STEEL FIBRE REINFORCED CONCRETE FOR ROAD PAVEMENT APPLICATIONS

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ABSTRACT

Recently, considerable interest has been generated in the use of Steel Fibre Reinforced Concrete (SFRC). The most significant influence of the incorporation of steel fibres in concrete is to delay and control the tensile cracking of the composite material. This positively influences mechanical properties of concrete. These improved properties result in SFRC being a feasible material for concrete road pavements. The aim of this paper is to evaluate the use of SFRC for road pavements and compare its performance to plain concrete under traffic loading. The influence of SFRC properties on performance and design aspects of concrete roads are discussed. Results from road trial sections, tested under in-service traffic, are used to validate the use of the material in roads. Performance and behaviour of a SFRC test section is compared to a plain concrete section. The performance of thinner SFRC ground slabs is found comparable to thicker plain concrete slabs. A design approach for SFRC is recommended in which an existing method for the design of plain concrete slabs is extended by incorporating the post-cracking strength of SFRC.

1. INTRODUCTION

Steel Fibre Reinforced Concrete (SFRC) is concrete containing dispersed steel fibres. The most significant influence of the incorporation of steel fibres in concrete is to delay and control the tensile cracking of the composite material. Concrete is a brittle material that will not carry loads under pure bending when cracked. By incorporating steel fibres the mechanical properties of the concrete is changed resulting in significant load carrying capacity after the concrete has cracked (Chen, 2004). Laboratory studies on SFRC specimens suggest that dispersion of steel fibres in concrete improves the mechanical characteristics of the composite, notably resistance to dynamic load (Banthia et al., 1995), shear strength (Khaloo and Kim, 1997), fatigue resistance (Johnston and Zemp, 1991) and post-cracking strength (Elsaigh and Kearsley, 2002). As far as slabs on the ground are concerned, the major incentive for adding steel fibres is to improve the flexural behaviour of the slab.

A full-scale accelerated trial road, consisting of different types of concrete pavements, was constructed at Roodekrans near Johannesburg. The various pavement sections were designed to exhibit failure within a short space of time and were therefore relatively thin. The traffic consisted of loaded trucks leaving a quarry. The performance of a SFRC section is compared to a similar plain concrete section. Results from this trial road are used to support the conclusion and recommendations made here. The main objectives of this paper are:

- To evaluate the use of SFRC for road pavements taking into account the influence of the SFRC properties on design and performance.
- To compare the performance of SFRC slabs on the ground to plain concrete slabs on the ground subjected to traffic loading.

2. FLEXURAL PROPERTIES OF SFRC

The addition of steel fibres to concrete was found to significantly improve the post-cracking strength of SFRC slabs (ACI Committee 544, 1982, Johnston, 1985 and Chen et al., 1995). This is evident from the load-deflection response (see Figure 1) of SFRC and plain concrete beams tested under displacement control (Elsaigh and Kearsley, 2002). Displacement controlled tests are necessary to determine the complete load-deflection response (JCI-SF4, 1983 and ASTM, 2004). While the behaviour up to the cracking load can be obtained from either a load or displacement controlled test, the post-cracking response can only be determined from a displacement controlled test.

The post-cracking strength of SFRC can be attributed to the crack controlling mechanism provided by steel fibres. The steel fibres across the crack transmit some of the tensile stresses across the crack while steel fibres at the tip of the crack resist the growth of these cracks. The ability of the steel fibres to resist crack propagation is primarily dependent on the bond between the concrete and the fibres as well as the fibre distribution (spacing and orientation).

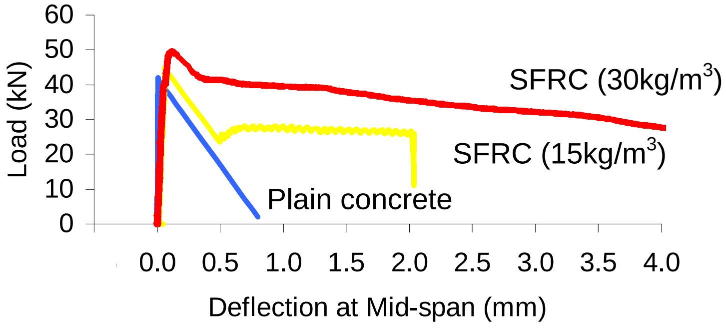

Figure 1: Load-deflection responses for simply supported beams (Elsaigh and Kearsley 2002)

