STEEL FIBER REINFORCED CONCRETE

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SUMMARY

It is now well established that one of the important properties of steel fibre reinforced concrete (SFRC) is its superior resistance to cracking and crack propagation. As a result of this ability to arrest cracks, fibre composites possess increased extensibility and tensile strength, both at first crack and at ultimate, particular under flexural loading; and the fibres are able to hold the matrix together even after extensive cracking. The net result of all these is to impart to the fibre composite pronounced post – cracking ductility which is unheard of in ordinary concrete. The transformation from a brittle to a ductile type of material would increase substantially the energy absorption characteristics of the fibre composite and its ability to withstand repeatedly applied, shock or impact loading.
In this paper, the mechanic properties, technologies, and applications of SFRC are discussed.

Keywords: *Steel fiber, concrete, properties, crack, ductility, technology.*

INTRODUCTION

Fibre reinforced concrete (FRC) may be defined as a composite materials made with Portland cement, aggregate, and incorporating discrete discontinuous fibres.
Now, why would we wish to add such fibres to concrete? Plain, unreinforced concrete is a brittle material, with a low tensile strength and a low strain capcity. The role of randomly distributes discontinuous fibres is to bridge across the cracks that develop provides some post-cracking "ductility". If the fibres are sufficiently strong, sufficiently bonded to material, and permit the FRC to carry significant stresses over a relatively large strain capacity in the post-cracking stage.

There are, of course, other (and probably cheaper) ways of increasing the strength of concrete. The real contribution of the fibres is to increase the toughness of the concrete (defined as some function of the area under the load vs. deflection curve), under any type of loading. That

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is, the fibres tend to increase the strain at peak load, and provide a great deal of energy absorption in post-peak portion of the load vs. deflection curve.

When the fibre reinforcement is in the form of short discrete fibres, they act effectively as rigid inclusions in the concrete matrix. Physically, they have thus the same order of magnitude as aggregate inclusions; steel fibre reinforcement cannot therefore be regarded as a direct replacement of longitudinal reinforcement in reinforced and prestressed structural members. However, because of the inherent material properties of fibre concrete, the presence of fibres in the body of the concrete or the provision of a tensile skin of fibre concrete can be expected to improve the resistance of conventionally reinforced structural members to cracking, deflection and other serviceability conditions.

The fibre reinforcement may be used in the form of three – dimensionally randomly distributed fibres throughout the structural member when the added advantages of the fibre to shear resistance and crack control can be further utilised . On the other hand, the fibre concrete may also be used as a tensile skin to cover the steel reinforcement when a more efficient two – dimensional orientation of the fibres could be obtained.

MIX DESIGN OF SFRC

As with any other type of concrete, the mix proportions for SFRC depend upon the requirements for a particular job, in terms of strength, workability, and so on. Several procedures for proportioning SFRC mixes are available, which emphasize the workability of the resulting mix. However, there are some considerations that are particular to SFRC.
In general, SFRC mixes contain higher cement contents and higher ratios of fine to coarse aggregate than do ordinary concretes, and so the mix design procedures the apply to conventional concrete may not be entirely applicable to SFRC. Commonly, to reduce the quantity of cement, up to 35% of the cement may be replaced with fly ash. In addition, to improve the workability of higher fibre volume mixes, water reducing admixtures and, in particular, superlasticizers are often used, in conjunction with air entrainment. The range of proportions for normal weight SFRC is shown in table 1.
For steel fibre reinforced shotcrete, different considerations apply, with most mix designs being arrived at empirically. Typical mix designs for steel fibre shotcrete are given in table 2.

A particular fibre type, orientation and percentage of fibers, the workability of the mix decreased as the size and quantity of aggregate particles greater than 5 mm increased; the presence of aggregate particles less than 5 mm in size had little effect on the compacting characteristics of the mix. Figure 1 shows the effects of maximum aggregate size on workability.
The second factor which has a major effect on workability is the aspect ratio (*l/d*) of the fibres. The workability decreases with increasing aspect ratio, as shown in figure 2, in practice it is very difficult to achieve a uniform mix if the aspect ratio is greater than about 100.

