Steel Fiber Reinforced Concrete: A Review

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Abstract

Concrete is one of the world most widely used construction material. However, since the early 1800's, it has been known that concrete is weak in tension. Weak tensile strength combined with brittle behavior result in sudden tensile failure without warning. This is obviously not desirable for any construction material. Thus, concrete requires some form of tensile reinforcement to compensate its brittle behavior and improve its tensile strength and strain capacity to be used in structural applications. Historically, steel has been used as the material of choice for tensile reinforcement in concrete. Unlike conventional reinforcing bars, which are specifically designed and placed in the tensile zone of the concrete member, fibers are thin, short and distributed randomly throughout the concrete member. Fibers are commercially available and manufactured from steel, plastic, glass and other natural materials. Steel fibers can be defined as discrete, short length of steel having ratio of its length to diameter (i.e. aspect ratio) in the range of 20 to 100 with any of the several cross-section, and that are sufficiently small to be easily and randomly dispersed in fresh concrete mix using conventional mixing procedure. The random distribution results in a loss of efficiency as compared to conventional rebars, but the closely spaced fibers improve toughness and tensile properties of concrete and help to control cracking. In many situations it is prudent to combine fiber reinforcement with conventional steel reinforcement to improve performance. Fibre Reinforced Concrete (FRC) is defined as a composite material essentially consisting of conventional concrete or mortar reinforced by the random dispersal of short, discontinious, and discrete fine fibres of specific geometry. Since Biblical times, approximately 3500 years ago, brittle building materials, e.g. clay sun baked bricks, were reinforced with horse-hair, straw and other vegetable fibres. Although reinforcing brittle materials with fibers is an old concept, modern day use of fibers in concrete is only started in the early 1960s. Realizing the improved properties of the fiber reinforced concrete products, further research and development on fiber reinforced concrete (FRC) has been initiated since the last three decades. This paper presents an overview of the mechanical properties of Steel Fiber Reinforced Concrete (SFRC), its advantages, and its applications.

Keywords: Fiber Reinforced Concrete (FRC), Steel Fiber Reinfoced Concrete (SFRC), Mechanical properties.

1. Introduction

One of the undesirable characteristics of the concrete as a brittle material is its low tensile strength, and strain capacity. Therefore it requires reinforcement in order to be used as the most widely construction material. Conventionally, this reinforcement is in the form of continuous steel bars placed in the concrete structure in the appropriate positions to withstand the imposed tensile and shear stresses. Fibers, on the other hand, are generally short, discontinuous, and randomly distributed throughout the concrete member to produce a composite construction material known as fiber reinforced concrete (FRC). Fibers used in cement-based composites are primarily made of steel, glass, and polymer or derived from natural materials. Fibers can control cracking more effectively due to their tendency to be more closely spaced than conventional reinforcing steel bars. It should be highlighted that fiber used as the concrete reinforcement is not a substitute for conventional steel bars. Fibers and steel bars have different roles to play in advanced concrete technology, and there are many applications in which both fibers and continuous reinforcing steel bars should be used.

Steel fiber (SF) is the most popular type of fiber used as concrete reinforcement. Initially, SFs are used to prevent/control plastic and drying shrinkage in concrete. Further research and development revealed that addition of SFs in concrete significantly increases its flexural toughness, the energy absorption capacity, ductile behaviour prior to the ultimate failure, reduced cracking, and improved durability (Altun et al., 2006). This paper reviews the effects of addition of SFs in concrete, and investigates the mechanical properties, and applications of SF reinforced concrete (SFRC).

2. Different Types of Fibers

There are two methods to categorize fibres according to their modulus of elasticity or their origin. In the view of modulus of elasticity, fibres can be classified into two basic categories, namely, those having a higher elastic modulus than concrete mix (called hard intrusion) and those with lower elastic modulus than the concrete mix (called soft intrusion). Steel, carbon and glass have higher elastic modulus than cement mortar matrix, and polypropylene and vegetable fibres are classified as the low elastic modulus fibres. High elastic modulus fibers simultaneously can improve both flexural and impact resistance; whereas, low elastic modulus fibres can improve the impact resistance of concrete but do not contribute much to its flexural strength.

