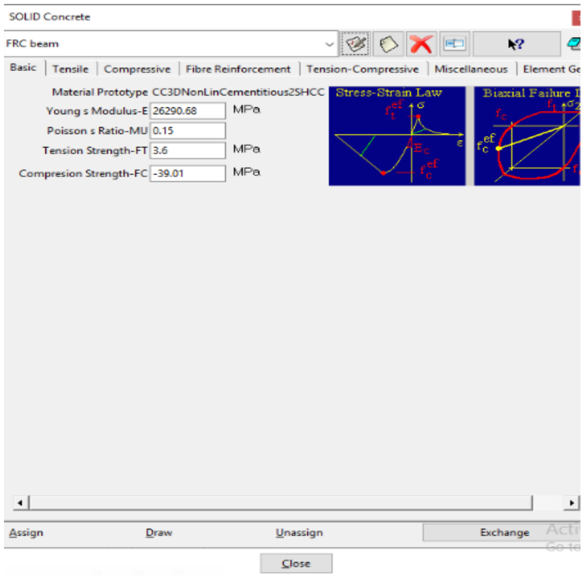

Figure 2 showing the concrete properties of FRC beam

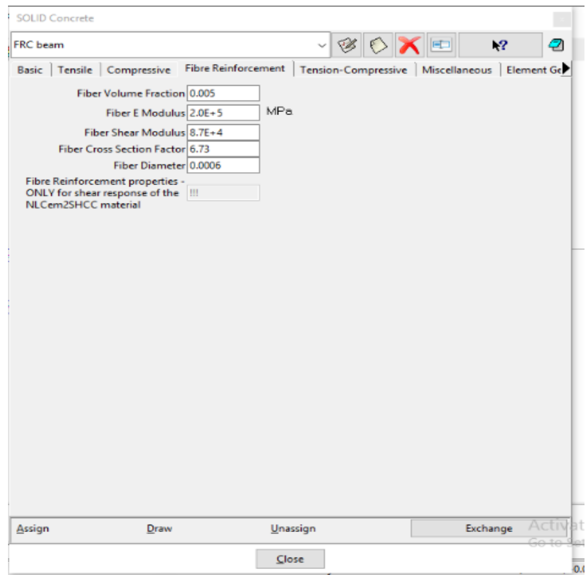

Figure 3 Figure showing the steel fibre properties of FRC beam

Analysis of a typical beam consists of the following steps.