Although the magnitude of the maximum flexural strength is increased, this increase is not significant and would thus not be the primary motivation for using steel fibres. Furthermore, statically determinate structures such as simply supported beams benefit little from the advantages of using SFRC. Considering the load-deflection response of SFRC in Figure 1, the load carrying capacity reduces after cracking and a sustained load equal to the cracking load cannot be supported in a statically determinate structure. Full advantage of the flexural characteristics of SFRC can only be utilized in statically indeterminate structures where plastic hinges and redistribution of stresses can occur (Nemegeer, 1996). In concrete pavements for example, a redistribution of stresses occurs after initial cracking, which allows the slab to perform in a ductile manner by sustaining the maximum load while the deformation increases. The greater the post-cracking capacity of the material, as illustrated in Figure 1, the more ductile the behaviour of the slab will be.

The ability of a ductile slab to sustain the maximum load would therefore not necessarily imply failure at first cracking. In general, a ductile structure would also have a better chance of survival when overloaded (Kwan et al., 2002).

In full-scale static testing of centrally loaded slabs on the ground, different researchers have compared SFRC slabs with plain concrete and conventionally reinforced concrete slabs. It has been fully demonstrated that the addition of the steel fibres increased the load bearing capacity, with a higher steel fibre content yielding a greater load bearing capacity (Beckett, 1990, Falkner et al., 1995, Bischoff et al., 1996 and Chen, 2004).

3. ANALYSIS OF SFRC SLABS ON THE GROUND

The existing analytical models for structural design of slabs on the ground can generally be divided into three categories:

- Methods using the elasticity theory, which is based on an uncracked slab.
- Methods using the yield line theory, which is based on a cracked but serviceable slab.
- Methods that use finite elements in which the full load-deflection response is generated and then the ultimate load can be determined based on specified or chosen extent of failure.

Westergaard (1926) developed an analytical model for analysing plain concrete slabs supported on a Winkler support. This and similar models are, however, restricted to the linear elastic regime, which assumes that the concrete deforms linearly up to failure and that failure occurs suddenly. Methods based on elastic analysis can lead to under-estimation of the load carrying capacity of SFRC slabs on the ground, as they do not take the post-cracking strength into account. In fact, the benefit from the steel fibres is only fully utilized after cracking of the concrete matrix so that design methods based on elastic theory is not appropriate.

Modern structural design concepts have changed from using “permissible stress” concepts to using the actual reserve strength of materials and members. A design approach based on the yield line theory may provide a better approximation of the ultimate load carrying capacity compared to the elastic theory approach. Meyerhof (1962) developed such a model based on the yield line theory. This model is used to determine the load carrying capacity of the SFRC by modifying the strength term (see Equation 4) to include the influence of post-cracking strength (The British Concrete Society Manual, 1994). Falkner et al. (1995) suggested a combination of the elastic theory and the yield line theory where Westergaard’s equations are adjusted to model SFRC slabs on the ground. A new trend for the thickness design of SFRC slabs on the ground is the use of a non-linear finite element method.

In the assessment of SFRC slabs on the ground, the ductility plays a decisive role in the load carrying capacity of these slabs. The influence of the post-cracking strength of SFRC is taken into account when designing SFRC slabs by introducing the term “design flexural strength” (f_d) which is the sum of the flexural strength (f_{ct}) and equivalent flexural strength ($f_{e,3}$) (The British Concrete Society Manual, 1994). The Japanese Concrete Institute (JCI-SF4, 1983) proposes a method to determine f_d using a beam supported over a span of 450 mm, with a cross section of 150 x 150 mm and loaded at third-points in displacement control.

