Steel Fibre Reinforced Concrete for Ports Infrastructure

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The use of steel fibres in applications such as industrial floors, warehouses, ports and highway pavements is prevalent in many countries. In India, thanks to the improvements in steel fibre technology and more user experiences in terms of economy and durability, the use of Steel Fibre Reinforced Concrete (SFRC) is gaining traction. It is very well known that concrete as such is a brittle material and steel fibres when added to concrete impart ductility to it. This added ductility in concrete allows for greater energy absorption and redistribution of stresses, thereby allowing designers to fully use these properties of SFRC and arrive at cost effective design solutions. This paper presents a holistic view of the theory and practicality of SFRC applications for ports and other associated infrastructure, especially for dock and container yards, and in underwater concrete applications.

SFRC is a concrete that has a homogenous distribution of randomly oriented discontinuous discrete steel fibres. Steel fibres are introduced in the matrix during the mixing phase of concrete and they are known to improve the properties of concrete such as ductility, fracture toughness, energy dissipation, impact and fatigue resistance. Steel fibres have been used in construction of ground slabs and pavements for more than 40 years now. Advancements in admixture technologies over the last few decades coupled with developments in fibre manufacturing technology (e.g. collated/glued fibres) have enabled easier mixing, batching and improved workability of SFRC – a cause of concern for most users. There is an increased understanding in the industry that each fibre type behaves differently and this fact must be considered while specifying steel fibres and designing SFRC pavement slabs for projects. Steel fibres have been used to provide durable concrete pavements with improved cracking resistance, reducing the required slab thickness and increasing the joint spacing. However, it must be noted that while the improved properties of SFRC have been well documented in the existing literature, existing guidelines and standards on concrete pavements have seldom given a serious consideration to them. Specifically in India, the main properties associated with SFRC such as ductility and toughness are enumerated as advantages but not reflected in the current design codes for SFRC pavements such as IRC: SP:46-1997.

Behaviour of SFRC

During the cracking phase of SFRC, steel fibres present in the concrete matrix bridge the cracks and transfer tension across them during this process (Figure 1). This leads to increased ductility, higher energy dissipation and crack resistance of concrete and ensures a post crack load carrying capacity. SFRC with normal commercial dosages of steel fibres actually causes no considerable increase in the flexural strength (modulus of rupture) of the concrete yet it increases the ultimate load capacity of the ground slab due to increased toughness of concrete thereby helping in redistribution of load stresses in such a highly indeterminate system.

The behaviour of SFRC is made clear with the help of a four point beam bending test as illustrated in Figure 2. When sufficient ductility is ensured in the beam with the addition of steel fibres in concrete, a strain softening phenomenon

Figure 1: Transfer of stresses across the crack
is observed after the load at first crack or peak load in the beam. Thus, with this kind of toughening behaviour in the beam, post-crack flexural strength of SFRC is guaranteed. This is in stark contrast with plain concrete, where a sudden and brittle mode of failure occurs after the peak load is reached.

This behaviour of SFRC allows for the use of plastic/ yield line theory models (Losberg, Meyerhoff etc.) to compute the ultimate design moments. Circumferential negative yield lines on top and positive radial yield lines at the bottom are generated as shown yielding a moment distribution of \( m' \) and \( m \) respectively (Figure 4).

This further opens a domain of possibilities for limit state design of SFRC pavements by fully utilizing its ductile properties. Once the ultimate moments been calculated from the plastic analysis of the pavement, the material resistance of SFRC is calculated by computing the equivalent flexural strength needed to resist the stresses due to the acting plastic moments based on the type of steel fibre used and its dosage in concrete. The salient points of the design include:-

One of the major goals of design of structures is to provide for predictable ductile failure modes and brittle unpredicted modes should be avoided. In other words, the first crack in the structural system must never be the last crack. When tested to characterize the behaviour of plain concrete vis-à-vis SFRC for slabs, it is found that distinct and large cracks appear in plain concrete slabs that run through the section, dividing the slab into various pieces as soon as the moment capacity is reached. This is in stark contrast with SFRC slabs where distinct circumferential cracks on top and radial cracks at the bottom appear due to the corresponding negative and positive moments respectively. The cracks in SFRC are more numerous, but the sum of crack widths is small and the slab still holds together as a system unlike observed (Figure 3) in plain concrete.

### Theory of Design for SFRC grade slabs

Concrete grade slabs typically rest on sufficiently compacted ground and are highly indeterminate. For such systems, one of the main advantages achieved with the addition of steel fibres in concrete is the improved redistribution of loads and formation of multiple and finer cracking patterns. With sufficient toughness and rotation capacity, the ductile behaviour of SFRC allows for the use of plastic/ yield line theory models (Losberg, Meyerhoff etc.) to compute the ultimate design moments. Circumferential negative yield lines on top and positive radial yield lines at the bottom are generated as shown yielding a moment distribution of \( m' \) and \( m \) respectively (Figure 4).

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![Figure 2: Behaviour of SFRC – Four Point Bending](image)

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![Figure 3: Plain Concrete & SFRC Slab – Brittle & Ductile Performance](image)

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- Limiting criterion is the onset of cracking on the top surface
- Negative Moment, \( m' \leq \frac{f_a h^3}{6} \)
- Post-crack Positive bending moment capacity, \( m \leq \frac{f_e h^3}{6} \)

The flexural resistance for SFRC pavements is given as:-

\[
m + m' \leq (f_a + f_e) \times \frac{h^3}{6}
\]

where,

\( f_a \) = First crack flexural strength of concrete
\( f_e \) = Equivalent flexural strength of SFRC at ULS

### Practical issues

One must keep in mind that the performance of SFRC slabs as designed can be guaranteed only if the assumption of homogeneous uniform distribution of steel fibres holds true. While dosing the fibres, it is often observed that there is a tendency of non-uniform mixing of fibres in the concrete matrix with “balling” effect, where steel fibres appear to get entangled together as lumps in the mix (Figure 5).
This problem on site is often "tackled" by either throwing such lumps out of the mix, or manually breaking them while pouring the concrete. Needless to say that this has undesirable consequences in the form of inhomogeneity of dispersion of fibres in the slab, which means that it’s always possible to find some section of the slab where the fibre dosage is less than what the design assumes. This problem is more pronounced for higher fibre dosages in concrete. Other factors which may also contribute towards non-uniform dispersion include excessive vibration, poor concrete recipes, insufficient mixing time etc.