1. Create a geometrical model in GID.

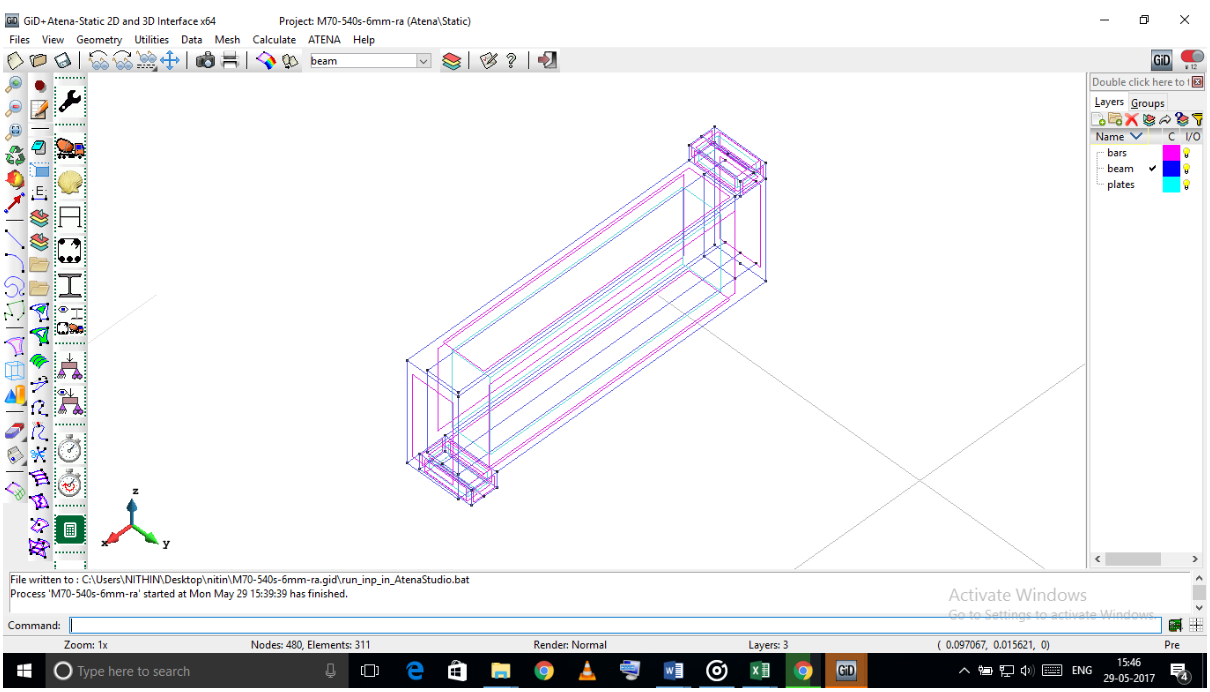

Figure 4 Geometrical model of beam showing plates and reinforcement

2. Impose conditions such as boundary conditions and loading on the geometrical model.

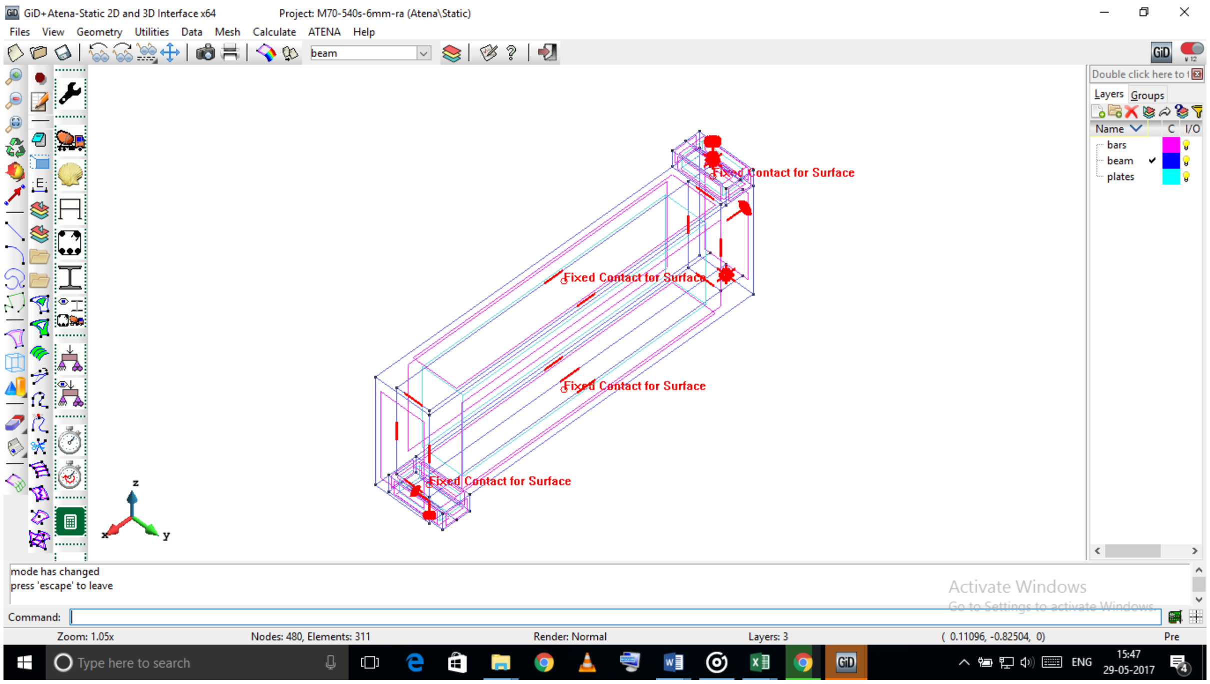

