A detailed review of literature on different aspects of the Self Compacting Concrete (SCC) will be presented in detail in this chapter. The development of SCC, materials used to produce SCC, the test methods for the self compacting properties under the fresh and hardened state are discussed. An account of the literature available on fibre reinforcement and the behaviour of wall panels is further provided in this chapter.

3.0. Self Compacting Concrete (SCC)- its Background

Ever since the invention of self-flowing and self-consolidating concrete in late 1980s so as to overcome the difficulties of normal cement concrete that can tend to cause honeycombs in spite of careful compaction process through vibration of fresh concrete in designed moulds, the SCC has made steady inroads into critical constructions.

The ease with which the SCC has taken the form into congested embedment has made several researchers dwell more on expanding the applications in pre-cast and site situations with increased use of structural elements, with the addition of fibres forming FRSCC. The fibres are mostly confined to steel and glass. But newly developed FRSCC does not have complete properties and hence required further research to obtain the necessary properties of both fresh and hardened states of concrete that makes it possible to assess the strength of the composite.
The publication of the European Guidelines for Self Compacting Concrete in May 2005 for Specification, Production and Use enabled the SCC to be used widely for ready-mixed, site mixed and pre-cast concrete applications.

The review of literature has been divided into four parts namely Admixtures, Development of SCC, Fibre Reinforced SCC and Fibre Reinforced Concrete Wall Panels as given below.

3.1 ADMIXTURES

3.1.1 MOuchi, Hajime Okamura (1997)

The authors have reported the effect of Super Plasticizers [SP] on the flowability and viscosity of Self Compacting Concrete quantitatively. From the results obtained from the experimental investigations, they have proposed an index for the effect of Super Plasticizer on the flowability and the viscosity for obtaining self compactability. This index is very useful for evaluating the quantity of the Super Plasticizer for proper viscosity and flowability of SCC by using one set of results.

3.1.2 Gao Peiwei., et al. (2000)

The traditional concrete, which is made of three fundamental ingredients of primary cement, aggregates and water, was in use for a long time. In recent years, the High Performance Concrete (HPC), which is the latest generation of concrete, became popular in the concrete construction industry. For producing high performance concrete, use of mineral and chemical admixtures, Viscosity Modifying
Agents (VMA), are necessary apart from aggregates, water and cement. The main aim of the present day concrete is to reduce the amount of cement in HPC. The reasons for this are threefold. The first reason is to conserve precious natural resources, the next reason is to reduce the cost and energy and the final reason is a longterm durability.

3.1.3 Neol P Mailvaganam (2001)

Mineral and Chemical admixtures interact with the compounds of cement and influence the hydration process. The performance of these admixtures in concrete depends on the type and dosage of admixtures, their composition, specific surface area of the cement, the nature, type and proportions of different aggregates, water/cement ratio. Humidity, temperature and the conditions of curing. compatibility study between admixtures and cement is important to decide the usage of these materials. The influence of admixtures on cement hydration is given in five stages.

Stage I : The Initial hydration process (0-15 minutes)
Stage II : The lag phase or Induction period (15 minutes – 4 hours)
Stage III : The acceleration or/and setting phase (4 hours – 8 hours)
Stage IV : The hardening phase (8 hours – 24 hours) and
Stage V : The curing phase (1 – 28 days).

3.1.4 Raghu Prasad P.S. et al. (2004)

According to these authors, both initial and final setting times are getting delayed because of the use of admixtures. This is due to the slow pozzolanic reaction caused by the addition of some admixtures. They report that this type of delayed setting is sometimes
beneficial during the concreting in hot weather. There will be considerable strength development for blended cements and concretes for longer periods beyond 28 days. This results in the reduction of corrosion of reinforcement in concrete.


The Usage of Viscosity Modifying Agents (VMA) has been proved to be very effective in stabilizing rheology of the SCC. The suitability of four types of polysaccharide-based Viscosity Modifying Admixtures in development of the SCC mixes has been examined. The studies on the new types of VMA are encouraging in the development of satisfactory SCC mixes with fresh and hardened properties which are comparable to or even better than those made with commercially available VMA and Welan gum. The suggested new Type VMA with 0.05% of dosage satisfies the fresh and hardened properties requirements of SCC resulting in 7% less VMA dosage than the commercial VMA resulting in cost-effective SCC mixes.

3.1.6 A. Borsoi, M. Collepardi, S. Collepardi, E.N. Croce, Passuelo (2006)

The purpose of this work is to study the role of VMA in the non-availability of the desired volume range 170-200 litres /m³ of powder material (max size = 75µm) to produce reliable SCC and concluded that the incorporation of VMA led to complete elimination of mineral filler. In such a case, a slight increase in cement content must be accompanied by a significant increase in the dosage of VMA (for
instance from 2 to 7 Kg/m³) in order to obtain an unsegregable SCC even in the absence of mineral filler.

In summary, the usage of mineral and chemical admixtures is essential in maintaining the fresh properties, strength and enhancing the durability characteristics of SCC.

3.2 Development of Self Compacting Concrete

3.2.1 Kuroiwa [1993], Developed a new type of concrete with materials normally used in conventional concrete, that is, cement, aggregates, water and admixtures. The chemical admixtures were used to improve the deformability and viscosity properties of the concrete. The newly developed concrete was named super-workable concrete. This has shown considerable resistance to segregation and deformability. It also filled heavily reinforced formworks completely without the use of any vibrators. The laboratory tests showed that the super-workable concrete has superior fresh and hardened state properties with improved durability. Because of this, this concrete was considered to be suitable for structures having heavy reinforcement areas and used in the construction of twenty-storied buildings.

3.2.2 Okamura et al. (1995), Developed a new concrete that flows and gets compacted at every place of the formwork by its own weight. In 1986, they started research on this project which was later called Self Compacting Concrete. This research work was started on the suggestions of professor Kokubu of Kobe University, Japan. He was one of the major advisors of Professor Hajime Okamura [1995]. They
thought of developing this new concrete as anti washout concrete which was already in use. The anti washout underwater concrete is used for underwater concreting without any segregation by adding a large viscosity modifying agent which prevents the particles of cement from dispersing into the surrounding water. However, it was observed that this anti washout concrete was not applicable for open air structures for two reasons: first, non elimination of entrapped air bubbles due to higher viscosity; and second, difficulty in compaction in the areas of confined reinforcing bars. They found that for achievement of the self compactability, usage of Super Plasticizer was indispensable. With the addition of Super Plasticizer, the paste flows with a little decrease in viscosity. The water/cement ratio can be between 0.4 and 0.6.