Table 1 Range of proportions for normal weight fibre reinforce Concrete [6]

Property	Mortar	9.5mm Maximum aggregate size	19 mm Maximum aggregate size
Cement (kg/m^3)	415-710	355-590	300-535
w/c ratio	0.3-0.45	0.35-0.45	0.4-0.5
Fine/coarse aggregate(%)	100	45-60	45-55
Entrained air (%)	7-10	4-7	4-6
Fibre content (%) by volume			
smooth steel	1-2	0.9-1.8	0.8-1.6
deformed steel	0.5-1.0	0.4-0.9	0.3-0.8

Table 2 Typical steel fibre reinforce shotcrete mixes [7]

Property	Fine aggregate mixture (Kg/m^3)	9.5mm Aggregate mixture (Kg/m^3)
Cement	446-559	445
Blended sand (<6.35mm)[a]	1438-1679	697-880
9.5mm aggregate		700-875
Steel fibres[b, c]	35-157	39-150
Accelerator	Varies	Varies
w/c ratio	0.40-0.45	0.40-0.45

- [a] The sand contained about 5% moisture
- [b] 1% steel fibres by volume = 78.6kg/m^3
- [c] Since fibre rebound is generally greater than aggregate rebound, there is usually a smaller percentage of fibres in the shotcrete in place

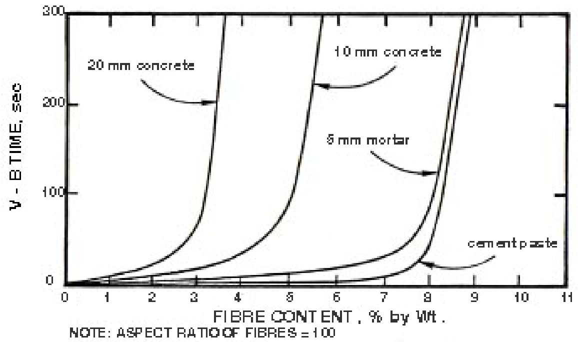

Figure 1 Workability versus fibre content for
Matrices with different maximum aggregate sizes [8]

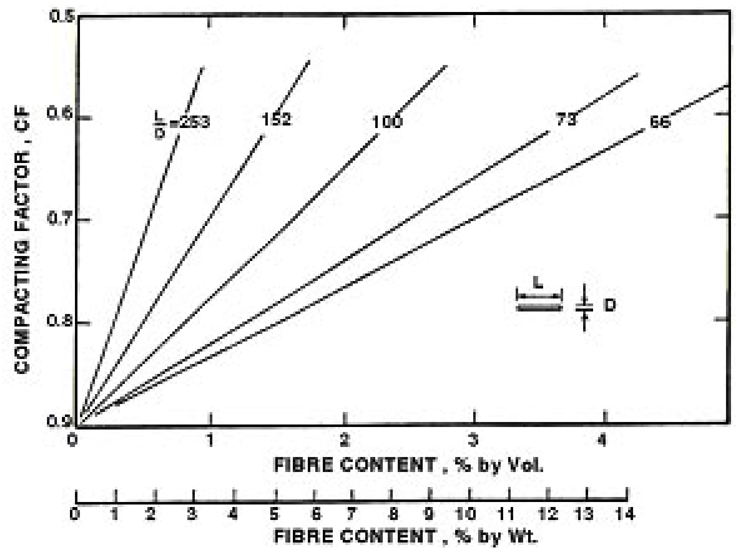

Figure 2 Effect of fibre aspect ratio on the workability of concrete, as measured by the compacting factor [8]

TECHNOLOGY FOR PRODUCING SFRC

SFRC can, in general, be produced using conventional concrete practice, though there are obviously some important differences. The basic problem is to introduce a sufficient volume of uniformly dispersed to achieve the desired improvements in mechanical behaviour, while retaining sufficient workability in the fresh mix to permit proper mixing, placing and finishing. The performance of the hardened concrete is enhanced more by fibres with a higher aspect ratio, since this improves the fibre-matrix bond. On the other hand, a high aspect ratio adversely affects the workability of the fresh mix. In general, the problems of both workability and uniform distribution increase with increasing fibre length and volume.

One of the chief difficulties in obtaining a uniform fibre distribution is the tendency for steel fibres to ball or clump together. Clumping may be caused by a number of factors:

i The fibres may already be clumped together before they are added to the mix; normal mixing action will not break down these clumps.
ii Fibres may be added too quickly to allow them to disperse in the mixer.
iii Too high a volume of fibres may be added.
iv The mixer itself may be too worn or inefficient to disperse the fibres.
v Introducing the fibres to the mixer before the other concrete ingredients will cause them to clump together.