Figure: 5 Beam showing boundary and loading conditions

3. Select material models, define parameters and assign them to the geometry.

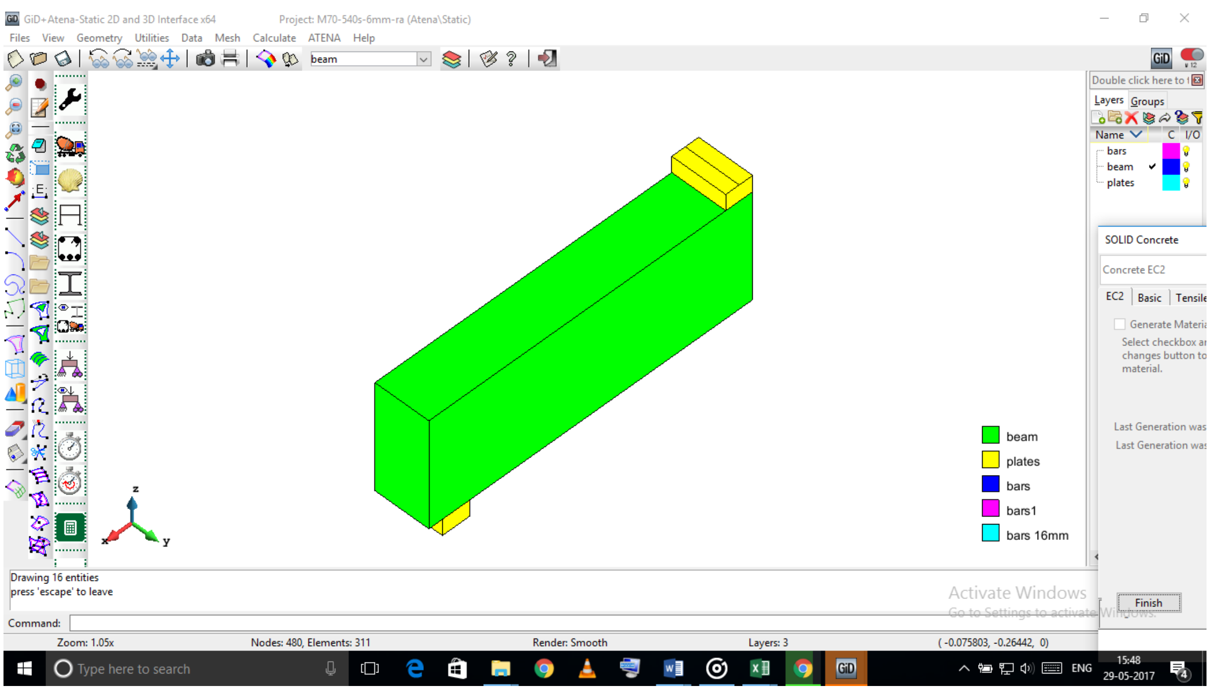

Figure: 6 Beam showing the type of materials for beam and plates

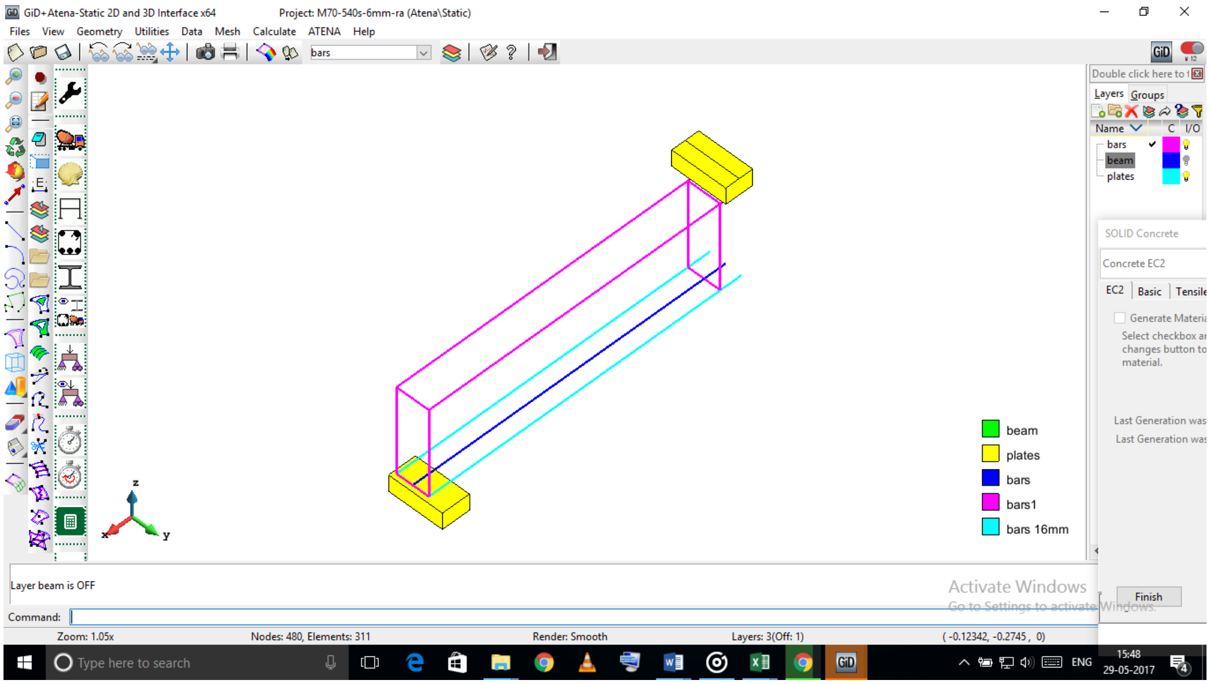