The self-compactability of the concrete is largely affected by the material characteristics and mix proportions. Okamura limited the content of coarse aggregate to 60% of the solid volume and the content of fine aggregate to 40% to achieve self-compactibility.

3.2.3 Khayat K. H (1999) Studied the behaviour of Viscosity Enhancing Admixtures (VEA) used in cement-based materials. He has concluded that by suitably adjusting the combinations of VEA and High Range Water Reducing (HRWR) agents, a fluid without washout-resistant can be produced. This will enhance properties of underwater cast grouts, mortars, and concretes, and reduces the turbidity, and increases the pH values of surrounding waters.
3.2.4 Victor C. Li, H.J.Kong, Yin-Wen Chan (1999) The authors present a self-compacting Engineered Cementitious Composite (ECC) developed by optimizing the micromechanical parameters that control composite properties in the hardened state, and the processing parameters, that control the rheological properties in the fresh state. In the development concept of self-compacting ECC, micromechanics is adopted to properly select the matrix, fibre, and interface properties in order to exhibit strain hardening and multiple cracking behaviour in the composites. With the selected ingredient materials, the self-compactibility of ECC is then realized by the controlled rheological properties of fresh matrix, including deformability and flow rate. Self-compactibility is a result of adopting an optimal combination of a super plasticizer and a viscosity agent. According to the measurements of slump flow and the self-placing test result, what the ECC developed in this study is proved to be self-compacting. Flexural tests demonstrate that the mechanical performance of self-compacting ECC is insensitive to the extremely applied consolidation during placing. This result confirms the effectiveness of the self-compactibility in maintaining the quality of structural elements.

3.2.5 Paul Ramsburg and Robert E. Neal (2000) Their research was focused on the development of SCC mixes making use of a natural pozzolona to enhance the SCC properties at Rotondo Precast. The calcined shale produced by the Lehigh Cement Company was used as natural pozzolona under a trade name XPM. The calcined shale characteristics improved the cohesion of the concrete mix with a
better control of segregation, avoiding the necessity of a viscosity-modifying agent. In addition, it is found that the total cementitious material content needed in the concrete was found to be less than the cement content required for the conventional SCC mixes. A natural pozzolona of 30% was found to be optimum for eliminating segregation and sufficient early age strengths.

3.2.6 Nan Su, Kung-Chung Hsu and His-Wen Chai (2001) Authors proposed a simple mix design procedure for SCC and their main focus was to fill voids of loosely filled aggregate with binder paste. They introduced a factor called Packing Factor (PF) for aggregate. It is the ratio of mass of aggregates in tightly packed state to the one in loosely packed state. The procedure totally depends upon the Packing Factor (PF). A higher value of PF indicates the larger aggregate content, which requires less binder and will have less flow ability. It was concluded that the packing factor determines the aggregate content and influence the properties like flow ability, self-consolidating ability and strength. In his mix design, the volume of FA to mortar was in the order of 54 – 60% and found that PF value will be the controlling factor for the U-box test.

3.2.7 Ho.D et al. (2002) Studied the usage of quarry dust in SCC applications. Rheological studies on pastes and SCC mixes were made and compared with SCC mixes with limestone powder. It was observed that quarry dust can be used in SCC production, but requires higher super plasticizer dosages.
3.2.8 M. Sonebi and P.J.M. Bartos (2002) This paper shows results of an investigation of fresh properties of self-compacting concrete, such as, filling ability (measured by slump flow) and flow time (measured by orimet) and plastic fresh settlement measured in a column. The results of SCC were compared to a control mix. The compressive strength and splitting tensile strength of SCC were measured.

The effects of water/powder ratio, slump and nature of the sand on fresh settlement were also evaluated. Keeping the volume of coarse aggregate and the dosage of Super Plasticizer constant, it was concluded that the settlement of fresh self-compacting concrete increased with the increase in water/powder ratio and the nature of sand influenced the maximum settlement.

3.2.9 Hajime Okamura and Masahiro Ouchi (2003) The authors report that self-compacting concrete was first developed in 1988 to achieve durable concrete structures and since then, various investigations have been carried out and this type of concrete has been used in practical structures in Japan, in order to shorten the construction period by large-scale constructions, such as, the anchorages of Akashin-Kaikyo (Akashi Straits) Bridge opened in April 1988, and a suspension bridge with the longest span in the world (1,991 meters) is a typical example (Kashima 1999). It is further reported that, SCC was used for the wall of a large LNG tank belonging to the Osaka Gas Company and the adoption of SCC in this project resulted in:
(i) Decrease of the construction period of the structure from 22 months to 18 months

(ii) Reduction of the number of concrete workers from 150 to 50

(iii) Decrease of the number of lots from 14 to 10 as the height of one lot of concrete was increased.

The authors noted that when self-compacting concrete becomes so widely used that it is seen as the “Standard Concrete” rather than a “Special Concrete”, it will have succeeded in creating durable and reliable concrete structures that require very little maintenance work.

3.2.10 R. Sri Ravindrarajah, D. Siladyi and B. Adamopoulos (2003)

This paper reports an investigation into the development of self-compacting concrete with reduced segregation potential. The self-compacting concrete mix having satisfied the criterion recognized by the differential height method is modified in many ways to increase the fine particle content by replacing partially the fine and coarse aggregates by low-calcium fly ash. It is reported that the systematic experimental approach showed that partial replacement of coarse and fine aggregate could produce self-compacting concrete with low segregation potential as assessed by the V-Funnel test. It further reports the results of bleeding test and strength development with age and concludes that fly ash could be used successfully in producing self-compacting high-strength concrete with reduced segregation potential.

3.2.11 Amit Mittal, Kaisare M.B and Shetty R.G (2004) Self compacting concrete is suitable for the concreting congested reinforcement structures or where the access is difficult for
concreting. The authors in their topic “Use of SCC in a pump house at TAPP 3 & 4 Tarapur”, explained in brief the methodology adopted for the design and testing of SCC mixes and the methods adopted for concreting walls and structures housing a condenser cooling water pump at Tarapur Atomic power project 3 & 4 (TAPP).

3.2.12 Frances Yang (2004) The author in his report describes the self-consolidating concrete as a concrete that exhibits high deformability while maintaining resistance to segregation. This paper investigates the technology behind creating SCC including its components and mix proportioning techniques. It highlights numerous benefits in using SCC and refers to various tools used to parameterize its properties. Further, it reports the precautionary measures that should be taken for developing and working with the mix, and lists some exemplary applications of SCC, such as, Toronto International Airport, where concrete had to be pumped upwards from the ground to form 101 foot tall columns. In the US, a high strength SCC was imperative for constructing tightly reinforced elements poured in below freezing weather for the 68 Story Trump Tower in New York city.