Referring to Figure 2, f_{ct} is calculated as in Equation 1,

$$f_{ct} = P_{max} \frac{L}{bh^2} \text{ .... (Equation 1)}$$

The post-cracking strength of the beam is accounted for by introducing $f_{e,3}$, which is a stress capacity derived from the mean load ($P_{e,3}$) of a load test up to a maximum deflection of L/150. The mean load $P_{e,3}$ is determined by dividing the total area under the load-deflection curve by L/150 (see Figure 2) and is given in Equation 2,

$$f_{e,3} = P_{e,3} \frac{L}{bh^2} \quad \ldots\ldots\ldots\ldots\ldots\text{(Equation 2)}$$

The design flexural strength is then given by Equation 3,

$$f_d = f_{ct} + f_{e,3} \quad \ldots\ldots\ldots\ldots\ldots\text{(Equation 3)}$$

Equation 2 and 3 will be used when designing the SFRC slabs.

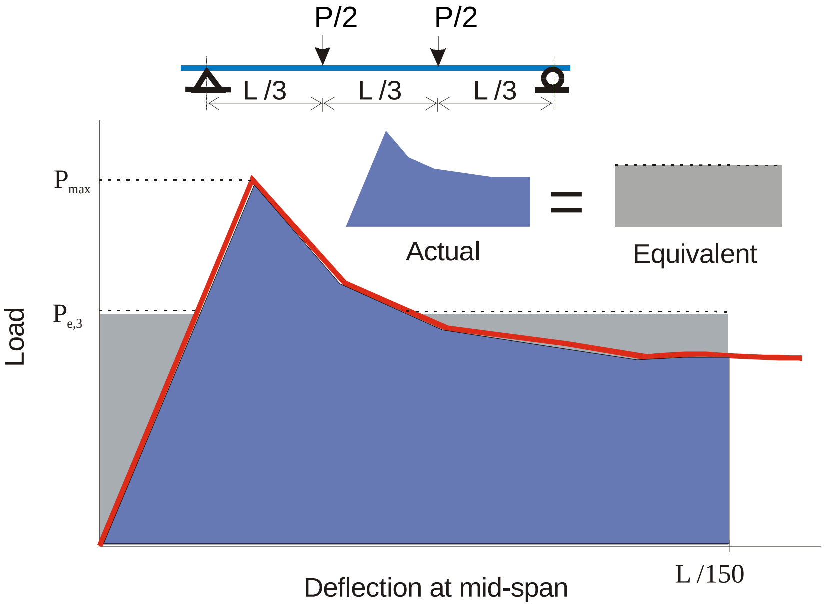

Figure 2: Schematic load-deflection curve for a beam loaded at third-points

4. EXPERIMENTAL DESIGN

The increased static strength of the SFRC suggests that thinner SFRC slabs on the ground can be designed compared to plain concrete slabs. There is always a concern that thinner slabs are likely to generate higher potential for curling and warping and yield larger deflections. High stresses caused by curling and warping combined with traffic loading can cause damage to edges and corners and hence failure of the slab. Excessive deflection can stimulate pumping and consolidation of the support layer material resulting in failure of the slab due to formation of voids below these slabs. To take the effect of all these factors into account, it was decided to conduct this research project on a full-scale experimental road section.

A single-track experimental road was built on an exit road from a relatively busy quarry located west of Johannesburg. The 3.6 m wide road used was a combined research project of the Cement and Concrete Institute (C&CI), CSIR Transportek and the University of Pretoria, and was divided into eleven sections. SFRC was used in three sections and Continuously Reinforced Concrete Pavement (CRCP) using a light mesh in three sections.

Five sections were constructed using plain concrete with varying joint types. The support conditions were varied along the length of the road. The SFRC slabs in section 2 were designed to yield the same load bearing capacity as the plain concrete slabs of section 7. The support condition and the joint type of these slabs were the same while the thickness of the SFRC slab was reduced to account for the benefit of the steel fibre reinforcement. The SFRC slab in section 3 was designed to serve as comparison to CRCP of section 5. The thickness of the SFRC was kept the same but an approximately equal volume of steel fibres replaced the conventional mesh reinforcement. For the purposes of this paper only sections 2 and 7 are considered because the support conditions and joint configuration were the same. Detailed information about the entire experiment is found elsewhere (Steyn, 2002).

