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## Chapter 2

### Steel Fiber Reinforced Concrete

#### 2.1 Synopsis

Different types of steel fibers can be used to reinforce concrete. Steel fibers are generally classified depending on their manufacturing method. Hooked-end stainless steel has proven to give the best performance. The addition of steel fibers to concrete necessitate an alteration to the mix design to compensate for the loss of workability due to the extra paste required for coating the surface of the added steel fibers. While many technical and economical advantages are benefited from using SFRC, drawbacks can also be found. They are however not likely to cause major problems. It was thought that steel fibers will have negative implications in concrete practice (i.e. transporting, surfacing, finishing etc), but experience has shown that the influence of steel fibers on these practical aspects is negligible.

Dispersion of steel fibers in concrete alter its engineering characteristics. The after-crack mechanism associated with the SFRC positively influences its mechanical and physical properties. The improvement differs depending upon the dosage and the steel fiber parameters considering the other strength-determining factors to be constant.

#### 2.2 Steel Fibers

There are a number of different types of steel fibers with different commercial names. Basically, steel fibers can be categorized into four groups depending on the manufacturing process viz: cut wire (cold drawn), slit sheet, melt extract and mill cut. It can also be classified according to its shape and/or section. Various notations were previously used to nominate the specific type of the steel fibers but in this dissertation the following notations are used:

- (h x w x l) to nominate the straight rectangular section steel fibers. The letters h, w and l stand for section depth, width and the fiber length respectively.
- (d x l) was used to name circular or semi-circular section straight or deformed steel fibers, d and l stand for diameter and length respectively.
- Hook-ended steel fiber (i.e. 80/60 H means aspect ratio/Length of steel fiber).

The popular shapes, sections used and the recent standard notations are compiled in figure 2-1.


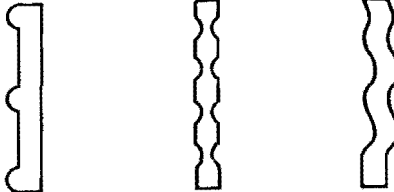
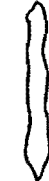
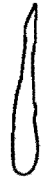
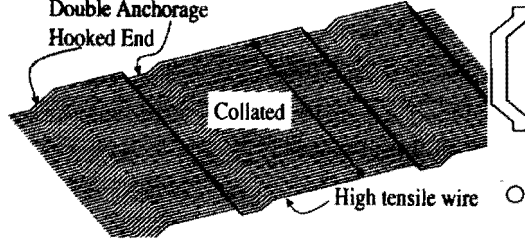

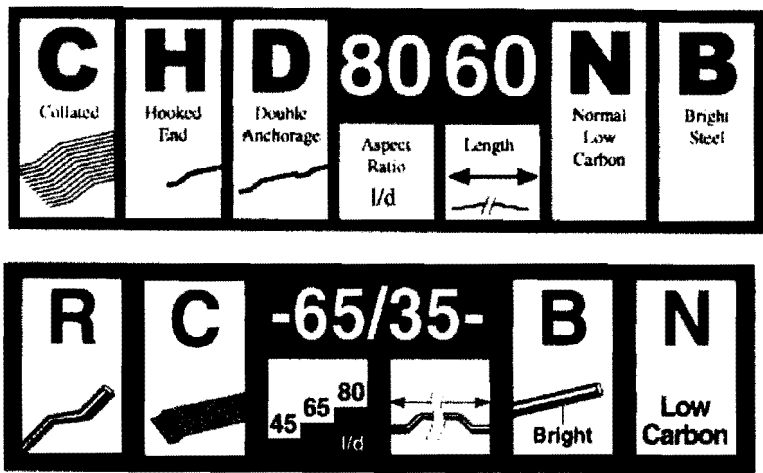
Straight slit sheet or wire	Deformed slit sheet or wire	Machined chips
 <p>□ or ○</p>	 <p>□ ○ ○ or ◡</p>	 <p>◡</p>
Melt extract	Hooked-end wire (Crimped)	Enlarged-end
 <p>◡</p>	 <p>Double Anchorage Hooked End Collated High tensile wire</p>	
Steel Fiber Manufacturers Notations		
		

Figure 2-1: Types and Notations of Steel Fibers

Major efforts have been made in recent years to optimize the shape and size of the steel fibers to achieve improved fiber-matrix bond characteristics and to enhance fiber dispersability [6]. It was found that SFRC containing hook-ended stainless steel wires has better physical properties than that containing straight fibers. This is attributed to the better anchorage provided and higher effective aspect ratio than that for the equivalent length of straight fiber [7]. In addition, the high tensile stresses localized at cracks necessitate that steel fibers have high tensile strength. Typical steel fiber tensile strengths are ranged between 1100 and 1700MPa.

Apart from other mix constituents, there are four important parameters found to affect the properties of, namely, type and shape of fibers, dosage, aspect ratio, and orientation of fibers in the matrix. The effect of each shall be clarified when discussing the physical and mechanical properties of SFRC.

### 2.3 Mix Design

The main objective in designing a structural fiber concrete mix is to produce adequate workability, ease of placing and efficient use of fibers as crack arrestors, besides the other objectives desired in any normal concrete.

Preliminary trial mixes indicated that the addition of steel fibers to a properly designed concrete mix reduced the slump. To maintain the level of workability and to ensure adequate bond of the fibers to the concrete matrix, it was concluded that the addition of steel fiber to the concrete mix should be accompanied by the addition of cement paste. The amount of added cement paste depends on three principal factors as follows [3]:

- Amount of fibers.
- Shape and surface characteristics of the fibers.
- Flow characteristics of the cement paste.

The concept of coupling is used to design mixes having steel fibers. In other words, normal concrete mix proportioning criteria's can be used for the designing of trail mix; thereafter the workability can be adjusted when adding steel fibers.

The mechanistic mix proportioning design method, introduced by the Portland Cement Association in 1977 [3] was based on three principles:

- (a) The addition of steel fibers should be accompanied by the addition of an amount of cement paste sufficient to coat the fibers and to ensure their

bond in the concrete mix.

(b) The added fibers and cement paste should be treated as a replacement for an equivalent volume of the plain concrete mix and.

(c) Water cement ratio in both plain and SFRC mixes remains unchanged.

The method is given in Appendix A

A holistic mix proportioning approach does not exist yet and the reason for this could be the large variety of steel fiber types available, as well as the high number of parameters influenced by the use of SFRC. In practice an indication of the mix proportioning is normally given. It has been recommended that large aggregates (38mm) are suitable for SFRC pavements bearing in mind that the steel fibers should have lengths greater than the largest aggregates <sup>[4]</sup>. The ACI committee has given the following guidelines to serve the purpose of SFRC mix design <sup>[8]</sup>:

- Coarse aggregates should be limited to 55% of the total aggregate.
- W/C should be kept below 0.55 (0.35 is recommended).
- Minimum cement content of 320 kg/m<sup>3</sup> should be used.
- Reasonable sand content of 750 – 850 kg/m<sup>3</sup> is recommended.
- The workability could be improved by increasing the cement paste, which is possible by addition of slag or fly ash to replace the cement.
- Maximum aggregate size is to be 19 mm.