In conclusion, the author states that self-consolidating concrete is an exciting technology that has found many successful applications. However, he cautioned that educating manufacturers and contractors is the crucial step in expanding the use of SCC’s extremely promising technology.
3.2.13 W.Zhu, M.Sonebi and P.J.M. Bartos (2004) The paper reports a study carried out to assess the impact of the use of SCC on bond and interfacial properties around steel reinforcement in practical concrete element. The pullout tests were carried out to determine bond strength between reinforcing steel bar and concrete. The depth sensing nano-indentation technique was used to evaluate the elastic modulus and micro-strength of the Interfacial Transition Zone (ITZ) around steel reinforcement. The bond and interfacial properties around deformed steel bars in different SCC mixes with strength grades of 35 MPa and 60 MPa were examined together with those in conventional vibrated reference concrete with the same strength grades.

It is reported that the results showed that the maximum bond strength decreased when the diameter of the steel bar increased from 12 to 20mm. It is also reported that the normalized bond strengths of the SCC mixes were found to be about 10-40% higher than those of the reference mixes for both the bar diameters (12 and 20mm).

The study of the interfacial properties revealed that the elastic modulus and the micro-strength of the ITZ were lower on the bottom side of a horizontal steel bar than on the topside, particularly for the vibrated reference concrete, while the difference of ITZ properties between top and bottom side of the horizontal steel bar appeared to be less pronounced for the SCC mixes than for the corresponding reference mixes.
3.2.14 Anne-Mieke Poppe and Geert De Schutter (2005) In this research, results pertaining to the creep and shrinkage of SCC are reported. Comparison of experimental results were made with some traditional models and it is shown that the ACI model gives accurate prediction. The models suggested by “Delarrard” and “Model Code” resulted in underestimation of the deformations. The use of SCC requires no extra precautions while considering the shrinkage and creep of the structure.

3.2.15 Cho-Lung Hwang And Chich-Ta-Tsai (2005) Three different types of aggregate packing and five different paste contents with 1.2, 1.4, 1.6, 1.8, and 2.0 % of voids within aggregate were major parameters for the evaluation the properties of SCC. The results indicate that better workability and engineering properties under sufficient paste content were obtained with denser aggregate packing. The Densified Mixture Design Algorithm (DMDA) for designing the SCC for different aggregate packing types can give a high flow ability. The strength efficiency of self-compacting concrete designed by DMDA method is much higher than the traditional one.

3.2.16 “The European Guidelines for Self-Compacting Concrete” (2005) These guidelines were prepared by a project group comprising five European Federations which were dedicated to the promotion of advanced materials and systems for the supply and use of concrete. The Self-Compacting Concrete European Project Group was founded in January 2004 with representatives from:
BIBM: The European Precast Concrete Organization
CEMBUREAU: The European Cement Association
ERMCO: The European Ready-Mix Concrete Organization
EFCA: The European Federation of Concrete Admixture Associations
EFNARC: The European Federation of Specialist Construction Chemicals and Concrete Systems

These guidelines represent a state of the art document addressed to those specifiers, designers, purchasers, producers and users who wish to enhance their expertise and use of SCC. The Guidelines have been prepared using the wide range of experience and knowledge available to the European Project Group. The proposed specifications and related test methods for ready-mixed and site-mixed concrete are presented intending to facilitate standardization at European level. The approach is to encourage increased acceptance and utilization of SCC.

"The European Guidelines for Self Compacting Concrete" defines SCC and many of the technical terms used to describe its properties and use. They also provide information on standards relating to testing and to associated constituent materials used in the production of SCC. The guidelines are drafted with an emphasis on ready-mixed and site-mixed concrete where there are requirements between supplier and user in relation to the specification of the concrete in both fresh and hardened states. In addition, the guidelines cover specific and important requirements for the user of SCC regarding the site preparation and methods of placing where these are different from traditional vibrated concrete.
The document describes the properties of SCC in its fresh and hardened states and further gives an account of the test methods used to support the specification for structural concrete.

Advice is given to the producer on constituent materials, their control and interaction. Further, advice is also given to the user of ready-mixed and site mixed concrete on delivery and placing.

3.2.18 H.J.H. Brouwers and H.J. Radix (2005) This paper addresses experiments and theories on SCC. The ‘Chinese Method’ as developed by Su et al and Su and Miao and adapted to European circumstances, serves as a basis for the development of new concrete mixes. Mixes consisting of slag blended cement, gravel (4-16mm), three types of sand (0-1, 0-2, and 0-4mm) and a polycarboxylic ether type super plasticizer were developed. These mixes are extensively tested, both in fresh and in hardened states and meet all practical and technical requirements, such as, low cement and powder content (Medium strength and low cost). The paper concludes that a theoretical analysis reveals that the packing of all solids in the mix (gravel, sand, filler and cement) is of major importance and the grading curve of all solids follow the modified Andreasen and Andersen curve, ideally. Using the packing theory of Andreasen and Andersen and its unification by Funk and Dinger, cheap SCC mixes can be composed that meet the standards and requirements in fresh state. Further more, a carboxylic polymer type super plasticizer is employed as sole admixture; an auxiliary viscosity enhancing admixture is not needed to obtain the required properties.
3.2.19 Roberto Troli, Antonio Borsoi, Silvia Collepardi, Glenda Fazio, Mario Collepardi, Saveria Monosi, (2005)

A group of Italian concrete technologists have presented this paper giving an account of innovative experimental tests on the combined use of CaO based expansive agents and Shrinkage Reducing Admixture (SRA) which allow manufacture of shrinkage-compensating concrete even in the absence of any early water curing. This technology appears to be very interesting in producing self-curing and self-compressing concretes with the reinforcing bars under tensile stress and the cementitious material under compressive stress. This technique has been combined with that of self-compacting concrete in order to manufacture a very innovative concrete which is “3 times self” : self-compacting, self-curing and self-compressing concrete

3.2.20 Anirwan Senguptha and Manu Santhanam (2006)

The authors worked to arrive at the optimum mix proportions of SCC for various consistency classes with the materials locally available. Six different classes of SCC according to EFNARC 2005 were developed in the laboratory with the materials locally available. All mixes satisfied the EFNARC criteria and showed good segregation resistance, passing ability, and so on. Higher amounts of powder contents were required to design SCC. The SCC mixes with higher powder contents resulting in higher compressive strengths. A good correlation was observed between V- funnel time and T-50 slump flow test.
3.2.21 M. Collepardi (2007) Comparative studies have been made by the author by producing a flowing concrete and two self-compacting concretes at given Portland cement content (400Kg/m3) and water-cement ratio (0.45) in order to obtain it with 28-days strength. Ground limestone or fly ash was used to manufacture SCC. A polycarboxylate based super plasticizer was adopted to produce SCCs with a slump flow of about 750 mm and a flowing concrete with a slump of 200mm, and found that compressive strengths of SCCs were higher than that of the flowing concrete. It was further reported that the steel bond strength in SCCs is higher than in the corresponding ordinary flowing concrete. It was concluded that the mechanical behavior of the SCC with respect to that of the ordinary flowing concrete could be ascribed to the filling effect of the fine particles of ground limestone or fly ash in the micro-voids of the cement matrix.


