Effect of ductility on load-carrying capacity of steel fibre reinforced concrete ground slabs

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Steel fibre reinforced concrete (SFRC) is increasingly being used for ground slab applications. The addition of steel fibres to concrete imparts significant post-cracking ductility (toughness). This ductility is used to determine a post-cracking strength, which when combined with the pre-cracking strength forms the so-called 'design strength' for SFRC ground slabs. Consequently, the SFRC slab thickness can be reduced in comparison with plain concrete (brittle) slabs. The aim of this paper was to assess the effect of ductility on the load-carrying capacity of SFRC slabs and subsequently compare the deformation behaviour of the SFRC slab to an equivalent plain concrete slab. Based on the post-cracking strength specified by the steel fibre manufacturer, an SFRC ground slab was designed to collapse at the same load as the failure load of a plain concrete slab. The two slabs were then cast, cured for 28 days and afterwards loaded at their centre points till failure. Although the SFRC slab was designed to be 16,6 % thinner, the measured failure load and deflection were found to be approximately equal for the two slabs. These test results indicate that the load-carrying capacity of concrete ground slabs can be increased by inclusion of nominal steel fibre contents.

INTRODUCTION

Steel Fibre Reinforced Concrete (SFRC) is defined as concrete containing randomly oriented discontinuous discrete steel fibres (ACI Committee 544 1982). A number of different types of steel fibres have been used in the past and recently efforts have been made to optimise the shape and size of the steel fibres to achieve improved fibre-matrix bond characteristics and to enhance fibre dispersability (Soroushian & Bayasi 1991). It has been found that SFRC containing hook-ended stainless steel wires has better physical properties than that containing straight fibres (Ramakrishnan 1985).

Laboratory-scale tests conducted by many agencies and researchers indicate that the addition of steel fibres to concrete significantly increases the total energy absorbed prior to complete separation of the specimen (Johnston 1985). The presence of steel fibres can also increase the flexural strength of concrete (Snyder & Lankard 1972; Edgington *et al* 1974; Ramakrishnan 1985), improve fatigue endurance (Johnston & Zemp 1991), impact strength (Morgan & Mowat 1984; Lankard & Newell 1984) and shear strength (Jindal 1984).

In the assessment of slabs on an elastic support, the ductility (toughness) plays a decisive role in the load-carrying capacity and deformation behaviour of these slabs. Design manuals and catalogues recommend the use of the equivalent flexural tensile strength, which takes the ductility into account when SFRC slabs are designed. The general purpose of this investigation was to validate these design principles and to evaluate the use of SFRC for ground slab applications by using full-scale tests. The main objectives of this paper are to

- investigate and assess the effect of ductility on the load-carrying capacity of SFRC ground slabs on a support stiffness much higher than tested previously
- compare the deformation behaviour of a SFRC slab to a plain concrete slab with the same theoretical design strength as a first step in the overall validation

The paper presents the theoretical background to the strength of SFRC slab and then develops the experimental programme. An SFRC ground slab was designed to fail at the same load as the failure load of a plain concrete slab. Owing to the greater flexural strength of the SFRC (combined pre-cracking and post-cracking strength), the theoretical design yielded a reduction in thickness for the SFRC compared to the plain concrete counterpart. A point load was applied to the centre of each of the slabs and the measured loads as well as deflections were compared.

STRENGTH AND POST-CRACKING DUCTILITY OF SFRC

Usually there are two major incentives for adding fibres to the concrete used for ground slabs, namely

- to enhance the toughness of the structure
- to distribute the cracking of concrete due to restraint stresses (shrinkage and thermal movement)

The main issue in both cases is the crack-arresting effect of the steel fibres (Bekeart NV Steel Fibre Concrete Floors 1998). Unlike plain concrete, SFRC has considerable post-

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cracking strength. A third-point flexural test (as shown in figure 1) is used to quantify the post-cracking strength caused by the presence of steel fibres in the concrete (JCI–SF4 1983). When SFRC fails in flexure the following properties can be determined:

- *The flexural strength* (f_{ct}), which is the stress at maximum load on the load-deflection curve.

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

Where P_{max} is maximum load on the load-deflection curve, L is the tested span, b and h are the width and depth of the beam.

The equivalent flexural strength ($f_{e,3}$) is the post-cracking strength. According to the Japanese standard (JCI–SF4 1983) this is the stress capacity derived from the mean load ($P_{e,3}$) over a deflection of $\frac{L}{150}$ in a third-point loading test. The mean load $P_{e,3}$ is calculated by dividing the area under the load-deflection curve (energy) by the deflection value used in determining this energy ($\frac{L}{150}$). Refer to figure 1.