## 2.4 Advantages and Disadvantages

Generally the increase of ductility, toughness, strength, fatigue endurance, deformation characteristics are the reasons for major saving in time, cost, and materials when using the SFRC <sup>[9]</sup> <sup>[10]</sup> <sup>[11]</sup>.

Despite of SFRC excellence and superiority, drawbacks exist. Loose fibers at the hardened surface might be blown onto aircraft engines or tyre, which leads to unsafe operation. Injury to personnel being scraped or cut by an exposed fiber while working on the concrete surface is also possible, however, no accident has been reported regarding any of the above two scares <sup>[4]</sup>. Packard et al <sup>[12]</sup> reported that, the residential street project was overlaid due to complaints from some residents because children suffered skin abrasions from falls on the pavements. Safety equipment is recommended to protect the personnel during construction <sup>[1]</sup>, magnetic fields can be used to collect the loose fiber prior to opening to traffic <sup>[4]</sup> and finishing techniques

can be applied to knock fibers down while surfacing <sup>[13]</sup>. Another possible drawback, at aggressive exposure conditions, is that corrosion of the surface could take place, eventually influencing the appearance of the surface <sup>[14]</sup>.

### 2.5 Practical aspects

Steel fibers should be dispersed with care to avoid clumping and non-homogeneity. Based on previous experience, possible non-problematic sequences were given by the ACI committee 544 <sup>[1]</sup>. The procedure is summarized in the diagram in figure 2-2.

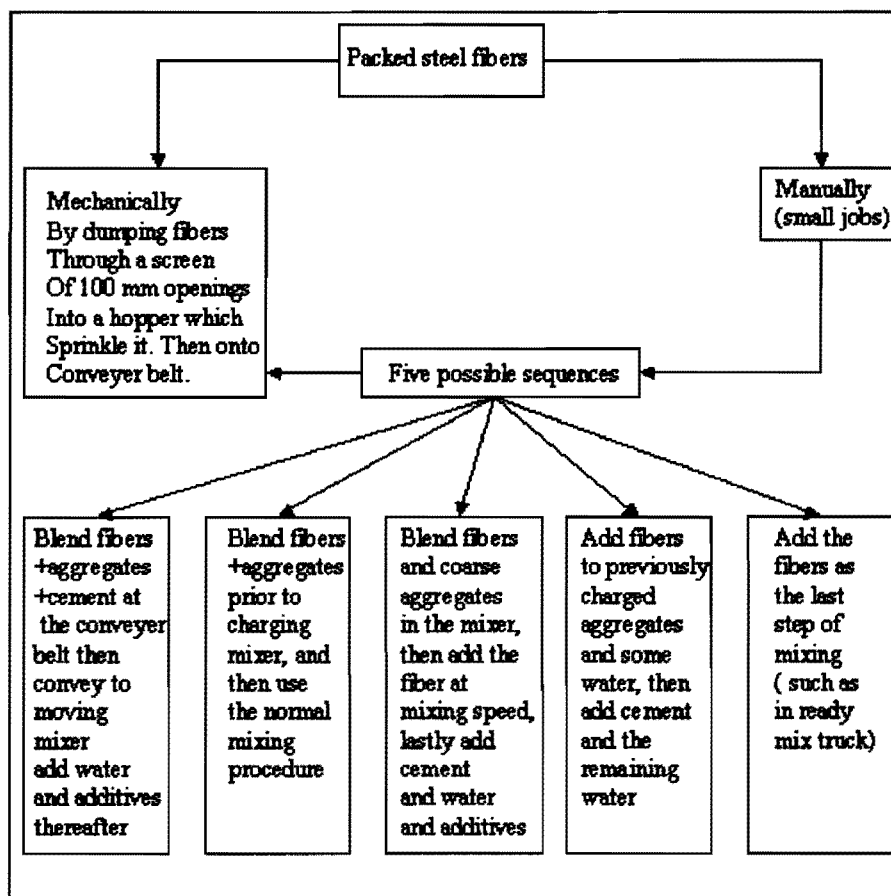


Figure 2-2: Mixing Sequences for SFRC

The addition of steel fibers to concrete reduces the workability, as additional water and cement are required to coat the surfaces of these steel fibers. Edgington et al found that the conventional slump test is unsatisfactory; they further recommended the V-B time method due to its merit in simulating field compaction <sup>[2]</sup>. ACI

Committee 544 recommended the use of inverted slump cone procedure. The test involves, the conventional cone inverted, centered and rigidly held by supports so that the small end of the cone is 4 inch (76 mm) above the bottom of a 1-cubic-foot (0.02832 cubic m) yield bucket. Concrete is to be placed in three un-compacted layers and the time required to empty the cone from the moment a vibrator has contacted the concrete up to the time of the slump cone first becomes empty is recorded. Inverted -slump-cone time should not be less than about 10 seconds or more than 30 seconds. Further details on the test can be found in ASTM C995 <sup>[15]</sup>. The conventional slump cone might however be beneficial to specify the consistency of the concrete. It was found that a slump range between 25 to 100 mm is satisfactory. It was also stated that the appearance of SFRC is deceiving, in other words, although the SFRC looks stiff and unworkable, it can still easily be placed when using the vibrator. Water should therefore not be added relying on the appearance of the concrete <sup>[8]</sup>.

SFRC can be transported, placed, and finished using the same equipments and methods used for conventional concrete. In some cases the SFRC was found much easier to deal with for instance, pumping of SFRC is easier and less trouble than that of the plain concrete because of the greater paste content <sup>[8]</sup>.

## 2.6 Mechanical properties

### 2.6.1 Toughness

Toughness as defined by the ACI committee 544 is the total energy absorbed prior the complete separation of the specimen <sup>[1]</sup>. It can be calculated as the area under the load-deflection curve plotted for beam specimen used in a flexure test. Although, it was well established that the steel fibers significantly improve concrete toughness and it is widely agreed that toughness can be used as a measure of the energy absorption of the material, there is a doubt about the way that SFRC toughness should be measured and used.

Two methods to interpret and calculate the toughness of SFRC are widely used. The ASTM C1018-97 method in which the energy absorbed up to a certain specified deflection is normalized by the energy up to a point of first cracking <sup>[15]</sup>. The Japanese Institute of Concrete standards interprets the toughness in absolute terms, as the energy required to deflect the beam specimen to a mid point deflection of 1/150 of its span <sup>[16]</sup>.





The ASTM method evaluates the flexural performance of toughness parameters derived from SFRC in terms of areas under the load-deflection curve obtained by testing a simply supported beam under third-point loading. It provides for determination of a number of ratios called toughness indices that identify the pattern of material behaviour up to the selected deflection. These indices are determined by dividing the area under the load-deflection curve up to a specified deflection by the area up to the deflection at first crack. Schematic diagrams are given in figure 2-3 and figure 2-4 to illustrate the American and the Japanese methods respectively.