In view of this, care must be taken in the mixing procedures. Most commonly, when using a transit mix truck or revolving drum mixer, the fibres should be added last to the wet concrete. The concrete alone, typically, should have a slump of 50-75 mm greater than the desired slump of the SFRC. Of course, the fibres should be added free of clumps, usually by first passing them through an appropriate screen. Once the fibres are all in the mixer, about 30-40 revolutions at mixing speed should properly disperse the fibres. Alternatively, the fibres may be added to the fine aggregate on a conveyor belt during the addition of aggregate to the

concrete mix. The use of collated fibres held together by a water-soluble sizing which dissolves during mixing largely eliminates the problem of clumping.
SFRC can be placed adequately using normal concrete equipment. It appears to be very stiff because the fibres tend to inhibit flow; however when vibrated, the material will flow readily into the forms. It should be noted that water should be added to SFRC mixes to improve the workability only with great care, since above a w/c ratio of about 0.5, additional water may increase the slump of the SFRC without increasing its workability and place ability under vibration. The finishing operations with SFRC are essentially the same as for ordinary concrete, thought perhaps more care must be taken regarding workmanship.

STATIC MECHANICAL PROPERTIES

Compressive Strength

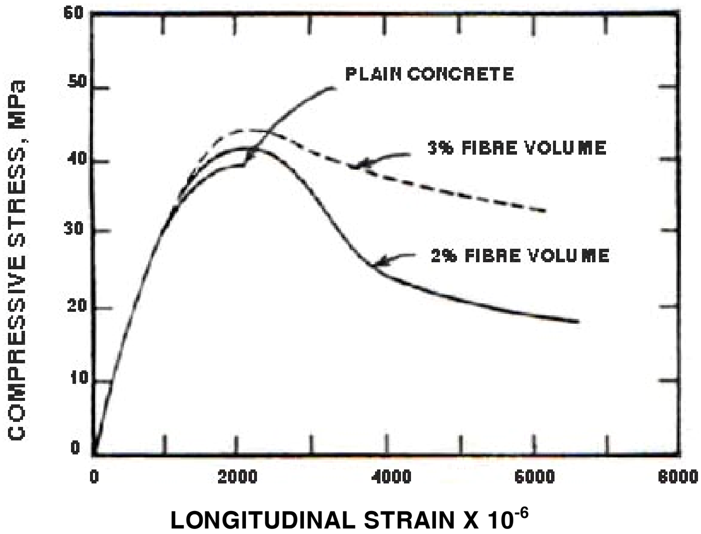

Figure 3 Stress-Strain curves in compression for SFRC [9]

Fibres do little to enhance the static compressive strength of concrete, with increases in strength ranging from essentially nil to perhaps 25%. Even in members which contain conventional reinforcement in addition to the steel fibres, the fibres have little effect on compressive strength. However, the fibres do substantially increase the post-cracking ductility, or energy absorption of the material.
This is shown graphically in the compressive stress-strain curves of SFRC in figure 3

Tensile Strength

Fibres aligned in the direction of the tensile stress may bring about very large increases in direct tensile strength, as high as 133% for 5% of smooth, straight steel fibres. However, for more or less randomly distributed fibres, the increase in strength is much smaller, ranging from as little as no increase in some instances to perhaps 60%, with many investigations indicating intermediate values, as shown in figure 4. Splitting-tension test of SFRC show similar result. Thus, adding fibres merely to increase the direct tensile strength is probably not worthwhile. However, as in compression, steel fibres do lead to major increases in the post-cracking behaviour or toughness of the composites.