Figure: 7 Beam showing the type of materials for the reinforcement

4. Generate finite element mesh.

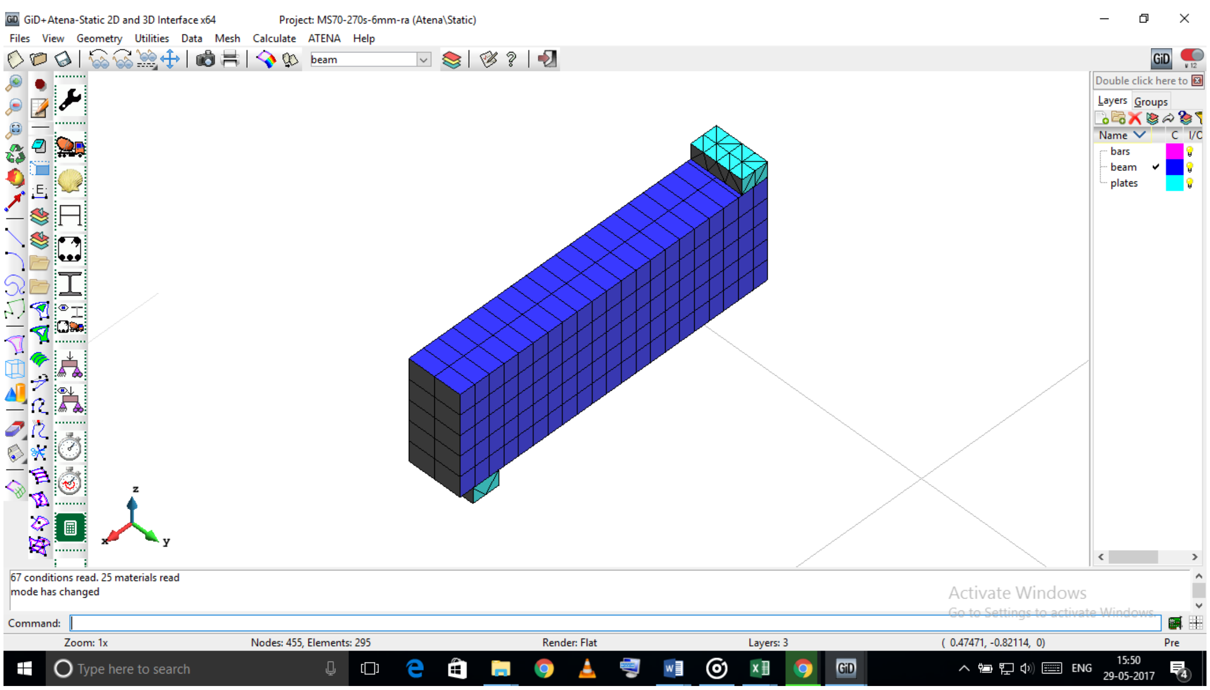

Figure: 8 Beam showing the finite element mesh

5. Create loading history by defining interval data.

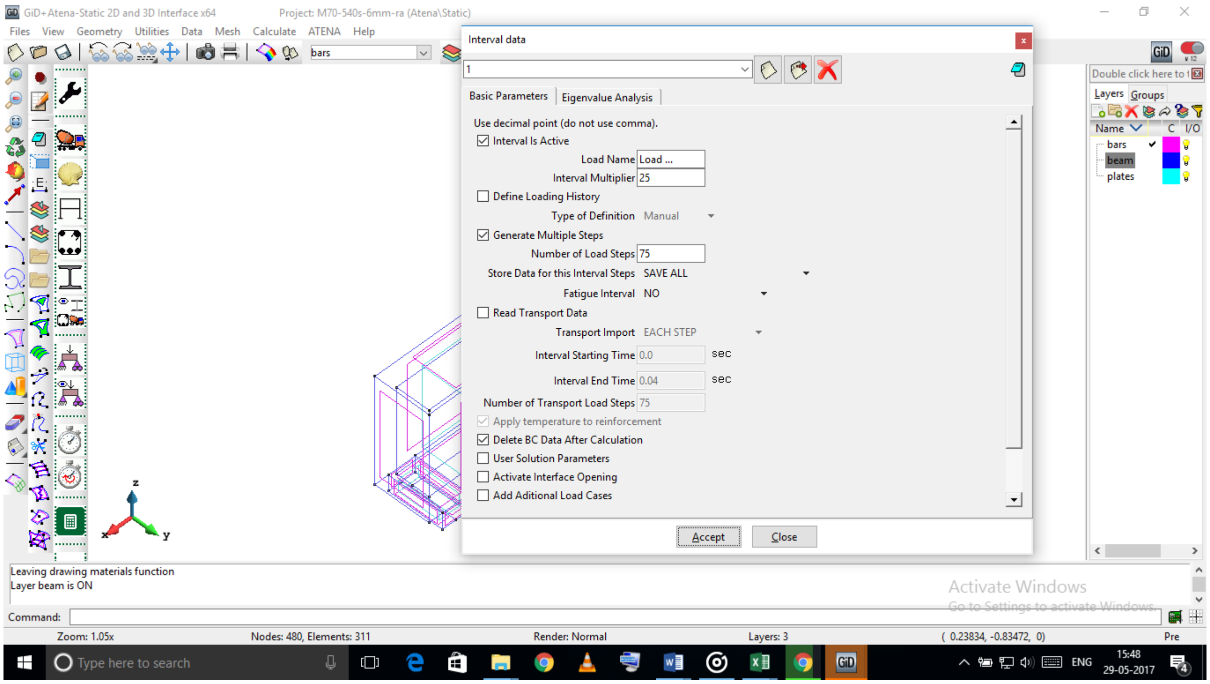