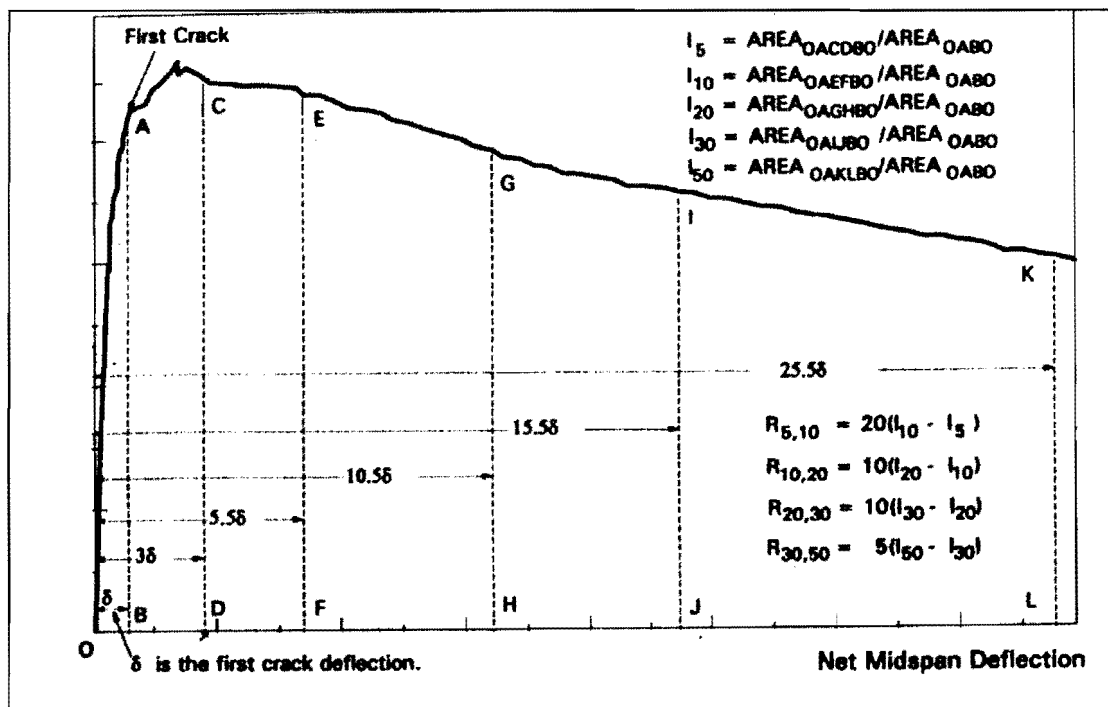


Figure 2-3: Schematic Diagram Showing (ASTM C1018) Toughness Parameters (Chen et al)

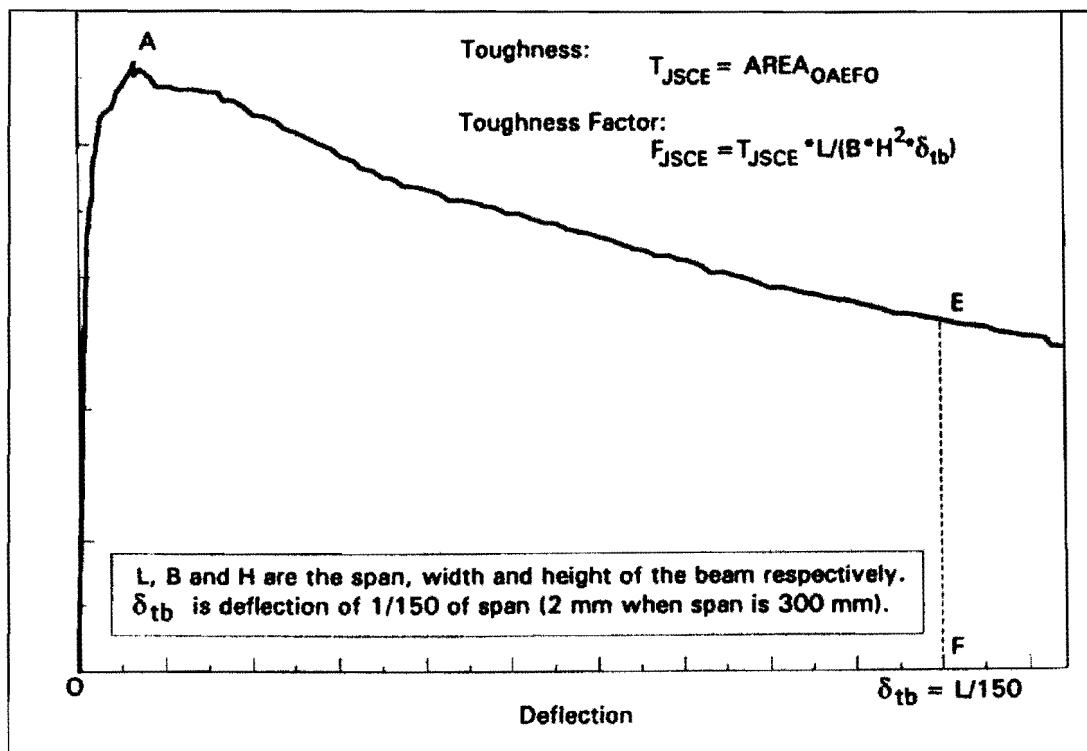


Figure 2-4: Schematic Diagram Showing the JSCE-SF4 Toughness Parameters (Chen et al)

Many criticisms have been directed at the ASTM method. Gopalaratnam et al carried out an investigation on about 750 beams. Two beam sizes (152x152x533 mm) and (102x102x356 mm); each with two different types of fibers and two different fiber contents were used. It was found that the ASTM C1018 is not sensitive to fiber content, fiber type and the size of the specimen. In addition to that the method is more dependent on the measurement accuracy of the deflection. The effect of the extraneous deformations are found to influence the first crack deflection significantly and its effect is less for greater values of deflection on the load-deflection curve, therefore an erroneous first crack deflections leads to unreal values for the area of the curve up to the first crack deflection and eventually an error in measuring the toughness indices. In contrast the JSCE-SF4 approach was found to be sensitive for the specimen size and fiber type and content, moreover, extraneous deformation problem is mitigated by considering higher deflection values (1/150 of the span). The study concluded that the JSCE-SF4 method is more reliable than the ASTM C1018 and recommendations were made for its usage <sup>[17]</sup>. Chen et al also came to the same conclusion, they further added that in some cases the first crack point is difficult to determine. Great uncertainty about the shape of the curve in the



vicinity of the first crack exist, hence indices with in the area (OAEF) as shown in figure 2-3 is questioned <sup>[18]</sup>.

### 2.6.2 Flexural strength

The low flexural strength of plain concrete could possibly be over-come by the addition of steel fibers. A review of the literature on SFRC indicates that in general, the addition of short, randomly-oriented steel fibers increases the flexural strength of plain concrete by about 1.5 to 3.0 times, taking into account type and content of the steel fibers <sup>[19] [2] [7]</sup>.

The term flexural strength for SFRC is more complicated compared to that of the plain concrete. Flexural strength for plain concrete is the stress capacity determined through a third-point loading test, which strive to find the stress at maximum load that can be sustained by a prismatic beam. The situation is different when speaking about SFRC due to the after crack toughness imparted by the presence of the steel fibers. One should distinguish between the different terms viz, first crack strength, ultimate strength, and equivalent strength. These terms have different implications to the application of the SFRC and they are indicated in figure 2-5 and defined as follows:

- First crack flexural strength (or some times termed as the proportional limit): recognized as the stress at point at which the load-deflection curve first becomes non-linear.
- Ultimate flexural strength: defined as the stress at the point of maximum load that can be sustained during the third-point test.
- Equivalent flexural strength: It is the stress capacity derived at a point of specific mean load corresponding to specific deflection in a third-point loading test.