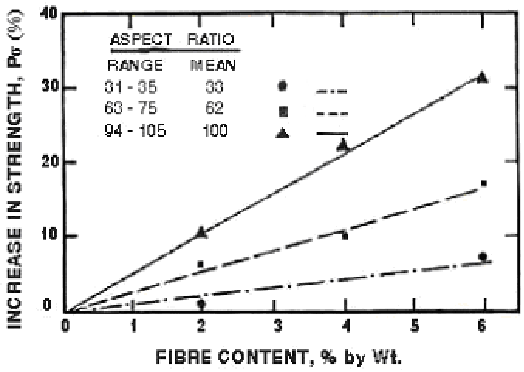

Figure 4 Influence of fibre content on tensile strength [9]

Flexural Strength

Steel fibres are generally found to have aggregate much greater effect on the flexural strength of SFRC than on either the compressive or tensile strength, with increases of more than 100% having been reported. The increases in flexural strength is particularly sensitive, not only to the fibre volume, but also to the aspect ratio of the fibres, with higher aspect ratio leading to larger strength increases. Figure 5 describes the fibre effect in terms of the combined parameter W*l/d*, where *l/d* is the aspect ratio and W is the weight percent of fibres. It should be noted that for W*l/d* > 600, the mix characteristics tended to be quite unsatisfactory. Deformed fibres show the same types of increases at lower volumes, because of their improved bond characteristics.

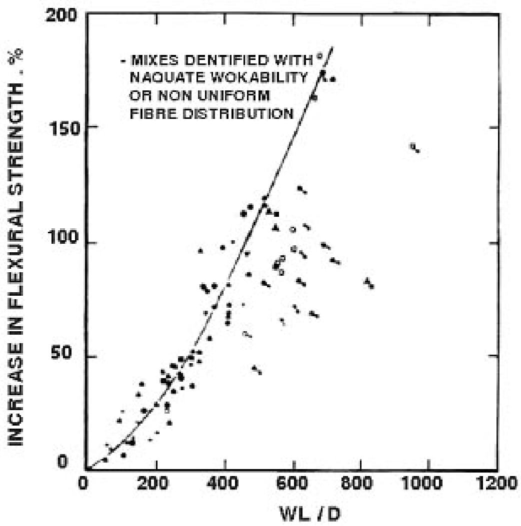

Figure 5 The effect of Wl/d on the flexural strength of mortar and concrete [9]

As was indicated previously, fibres are added to concrete not to improve the strength, but primarily to improve the toughness, or energy absorption capacity. Commonly, the flexural toughness is defined as the area under the complete load-deflection curve in flexure; this is sometimes referred to as the total energy to fracture. Alternatively, the toughness may be defined as the area under the load-deflection curve out to some particular deflection, or out to the point at which the load has fallen back to some fixed percentage of the peak load. Probably the most commonly used measure of toughness is the toughness index proposed by Johnston and incorporated into ASTM C1018. As is the case with flexural strength, flexural toughness also increases at the parameter W*l/d* increases, as show in figure 6.

The load-deflection curves for different types and volumes of steel fibres can vary enormously, as was shown previously in figure 7. For all of the empirical measures of toughness, fibres with better bond characteristics (i.e. deformed fibres, or fibres with greater aspect ratio) give higher toughness values than do smooth, straight fibres at the same volume concentrations.

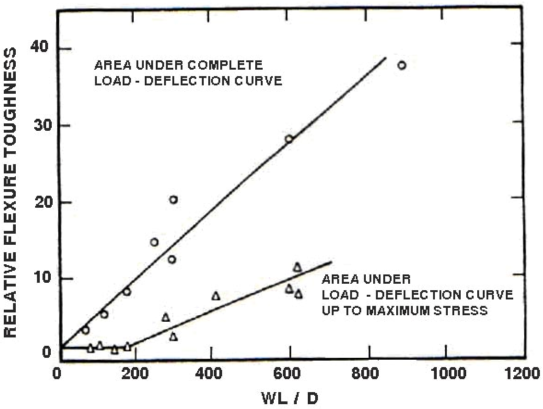

Figure 6 The effect of Wl/d on the flexural toughness of SFRC, based on data from [9].

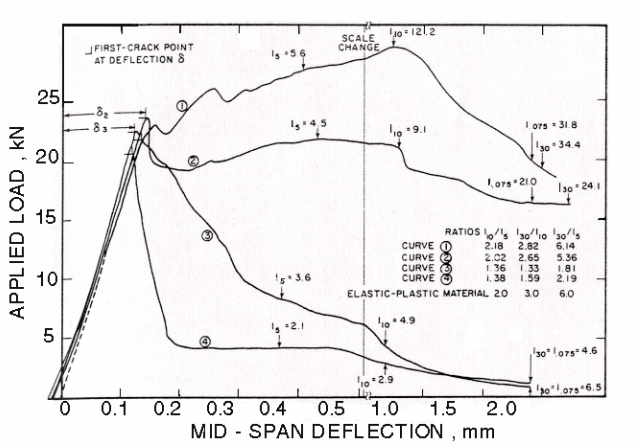

Figure 7 A range of load – deflection curves obtained in the testing of steel fibre reinforced concrete [10]