(1) Robustness of SCC: Robustness can be reported as the ability of the SCC mixture to maintain both the fresh properties and the composition pre-and post-casting of one batch or successive batches due to the composition of the mixture and the small changes in the contents of the ingredients of the mixture. Robustness depends on a number of different attributes including the specific composition of the mixture, the mixing history, that is, the sheer energy and sheer rate, and the specific application, and concludes that robustness issues can be overcome if a greater attention is paid to the moisture
variation in aggregate and careful metering of all ingredients, especially chemical admixtures and water. Higher robustness is achieved by increasing the viscosity of the mixture via materials selection and incorporation of more VMA and/or powder. With regard to the latter, incorporation of supplementary cementitious materials of high specific gravity, such as, slag, dolomite or limestone increase the robustness considerably.

(2) Innovations in Testing SCC: Researchers of ACBM are targeting development of new test equipment and methods for in-situ evaluation of SCC with an emphasis on viscosity, yield stress, and segregation resistance with research strategies of

(i) Understanding the fundamental aspect or rheology better;
(ii) Developing new techniques based on simple concepts; and
(iii) Developing the corresponding equipment that is both lab-and field-friendly.

To be different from the existing methods for testing SCC, it is required that these new methods help to evaluate the properties of SCC not only qualitatively but quantitatively too in two different research tracks to find out.

(a) Rheological properties,
(b) Segregation Resistance

Test procedures for them have been suggested.

(3) Formwork pressure: A major thrust area for research in SCC is in understanding formwork pressure, as formwork should be designed to withstand the full hydro-static head of fluid concrete and hence
there is a need for better understanding of the pressures that are actually seen in cast-in-place applications in the field. The researchers felt the need to study this in order to develop equations to reliably predict formwork pressures for a range of casting rates, and to calculate allowable casting rates based on form work strength. They observed that SCC exerts greater formwork pressure than normal concrete because SCC generally takes a greater period of time for its thixotropy to develop “Self-Supporting” structure in the fresh material. Formwork pressure can be measured by using pressure sensors mounted in formwork to develop formwork pressure models.


SCC has been developed using fly ash and ground glass by replacement of 15% cement and 14% of sand or with a glass/cement volume ratio up to 6.4% without the need for Viscosity Modifying Agent (VMA). Inclusion of ground glass leads to a required increase in w/p ratio and a slight reduction in super plasticizers dosage. Comparing the results with control mix, the mix with 40% fly ash with a volume ratio in the concrete of 7%, had 32% decrease in the super plasticizers dosage while the mix with white glass of 6.4% concrete volume had a 17% decrease in the super plasticizers dosage.

Normal & SCC of M60 grade concretes have been developed by the authors altering the ingredients of mix in order to find the mechanical properties by testing their compressive, tensile and flexural strengths for comparative study of both the mixes. Based on the experimental results, stress-strain curves have been plotted and the behaviour is observed to be almost similar to conventional concrete & SCC. Analytical equations have been proposed based on existing empirical models of ‘Carriera & Chu’(1985) as modified for descending portion from ‘Popovics’ (1973) model which represents only ascending portion and ‘Saenz Model’ as also modified from ‘Desayi’s model’ of only ascending portion. It was concluded that values of strain at peak stress under axial compression for both the concretes are close to 0.002 as given in IS:456-2000. It was further reported that the theoretical and experimental stress-strain values have good correlation.


The authors developed SCC mixes of grades M30, M40, M50 & M60 and cast 50 mm dia. cylinders in order to test the permeability characteristics by loading in the cells duly applying constant air pressure of 15 kg/mm² along with water pressure of 2Kg/mm² for a specified period of time and obtained coefficient of permeability to conclude that the higher the grade of SCC mixes, the more the resistance to the permeability compared to the lower grade of SCC.
mixes because of the transformation of large pores to fine pores as a consequence of the pozzolonic reaction between cement paste and fly ash to substantially reduce the permeability in the cementitious matrix.


The authors present the compositions, the performances and some practical applications of high-performance SCCs in this study. In particular, they report some performance improvements carried out in their laboratories as evidences for the following specific uses:

(a) SCC for a building engineering application (S. Peter Apostle Church in Pescara, Italy) with white concrete characterized by a marble-like skin;

(b) SCC in the form of high-strength concrete with compressive strength over 90 MPa devoted to a work in the field of Civil Engineering (World Trade Centre in San Marino);

(c) SCC in the form of mass concrete structure with a reduced risk of cracking induced by thermal difference between the nucleus and the skin of the elements and conclude that the results obtained in the present paper show the extra-ordinary properties which can be obtained by using the innovative concretes as developed, in particular SCC, and states that the architectural SCC presented in this paper is a very special concrete even for an excellent surface (white and with marble like aspect) required for architectural reasons.
In a nutshell, a super workable concrete was developed in 1993 by Kuroiwa which was named by Okamura in 1995 as anti-washout concrete with self compacting property.

Later on many researchers worked on the same concrete adding different types of chemical and mineral admixtures like fly ash, GGBS, super-plasticizers and viscosity modifying agents, and finally developed the present stage of SCC with enhanced self-compacting and durability characteristics.

3.3 Fiber Reinforced Concrete/Self-Compacting Concrete

3.3.1 M.A. Mansur, M.S. Chin and T.H. Wee(1997)

The authors developed experimental stress-strain curves for high strength plain and fibre concrete with confinement in the form of lateral ties duly considering test parameters of the diameter of the tie, spacing, core area of concrete and specimen casting direction. The results obtained do not effect Initial Tangent Modulus and Poisson’s Ratio of the concrete due to confinement. Vertically cast fibre concrete specimen with confinement exhibits larger strain at peak stress and has higher post peak ductility when compared to a similar specimen cast horizontally. However, improvement of ductility remains more or less the same for both horizontal and vertically cast specimen. An analytical model has been developed (presented in section 3.5 of Mathematical Models of Stress-Strain Behaviour of Concrete ) based on the experimental data for stress-strain curves for confined high strength concrete and found it to tally well with the experimental stress-strain curves.
3.3.2 M. Veera Reddy and M.V. Seshagiri Rao (2007)

The authors present a mathematical model for complete stress-strain relationship for steel fibre reinforced high-strength concrete and found that the analytical model developed is in close comparison with the experimental test data, and report that the second degree polynomial form of stress-strain relation suggested by Saenz is of the better fit which is the same as reported by MLV Prasad, P. Rathish Kumar et al (2009) in the case of GFRSCC.