Considering a prismatic beam (150x150x450 mm), the values at a deflection of (span/300) and (span/150) ratios are being adopted; therefore, flexural strengths corresponding to these deflection values can be successfully used.

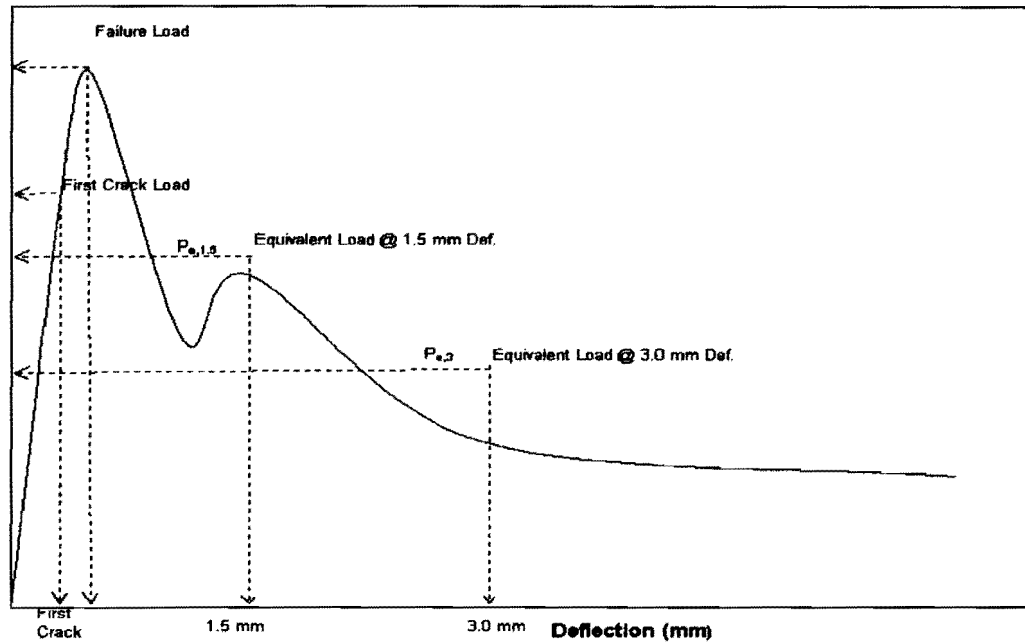


Figure 2-5: Schematic Load - Deflection Diagram

Main factors influencing the flexural strength of SFRC <sup>[19]</sup> are:

- Degree of consolidation of the matrix, which is a function of water to cement ratio, consolidation technique, and type and content of the steel fiber.
- Uniformity of fiber distribution, which is mainly influenced by the workability and mixing procedure used.
- The surface conditions of the steel fibers, which relates to the bond stresses generated between the steel fibers and the concrete, for instance a hydrophobic film on the steel fiber surface can prevent the development of an adequate fiber bond.

Theoretically, the improvement in flexural strength of SFRC is being brought by the crack arresting mechanism that the steel fiber provides. In fact, the steel fibers can sustain stress after cracking at strains beyond the normal for failure of plain concrete. Some sort of stress distribution is promoted which approaches the fully plastic condition in the tension zone, while remaining elastic in the compression zone. This mechanism causes the neutral axis of the section to move up, thus, the moment of resistance and ultimate load be increased significantly <sup>[20]</sup>.

Due to the post cracking behavior of SFRC unlike plain concrete, the total flexural strength (design flexural strength) is to be taken as the sum of the flexural strength up to the point after which the elasticity zone of the material is exceeded (first crack strength) and the strength that resulted from the plastic phase (equivalent flexural strength). Equation 2-1, equation 2-2 and equation 2-3 can be used <sup>[11]</sup>:

$$f_d = f_{ct} \left( 1 + R_{e,3} / 100 \right) \quad \Longrightarrow \quad \text{Eq.2-1}$$

$$f_d = f_{ct} + f_{e,3}$$

Where :

$f_d$  = Design Flexural Strength.

$f_{ct}$  = First Crack Strength.

$$f_{e,3} = P_{e,3} * \frac{L}{bh^2} \quad \Longrightarrow \quad \text{Eq.2-2}$$

$$R_{e,3} = \frac{f_{e,3}}{f_{ct}} * 100 \quad \Longrightarrow \quad \text{Eq. 2-3}$$

$h, b$  = the depth and width of a uniform prismatic beam.

$P_{e,3}$  = Mean Load Over a Deflection of Length/150.

### 2.6.3 Fatigue Endurance

Fatigue endurance could be expressed by the so-called S-N curves, where S is the ratio of the maximum stress to the statistic strength and N is the number of the cycles at failure. The maximum value of S below, which no failure occurs, is known as endurance limit <sup>[21]</sup>. Previous investigations <sup>[22][23]</sup> have shown that the relationships are linear up to at least 2 million cycles; therefore, the term 2-million cycle endurance limit is commonly used to quantify the fatigue strength of SFRC.

Figure 2-6 shows results of fatigue tests conducted by Johnston et al <sup>[24]</sup> on prismatic specimens with nine different mixtures and varied fiber parameters (type, content, and aspect ratio). It was concluded that, the addition of steel fibers has improved the fatigue endurance of concrete and the improvement ranges between little and significant depending on the fiber parameters.

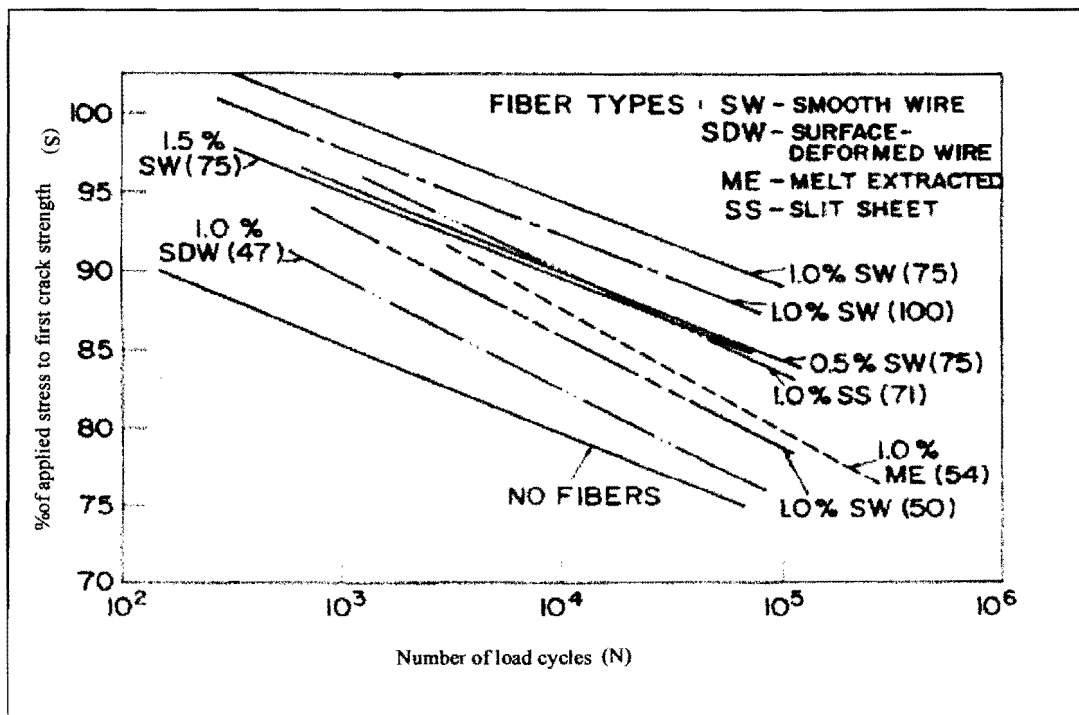


Figure 2-6: S-N relationship based on First Crack Strength (Johnston et al)