However, with the advent of advances in fibre technology, the problem of balling is being eliminated to ensure homogenous fibre distribution. Glued/Collated Fibres (Figure 6) - fibres that are held together by water soluble glue which eliminate the formation of fibre lumps while dosing have found favour with users. Similarly, small quantities of loose fibres packed in water soluble bags attached together in the form of a chain and dosed mechanically also eliminate balling.

Dosing fibres purely on a volume fraction basis has its disadvantages in that it fails to differentiate between various kinds of steel fibres and considers the volume of steel added as the only criterion. This is obviously not true because we know that the shape, size, mechanical strength of fibres play a pivotal role in the overall performance of SFRC. For example, for a given volume of fibres added in concrete, smaller diameter fibres would be found more in number than the larger ones, and consequently a larger network of fibres within the concrete matrix which would definitely alter the performance of the concrete.

**Durability issues**

Steel fibres in concrete are known to have a positive effect on the long term service life of structures. Some of the common performance related problems that plague plain and rebar reinforced concrete such as chipping and spalling (due to weak zones in impact areas) are literally eliminated through the use of steel fibres in concrete. SFRC normally consists of a huge network of steel fibres, which can be as high a 12 km of wire length in a cubic metre of concrete. With this kind of confinement, there is no section in the structure left unreinforced, thereby offering superior splitting resistance which goes a long way in reducing maintenance and other associated costs with SFRC structures.

At the splash zone of marine structures, the superior mechanical properties of SFRC can be of greatest advantage. However, it is also true that this is also a region where the combination of salt water and oxygen, wave action etc. results in an extremely aggressive environment for fibre corrosion. Fibres in the vicinity of concrete surface are particularly vulnerable and conclusive proof of their corrosion resistance was felt to be needed for SFRC to be used in such applications. Thanks to some path breaking long term research that has been conducted in different parts of the world on this topic, steel fibres have been known to perform well under such severe conditions. Even at a very high activation level beyond 0.4% Cl- (by weight of cement), tests conducted after subjecting the specimen after 2000 cycles (1250 days) of wetting and drying under marine exposure have conclusively proved that corrosion at best get localized on the exposure surface, but never penetrates in a manner to make SFRC structurally lose its properties. Thus, while the exposed fibres ( upto 2mm in concrete) do get corroded, it never progresses inside.

Many reasons are attributed to this remarkable performance of steel fibres in the matrix. Firstly, steel fibres stick out as individual discontinuous pieces of reinforcement in the concrete matrix which never allow the completion of electrochemical cell so necessary to continue the corrosion process. So while the exposed fibres get corroded at the surface, the process itself is seldom allowed to proceed due to the nature of discontinuity of the reinforcement. Furthermore, the specific surface area available for SFRC in much more than regular RCC structured while leads to enhanced passivation due to concrete alkalinity. Even at the exposure surface, individual fibres can in no way cause spalling and other related volume expansion phenomena.
commonly observed with conventional RCC elements under corrosion attack, simply because the volume expansion with fibres is not sufficient to cause this problem due to their small diameters compared to conventional steel. All these positives of SFRC make it an ideal durable material that can be used even in marine environments.

Acceptability of SFRC solution by International Standards

A key element that has facilitated the rapid use of the concept of using steel fibres as reinforcement for concrete over the years in port infrastructure has been the acceptance of numerous world bodies in the fact that steel fibres have a positive effect on such constructions. Notably are the monographs and reports of United Nations Conference on Trade and Development (UNCTAD) and International Association of Ports and Harbours (IAPH) on Port management and British Port Federation (BRF) and American Association of Port Authorities where heavy duty port pavement design procedures and specifications with SFRC have been considered. UNCTAD and IAPH Monograph No. 5 on Port management (Table 1) even details the suitability of pavements for various port operations taking into account, the cost effectiveness and performance.

Two key requirements of port operations – namely pavement performance (due to heavy impact, fatigue and handling loads) and low maintenance (due to chipping and spalling) are excellently handled through the use of SFRC for pavements. Thus, it can be readily deduced from the table above that SFRC is found to be the most advantageous of the available alternatives for ports infrastructure.

Concluding Remarks

India has seen a stupendous growth in the ports infrastructure sector which has necessitated the demand for quick, cost effective and durable construction of pavements – a space where SFRC can thrive. Investments in the infrastructure sector coupled with mushrooming of several SEZs further provides for opportunities for SFRC. Improved mechanical properties and performance (impact, fatigue, ductility and toughness), reduced costs, construction time, enhanced job safety and increased durability are only some main benefits of SFRC which make it an attractive alternative to the end user. At the same time it needs some special knowledge to understand, design and execute this special building material.

References

- The Concrete Society: Technical Report No.34 (2003), "Concrete industrial ground floors – A guide to design and construction", pp. 50-64
- Ramakrishnan, V., Coyle, W. V., Kopac, P. A. and Pasko, T. J. (1981), "Performance Characteristics of Steel Fibre Reinforced Superplasticized Concrete," Developments in the use of superplasticizers, SP-68, American Concrete Institute, Detroit, pp. 515-534

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