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

- *The residual flexural strength ratio* ($R_{e,3}$) is the ratio between the equivalent flexural strength and the flexural strength. It represents the percentage of improvement of the flexural strength of SFRC compared to plain concrete (JCI–SF4 1983).

$$R_{e,3} = \frac{f_{e,3}}{f_{ct}} 100 \quad (3)$$

- *The design flexural strength for the SFRC slabs* (f_d) is the sum of the flexural strength and the equivalent flexural strength (Bekaert NV Design Manual 1998).

$$f_d = f_{ct} + f_{e,3} \quad (4)$$

The design flexural strength value (f_d) used to design ground slabs is greater than the maximum flexural strength of the beam. Both the British Concrete Society (British Concrete Society 1995) and the Steel Fibre Manufacturer Manuals (Bekaert NV Design Manual 1998) recommended the use of this value for designing of SFRC ground slabs.

PREVIOUS FULL-SCALE SLAB TESTS

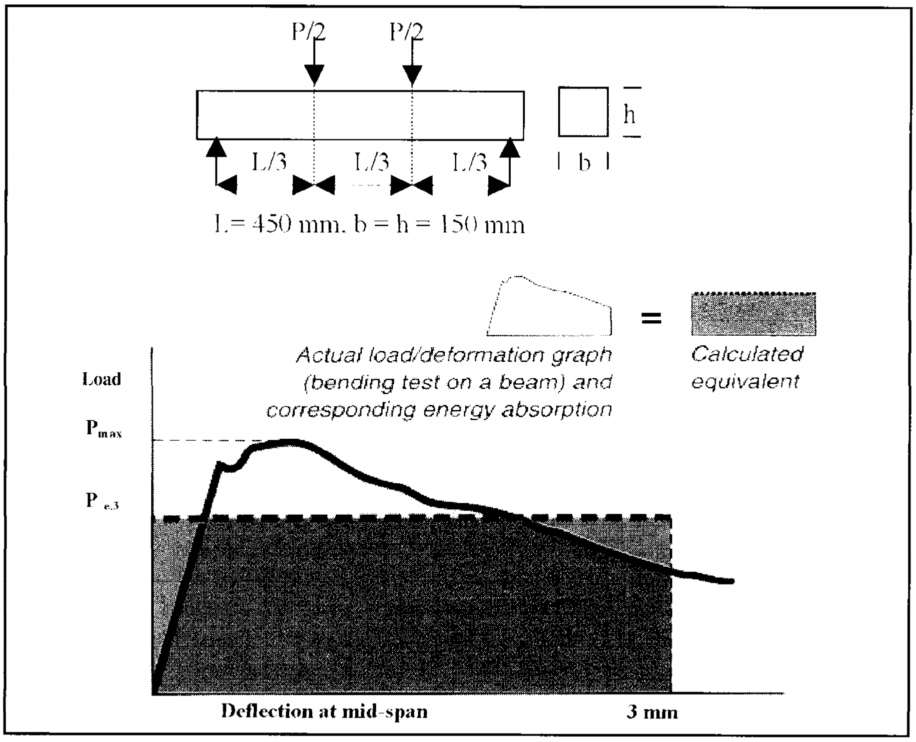

Figure 1 Schematic load-deflection curve for a beam loaded at third points (Bekaert NV 1999)

The load-carrying capacity of ground slabs has been extensively studied by various researchers (Kaushik *et al* 1989; Beckett 1990; Falkner *et al* 1995; Bischoff *et al* 1997). Full-scale tests on ground slabs have been conducted by different researchers who compared centrally loaded SFRC slabs to plain concrete and lightly mesh-reinforced concrete slabs. The published results are summarised in table 1. Regardless of support stiffness, slab size and loading plate size, it has been demonstrated that the addition of the steel fibres increased the load-carrying capacity dramatically. It is also prominent that a higher steel fibre content yields greater load-carrying capacity up to a limit. It is therefore deduced that a thinner SFRC section can sustain a load equal to the load that can be sustained by a thicker plain concrete slab. Thinner slabs