Figure: 9 showing loading history and interval data

6. Execute finite element analysis with ATENA Studio.

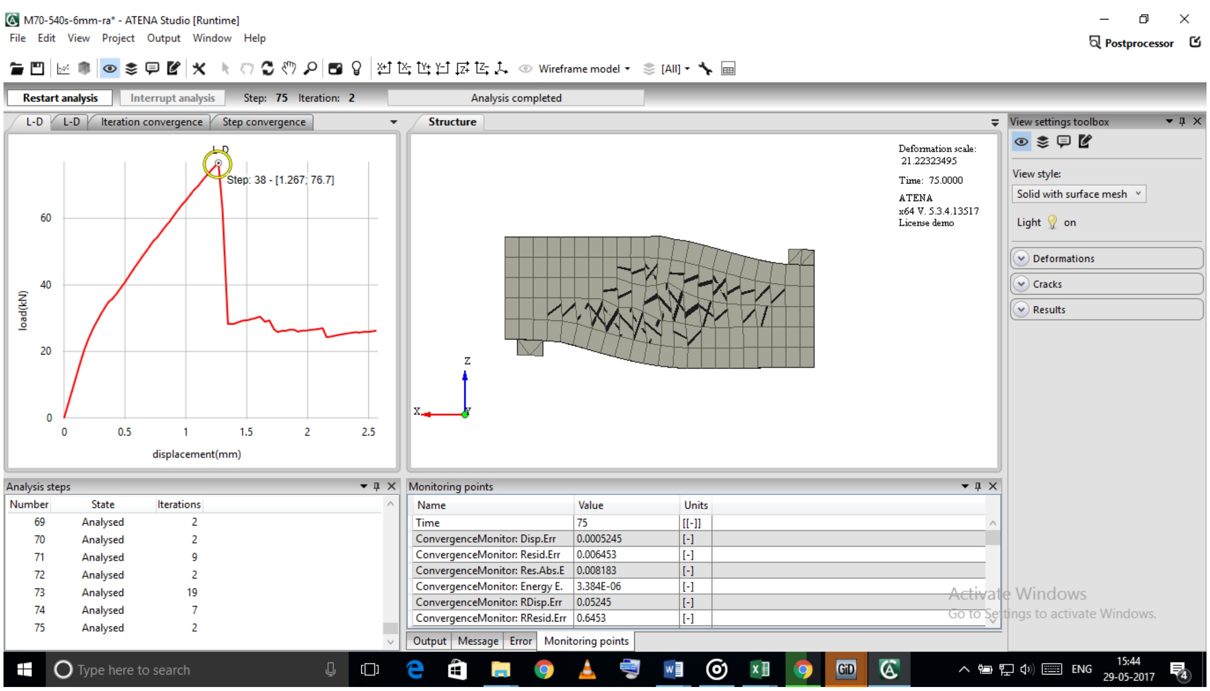

Figure: 10 showing the deformation and failure pattern along with Load-Deflection diagram during analysis