According to the origin of fibres, they are classified in three categories of metallic fibers (such as steel, carbon steel, and stainless steel), mineral fibers (such as asbestos and glass fibers), and organic fibers. Organic fibers can be further divided into natural and man-made fibers. Natural fibers can be classified into vegetable origin or sisal (such as wood fibers and leaf fibers), and animal origin (such as hair fibers and silk). Man-made fibers can also be divided into two groups as natural polymer (such as cellulose and protein fibers), and synthetic fibers (such as nylon and polypropylene). Figure 1 shows the classification of fibers based on this method **(**James Patrick Maina Mwangi, 1985). Table 1 shows the properties of different types of fibers can be used in the concrete industry (Johnson and Colin, 1982).

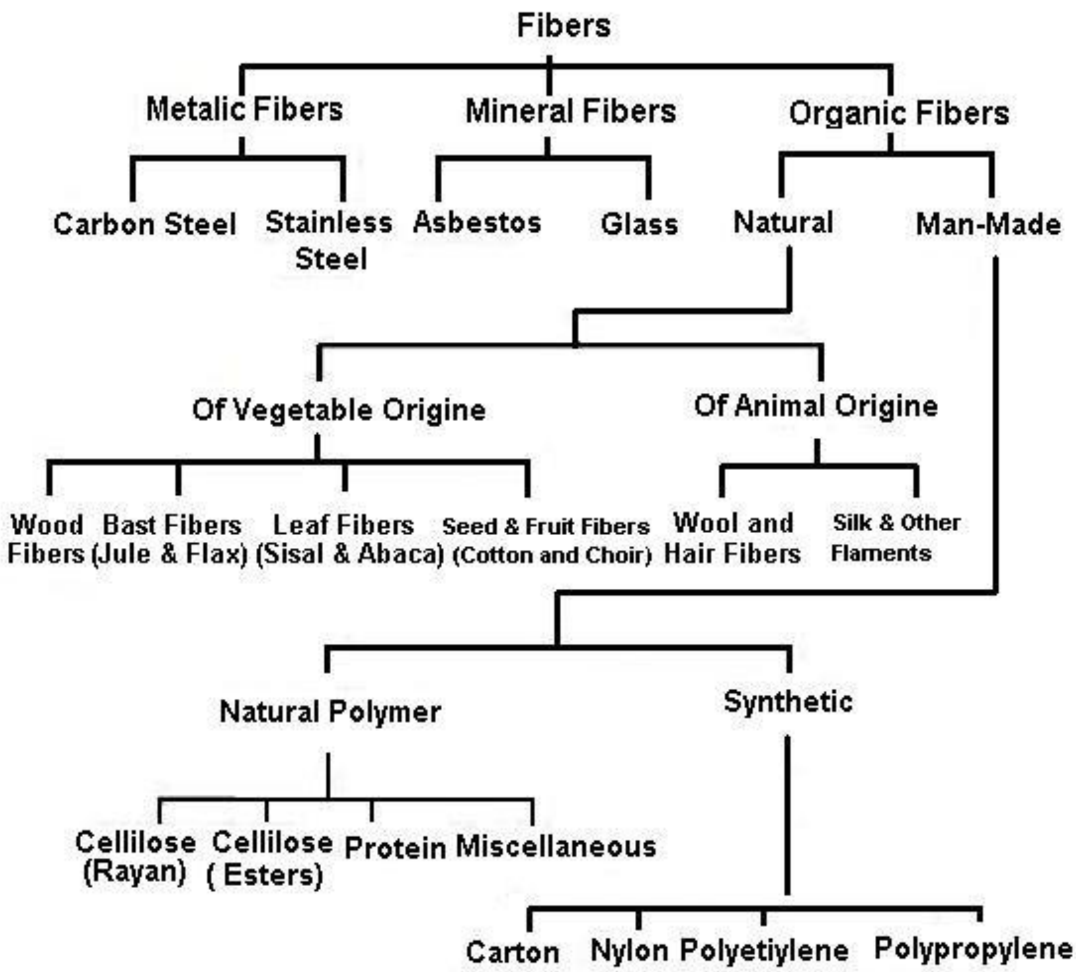

Figure1: Fibers Classification (James Patrick Maina Mwangi, 1985)

Table1: General Properties of Fibres (Johnson and Colin, 1980)

Fibers	*Diameter (μm)*	*Specific Gravity*	*Modulus of Elasticity (GPa)*	*Tensile Strength (GPa)*	*Elongation to Failure (%)*
Chrysotile Asbestos	*0.02-20*	*2.55*	*164*	*3.1*	*2-3*
Crocidolite Asbestos	*0.1-20*	*2.55*	*196*	*3.5*	*2-3*
E-Glass	*9-15*	*2.56*	*77*	*2-3.5*	*2-3.5*
AR-Glass	*9-15*	*2.71*	*80*	*2-2.8*	*2-3*
Fibrillated Polypropylene	*20-200*	*0.91*	*5*	*0.5*	*20*
Steel	*5-500*	*7.84*	*200*	*1-3*	*3-4*
Stainless Steel	*5-500*	*7.84*	*160*	*2.1*	*3*
Carbon Type I	*3*	*1.90*	*380*	*1.8*	*0.5*
Carbon Type II	*9*	*1.90*	*230*	*2.6*	*1.0*