Hook-ended steel fibers appeared to have a superior influence in the 2 million-cycle endurance limit. An endurance limit of 76% and 80% were found for 0.5% and 1.0% volumes of hook-ended fibers respectively, whilst, 67% and 59% for similar volumes of slit sheet fibers [23].

The fatigue capacity of plain concrete is generally regarded as equivalent to an endurance limit equal to 50 to 55% of the static modulus of rupture [25]. Thus designs based on half the static strength is appropriate for conventional concrete [26]. By implication either thinner section is required to withstand the same load repetition or the same thickness could last for longer, and that is key benefit behind the usage of SFRC.

Bernard et al [27] suggested that fatigue performance for SFRC, expressed as an endurance limit can conservatively be taken as 65% of the stress to cause the first crack. Schrader [26] argued that the long term strength gain for SFRC is higher than that for the plain concrete, therefore, the fatigue performance should be improved as a result of strength compensation. Eventually it was stated that 85% of the ultimate strength has the same conservatism, as does 50% for conventional concrete.

#### 2.6.4 Impact Strength

Pavements are in many cases subjected to dynamic load either due to the impact nature of the load itself or due to the high rate of gradual load applications. Runways are normally subjected to direct impact loads caused by the landing process and unevenness of aircrafts while roads are subjected to impacts in cases of unevenness, rutting, artificial bumps, and at faulting joints. It is seldom found that a pavement is thoroughly subjected to static loads during its useful life, even aprons and container terminals are subjected to dynamic loads prior to parking of aircrafts or containers respectively.

Although different type of tests and load application rates were employed by different researches, it is widely agreed that the addition of steel fibers improves the impact resistance of concrete. A significant increase was found by using the pendulum machine; the improvement was being especially favorable with crimped fibers <sup>[2]</sup>. Tests carried out using the ACI committee technique <sup>1</sup> reported that SFRC has increased the impact resistance in order of three to four times relative to their un reinforced counterparts <sup>[28] [29]</sup>. In another set of test carried out on concrete slabs with and without steel fibers, supported on their edges, a falling weight was employed from different distanced to represent different energies. The results showed that the SFRC slabs absorbed about 4 times the impact energy of the plain concrete for equivalent damage <sup>[30]</sup>.

Gopalaratnam et al <sup>[31]</sup> and Banthia et al <sup>[32]</sup>, both came to conclusion that, the impact data is mostly sensitive to the stress-rate, in other words for different stress-rates there are different values for the impact strength. It was also agreed that the higher the rate of the load application the higher the impact resistance for both plain and SFRC, that can be seen from figure 2-6.

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<sup>1</sup> The test involves dropping of 10 lb soil compaction hammer 18 inches onto a hardened steel ball placed in the center of the concrete specimen, which measures 6 inches in diameter and 2.5 inches thick. The number of blows required to crack the material is used to quantify the impact resistance of concrete

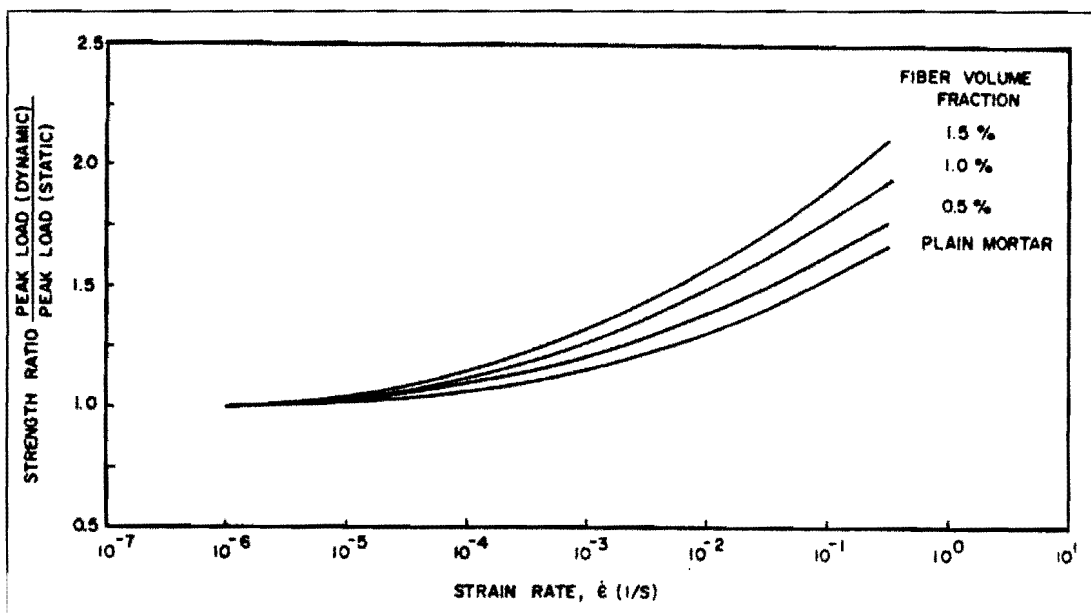


Figure 2-7: Effect of Strain-Rate and Fiber Content on Flexural Strength

(Gopalaratnam et al)

It is apparent from the above discussion that SFRC flexural strengths gained from relatively static load type of tests are less than those obtained from increased stress-rate tests. Designs based on static strengths are therefore satisfactory and safe.

### 2.6.5 Compressive strength

It has been found by many researchers that the inclusion of steel fiber in concrete increases its compressive strength value relative to the fiber content. Their findings ranged between marginal and significant increases in compressive strength.

Experimental work conducted in India, using straight steel fiber ( $L/D = 46/0.91$  mm) and fiber content ranges between (0 and 3% by volume) found that, significant increase in compressive strength is achieved (about 40% increase when using 3% fiber content). Moreover, test results have shown a linear relation between the fiber content and the compressive strength of the concrete if fiber is being added. The following empirical equation was generated <sup>[33]</sup>.



$$F_f = F_c(1 + K_1 P) = F_c * \alpha \quad \longrightarrow \quad \text{Eq.2-4}$$

Where:

$F_f$  = Compressive strength of the SFRC.

$F_c$  = Compressive strength of the parent concrete.

$K_1$  = Empirical constant (0.123).

$P$  = Percentage of steel fiber (by volume)

$\alpha$  = Amplification factor.