A standard grade self-compacting concrete of mix M30 has been developed in order to develop fibre reinforced self compacting concrete using different mineral admixtures of Fly Ash, Ground Granulated Blast- furnace Slag (GGBS) and the combination of both in suitable proportions. Studies were conducted on the mechanical behaviour like stress-strain properties and modulus of elasticity.

An equation relating Compressive Strength (f_{ck}) and Modulus of Elasticity (E_c) has been proposed for plain SCC and GFRSCC mixtures as $E_c = 4700 \sqrt{f_{ck}}$ and $E_c = 5700 \sqrt{f_{ck}}$ respectively, and an increase of 21.5% in the value of modulus of elasticity was observed following the addition of glass fibres to the SCC mix. Toughness or energy absorption capacity of GFRSCC mixture is improved by 40% compared to plain SCC mix whose ductility has improved by over 21% due to the addition of 600 grams/cubic metre of glass fibre to SCC mix. Hence it can be concluded that GFRSCC can be adopted for any structural applications. The investigations have been further extended
for the study of application in flexures by casting and testing under-reinforced SCC and GFRSCC beams, and it is found that load carrying capacity of GFRSCC increased from 7.5% to 20%.

3.3.4 MLV Prasad, P. Rathish Kumar and Toshiyuki Oshima (2009)

The authors observed that inclusion of glass fibres in SCC improved the strain at peak stress and report that strain at peak stress varies linearly with fibre index. A mathematical model has been developed using a polynomial of the form shown as \[
A + D = \frac{1 + B + C}{1 + B + C} 
\]
where \(f\) is the stress and \(\varepsilon\) is the strain at every loading.

3.3.5 VMCF Cunha (2010) PhD Thesis

The author intends to obtain the knowledge on the behaviour of SFRSCC, the use of which is promising to increase considerably in the coming years as this composite material is likely to replace the conventional reinforcement thereby reducing man-labour cost. In this process, investigations have been carried out to obtain the micro mechanics aspects of fibre reinforcement and fibre distribution structure in the hardened concrete. This study provides deeper understanding of mechanisms of multiple reinforcement and composite behaviour of compression, uniaxial tension and flexure. Finally, a numerical model was developed to predict the mechanical properties based on micro-mechanical properties of fibres.
3.3.6 Pedro J.D. Mendes, Joaquim A.O. Barros, Jose M. Sena-Cruz and Mahsa Taheri (2011)

The paper deals with 12-metre long pedestrian bridge consisting of two composite “I-profiles”. The combination of fibre reinforced SCC and Steel Reinforced Polymer (SRP) has shown improved post crack tensile strength, stiffness and ductility.

3.3.7 Valeria Corinaldesi and Giacomo Moriconi (2011)

The authors have investigated the properties of SCC using three types of fibres, namely, Steel, Poly-Vinyl-Alcohol and Poly Propylene high tough fibres. They have added limestone powder and recycled concrete powder as mineral additions. The fresh and hardened concrete properties like workability, strength and shrinkage were evaluated and they found that SCC with the above fibres and additions behaved well with improved durability.

3.3.8 Alessandro P. Fantilli, Paolo Vallini and Bernardino Chiaia (2011)

This paper reports the behavior of plain SCC and steel fibre SCC under multi-axial compression. In the first stage, the loading is applied in the form of confining pressures and hydraulic stress was applied at the later stage till failure. They reported that the ductility in compression increases with confinement in the form of outside pressure or fibre reinforcement and that low fibre content less than 0.45% has no significant advantage.
3.3.9 V.M.C.F. Cunha, J.A.O. Barros and J.M. Sena-Cruz (2011)

The paper presents the work carried out to develop numerical model for the tensile behavior of SFRSCC. They have assumed SFRSCC as two phase material. The nonlinear material behavior of self compacting concrete is given by 3-D smeared crack model. The numerical model showed good correlation with experimental values.

3.3.1 S.Grunewald, F. Laranjeira, J.Walraven, A. Aguado and C. Molins, (2012)

This paper discusses the potential for an improved performance of fibres in self-compacting concrete. Significant differences were observed between conventional and SCC at a given fibre type and dosage concerning the variation of results and flexural performance. Mechanical testing and image studies on concrete cross-sections indicate how the flow influences performance, the orientation and the distribution of the orientation of fibres and differences between traditionally compacted and flowable concrete are pointed out.

3.3.11 E. Marangon, R.D. Toledo Filho; and E.M.R Fairbairn, (2012)

It was attempted to find out the contribution of steel fibres in Self-Compacting Steel Fibre Reinforced Concrete (SCSFRC) with regard to the creep under tension and compression. In the experimental investigation, tests were carried out on self-compacting mixes by providing reinforcement with volume fractions of 0%, 1% and 1.25% of steel fibres, 35mm and 65mm long. It was found that tensile creep is smaller than compressive creep. This agrees with the findings
of the French researchers of Institute for Radiation Hygiene and Nuclear Safety (IRSN) and French Public Works Research Laboratory (LCPC). Moreover, the effect of fibres on tensile creep is not evident. For a volume fraction of 1%, the creep of the SCC was reduced and for 1.25% fraction, the tensile creep increased. The different types of fibres also did not show significant influence on compressive creep behavior. Hence, further studies are required for complete understanding of this aspect.

It is understood that just like conventional concrete, the SCC is also brittle in nature. Hence, researchers have worked on the development of SCC with improved ductility, impact resistance, energy absorption, and so on by introducing different types of small discrete fibres, and arrived at FRSCC with improved performance characteristics enabling the use of the material for various Civil Engineering applications.

3.4 Fibre Reinforced Concrete Wall Panels

3.4.1 Maganti Janardhana, A. Meher Prasad and Devdas Menon (2006)

Investigations were carried out on lateral resistance of Glass Fibre Reinforced Gypsum (GFRG) wall panel as a component of buildings. Numerical analytical procedures have been developed to predict the capacity under axial compression, compression with in-plane bending and shear. The authors report that the failure load is dependent on the plaster strength for unfilled wall panels and on out-of-plane buckling for concrete-filled wall panels. Further, it is reported
that the axial load carrying was influenced by eccentricity and support conditions in respect of concrete filled wall panels. The shear failure is longitudinal for concrete filled GFRG panel, which is different from that of traditional RC wall panel.

An interaction diagram was developed to arrive at the reinforcement required for a concrete filled GFRG wall panel to carry a given load.