Aramid (Kevlar)	*10*	*1.45*	*65-133*	*3.6*	*2.1-4.0*
Cellulose	*-*	*1.2*	*10*	*0.4*	*-*
Wood	*-*	*1.5*	*71*	*09*	*-*
Nylon(Type 242)	*>4*	*1.14*	*4*	*0.9*	*15*

3. Steel Fiber Reinforced Concrete (SFRC)

In 1910, Porter first suggested the use of SFs in concrete (Naaman, 1985). However, the first scientific research on fibre reinforced concrete (FRC) in the United States was done in 1963 (Romualdi and Baston, 1963). SFRC is produced using the conventional hydraulic cements, fine and coarse aggregates, water, and SFs. American concrete institution (ACI 544.IR, 1996) defines SFs as discrete, short lengths of steel having aspect ratio (ratio of lenth to diameter) in the range of 20 to 100 with any of the several cross-section which are sufficiently small to be easily and randomly dispersed in fresh concrete mix using conventional mixing procedures. To enhance the workability and stability of SFRC, superplasticizers (chemical admixtures) may also be added into the concrete mix. Figure 2 shows the engineering specifications of the SFs such as their shape, material, length, diameter, and type of cross-section (ACI 544.IR, 1996).

The behavior of SFRC can be classified into three groups according to its application, fiber volume percentage and fiber effectiveness; for instance SFRC is classified based on its fiber volume percentage as follows: 1-Very low volume fraction of SF (less than 1% per volume of concrete), which has been used for many years to control plastic shrinkage and as pavement reinforcement. 2-Moderate volume fraction of SFs (l% to 2% per volume of concrete) which can improve modulus of rupture (MOR), flexural toughness, impact resistance and other desirable mechanical propertie of concrete. 3-High volume fractionof SFs (more than 2% per volume of concrete) used for special applications such as impact and blast resistance structure; these include SIFCON (Slurry Infiltrated Fiber Concrete), SIMCON (Slurry Infiltrated Mat Concrete).

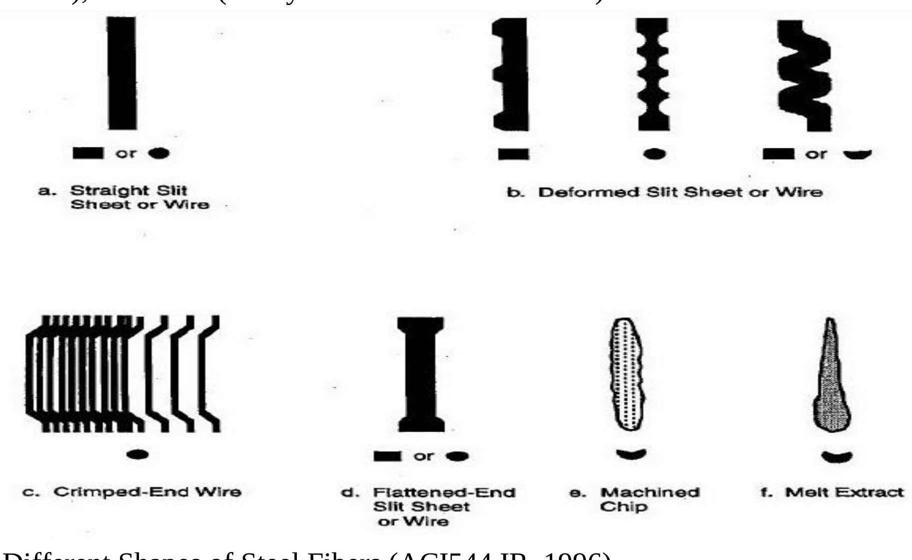

Figure2: Different Shapes of Steel Fibers (ACI544.IR, 1996)

In most cases, SFs may act as secondary reinforcement used along with conventional steel bars or prestressing strands as the main reinforcement. In the class of high volume fraction of SFs (more than 2% per volume of concrete), the SFs have excellent mechanical properties and can be used without other continuous reinforcement; however, these composite materials are often suited for highly specialized applications due to the limitations associated with processing and cost.