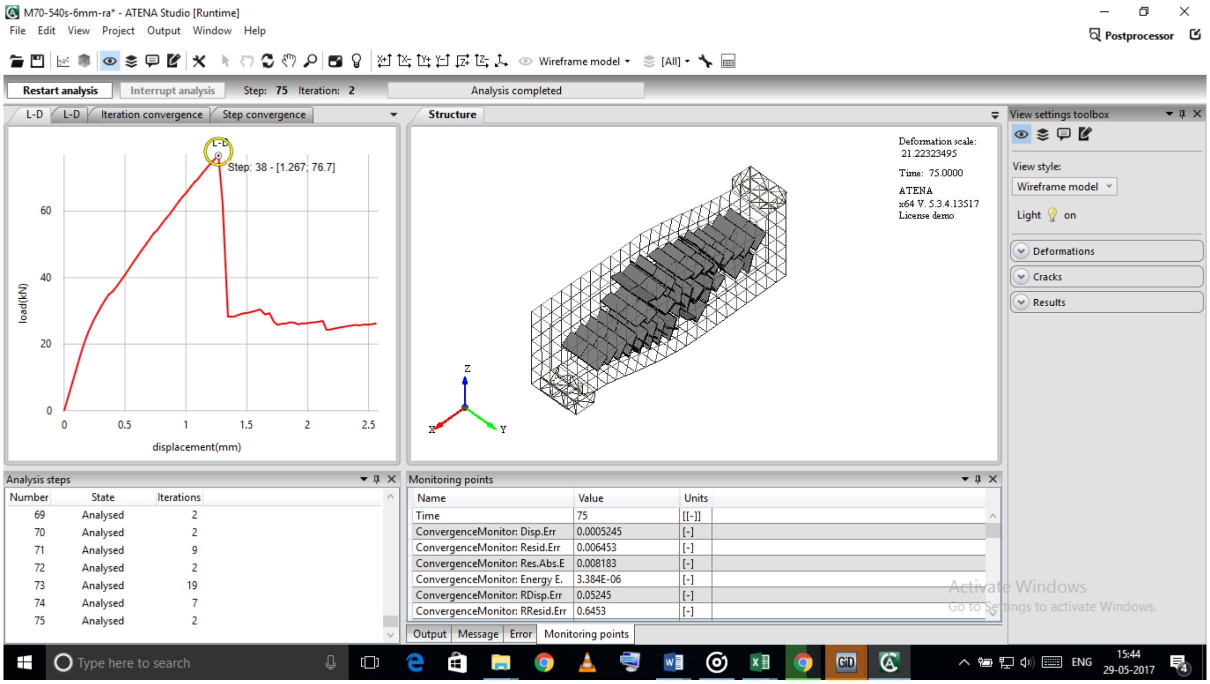

Figure: 11 showing the propagation of crack inside the beam

Appendix –D

Prediction of Empirical formulae to predict analytical shear strength of NASCC and RASCC

An equation to predict ultimate shear strength is proposed by performing non-linear regression analysis, using SPSS Software the empirical formula for NASCC beams is given by:

$$V_u = (0.3*f_{ck})+(0.016*A_{sv})-(0.001*S_v)-(0.038*A_{st})-(0.712*a/d) + (0.8*V_f) \quad \text{Eq (1)}$$

Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5). Table 1 and 2 shows the Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 6mm and 8mm diameter stirrup.

Nonlinear Regression using SPSS Software:

Nonlinear Regression was performed using SPSS Software. The input data and the output file is shown below.

Input data:

Model Program a=0 b=0 c=0 d=0 e=0 f=0.

Compute Predicted =(a*S_V)+(b*V_f)+(c*a/d)+(d*As_v)+(e*F_{ck})+(f*A_{st}).

Output:

Correlations of Parameter Estimates

	a	b	c	d	e	f
a	1.000	.000	-.295	-.769	.216	-.211
b	.000	1.000	.000	.000	-.141	.138
c	-.295	.000	1.000	.227	-.889	.867
d	-.769	.000	.227	1.000	-.281	.274
e	.216	-.141	-.889	-.281	1.000	-.998
f	-.211	.138	.867	.274	-.998	1.000

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
a	-.001	.000	-.002	.000
b	.798	.200	.399	1.197
c	-.712	.128	-.968	-.456
d	.016	.002	.012	.020
e	.296	.041	.214	.379
f	-.038	.006	-.050	-.026

ANOVA

Source	Sum of Squares	df	Mean Squares
Regression	541.395	6	90.233
Residual	11.864	66	.180
Uncorrected Total	553.259	72	
Corrected Total	54.295	71	

Dependent variable: exp[a]

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .88

Table: 1 Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 6mm diameter stirrup.

Designation	Experimental	Analytical	Exp/Analytical
	SCC30		
SCC30-0	1.73	1.77	0.98
SFRSCC30-0	2.14	2.17	0.99
SCC30-180	2.66	2.49	1.07
SCC30-360	2.41	2.31	1.04
SFRSCC30-180	3.28	2.89	1.13
SFRSCC30-360	2.84	2.71	1.05
SCC30-0	1.64	1.42	1.15
SFRSCC30-0	1.94	1.82	1.07
SCC30-225	2.29	2.09	1.10
SCC30-450	1.98	1.86	1.06
SFRSCC30-225	2.82	2.49	1.13
SFRSCC30-450	2.53	2.26	1.12
SCC30-0	1.34	1.06	1.26
SFRSCC30-0	1.41	1.46	0.97
SCC30-270	1.73	1.69	1.02
SCC30-540	1.42	1.41	1.01
SFRSCC30-270	2.6	2.56	1.02
SFRSCC30-540	2.25	2.19	1.03
	SCC70		
SCC70-0	2.45	2.6	0.94
SFRSCC70-0	2.55	3	0.85
SCC70-180	3.21	3.31	0.97
SCC70-360	3.04	3.13	0.97
SFRSCC70-180	4.44	3.71	1.20
SFRSCC70-360	3.86	3.53	1.09
SCC70-0	1.97	2.24	0.88
SFRSCC70-0	2.2	2.64	0.83
SCC70-225	2.8	2.91	0.96
SCC70-450	2.47	2.68	0.92
SFRSCC70-225	3.65	3.31	1.10
SFRSCC70-450	3.26	3.08	1.06
SCC70-0	1.9	1.88	1.01
SFRSCC70-0	1.98	2.28	0.87
SCC70-270	2.79	2.51	1.11
SCC70-540	2.1	2.24	0.94
SFRSCC70-270	3.56	3.36	1.06
SFRSCC70-540	2.55	2.63	0.97