3.4.1 Joaquim Barros, Eduardo Pereira and Simao Santos (2007)

This paper deals with the study of the behavior of light weight precast SFRSCC panels used for building facades. Attempts were made to obtain the SFRSCC post crack behavior. These panels are studied to assess the effect of age on the SFRSCC fracture behavior. To obtain the punching resistance and flexural strength, SFRSCC prototype panels were tested. They have concluded that negative bending moments were formed and then punch cracks occurred along the bending of the steel plates.


Experiments were conducted on steel fiber reinforced wall panels under axial compression with pinned-fixed end conditions until failure.

The results indicated that the steel fibre wall panel has sustained more than 30% carrying capacity compared to the maximum design axial load. The lateral displacement is about 14.5% less than the theoretical value, even though the load is 30% more
than the calculated magnitude. The finite element analysis confirmed the experimental findings.


Experiments were conducted to find out the axial compressive strength and stiffness of unfilled, concrete filled (M20) and RC filled GFRG wall panels. It is found that there is a substantial increase in axial strength and stiffness with filling of wall panels. Similar increase is found for eccentric loading for filled wall panels compared to unfilled wall panels. It was observed that numerical analysis using finite element methods for assessing the strength of wall panels give values that are very close to experimental results.

3.4.4 **N. Ganesan, P.V. Indira and S. Rajendra Prasad (February 2010)**

The authors have reported investigations on the behavior of SFRC and normal concrete wall panels in one-way in-plane subject to load at the minimum eccentricity of t/6. They have developed models to predict the ultimate loads.

3.4.5 **N. Ganesan, P.V. Indira and S. Rajendra Prasad (October 2010)**

This paper discussed the effect of steel fibres on the two-way R.C wall panels. A minimum eccentric load was applied as a uniformly distributed vertical load to study the effect of slenderness ratio and aspect ratio of steel fibres. The volume of steel fibres used is 0.50%. They found that the ultimate strength of SFRC is higher. Load
Deflection curves indicate more softening behavior and higher ductility. The authors have proposed a method to predict the ultimate strength of the SFRC panels.

**3.4.6 Ruzitah Supinyeh and Siti Hawa Hamzah (2010)**

The authors have studied the behavior of steel fabric reinforced concrete on M30 grade 1.0m x 1.5m x 0.075m wall panel under load at minimum eccentricity of t/6 for pinned and fixed support conditions. They found that under eccentric loading, all wall panels failed in compression shear under single curve pattern where the panels bend towards rear side. No cracks were seen on front or rear surfaces of the panels until crushing. They also carried out numerical analysis using different softwares and found good agreement with experimental values.

It is inferred that normally unreinforced in-fill wall panels are used in the multistoried framed building construction, but it was proved that reinforced in-fill walls behave better under lateral loading. If fibres are introduced in the concrete wall panels, they further improve the crack resistance, energy dissipation and ductility of the highly stressed structural elements.

It was reported that the fibre reinforced structural walls made with normal concrete behaved in a better way under eccentric vertical loadings.
3.5 Mathematical Models Available for Stress-Strain Behaviour of Concrete and Fibre Concrete

Much work was reported by many researchers and many models were developed for the Stress-Strain behaviour prediction of concrete. Some models are considered below.

3.5.1 Desayi and Krishnan’s model (1964)

For Normal strength concrete, the stress-strain relationship is given by

\[
f = \frac{E \varepsilon}{1 + \left(\frac{\varepsilon}{\varepsilon_o}\right)^2}
\]

Where \(f\) = stress at any strain \(\varepsilon\)

\(\varepsilon_o\) = strain at the maximum stress of \(f_o\)

\(f_o\) = stress at failure at \(\varepsilon_c\)

\(\varepsilon_c\) = maximum strain at failure

E = a constant (same as initial tangent modulus), so that \(E = 2 f_o / \varepsilon_o\)

This model is a derivation of Saenz’s original equation

\[
f = \frac{\varepsilon}{A + B \varepsilon + C \varepsilon^2}
\]

for a special case of concretes which have the ratio of \(E/E_s\) equal to 2.

This aspect has been amply discussed by the author and concluded that “Saenz’s derivation of the author’s equation as a special case of his equations is revealing”. In view of this clarification by the authors, the simplified model has been used in the present work called Saenz model. However, this model being simpler in form, is found to be
closer in agreement only with the ascending portion of the stress-strain curve.

**3.5.2 Saenz Model. (1964)**

Considering the limitation of analytical equation proposed by Desayi et al (a derivation of Saenz’s original equation for a special case of concrete), Saenz proposed a mathematical model considering both ascending and descending portions of the stress-strain curve which is a function of three ratios, namely, modular, stress and strain ratios. This model is proposed in the form of:

$$f = \frac{\varepsilon}{A + B\varepsilon + C\varepsilon^2 + D\varepsilon^3}$$

The conditions to be fulfilled are

For $\varepsilon = 0$, $f = 0$ or point of origin

For $\varepsilon = \varepsilon_o$, $f = f_o$ or point of maximum stress

For $\varepsilon = \varepsilon_c$, $f = f_f$ or point of maximum strain

$$f_f = \text{stress at point of failure}$$

For $\varepsilon = 0$, $\frac{df}{d\varepsilon} = E$ or value of the dynamic modulus

For $\varepsilon = \varepsilon_o$, $\frac{df}{d\varepsilon} = 0$ or maximum of the curve

Fulfilling these conditions, the value of the parameters are:
Where

\[ R = \frac{R_E (R_f - 1)}{(R_e - 1)^2} - \frac{1}{R_e} \]

is the ratio's relation

\[ R_E = \frac{E}{E_s} \]

is the modular ratio

\[ R_f = \frac{f_o}{f_f} \]

is the stress ratio

\[ R_e = \frac{\varepsilon_i}{\varepsilon_o} \]

is the strain ratio

Therefore the general equation for all concretes is

\[ f = \frac{E \varepsilon}{1 + (R + R_E - 2) \frac{\varepsilon}{\varepsilon_o} - (2R - 1) \left( \frac{\varepsilon}{\varepsilon_o} \right)^2 + R \left( \frac{\varepsilon}{\varepsilon_o} \right)^3} \]

Thus, the above equation is a function of three ratios: modular, stress and strain ratios.

If in the above equation \( R = 0 \) (ignoring all the three ratios), the equation is reduced to
Further, if $E/E_s = 2$ (for only one chosen concrete), the above equation is simplified as

$$f = \frac{E\varepsilon}{1 + \left(\frac{E}{E_s} - 2\right)\varepsilon + \left(\frac{\varepsilon}{\varepsilon_0}\right)^2}$$

It may be noted that this equation is the same as the one proposed by Desayi et al in 3.5.1.