3.1. SFRC Benefits

The beneficial influence of SFs in concrete depends on many factors such as type, shape, length, cross section, strength, fiber content, SFs bond strength, matrix strength, mix design, and mixing of concrete. Typical load-deflection curves for plain concrete and FRC are shown in Figure 3 (ACI 544.IR, 1996). The addition of SFs in the conventonal reinforced concrete (RC) members has several advantages such as 1- SFs increase the tensile strength of the matrix, thereby improving the flexural strength of the concrete. 2- The crack bridging mechanism of SFs and their tendency to redistribute stresses evenly throughout the matrix contribute to the post-cracking strength and restraining of the cracks in the concrete. 3- Increase ductility of the concrete. 4- SFRC is more durable and serviceable than conventional RC (Rapoport et al., 2001; Grzybowski and Shah, 1990; Grzybowski 1989).

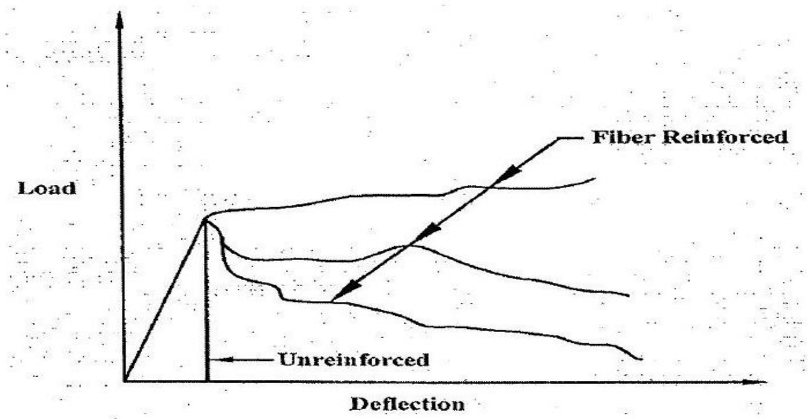

Figure3: Load-Deflection Curves for Plain and Fibrous Concrete (ACI 544.IR, 1996)

The only disadvantage of SFRC would be its decreased workability and accelerated stiffening of fresh concrete due to the addition SFs, thereby increasing the construction labor and time due to the excess vibration required to make the SFRC workable. This problem could be partially overcome with the use of newly developed high range superplasticizers which not only enhance the workability of SFRC but also maintain the plasticity of the mix for a longer time.

3.2. SFRC Application

Nowadays, SFRC is used at an increasing rate in various applications such as the followings.

3.2.1. Highway and air-field pavements

SFRC can be used in the construction of new pavements or for the repair of existing pavements by the use of bonded or un-bounded overlays to the beneath slab. It leads to a higher flexural strength causing a decrease in the pavement's thickness required. Besides, the resistance to impact and repeated loading will be increased. The greater tensile strain capacity of SFRC leads to a drop in the maximum crack widths than in plain concrete.

3.2.2. Hydraulic Structures

The most important advantage of using SFRC in hydraulic structures is the resistance of SFRC to cavitation or erosion due to the high velocity of water flow compared to conventional RC.

3.2.3. Fibre Shotcrete

Fibre shotcrete are used in rock slope stabilization, tunnel lining and bridge repair. A thin coating of plain shotcrete applied monolithically on top of the fiber shotcrete, maybe used to prevent surface staining due to rusting of SFs. The fiber shotcrete can be used in the protection of steel structures.

3.2.4. Refractory Concrete

Steel-fiber reinforced refractory concretes have been reported to be more durable than their unreinforced counterpart when exposed to high thermal stress, thermal cyclic, thermal shock or mechanical abuse. The increased service span is probably due to the combination of crack control, enhanced toughness, spalling and abrasion resistance imparted by the SFs.

3.2.5. Precast Application

SFRC can be used in the construction of precast products such as manhole covers, concrete pipes, and machine bases and frames. Improved flexural strength and impact resistance of SFRC may allow the use of these products in rough handling situations.

3.2.6. Structural Applications:

Addition of SFs into the conventional RC members has several addvantages such as the followings, therby increasing the use of steel-fiber-added RC (SFARC) structures compared to conventional RC members.

(i) Addition of SFs can provide an increased impact resistance to conventional RC members, therby enhancing the resistance to local damage and spalling.

(ii) Addition of SFs can inhibit crack growth and crack widening; this may allow the use of high strength steel bars without having excessive crack width or deformation at service loads.