Table 1 Slab full-scale tests adapted from other researches

Fibre content (kg/m^3)	Failure load (kN)	Slab size (mm)	K-value MPa/m	Loading plate (mm)
(Kaushik 1989)				
no fibre	45	1 800 x 1 800 x 100	35	300 dia (circular)
40	80			
80	120			
120	150			
160	145			
(Beckett 1990)				
no fibre	200	3 000 x 3 000 x 150	35	100x100 (square)
20	350			
20	300			
30	390			
30	340			
(Falkner *et al* 1995)				
no fibre	180	3 000 x 3 000 x 150	25	120 x 120 (square)
20	240			
no fibre	220	3 000 x 3 000 x 150	50	120 x 120 (square)
20	380			
(Bischoff *et al* 1997)				
10 (wire mesh)	222	2 500 x 2 500 x 150	15	100 x 100 (square)
30	310			
10 (wire mesh)	274	2 500 x 2 500 x 150	73	100 x 100 (square)
30	337			

Hook-end steel fibres were used in all investigations.
(The K-value units given in these studies were adjusted to conform to the units used in this paper.)

might yield excessive deflections, which could result in serviceability problems.

The contribution of the steel fibre to the load-carrying capacity of ground slabs might be affected by the support stiffness, as reported in table 1. With stiffer support, different failure mechanisms to that observed with the softer supports are possible. It was therefore important to determine the influence of the steel fibres on the load-carrying capacity of slabs on supports that have a stiffness higher than those tested by other researchers as presented in table 1.

EXPERIMENTAL PROGRAMME

Slab design

The aim was to theoretically calculate the thickness of an SFRC slab that would have the same load-carrying capacity of a 150 mm plain concrete slab. The design method described in appendix F of the Technical Report No 34 (British Concrete Society 1994) and the Steel Fibre Manufacturers Manual (Bekaert NV Design Manual 1998) was used. Meyerhof formulae were used as a base for the calculation of the load-carrying capacity of the slabs and are given in the appendix for the interior loading condition together with the calculation procedure.

According to the design tables of a steel fibre manufacturer (Bekaert NV Design Manual 1998) the addition of 15 kg/m^3 of steel fibres should increase the *design flexural strength* (f_d) by 42 % ($R_{e,3}$ = 42 %) relative to that of plain concrete. The $R_{e,3}$ value will later be verified experimentally by conducting a third-point beam test.

In an attempt to obtain equal load-carrying capacity for the two slabs, the Meyerhof formula for interior load case was used as the base for the theoretical calculation, bearing in mind that Meyerhof formulae do not calculate the deflection. It should be emphasised that the two slabs were designed to be equal only in terms of the load-carrying capacity. For the SFRC slab and the plain concrete slab, equal values for support stiffness, flexural strength (stress at maximum load attained), size of loading plate, Poisson's ratio and modulus of elasticity were used to serve as input values to the formula. Poisson's ratio and modulus of elasticity were assumed equal for both slabs because the effect of the steel fibre on their values is negligible (Elsaigh 2001). The only differences were the strength value (f_{ct} in the case of the plain concrete slab and f_d in the case of the SFRC slab) and the thickness of the slabs. The load-carrying capacity of plain concrete having a thickness of 150 mm and flexural strength of f_{ct} was calculated. The SFRC slab thickness that would carry a load equal to that calculated for the plain concrete slab was then determined, taking into account that the design flexural strength is equal to f_d which is 1,42 f_{ct} (this is where the post-cracking strength of the SFRC contributes to the strength of the SFRC slab load-carrying capacity). The calculated equivalent SFRC slab thickness was 125 mm. The SFRC slab is 16,6 % thinner than the plain concrete slab, which theoretically had the same interior load-carrying capacity.

Materials and testing

The concrete mix used is indicated in table 2. A steel fibre content of 15 kg/m^3 was used in the SFRC slab mix. Steel fibres used in this investigation (CHD 80/60 NB) were hook-ended wires with an aspect ratio of 80, length of 60 mm and a tensile strength of 1 100 MPa. Fly ash was used as cement replacement to improve the workability of the mix and to increase the mix paste content.

A stiff support was created, on the testing floor facility at University of Pretoria, by using a foamed concrete support. The value of the subgrade stiffness was measured by conducting a plate-loading test and a support stiffness (K) of 250 MPa/m was measured. This is considerably higher than used in published tests.