**3.5.3 Hognestad Model (1955)**

For Normal strength concrete up to ascending portion, the stress-strain model, is

$$f_c = f'_c \{2 \left(\frac{\varepsilon}{\varepsilon_o}\right) - \left(\frac{\varepsilon}{\varepsilon_o}\right)^2\}$$

Where $f'_c =$ compressive strength

$$\varepsilon_o = \text{strain at peak stress} = 0.0078 \left( f'_c \right)^{1/4}$$

**3.5.4 Wang et.al. Model (1978)**

The model used by Wang et al. is in the form of

$$K = \frac{6.7f_c^{0.83}}{f'_c} \quad f_c = f'_c \left[ \frac{A\left(\frac{\varepsilon}{\varepsilon_o}\right) + B\left(\frac{\varepsilon}{\varepsilon_o}\right)^2}{1 + C\left(\frac{\varepsilon}{\varepsilon_o}\right) + D\left(\frac{\varepsilon}{\varepsilon_o}\right)^2} \right]$$

In this model instead of using one set of the coefficients A, B, C, and D to generate the complete stress strain curve, Wang et al., used two sets of coefficients – one for the ascending portion and the other for the descending portion, the respective coefficients being obtained by applying relevant boundary conditions assigned to each part of the curve.
3.5.5 Carriera and Chu Model (1985)

This model is in the form of

\[
f_c = f'_c \left( \frac{\beta (\varepsilon / \varepsilon_o)}{\beta - 1 + (\varepsilon / \varepsilon_o)^\beta} \right)
\]

In which \( \beta = \frac{1}{1-f'_c/\varepsilon_o E_{it}} \) for \( \beta \geq 1.0 \) and \( \varepsilon \leq \varepsilon_o \)

Where \( \beta \) is a material parameter that depends on the shape of the stress-strain diagram.

\( f'_c \) = cylinder ultimate compressive strength and

\( \varepsilon_o \) = strain at ultimate stress; \( E_{it} \) = initial tangent modulus.


The author has compared several analytical Models for Stress-Strain curves for confined concrete. Based on experimental test results, different stress-strain models were proposed for confined and unconfined concrete by many researchers like Sheikh and Uzumer (1982), Mand et al (1988), and Curson and Paulitre (1995). The available stress-strain models for unconfined and confined concrete, both normal strength and high strength, can be broadly divided into three categories. The form of equation proposed by Sargin et al (1971) was used by a group of researchers as shown in Table 3.5.6.1. Some other group has suggested a model with a second order parabola for the ascending portion of the curve and straight line for the descending portion which were based on the equations given by Kent and Park (1971) as shown in Table 3.5.6.2. Some other relationships were
developed based on the equations as suggested by Popovics (1973) as shown in Table 3.5.6.3.

**Table 3.5.6.1: Stress-strain models for confined concrete based on Sargin et al. (1971)**

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Equation</th>
<th>Parameter(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sargin et al. (1971)</td>
<td>[ Y = \frac{AX + (D-1)X^2}{1 + (A-2)X + DX^2} ]</td>
<td>[ A, D ] 0.65 – 7.25f_c x 10^{-3}</td>
</tr>
<tr>
<td>Wang et al. (1978)</td>
<td>Different parameters for ascending and descending branches</td>
<td></td>
</tr>
<tr>
<td>Ahmed and Shah (1982)</td>
<td>[ \frac{E_i}{E_f} ] [ 1.111 + 0.876A - 4.0883 \frac{f_{sci}}{f_c} ]</td>
<td></td>
</tr>
<tr>
<td>El-Dash and Ahmad (1995)</td>
<td>[ \frac{E_c}{E_f} ] [ \frac{16.5}{\sqrt{f_c}} \left( \frac{f_i}{(s/d)} \right)^{0.33} ]</td>
<td></td>
</tr>
<tr>
<td>Attard and Setunge (1996)</td>
<td>[ \frac{E_i}{f_{cc}} ] [ (A-1)^2 + \frac{A^2(1-\alpha)}{\alpha(1-\frac{f_i}{f_{cc}})} + \frac{A^2}{\alpha^2} \left( \frac{1}{f_i} - \frac{1}{f_{cc}} \right)^2 ]</td>
<td></td>
</tr>
<tr>
<td>Assa et al. (2001a)</td>
<td>[ \frac{E_c}{f_{cc}} ] [ \frac{(\varepsilon_{cc} / \varepsilon_{sci})^2}{0.2(\varepsilon_{sc} / \varepsilon_{sci})^2} ]</td>
<td></td>
</tr>
</tbody>
</table>

\( \varepsilon_{cc} \) is the axial strain corresponding to the peak stress of confined concrete( \( f_{cc} \))

\( \varepsilon_{sci} \) is the axial strain of confined concrete at 0.8 \( f_{cc} \) on descending branch

\( E_i \) is the initial tangent modulus

s = spacing of the confinement

d = diameter of the bar
Table 3.5.6.2: Stress-strain models for confined concrete based on Kent and Park (1971)

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Ascending Branch ($\sigma_1$)</th>
<th>Descending Branch ($\sigma_1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kent and Park (1971)</td>
<td>$f_{cc} \left[2 \left(\frac{\varepsilon_1}{0.002}\right) - \left(\frac{\varepsilon_1}{0.002}\right)^2\right]$</td>
<td>$f_{cc} \left[1 - Z_m \left(\varepsilon_1 - 0.002\right)\right]$</td>
</tr>
<tr>
<td>Sheikh and Uzumeri (1982)</td>
<td>$K_f \left[2 \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right) - \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right)^2\right]$</td>
<td>$f_{cc} \left[1 - Z_m \left(\varepsilon_1 - \varepsilon_{cc}\right)\right]$</td>
</tr>
<tr>
<td>Park et al. (1982)</td>
<td>$K_f \left[2 \left(\frac{\varepsilon_1}{0.002K}\right) - \left(\frac{\varepsilon_1}{0.002K}\right)^2\right]$</td>
<td>$K_f \left[1 - Z_m \left(\varepsilon_1 - 0.002K\right)\right]$</td>
</tr>
<tr>
<td>Scott et al. (1982)</td>
<td>Same as Park et al. (1982)</td>
<td></td>
</tr>
<tr>
<td>Samra (1990)</td>
<td>Same as Kent and Park (1971)</td>
<td></td>
</tr>
<tr>
<td>Saatcioglu and Razvi (1992)</td>
<td>$f_{cc} \left[2 \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right) - \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right)^2\right]^{1/(1+2K)}$</td>
<td>$f_{cc} \left[1 - Z_m \left(\varepsilon_1 - \varepsilon_{cc}\right)\right]$</td>
</tr>
<tr>
<td>Saatcioglu et al. (1995)</td>
<td>Same as Saatcioglu and Razvi (1992)</td>
<td></td>
</tr>
<tr>
<td>Razvi and Saatcioglu (1999)</td>
<td>$f_{cc} \left[\frac{K_r e^{r(\varepsilon_1 - \varepsilon_{cc})}}{r-1-x^f}\right]$</td>
<td>$f_{cc} \left[1 - Z_m \left(\varepsilon_1 - \varepsilon_{cc}\right)\right]$</td>
</tr>
<tr>
<td>Mendis et al. (2000)</td>
<td>$K_f \left[2 \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right) - \left(\frac{\varepsilon_1}{\varepsilon_{cc}}\right)^2\right]$</td>
<td>$K_f \left[1 - Z_m \left(\varepsilon_1 - \varepsilon_{cc}\right)\right]$</td>
</tr>
<tr>
<td>Shah et al. (1983)</td>
<td>$f_{cc} \left[1 - \left(1 - \frac{\varepsilon_1}{\varepsilon_{cc}}\right)^4\right]$</td>
<td>$f_{cc} e^{-k(\varepsilon_1 - \varepsilon_{cc})^{1.15}}$</td>
</tr>
</tbody>
</table>