(iii) Addition of SFs increses the ductility of conventionally RC members, and hence, enhances their stability and integrity under earthquake and blast loadings.

(iv) Addition of SFs increases the shear strength of RC members. As a consequence punching shear strength of slabs will be increased and sudden punching failure can be transformed into a gradual ductile failure (Gambhir, 1995).

4. Mechanical Properties of SFRC

The crack-arrest and crack-control mechanism of SFs has three major effects on the behaviour of SFRC structures (Ocean Heidelberg Cement Group, 1999). 1- The addition of SFs delays the onset of flexural cracking. The tensile strain at the first crack can be increased as much as 100 percent and the ultimate strain may be as large as 20 to 50 times that of plain concrete. 2- The addition of SFs imparts a well-defined post-cracking behaviour to the structure. 3- The crack-arrest property and the consequence increase in ductility impart a greater energy absorption capacity (higher toughness) to the structure prior to failure.

4.1. Compressive Strength

Johnston (1974), and Dixon and Mayfield (1971) found that an addition of up to 1.5% of SFs by volume increases the compressive strength from 0 to 15%. A gradual slope in the descending part of the stress-strain curves indicates the improved spalling resistance, ductility and toughness of SFRC as shown in Figure 4 (Padmarajaiah and Ramaswamy, 2002).

4.2. Shear Strength

Previous research has shown that addition of SFs substantially increases the shear strength of concrete (Noghabai, 2000; Oh et al., 1999; Narayanan and Darwish, 1987; Barr, 1987). The ultimate shear strength of SFRC containing 1 % by volume of SFs increases up to 170% compared to RC without SFs (Narayanan and Darwish, 1987). Traditional transverse shear reinforcement can be completely replaced by addition of SFs as an effective alternative (Noghabai, 2000; Williamson, 1978). Rather than using a single type of SF, a combination of SFs with various aspect ratios is more effective in improving the mechanical performance of SFRC (Noghabai, 2000).

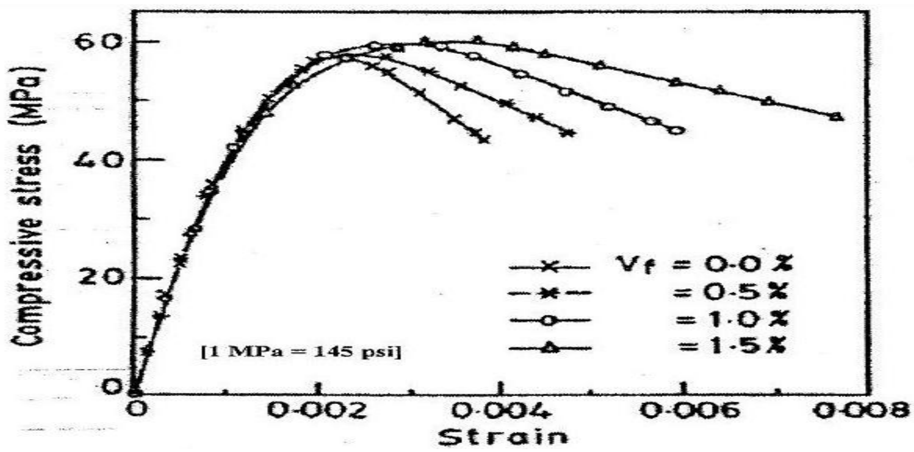

Figure4: Effects of SFs Content on Compressive Stress-Strain Curve of FRC (Padmarajaiah and Ramaswamy, 2002)

4.3. Tensile Strength

Addition of 1.5% by volume of SFs can improve the direct tensile strength of concrete up to 40% (Williamson, 1974). Those SFs aligned in the direction of the tensile stress contribute to an appreciable increase in the direct tensile strength of concrete as up to 133% for the addition of 6% by weight of smooth, straight SFs. However, for more or less randomly distributed fibers, the increase in strength is much smaller, ranging from as low as no increase in some instances to perhaps 60%, with many investigations indicating intermediate values, as shown in Figure 5. Splitting-tension test of SFRC show similar result. Thus, adding fibers merely to increase the direct tensile strength is probably not worthwhile. However, as in compression, steel fibers do lead to major increases in the post-cracking behaviour or toughness.