Table 2 Mix composition

Material	Mass (kg/m^3)
Portland cement	282
Water*	194
Fly ash (unclassified)	78
19 mm stone (granite)	883
13 mm stone (granite)	222
Crusher sand (granite)	662
Filler sand	72

* *Water-reducing agent was used.*

The 3 000 x 3 000 x 150 mm plain concrete slab was cast on the foamed concrete support. Three beams, for flexural testing (toughness beams), measuring 750 x 150 x 150 mm, were also made. Steel fibre was added to the concrete (15 kg/m^3) and the mix was used to cast the second slab, next to the plain concrete slab, measuring 3 000 x 3 000 x 125 mm. Three beams from this mix, similar in size to the first set, were cast.

The slab testing was conducted using a closed-loop material testing system in displacement control (1,5 mm/min). The load was applied via a hydraulic twin jack pressing on a loading plate (measuring 100 x 100 mm) placed at the centre of the slab. Vertical deflections were measured (100 readings per second) by using linear variable displacement transducers (LVDTs). The LVDTs were mounted on a steel beam spanning over the slabs to measure the vertical deflection at the loading point as well as along the width of the slabs. The test arrangement and the measuring points are indicated in figure 2. The test was conducted 28 days after casting.

The beam specimens were subjected to a third-point loading test using material testing system (MTS) under

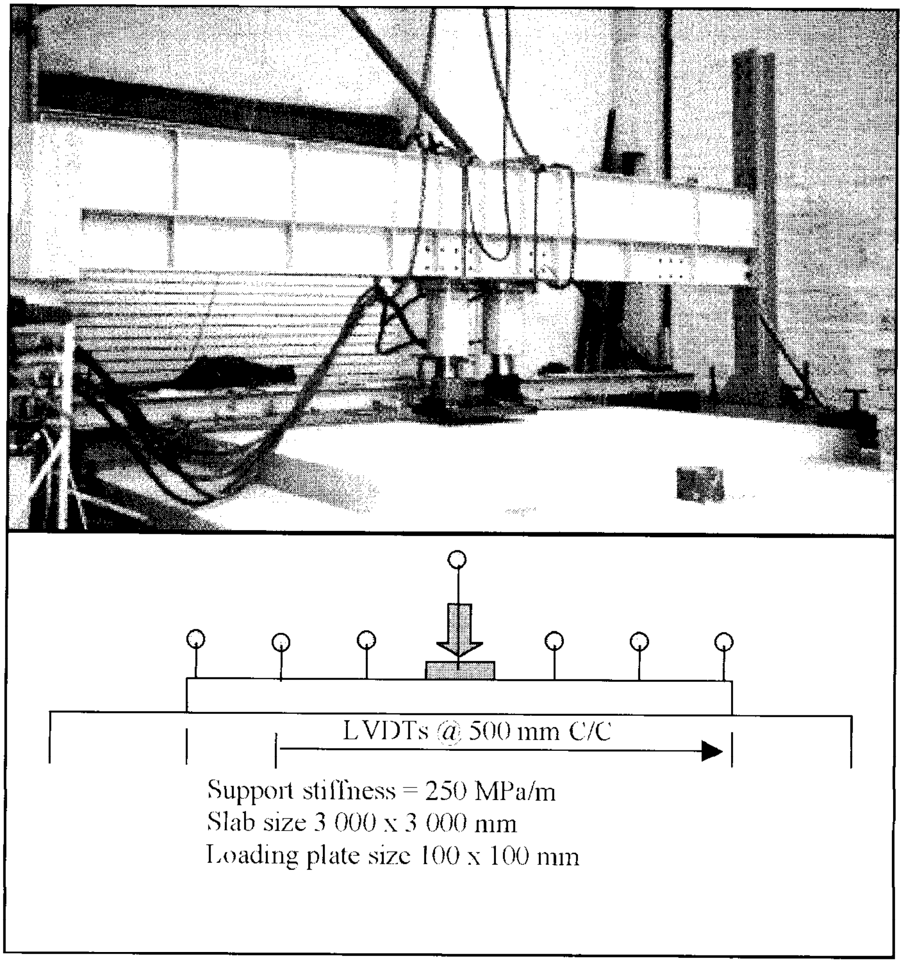

Figure 2 Arrangement for slab full-scale test

displacement control (0,02 mm/sec). The test arrangement and testing procedure are reported elsewhere (Elsaigh & Kearsley 2002).

RESULTS AND ANALYSIS

Flexural strength tests (toughness test)

Figure 3 shows the load-deflection diagram for the plain concrete and SFRC beams in the third-point loading test. The plain concrete beam failure was brittle and the beam was completely separated into two segments immediately after cracking. Although the steel fibre content added was small, the SFRC beams behaved in a ductile manner compared to the plain concrete beams. SFRC beam tests, conducted by the authors and reported elsewhere, however, have shown that higher steel fibre contents yield greater ductility (Elsaigh & Kearsley 2002).