$f_{cc}$ is the peak axial stress and the corresponding axial strain is $\varepsilon_{cc}$ of confined concrete

$$K = \frac{6.7f_1^{0.83}}{f_c}$$
### Table 3.5.6.3: Stress-strain models for confined concrete based on Popovics (1973)

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Ascending Branch ($\sigma_a$)</th>
<th>Descending Branch ($\sigma_d$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Popovics (1973)</td>
<td>$f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^n \frac{n}{n-1+ \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^n}$</td>
<td></td>
</tr>
<tr>
<td>Carreira and Chu (1985)</td>
<td>$f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta} \frac{\beta}{\beta-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}$</td>
<td></td>
</tr>
<tr>
<td>Mander et al. (1988)</td>
<td>$f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{f} \frac{f}{r-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)}$</td>
<td></td>
</tr>
<tr>
<td>Hsu and Hsu. (1994)</td>
<td>$\frac{f_{cc} n \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}{n^{\beta-1} + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}$</td>
<td>$0.3f_{cc} e^{0.3 (\varepsilon_1/\varepsilon_{cc})^x \delta}$</td>
</tr>
<tr>
<td>Cusson and Paultre (1995)</td>
<td>$f_{cc} \left( \frac{k (\varepsilon_1/\varepsilon_{cc})}{k-1 + (\varepsilon_1/\varepsilon_{cc})^k} \right)$</td>
<td>$f_{cc} e^{k_1 (\varepsilon_1/\varepsilon_{cc})}$</td>
</tr>
<tr>
<td>Wee et al. (1996)</td>
<td>$\frac{f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}{\beta-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}$</td>
<td>$\frac{f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{\beta}}{k_1 \beta-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{k_1 \beta}}$</td>
</tr>
<tr>
<td>Hoshikuma et al. (1997)</td>
<td>$E_{c1} \left[ 1 - \frac{1}{n} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^n \right]$</td>
<td>$f_{cc} - E_{dec} \left( \varepsilon_u - \varepsilon_{cc} \right)$</td>
</tr>
<tr>
<td>Martirosyan and Xiso (2001)</td>
<td>$\frac{f_{cc} \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{r}}{r-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^{kr}}$</td>
<td></td>
</tr>
<tr>
<td>Chung et al. (2002)</td>
<td>$f_{cc} \left[ \frac{k \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)}{k-1 + \left( \frac{\varepsilon_1}{\varepsilon_{cc}} \right)^k} \right]$</td>
<td>$f_{cc} + \frac{0.15 f_{cc}}{\varepsilon_{cc} - \varepsilon_1} \left( \varepsilon_{cc} - \varepsilon_1 \right)$</td>
</tr>
</tbody>
</table>
Of the above said models, a modified equation by Carriera and Chu has been recommended because of its simplicity and close agreement with unconfined concrete. The equations were further modified by M.A. Mansur et al. in 1997. They found that the original form of Carriera and Chu (1985) model describes the ascending portion of the stress-strain curve, provided, appropriate values of concrete peak stress, initial tangent modulus and the strain at peak stress are used. For the ascending portion, the equation is:

\[
f = f_o \left[ \beta \left( \frac{\varepsilon}{\varepsilon_o} \right) \right]^{-1 + \left( \frac{\varepsilon}{\varepsilon_o} \right)^\beta} \]

Where, \( f \) and \( \varepsilon \) are the stress and strain of concrete and \( \beta \) is the material parameter that depends on the shape of the stress-strain diagram given by

\[
\beta = \frac{1}{1 - \frac{f_o}{\varepsilon_o E_{it}}} \]

For descending portion of the stress-strain curve, two correction factors \( k_1 \) and \( k_2 \) are proposed to take into account the confinement effect. The equation for the descending portion is modified as,

\[
f = f_o \left[ \frac{k_1 \beta \left( \frac{\varepsilon}{\varepsilon_o} \right)}{k_1\beta - 1 + \left( \frac{\varepsilon}{\varepsilon_o} \right)^{k_2\beta}} \right]^{-1 + \left( \frac{\varepsilon}{\varepsilon_o} \right)^\beta} \]
The values of $k_1$ and $k_2$ proposed by Mansur et al are given below.

For confined non-fiber concrete both horizontally and vertically cast

$$k_1 = 2.77 \left[ \frac{\rho f_y}{f_o} \right] \quad \text{and} \quad K_2 = 2.19 \left[ \frac{\rho f_y}{f_o} \right] - 0.17$$

For horizontally cast confined fibre concrete,

$$k_1 = 3.33 \left[ \frac{\rho f_y}{f_o} \right] + 0.12 \quad \text{and} \quad k_2 = 1.62 \left[ \frac{\rho f_y}{f_o} \right] + 0.35$$

Where, $f_o$ is the stress of unconfined concrete and $\rho_s$ is the volumetric ratio of confining steel.

In summary, of all the above stress-strain models, derived and simplified, the modified Saenz Model which is more appropriate for ascending portion of the curve, seems to be valid for both ascending and descending curves, while the model proposed by Mansur et al (1997) that considers fibre content has been taken up for comparing the experimental stress-strain relations in the present investigations.

An attempt has been made in this thesis to develop normal grade (30 MPa) FRSCC using various kinds of fibres and to study the behavior of FRSCC wall panels under vertical loading including the effect of minimum eccentricity.