Table: 2 Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 8mm diameter stirrup.

Designation	Experimental	Analytical	Exp/Pre
SCC30-0	1.73	1.77	0.98
SFRSCC30-0	2.34	2.17	1.08
SCC30-180	3.16	3.19	0.99
SCC30-360	2.8	3.01	0.93
SFRSCC30-180	3.53	3.59	0.98
SFRSCC30-360	3.4	3.4	1.00
SCC30-0	1.64	1.42	1.15
SFRSCC30-0	1.94	1.82	1.07
SCC30-225	2.51	2.79	0.90
SCC30-450	2.14	2.56	0.84
SFRSCC30-225	3.04	3.19	0.95
SFRSCC30-450	2.55	2.96	0.86
SCC30-0	1.34	1.06	1.26
SFRSCC30-0	1.41	1.46	0.97
SCC30-270	2.34	2.39	0.98
SCC30-540	1.55	2.11	0.73
SFRSCC30-270	2.61	2.78	0.94
SFRSCC30-540	2.42	2.51	0.96
	SCC70		
SCC70-0	2.45	2.6	0.94
SFRSCC70-0	2.55	3	0.85
SCC70-180	4.85	4.78	1.01
SCC70-360	3.98	3.83	1.04
SFRSCC70-180	5.53	4.41	1.25
SFRSCC70-360	4.41	4.23	1.04
SCC70-0	1.97	2.24	0.88
SFRSCC70-0	2.2	2.64	0.83
SCC70-225	4.04	3.61	1.12
SCC70-450	2.61	3.38	0.77
SFRSCC70-225	4.3	4.01	1.07
SFRSCC70-450	3.54	3.78	0.94
SCC70-0	1.9	1.88	1.01
SFRSCC70-0	2.03	2.28	0.89
SCC70-270	3.07	3.21	0.96
SCC70-540	2.37	2.93	0.81
SFRSCC70-270	4.19	3.61	1.16
SFRSCC70-540	2.8	3.33	0.84

Empirical formulae to predict ultimate shear strength of RASCC beams:

An equation to predict ultimate shear strength of RASCC beams is proposed by performing non-linear regression analysis, using SPSS Software the empirical formula to predict shear strength for RASCC beams is given by:

$V_u = (0.35*f_{ck})+(0.014*A_{sv})-(0.001*S_v)-(0.04*A_{st})-(0.73*a/d) + (0.24*V_f)$ Eq (2)

Where, f_{ck} = Compressive strength of concrete; A_{sv}= Area of shear reinforcement, S_v = Spacing of stirrups, A_{st} = area of longitudinal reinforcement; a/d= shear span to depth ratio and V_f = Percentage of fiber (0.5). Tables 3 and shows the Experimental vs Analytical Shear Strength for NASCC30 and NASCC70 for 6mm and 8mm diameter stirrup.

Nonlinear Regression using SPSS Software:

Nonlinear Regression was performed using SPSS Software. The input data and the output file is shown below.

<u>Input data:</u>

Initially the constants are assigned the values as a=0 b=0 c=0 d=0 e=0 f=0.

Compute Predicted =$(a*S_V)+(b*V_f)+(c*a/d)+(d*Asv)+(e*F_{ck})+(f*A_{st})$.