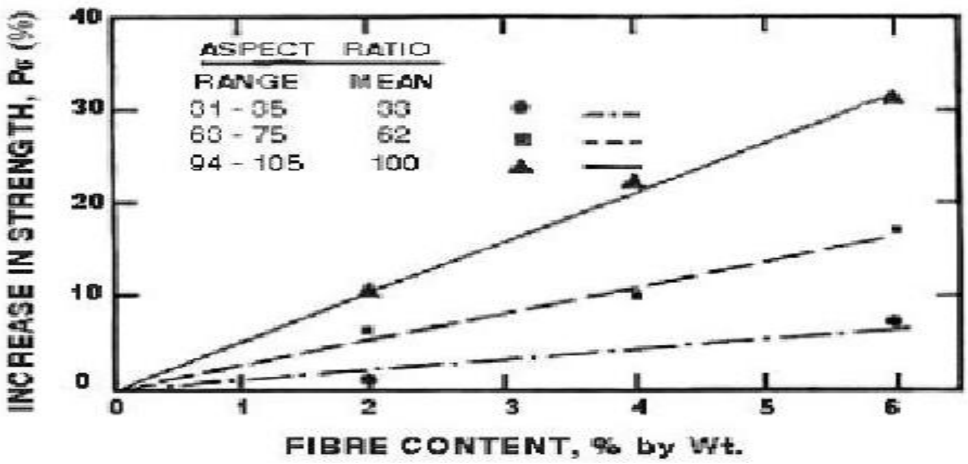

Figure 5: Influence of Fibre Content on Tensile Strength (Johnston ACI-SP44-Detrpit 1974)

4.4. Impact Resistance

The impact resistance of SFRC against dynamic loads due to the dropped weights or explosives is 8 to 10 times higher than that of the plain concrete. The test results of the specimens containing high tensile strength, crimped SFs with the diameter of 0.50mm indicate an improvement in the concrete toughness under impact loading more than 400 percent. An increase in fatigue strength with increasing the percentage of SFs has also been noticed.

4.5. Durability

Corrosion in concrete structures due to the cracks is less severe in the SFRC structures compared to conventional RC ones (Mangat and Gurusamy, 1987; Williamson and Morse, 1977; Halvorsen et al., 1976; Aufmuth et al., 1974). Schupack (1985) found that a well-compacted SFRC has a limited corrosion of fibers close to the surface of the concrete even when concrete is highly saturated with chloride ions.

Turatsinze et al. (2005) conducted a research to investigate the corrosion of SFRC due to the cracks. Prismatic SFRC specimens with the dimensions of 100*100*500mm containing hook-end SFs with the dimensions of 60 mm in length and 0.8 mm in diameter were prepared.

Specimens with vertical cracks were exposed to a marine-like environment for 1 year. After 1 year, the prisms were tested in three-point bending setup with the span of 200 mm and load-deflection graphs were plotted and concluded that only those SFs crossing the crack within a 2 to 3mm rim from the external faces of the specimens exhibited extensive corrosion. Besides, no SFs corrosion was observed in narrower parts of the cracks (i.e. where crack mouth opening was about 0.1 mm) whilst in the wider parts of the cracks (i.e. where crack mouth opening was equal to 0.5mm) a light corrosion of the fibers with no reduction in their section was observed. Furthermore, no concrete bursting or sapling was recorded due to the corrosion of the fibers.

The measurement of concrete electrical resistivity can give an indication of concrete durability (Chen and Hwang, 2001; Woodrow 1980). Figure 6 shows the relationship between the concrete electrical resistivity and curing ages, and it indicates the reduction of concrete electrical resistivity with the increase in the percentage of SFs due to the conductivity of the fibers (Tsai et al., 2009). However, the gel formation due to the cement hydration and pozzolanic reaction causing a dense microstructure and fills the conductive channel, thereby it decreases the effect of SFs conductivity. In the long run, with the addition of 1.0% of SFs the desired concrete electrical resistivity of over 20 kΩ-cm can be reached (Woodrow 1980).

4.6. Flexural Strength and Toughness

Hartman (1987) found that the influence of SFs on the flexural strength of concrete is much greater than its influence on direct tension or compression. Oh et al. (1999) reported that the flexural strength of SFRC is increased by about 55% with the addition of 2% of SFs.

Hartman (1999) experimented with 12 different SFRC beams produced by SFs of Dramix RC-65/35-BN type with two different dosages of 60 kg/m^3 and 100 kg/m^3, and concluded that the ratio of the measured ultimate load to the theoretical ultimate load turned out to be greater for those SFRC beams having the dosage of 60 kg/m^3.