Tests in Australia showed that, the addition of steel fiber to concrete matrix may produce marginal gains in compressive strength at constant water cement ratio. At steel fiber concentrations of (50 to 90 kg/m<sup>3</sup>) the increase in compressive strength is not usually statistically discernible [30].

Tests, on SFRC cubes made from same mix and containing bent fiber, carried out at the CSIR (South Africa), revealed that the addition of steel fibers with various contents may increase the compressive strength slightly (approximately 10%) and the highest increase occurred at low steel fiber contents (up to 20 kg/m<sup>3</sup>). In addition of that, specific limits exist after which a reduction or less increase on compressive strength is expected with addition of more steel fibers. In other words an excessive increase of fiber content will not affect the compressive strength as prior to that limit. This confirms that the addition of steel fibers is not a cost effective way of improving the compressive strength of concrete [34].

Results from cubes and cylinders tested in compression might differ significantly because the vibration tends to align the fibers in certain planes. In cylinders they tend to align perpendicular to the axis of loading where they could help to inhibit lateral bursting, while in cubes they tend to align parallel to the axis of loading [20].

According to Edgington et al, fibers in SFRC compacted by means of table vibration have a tendency to align themselves in planes at right angles to the direction of vibration. This indicates, that the method of compaction can be an important parameter influencing the compressive strength of SFRC [2].

Perrie argued that, since the failure is initially due to breakdown at the aggregate interface, fibers are expected to have little effect on compressive strength of concrete [20].

The author's opinion is that, the influence of steel fiber on the compressive strength should be taken as insignificant and the increase in compressive strength developed as the result of the presence of steel fibers should be considered to compensate for the variation of the testing results due to variation of fiber orientation and content in different specimens. Thus, the compressive strength of the parent plain mix should be considered as the target compressive strength.

### 2.6.6 Shear strength

Steel fibers are found to increase the shear capacity of concrete significantly <sup>[35]</sup> <sup>[36]</sup>. It was found that the inclusion of 1% by volume of hook-ended steel fibers could increase the shear strength of the SFRC by about 144% to 210% relative to the plain concrete depending on the aspect ratio of the steel fibers <sup>[37]</sup>. Punching shear tests show that the addition of 75 kg/m<sup>3</sup> of steel fibers with enlarged ends increase the punching resistance by about 51% in comparison to plain concrete <sup>[30]</sup>. The mode of failure is also found to be changed due to the extra-enhanced shear capacity. Ductile failure was experienced instead of sudden diagonal failure <sup>[36]</sup> and in some cases the mode of failure changed from shear failure to a moment failure <sup>[37]</sup>.

Shear strength capacity is important for pavements. Corner and edge break-off might occur as the result of exceeding the shear capacity of concrete; storage racking or raised storage legs can also punch on the floor. The knowledge of the shear capacity and behaviour of materials should therefore be applied to pavements. Grondziel <sup>[38]</sup> state that using SFRC at Frankfurt International Airport has virtually eliminated the joint shear failure due to its homogeneity and increased shear strength. He gave the model as shown in figure 2-7 to illustrate the benefit of using SFRC instead of conventionally reinforced concrete.

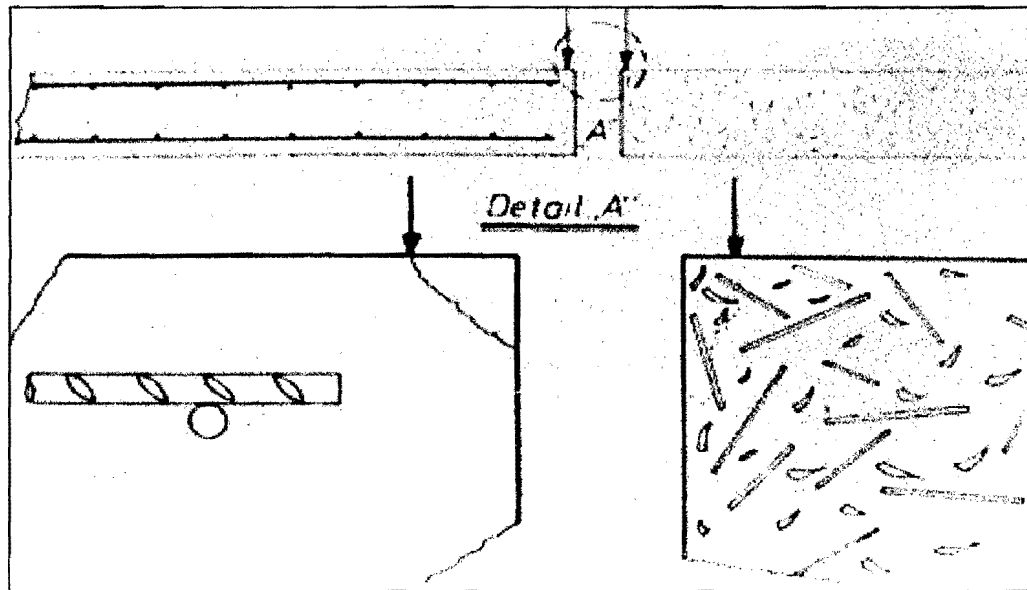


Figure 2-8: Shows the Influence of the Steel Fibers on Shear Capacity of Edges (Grondziel)

Despite the considerable laboratory data indicating that steel fiber is superior as far as the shear capacity and behaviour is concerned, design procedures are found not to consider that increase in shear strength of SFRC and the shear strength of plain concrete is still in use<sup>[39]</sup>.

### 2.6.7 Modulus of Elasticity

The fact that the inclusion of steel fibers in concrete marginally influences the modulus of elasticity is widely agreed upon. Uniaxial tensile stress-strain measurements on (100x100x500 mm) plain and fiber reinforced specimens show an increase of 7.5% for the specimens having a dosage of 2.7% by volume of straight steel fibers<sup>[2]</sup>. Similar results were gained from a third-point test carried out on beam specimens, where it was found that the calculated modulus of elasticity increases very little relative to plain concrete<sup>[30]</sup>. The E-value is found to be in the same order of magnitude than the values for plain concrete from the parent mix<sup>[3]</sup>. Recent studies also show that 0.76% by weight of hook-ended and crimped steel fiber has a positive effect with increase in E-value ranging between 0% and 2.8%<sup>[40]</sup>.

Modulus of elasticity could also be found from a third-point loading test as an alternative method to the standard cylinder compression test. It has the advantage that a number of material parameters can be calculated in a single test. The following

formula has been derived to calculate the modulus of elasticity <sup>[41]</sup>.

$$E(\text{M.Pa}) = \frac{23}{1296} * \frac{F}{\delta} * \frac{l^3}{I} \left[ 1 + \frac{216}{115} * \left( \frac{d}{l} \right)^2 (1 + \mu) \right] * 10^3 \implies \text{Eq.2-5}$$

Where:

$\frac{F}{\delta}$  = the slope of the best - fit straight line drawn through the plotted points  
of the initial portion of the load - deflection curve (N/mm<sup>2</sup>).

$l$  = support span, (mm).

$I$  = second moment of area of the section  $\left( \frac{bd^3}{12} \right)$ .

$b, d$  = width and depth of the prism section respectively (mm).