<u>Output:</u>

Iteration History

Iteration Number	Residual Sum of Squares	Parameter					
		a	b	c	d	e	f
1.0	457.600	.000	.000	.000	.000	.000	.000
1.1	14.180	-8.449E-6	.318	-.335	.012	.165	-.018
2.0	14.180	-8.449E-6	.318	-.335	.012	.165	-.018
2.1	12.052	.000	.222	-.724	.010	.334	-.040
3.0	12.052	.000	.222	-.724	.010	.334	-.040
3.1	12.052	.000	.222	-.724	.010	.334	-.040

Parameter Estimates

Parameter	Estimate	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
a	.001	.000	-.001	.001
b	.24	.201	-.180	.624
c	-.724	.129	-.981	-.466
d	.014	.002	.006	.014
e	.354	.050	.235	.433
f	-.040	.007	-.054	-.027

ANOVA

Source	Sum of Squares	df	Mean Squares
Regression	445.548	6	74.258
Residual	12.052	66	.183
Uncorrected Total	457.600	72	
Corrected Total	46.998	71	

Dependent variable: exp

a. R squared = 1 - (Residual Sum of Squares) / (Corrected Sum of Squares) = .975.

Table: 3 Experimental vs Analytical Shear Strength for RASCC30 and RASCC70 for 6mm diameter stirrup.

Designation	Experimental	Predicted	Exp/Pre
	RASCC30		
RASCC30-0	1.52	1.66	0.92
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.31	2.28	1.01
RASCC30-360	1.96	2.34	0.84
RASFRSCC30-180	2.92	2.4	1.22
RASFRSCC30-360	2.61	2.45	1.07
RASCC30-0	1.13	1.3	0.87
RASFRSCC30-0	1.48	1.41	1.05
RASCC30-225	1.9	1.94	0.98
RASCC30-450	1.57	2.0	0.79
RASFRSCC30-225	2.65	2.56	1.04
RASFRSCC30-450	2.32	2.11	1.10
RASCC30-0	1.09	0.94	1.16

RASFRSCC30-0	1.34	1.05	1.28
RASCC30-270	1.73	1.59	1.09
RASFRSCC30-270	2.35	2.42	0.97
RASCC30-540	1.42	1.48	0.96
	RASCC70		
RASCC70-0	2.2	2.54	0.87
RASFRSCC70-0	2.48	2.65	0.94
RASCC70-180	3.07	3.16	0.97
RASCC70-360	2.92	3.22	0.91
RASFRSCC70-180	3.94	3.27	1.20
RASFRSCC70-360	3.31	3.33	0.99
RASCC70-0	1.87	2.18	0.86
RASFRSCC70-0	2.16	2.29	0.94
RASCC70-225	2.87	2.81	1.02
RASFRSCC70-225	3.37	2.88	1.17
RASCC70-450	2.32	2.52	0.92
RASFRSCC70-450	3.07	2.99	1.03
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.13	1.93	1.10
RASCC70-270	2.49	2.46	1.01
RASFRSCC70-270	3.38	3.28	1.03
RASCC70-540	2.14	2.23	0.96
RASFRSCC70-540	2.25	2.66	0.85

Table: 4 Experimental vs Analytical Shear Strength for RASCC30 and RASCC70 for 6mm diameter stirrup.

Designation	**Experimental**	**Predicted**	**Exp/Pre**
RASCC30-0	1.52	1.66	0.92
RASFRSCC30-0	1.77	1.77	1.00
RASCC30-180	2.32	2.73	0.85
RASCC30-360	2.12	2.58	0.82
RASFRSCC30-180	3.17	3.12	1.02
RASFRSCC30-360	2.72	2.89	0.94
RASCC30-0	1.19	1.3	0.92
RASFRSCC30-0	1.59	1.45	1.10
RASCC30-225	2.17	2.38	0.91
RASCC30-450	1.68	1.98	0.85
RASFRSCC30-225	3.05	2.49	1.22
RASFRSCC30-450	2.59	2.56	1.01
RASCC30-0	1.14	1.12	1.02
RASFRSCC30-0	1.40	1.05	1.33
RASCC30-270	2.27	2.03	1.12
RASFRSCC30-270	2.44	2.11	1.16
RASCC30-540	1.48	1.58	0.94
RASFRSCC30-540	1.78	2.22	0.80
	RASCC70		
RASCC70-0	2.09	2.54	0.82

RASFRSCC70-0	2.48	2.65	0.94
RASCC70-180	4.66	4.56	1.02
RASCC70-360	3.74	3.66	1.02
RASFRSCC70-180	4.97	4.81	1.03
RASFRSCC70-360	3.98	3.77	1.06
RASCC70-0	1.96	2.18	0.90
RASFRSCC70-0	2.24	2.29	0.98
RASCC70-225	2.98	3.25	0.92
RASFRSCC70-225	3.78	3.67	1.03
RASCC70-450	2.52	2.64	0.95
RASFRSCC70-450	3.10	3.23	0.96
RASCC70-0	1.88	1.82	1.03
RASFRSCC70-0	2.13	1.93	1.10
RASCC70-270	2.97	2.91	1.02
RASFRSCC70-270	3.45	2.99	1.15
RASCC70-540	2.38	2.55	0.93
RASFRSCC70-540	2.59	3.10	0.84