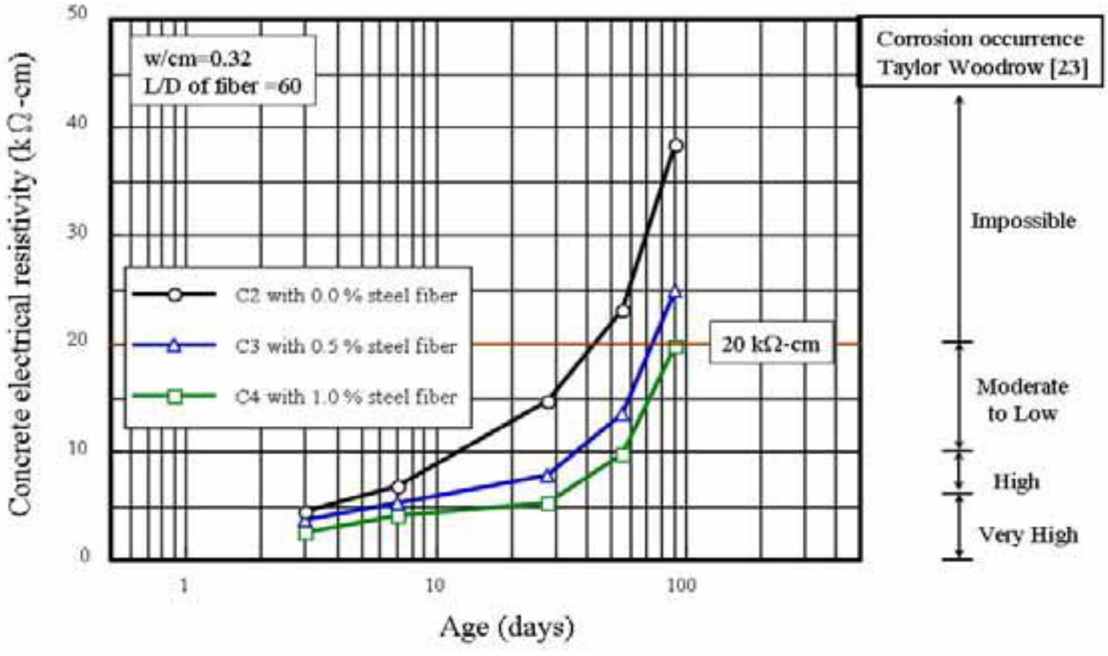

Figure6: Effects of Fibre Content on Concrete Electrical Resistivity (Tsai et al., 2009)

5. Conclusions

This paper presents an overview of the mechanical properties of Steel Fiber Reinforced Concrete (SFRC), its advantages, and its applications. During the last decades incredible development have been made in concrete technology. One of the major progresses is Fibre Reinforced Concrete (FRC) which can be defined as a composite material consisting of conventional concrete reinforced by the random dispersal of short, discontinious, and discrete fine fibres of specific geometry. Unlike conventional reinforcing steel bars, which are specifically designed and placed in the tensile zone of the concrete member, fibers are thin, short and distributed randomly throughout the concrete member. Among all kinds of fibers which can be used as concrete reinforcement, Steel Fibers are the most popular one. The performance of the Steel Fiber Reinforced Concrete (SFRC) has shown a significant improvement in flexural strength and overall toughness compared against Conventional Reinforced Concrete.

References

ACI 544.1R (1996). State-of-the-Art Report on Fiber Reinforced Concrete, American Concrete Institute, Farmington Hills, Michigan.

Aufmuth, R.E, Naus, D.G , Williamson, G.R. (1974). Effect of Aggressive Environment on Steel Fibre Reinforced Concrete, Letter Report M-113.US Army Corps of Engineers. Construction, Engineering Research Laboratory, Chaimpaign, IL.

Barr, B. (1987). Fracture Characteristics of FRC Materials in Shear. Fiber Reinforced Concrete Properties and Applications, ACI SP-105, American Concrete Institute, Farmington Hills, Michigan.

Chen, Y.Y. and Hwang, C.L. (2001). Study on Electrical Resistivity and Chloride Ion Penetrability Behavior of Concrete Material. Journal of the Chinese Civil and Hydraulic Engineering.13(2), pp. 293–302 (In Chinese).

Dixon, J. & Mayfield, B. 1971. Concrete reinforced with fibrous wire. Journal of the Concrete Society, Concrete, 5**,** 73-76.

F. Altun et al. (2006) “Effects of steel fiber addition on mechanical properties of concrete and RC beams” *Construction and Building Materials* **21**: 654–661.

Gambhir, M.L. (1995). Concrete Technology. (2nd Eddition).,NEW DELHI.Tata McGraw-Hill.