$\mu$  = poisson's Ratio

### 2.6.8 Poisson's Ratio

Poisson's Ratio is the ratio of the lateral strain to the vertical strain. Addition of steel fibers is found to have no or minimal effect on the value of Poisson's Ratio <sup>[30]</sup>. Value ranges between 0.15 and 0.21 are typical values assumed <sup>[42]</sup> or experimentally assessed <sup>[30][43]</sup> for SFRC ground floors.

## 2.7 Physical properties

### 2.7.1 Shrinkage

Shrinkage is the volume change exhibited by concrete bodies due to the loss of water. Two phases of shrinkage exist, the first one is the plastic shrinkage which takes place prior the final setting and the other one is the drying shrinkage which occurs in the long term <sup>[21]</sup>. Free and restrained are terms usually associated with shrinkage to define the constrain conditions of the concrete body under consideration.

Proof of the ability of steel fibers to limit the plastic shrinkage crack widths is widespread. Numerous investigations have shown that steel fibers reduce the plastic shrinkage crack widths relative to that of plain concrete <sup>[44][45]</sup>. Reduction in plastic shrinkage strain was reported to be as high as 20% relative to that of plain concrete <sup>[27]</sup>. Banthia et al have introduced a new concept to quantify shrinkage of concrete in their study on plastic shrinkage of SFRC. A fiber efficiency factor was adopted to compare the shrinkage capability of different concretes and this fibers efficiency

coefficient can be calculated as follows:

$$\text{Fiber Efficiency Factor} = L_c/W \implies \text{Eq.2-6}$$

Where

$L_c$  = Cumulative crack length.

$W$  = Cumulative crack width in the area under consideration

They further found the addition of 0.75 % by volume of crimped steel fibers will result in an effectiveness factor of 146.6 and 8 cracks while plain concrete yielded an effectiveness factor of 14.03 and one crack which proves that steel fibers can distribute cracks more evenly over the entire length resulting in closely spaced reduced widths cracks<sup>[44]</sup>.

Drying shrinkage strain is of considerable importance to pavement applications because it has a direct contribution to the spacing of the joints. There are conflicting evidences regarding the effectiveness of steel fibers in limiting both free and restrained drying shrinkage strain in SFRC. Edgington et al<sup>[2]</sup> found that the shrinkage of concrete over a period of three months was unaffected by the presence of the straight steel fibers used. A study by Grzybowski et al<sup>[46]</sup> found that steel fibers does not alter the free drying shrinkage properties of concrete, in the other hand many later investigations have proven that the steel fibers have a significant effect in improving the restrained shrinkage properties of concrete<sup>[47][48][49]</sup>.

Work was conducted by Chern et al<sup>[47]</sup> (on both beams and cylindrical specimens having crimped and straight steel fibers) to study the influence of steel fiber parameters testing age and ratio of the specimen volume to the exposed surface on shrinkage characteristics of concrete. It was found that, steel fibers restrain deformations more effectively at later ages due to the development of higher interfacial bond strength between fibers and matrix. Therefore, the older the SFRC the less shrinkage strains. It was also evident that both higher fiber content and aspect ratio was found to yield less shrinkage than those of lower values.

Despite the efforts directed towards developing a test method to examine shrinkage of slabs, which is more applicable to pavements, no published evidence exists that any substantive tests have been undertaken to quantify drying shrinkage strain in SFRC slabs. Most of the investigations mentioned, employed a ring or beam specimens with, at best, indirect relevance to concrete slabs, as the small cross-



sectional dimensions of the shrinkage moulds can result in preferential alignment of steel fibers in the direction of measured shrinkage. Standard size shrinkage specimens may therefore exhibit strains that are far different from the reality at which fibers are randomly oriented <sup>[27]</sup>.

Literature on shrinkage provides different theoretical models to assess the plastic shrinkage strain <sup>[45]</sup>, and crack spacing and widths resulting from drying shrinkage of SFRC <sup>[46]</sup> <sup>[50]</sup>. The author's view is that, these models should not be applied to pavements because of the above-mentioned reasons. Further work on shrinkage of slabs should be conducted.

### 2.7.2 Creep

Creep is the long-term deformation that a material exhibits under the application of a sustained load. Reasons for the concrete to creep are related to the movement of water out of the cement paste and more over, due to the prorogation of micro-cracks <sup>[21]</sup>.

Creep studies in compression have been carried out at a number of applied stress-strength ratios ranging between 0.3 to 0.9 using cement paste, mortar and concrete mixes. Melt extract and hooked fibers with volume contents ranging between 0 and 3% (about 0 and 235 kg/m<sup>3</sup>) were added to the mixes that were used to cast prismatic specimens (150x150x500mm). The results after 90 days loading and 60 days unloading indicate that steel fibers have a significant (ranges between 15 and 24% reduction) influence in restraining the creep of specimens under uniaxial compression. More over, it was reported that, the restraint provided by steel fiber to the creep becomes more pronounced with increasing time under load <sup>[51]</sup>.

Contradictory results were obtained on compressive creep test on concrete specimens having straight fibers with volumes ranging between 0 and 1.47 % (0 to 115 kg/m<sup>3</sup>). Specimens were loaded over 12 months. The results concluded that the effect of steel fibers on creep strains is negligible <sup>[2]</sup>.

Flexural creep test on SFRC (75 kg/m<sup>3</sup> enlarged end steel fibers) specimens (stress - strength ratios of 0.43 and 0.69), shows that the flexural creep is considerably less than for the identical concrete without steel fiber. The reported ratio of creep strain to load strain for plain concrete after 518 days loading was around 25% higher than for steel fiber reinforced concrete <sup>[30]</sup>.



Another series of tests on flexural creep shows that creep strains are much less in the compression zone of a specimen than in tension zone <sup>[49]</sup>. Typically, with 1% percent by volume (about 78 kg/m<sup>3</sup>) steel fibers and flexural stress-strength ratio of 0.35, creep strains in the tension zone of the specimens ranged between 50 to 60% of the strains in the plain concrete specimens. The creep strains in the compression zone of the steel fiber specimens were 10 to 20% of the plain concrete specimens.

It can be seen that, the steel fibers has a negligible effect when low fiber content is added while a significant improvement is gained with larger amount of steel fibers. It should also be noted that flexural creep is more important than compression creep for ground slabs.

### 2.7.3 Durability

Porosity and permeability are primary factors affecting the durability of the concrete due to it's effect on alkali-acid reaction, leaching characteristics, resistance to chloride or sulphate attack, reinforcement corrosion, and freezing and thawing characteristics <sup>[7]</sup>. Initially SFRC mixes had high porosities and permeabilities due to the higher W/C used to increase the workability. Recently, reductions in W/C ratio are possible, which result in relatively low porosities and permeabilities. Tests indicated that the SFRC has permeability values typical of those for the plain concrete <sup>[30]</sup>, therefore, apart from corrosion of steel fibers, the SFRC has the same durability (if not better) than the identical plain concrete.

Attention has to be given to the question of the corrosion of the steel fibers when added to concrete. Theoretically, one of the main problems associated with the use of steel fibers is their durability in concrete structures. In severe exposure condition, corrosion of steel fibers is more aggravated than that of steel bars, in other words, a significant decrease to the steel fibers diameter, contribute significantly to lessen the load capacity of the structure at service <sup>[52]</sup>. In contrast, unlike steel bars, only limited expansion force develops due to the corrosion of steel fibers <sup>[14]</sup>, which means less paste disruption and eventually minimal breakdown and weathering rates in comparison to conventional concrete reinforced by steel bars <sup>[27]</sup>.