Section 2 was composed of four slabs with joint spacings of 6 and 4 m while section 7 was composed of six slabs with joint spacings of 2 and 3 m. Butt joints were provided for both sections. The two sections were placed on a Cement Treated Subbase (CTS) that was 125 mm thick. The subbase was constructed by compacting a natural light brown sandstone (classified as G6) stabilised with 2% Portland Cement. The plain concrete slabs were designed using existing design methods to carry approximately $60x10^3$ equivalent 80 kN axles (E80s). The thickness for the SFRC slabs was then designed aiming for an equivalent load carrying capacity.

For design purposes it was assumed that concrete with a characteristic strength of 30 MPa would be used. Steel fibre (30 kg/m^3) was fed into the plain concrete during the mixing process. The steel fibre used were stainless hooked end wires with a length of 60 mm, diameter of 0.75 mm and a tensile strength of 1100 MPa. Addition of low steel fibre contents to concrete was found to have an insignificant effect on modulus of elasticity (Armelin and Helene, 1995) and marginal effect on the flexural and compressive strength (Elsaigh and Kearsley, 2002).

The SFRC slabs were designed by comparing their thickness to plain concrete slabs using the Meyerhof formula for an edge load (see Equation 4). All inputs to the formula are set to be equal for both slabs except the flexural strength term and the thickness of the slabs. The load bearing capacity of plain concrete with a thickness of 100 mm and flexural strength of (f_{ct}) was calculated. The SFRC slab thickness that would support an equal load to that of the plain concrete slab was then calculated taking into account that the flexural strength term f_d. The equivalent post-cracking strength of the SFRC containing 30 kg/m^3 was estimated using the design tables published by steel fibre manufacturers (Bekaert, 1998). Accordingly the equivalent flexural strength is estimated as 68 percent of f_{ct}. Therefore f_d is equal to 1.68 f_{ct}. The adequacy of this estimation was confirmed by casting beam specimens during the construction of the slabs and testing them in deflection control.

The edge load bearing capacity (P_e) of a slab as given by the Meyerhof formula is indicated in Equation 4,

$$P_e = 3.5\left[1 + \frac{2a}{L_s}\right]M_o \quad \text{…………… (Equation 4)}$$

where a is the radius of the loading plate (equivalent radius is used for a square plate), M_o is the moment carrying capacity for a unit length of the slab, L_s is the radius of relative stiffness which can be calculated using Equation 5,

$$L_s = \left[\frac{E\,h^3}{12\left(1-\mu^2\right)K} \right]^{0.25} \quad \text{..............(Equation 5)}$$

where E is the modulus of elasticity, h is the slab thickness, μ is Poisson's ratio and K is the support stiffness (modulus of subgrade reaction). Assuming that the plain concrete and the SFRC slabs have the same modulus of elasticity, Poisson's ratio and support stiffness, and a similar size for the loading plate, the term $\left[1+2a/L_s\right]$ of Equation 4 will be approximately equal for both slabs (the effect of the thickness in this term is assumed to be negligible). This assumption can be verified later, after determining the thickness for the SFRC slab.

For the plain concrete slab the moment carrying capacity (M_o) is limited by the maximum stress derived from a third-point flexural test as indicated in Equation 6,

$$M_o = f_{ct}\frac{bh_p{}^2}{6} \quad \text{.............. (Equation 6)}$$

For the SFRC slab, the post-cracking strength is assumed to contribute to the load bearing capacity and the moment carrying capacity is then given as in Equation 7,

$$M_o = 1.68 f_{ct}\frac{bh_f{}^2}{6} \quad \text{..............(Equation 7)}$$

where h_p and h_f denote the thickness for plain concrete and SFRC slabs respectively. Therefore, for the two slabs to yield equal load, the moment terms are set to be equal,

$$f_{ct}\frac{h_p{}^2 b}{6} = 1.68 f_{ct}\frac{h_f{}^2 b}{6} \quad \text{..............(Equation 8)}$$

By cancelling the equal terms of Equation 8 the magnitude of h_f is calculated to be 77 mm. The thickness specified for the construction of SFRC slab was 75 mm. A reduction in thickness of 25% is therefore achieved by adding 30 kg/m^3 hooked end steel fibres.

Kearsley and Elsaigh (2003) experimentally verified the adequacy of this comparative design approach for slabs on the ground subject to static loading. Full-scale plain concrete and SFRC slabs on the ground were designed using this approach. Static load was applied at the centre of these slabs. The resulting load-deflection response for both slabs correlated well. The validity of the approach with regard to traffic loading will be evaluated using the results of trial road experiment.