Grzybowski, M. (1989). Determination of Crack Arresting Properties of Fiber Reinforced Cementitious Composites. Chapter 12, Royal Institute of Technology, Stockholm, Sweden.

Grzybowski, M. & Shah, S. P. 1990. Shrinkage cracking of fiber reinforced concrete. ACI Materials Journal, 87.

Hannant, D.J. (1978).*Fiber Cements and Fiber Concrete.* John Wiley and Sons Ltd., Chichester, UK, pp 53.

Hartman, T. (1999). *Steel Fiber Reinforced Concrete*. Master Thesis., Department of Structural Engineering. Royal Institute of Technology, Stockholm, Sweden.

Halvorsen, G.T., Kesler,C.E., Robinson,A.R., Stout, J.A. (1976). Durability and Physical Properties of Steel Fiber Reinforced Concrete. Report n° DOT-TST 76T-31, US, Department of Transportation, Federal railway administration, Washington DC.

Johnston, C.D, Colin, D. (1982). “Fibre Reinforced Concrete.” *Progress in Concrete Technology CANMET, Energy, Mines and Resources,* Canada, pp 215-236.

Johnston, C. D. 1974. Steel fiber reinforced mortar and concrete: a review of mechanical properties. Special Publication, 44**,** 127-142.

Mangat, P. & Gurusamy, K. 1987. Permissible crack widths in steel fibre reinforced marine concrete. Materials and structures, 20**,** 338-347.

Naaman, A. E. 1985. Fiber reinforcement for concrete. Concrete International, 7**,** 21-25.

Narayanan, R., and Darwish, I. (1987). “Bond Anchorage of Pretentioned FRP Tendon at Force Release*.”ASCE Journal of Structural Engineering*,**118**:No.10,pp 2837-2854.

Noghabai, K. (2000). Beams of Fiberous Concrete in Shear and Bending: Experiment and Model. Journal of Structural Engineering ,ASCE, Vol.126,No.2,pp 243-251.

Ocean concrete products, Ocean Heidelberg Cement Group (1999). *Steel Fibre Reinforcement – Working Together to Build Our Communities Report*.

Oh,S.G., Noguchi T. and Tomosawa,F. (1999). “Evaluation of Rheological Constants of High-Fluidity Concrete by Using the Thickness of Excess Paste.” *Journal of the Society of Materials Science,* August, Japan.

Padmarajaiah, S. & Ramaswamy, A. 2002. A finite element assessment of flexural strength of prestressed concrete beams with fiber reinforcement. Cement and Concrete Composites, 24**,** 229-241.

Rapoport, J., Aldea, C., Shah,S.p., Ankenman, B., and Karr, A.F. (2001). Permeability of Cracked Steel Fiber-Reinforced Concrete.Technical Report No.115, National Institute of Statistical Sciences(NISS),Research Triangle Park,NC,USA.

Romualdi, J. & Baston, G. 1963. Mechanics of crack arrest in concrete with closely spaced reinforcement. Journal of the Engineering Mechanics Division., EM3. Proceedings of the American Society of Civil Engineers, 89**,** 147-168.

Schupack, M. (1985). Durability of SFRC Exposed to Sever Environments. Proceedings. Steel Fiber Concrete US-Sweden Joint Seminar (NSF-STU),Swedish Cement and Concrete Research Institute, Stockholm/Sweden,June,pp479-496.

Tsai, C. T., Li, L. S., Chang, C. C. & Hwang, C. L. 2009. Durability Design and Application of Steel Fiber Reinforced Concrete in Taiwan. Arabian Journal for Science and Engineering, 34.

Turatsinze, A., Granju, J. L., Sabathier, V. & Farhat, H. 2005. Durability of bonded cement-based overlays: effect of metal fibre reinforcement. Materials and structures, 38**,** 321-327.

Wiliamson, G.R (1978). Steel Fibers as Reinforcement in Reinforced Concrete. Proceeding, US Army Science Conference, West Point, Vol.3, pp 363-377.

Wiliamson, G.R. (1974). The Effect of Steel Fibers on Compressive Strength of Concrete,Fiber Reinforced Concrete.SP-44.ACI,pp 195-207, Detroit.Michigan, USA.

Williamson, G. & Morse, D. 1977. Corrosion Behavior of Steel Fibrous Concrete. Construction Engineering Research Lab (Army) Champaign Ill.

Woodrow, T. (1980). Marine Durability Survey of the Tongue Sands Tower. Concrete in the Oceans Technical Report No. 5, Taylor Woodrow Research Laboratories, Canada.