There is ample evidence that in practice, in good quality concrete, fibers corrosion does not penetrate into the concrete. Laboratory studies have shown that, stainless steel fibers can perform well even in a very aggressive type of exposure conditions

while the carbon steel fibers invite the corrosion and cracks development <sup>[53]</sup>. SFRC specimens exposed to a marine environment for about 10 years, show that the corrosion of fibers is limited to the surface of the un-cracked specimens and no noticeable reduction in flexural strength was found, whilst, for cracked specimens, corrosion does occur through the depth of the crack and reduction on flexural strengths were encountered <sup>[54]</sup>.

Under normal finishing processes very few fibers will be left exposed at the surface of slabs and any such fibers exposed to the surface is assumed to corrode and blow away under trafficking <sup>[39]</sup>. Schupack found that the corrosion depth is usually confined to the first 5 mm <sup>[54]</sup>, therefore, designs should consider cover depths of about 10 mm apart from recommending the knocking down of steel fibers while finishing the concrete surface.

#### **2.7.4 Abrasion and Skid Resistance**

Knowledge of abrasion and wear resistance of concrete is essential especially for pavement due to the continuous nature of its loads. Difficulties might be encountered concerning of the wear and abrasion resistance, as the damaging action varies depending on the cause of wear, and no single test procedure is satisfactory in evaluating the resistance of concrete to the various conditions of wear <sup>[21]</sup>.

Tests on hydraulic structures, which have the same effect of wear on slabs under traffic loads, revealed that the abrasion resistance of SFRC is not improved over that of the plain concrete <sup>[1]</sup>. Significant increases of abrasion resistance was found by other researchers, with about 15% higher resistance reported under drying, wet and frozen surface conditions <sup>[39]</sup>. Tests carried out to compare the abrasion resistance of plain concrete specimens (25 MPa) and SFRC having 75 kg/m<sup>3</sup> enlarged end type of fibers, reported that the SFRC specimens have a LA (Los Angeles abrasion wearing test value: it includes milling specimens in the presence of steel and concrete balls for a certain number of revolutions. LA is the increase in the percentage of the material passing the 1.7 mm sieve) value of 50% greater than that of plain concrete specimens <sup>[30]</sup>, which in turn proves the capability of steel fibers to resist abrasion and wear.

Wear tests were carried out using a pair of hardened steel wheels running in a circular path under load on flat specimen slabs. It was found that for specific number

of cycles, the SFRC exhibits average groove depths less than that of plain concrete, which in turn proves that the SFRC has a better wear resistance relative to an identical plain concrete <sup>[30]</sup>.

The skid resistance of SFRC was found to be same as that of the plain concrete at early stages prior the deterioration of the surface. In later stages, where abrasion and erosion of the surface had to taken place, steel fiber reinforced concrete has an up to 15 % higher skid resistance relative to plain concrete <sup>[1]</sup>.

It can be concluded that the SFRC has better performance regarding its erosion, abrasion and skid resistance, but how much better is dependent on the case of application.

### 2.7.5 Thermal Properties

There are three thermal properties that may be significant in the performance of concrete, viz, coefficient of thermal expansion, specific heat and conductivity <sup>[21]</sup>. To the author's knowledge little work on SFRC has been done in this area.

Thermal expansion is seen to be the most relevant to the ground slabs applications especially for concrete subjected to thawing and freezing action. Specific heat and conductivity are normally relative to applications whereby thermal insulations are provided <sup>[21]</sup>, or other applications such as rocket launch facilities or mass structures <sup>[55]</sup>.

The effect of steel fibers on coefficient of expansion factor was studied using beam specimens that have various steel fibers content (ranges between 0 and 2 % by volume). Specimens were subjected to temperatures ranges between 38 and 66 degree Celsius. Tests results indicate that the coefficient of thermal expansion factor was not significantly affected by fiber content <sup>[3]</sup>. Tests on relatively dry SFRC specimens at ages of about 220 to 250 days and 27 degree Celsius temperature rise, revealed that addition of steel fibers marginally influence the thermal expansion coefficient. Just to give an indication, for SFRC containing 75 kg/m<sup>3</sup> of enlarged-end steel fibers, the typical expansion coefficient is found to be  $8.2 \times 10^{-6}$  per degree Celsius <sup>[30]</sup>.

Thermal conductivity of SFRC is studied by Cook et al <sup>[55]</sup>, they found that an increase of 25 % to 50% in thermal conductivity could be achieved with specimens

having straight steel fiber contents of 1% and 2%. Another contradictory study reported that with 0.5% to 1.5% by volume steel fiber, a small increase in thermal conductivity could be obtained <sup>[1]</sup>.

It can be seen from the above discussion that the expansion of SFRC is the same (if not less) than plain concrete for identical mixes. The author's opinion is that, the only hazard is the expansion coefficient of the steel fibers, in other words, large differences between thermal coefficients of steel fibers and paste might cause the interface layers between them to damage and damage in many surfaces in different dimensions might weaken the entire matrix.

### 2.7.6 Electrical Conductivity

Steel fibers contents of up to 1% by volume ( $80 \text{ kg/m}^3$ ) has no significant effect on electrical conductivity <sup>[30] [39]</sup>, hence, wire guided vehicles may be operated without difficulties on SFRC floors, which can be taken as an advantage if compared with steel bars or mesh floors <sup>[39]</sup>. It can also be beneficial where traffic devices are needed e.g. vehicle detection loops for traffic counting and classification.

## 2.8 Conclusion

The following conclusions are drawn

- Although different types of steel fibers have been used, hook-ended steel fibers were found to perform better than the other types because of its hooked ends and/ or high tensile strength, which requires additional loads for pulling out and /or breaking.
- The mechanistic mix proportioning design approach for SFRC strives to adjust the additional paste required to coat the added steel fibers, therefore a some sort of coupling concept can be used, in other words, any of the plain concrete proportioning mix criterion can be used to design the mix and there after the mix can be adjusted for the added fibers.
- The normal transporting, placing and finishing methods used for plain concrete can also used for SFRC.
- Steel fiber has an effect ranging between little and significant on the mechanical properties. Endurance limit, impact strength and shear strength

are significantly improved while compressive strength, modulus of elasticity and Poisson's ratio improve slightly when the steel fiber is added. The flexural strength at first crack and maximum load is slightly improved, but on the other hand, the imparted toughness improves the equivalent strength (after crack) significantly (as high as 100%).

- The physical properties are also altered by the use of steel fibers. The steel fibers have a significant effect on the plastic shrinkage while little effect is found for the drying shrinkage. Methods used to measure the shrinkage are found not to simulate pavements. Creep is significantly influenced when using high dosage of steel fiber while little effect is found with low steel fiber dosages. The abrasion and skid resistance are also improved significantly. A negligible effect is found on the electrical conductivity. The thermal properties of the SFRC are not properly established and problems could be encountered as a result of the wide difference between the thermal expansion factor for the steel fiber and the other mixture constituents. Durability is not influenced by the use of steel fibers.