5. EXPERIMENTAL RESULTS AND DISCUSSION

Equivalent support conditions and joint configurations are considered crucial aspects with regard to the comparative evaluation carried out in this paper. In-situ density tests performed during the construction on the subgrade and the subbase have indicated that both section 2 and section 7 have uniform and fairly similar support condition (BKS, 2002). Minimum relative compactions of about 97.7 % and 97.5 % (MOD AASHTO) were achieved on the subgrade and the subbase respectively. Tests performed by the C&CI on concrete cubes, beams and cylinder specimens have shown that the concrete properties vary within each section and between the different sections. As an indication for this variability, the 28-day compressive cube strengths range between 23 and 28 MPa for the SFRC of section 2, and 32 and 37 MPa for the plain concrete of section 7 (Perrie, 2002).

The author prepared beam specimens for the sections intended for comparison to confirm the adequacy of the estimation made with regard to contribution of the post-cracking strength. Beams measuring 150 x 150 x 750 mm were tested in displacement control as prescribed by the Japanese Concrete Institute (JCI-SF4, 1983). The load-deflection responses for both the SFRC and the plain concrete are indicated in Figure 3.

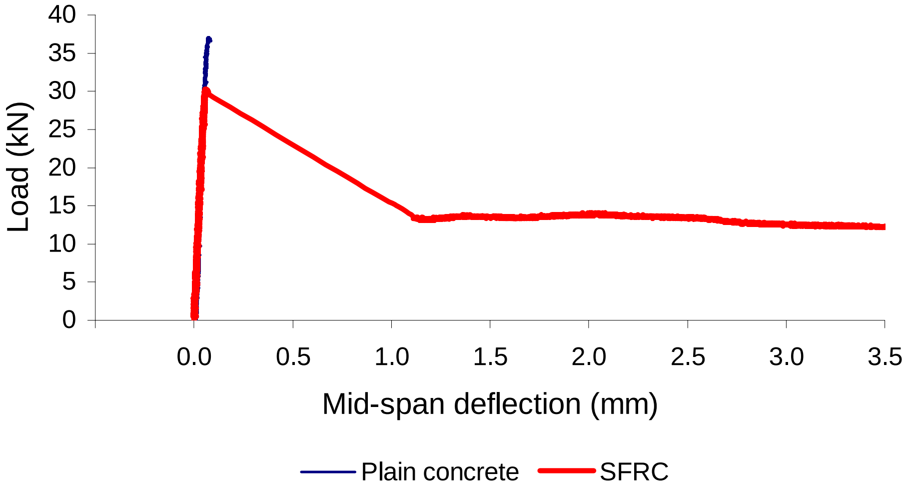

Figure 3: Load-deflection responses for SFRC and plain concrete beams

Referring to Figure 3 and using Equation 1, the flexural strength (f_{ct}) was calculated as 4.3 and 4.9 MPa for SFRC and plain concrete, respectively. With reference to the procedure explained in Figure 2 and Equation 2, the equivalent flexural strength for the SFRC is calculated as 55 percent of f_{ct}. Substitution of the actual strength values into Equation 8 will yield a thickness of 85 mm for the SFRC slabs. However, cores taken from the SFRC slabs have shown that the as-built thickness ranges between 70 and 85 mm.

The average Young's modulus were reported as 25 GPa for the SFRC of section 2 and 29 GPa for the plain concrete of section 7 (Perrie, 2002). It is worthwhile mentioning that the assumption made with regard to the term $\left[1+2a/L_s\right]$ of Equation 4 remains reasonable and does not violate the findings of Equation 8. This can be verified by substituting the actual Young's modulus and the thickness of the slab in Equation 5 and assuming reasonable values for the Poisson's ratio and the support stiffness.