STRUCTURAL USE OF SFRC

As recommended by ACI Committee 544, ‘when used in structural applications, steel fibre reinforced concrete should only be used in a supplementary role to inhibit cracking, to improve resistance to impact or dynamic loading, and to resist material disintegration. In structural members where flexural or tensile loads will occur ….. the reinforcing steel must be capable of supporting the total tensile load’. Thus, while there are a number of techniques for predicting the strength of beams reinforced only with steel fibres, there are no predictive equations for large SFRC beams, since these would be expected to contain conventional reinforcing bars as well. An extensive guide to design considerations for SFRC has recently been published by the American Concrete Institute. In this section, the use of SFRC will be discussed primarily in structural members which also contain conventional reinforcement.

For beams containing both fibres and continuous reinforcing bars, the situation is complex, since the fibres act in two ways:

(1) They permit the tensile strength of the SFRC to be used in design, because the matrix will no longer lose its load-carrying capacity at first crack; and

(2) They improve the bond between the matrix and the reinforcing bars by inhibiting the growth of cracks emanating form the deformations (lugs) on the bars.

However, it is the improved tensile strength of SFRC that is mostly considered in the beam analysis, since the improvements in bond strength are much more difficult to quantify.
Steel fibres have been shown to increase the ultimate moment and ultimate deflection of conventionally reinforced beams; the higher the tensile stress due to the fibres, the higher the ultimate moment.

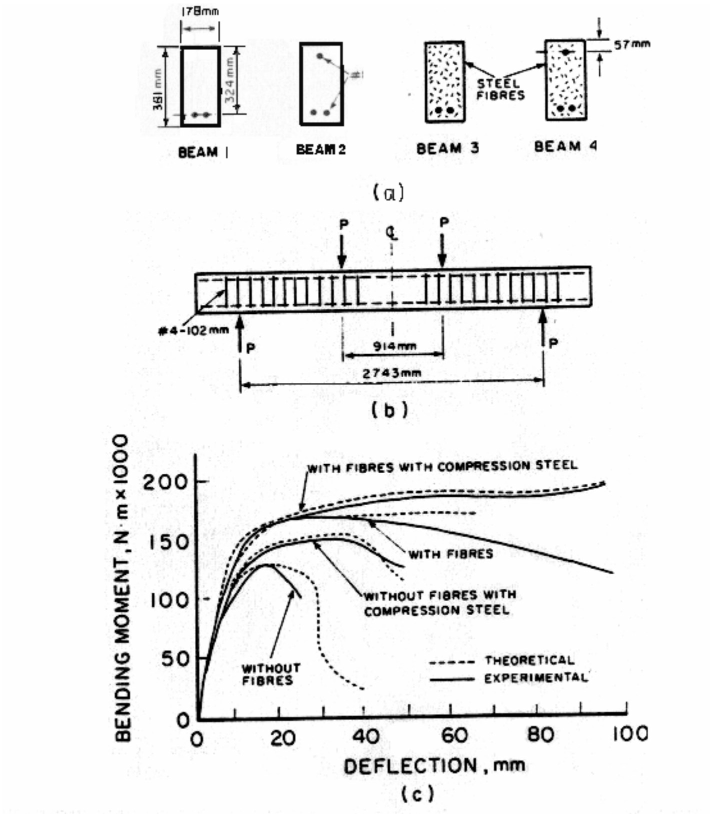

Figure 8 Experimental moment versus deflection curves for SFRC beams [11]

APPLICATION OF SFRC

The uses of SFRC over the past thirty years have been so varied and so widespread, that it is difficult to categorize them.The most common applications are pavements, tunnel linings, pavements and slabs, shotcrete and now shotcrete also containing silica fume, airport pavements, bridge deck slab repairs, and so on. There has also been some recent experimental work on roller-compacted concrete (RCC) reinforced with steel fibres. The list is endless, apparently limited only by the ingenuity of the engineers involved. The fibres themselves are, unfortunately, relatively expensive; a 1% steel fibre addition will approximately double the material costs of the concrete, and this has tended to limit the use of SFRC to special applications.

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