After 320 x 10^3 E80 axle loads have traveled over the test section, a panel composed of road designers and clients was invited to evaluate the performance of the road. The panel was asked to rate the sections against three different standards for highways, streets and parking areas. A zero rating represents a perfect condition while 100 percent represents complete failure. The results of the ratings for section 2 and section 7 are summarized in Figure 4 (Strauss, 2004). The SFRC slab (section 2) has a significantly lower failure rate than the plain concrete slab (section 7). For a 20 year life cycle (commonly used for concrete pavements), 320 x 10^3 E80 axle loads would amount to an average of 22 E80s per day. This is high compared to what similar classes of roads are designed to resist.

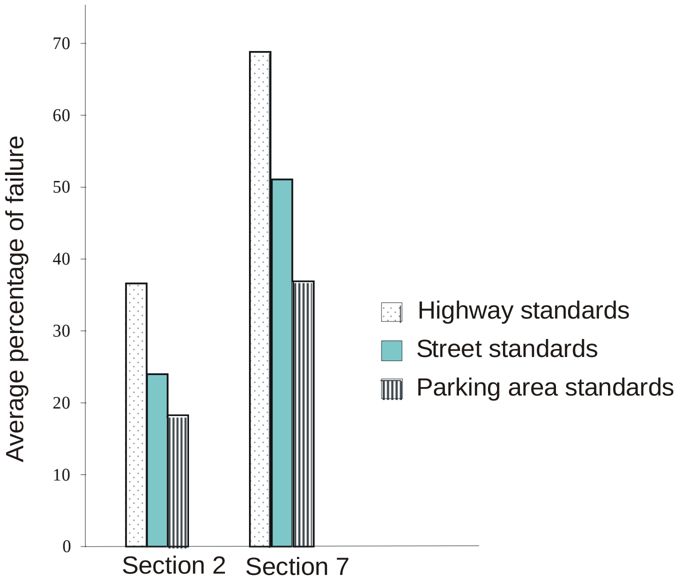

Figure 4: Road rating results (Strauss 2004)

The surface conditions of the slabs in sections 2 and 7 following 320 x 10^3 E80s are shown in Figures 5 and 6, respectively. It can be seen that neither section has failed and will be able to support further traffic loads. However, the surface of the SFRC slabs is less damaged compared to that of the plain concrete slabs. The appearance of the slabs presented in these photos confirms the results of the visual inspection carried out by the evaluation panel.

Figure 5: The surface of the SFRC slabs of section 2

Figure 6: The surface of the plain concrete slabs of section 7

The results of the inspection indicate that the thickness of concrete pavements can be reduced by the use of steel fibres in the concrete. The effect of curling and warping does not seem to affect the performance of the thinner slab more than the plain concrete. Only one incident of a corner break was found in the SFRC compared to many in the plain concrete slabs. Falling Weight Deflectometer measurements indicate that the SFRC slabs have a slightly higher deflection compared to the plain concrete slabs. However, the deflection capacity of the SFRC is seen to be useful as the slabs could maintain these relatively high deflections with the least amount of cracking. This suggests that the deflection of the SFRC slab is not vital to its structural performance under the support condition used in this experiment.

The results of this experiment indicate that the extended thickness design method proposed here for SFRC is also valid with respect to traffic loading. This design method produced a slab with the required load carrying capacity that performed well in service. This approach can be useful in the design SFRC roads. Firstly, the thickness for the plain concrete road can be calculated using conventional design methods. Thereafter, the equivalent SFRC thickness can be calculated using Equation 8. It should be noted that the experimental section has carried traffic that was more than five times greater than what it was designed for. The current conventional design methods for concrete roads seem to underestimate its performance. A need arises for refining the existing design methods used to analyse these slabs on the ground.

In South Africa the current cost of steel fibres may not justify a reduction in slab thickness. However, with increased use of steel fibres it is expected that the cost of these fibres will reduce and SFRC pavements will become an option to consider.

6. CONCLUSIONS AND RECOMMENDATIONS

- The performance of the thinner SFRC slabs on the ground is found comparable to thicker plain concrete slabs. Accordingly, a 25 percent thickness reduction is possible by incorporating 30 kg/m^3 of hooked end steel fibres.

- The extended design approach resulted in SFRC slabs that are equivalent to the plain concrete slab under in-service traffic loading. This approach can serve as an interim design approach for SRFC roads while our understanding of the behaviour of SFRC roads evolves and more advanced methods are developed.

7. ACKNOWLEDGMENTS

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