Based on the experimental load-deflection datum, the magnitude for the residual flexural strength was calculated.

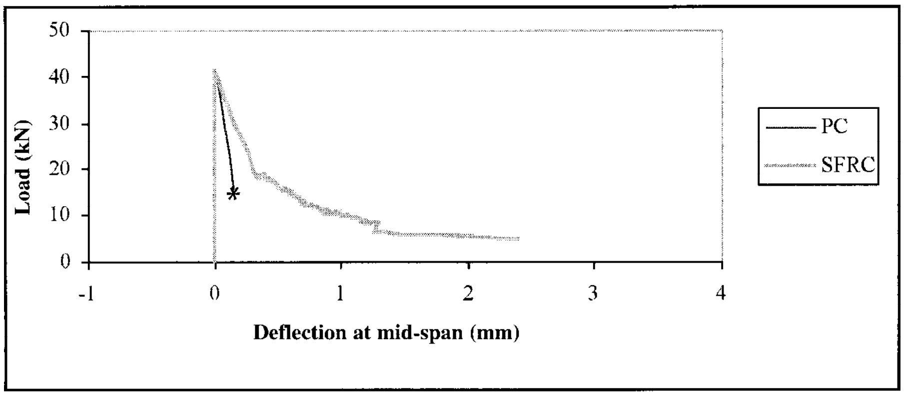

Figure 3 The load-deflection curve for third-point loading test on a flexural beam sample

(Note:*At this stage, the beam separated in two segments and the LVDT's needles fell out of its housing body, thus deflection readings were not possible past this point.)

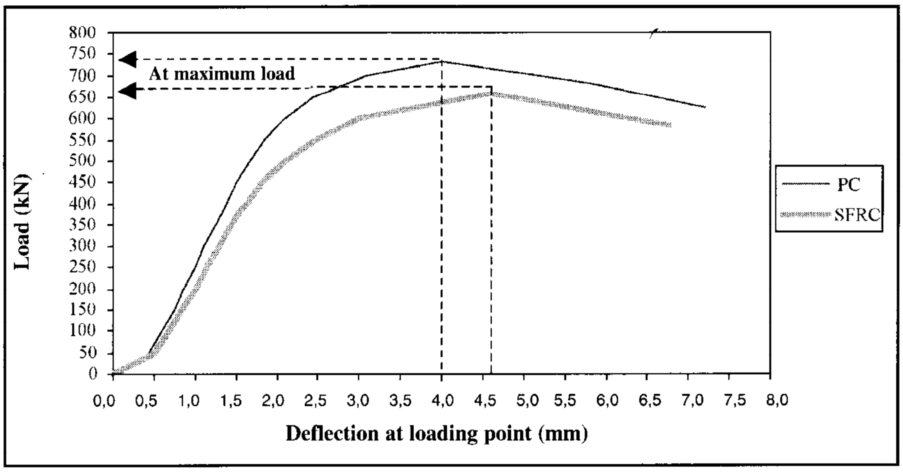

Figure 4 Load-deflection curve for centre-point loading on the slabs

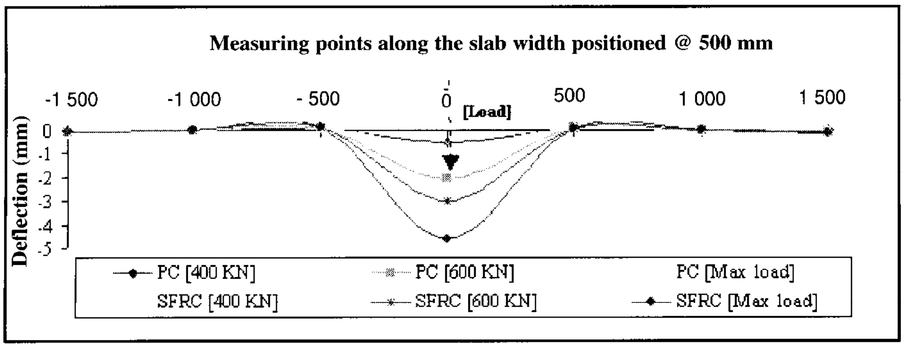

Figure 5 Deflection profile across the slab's width

An average value of $R_{e,3}$ = 35% was calculated, as indicated in table 3. This is less than the 42 % assumed in the design of the experiment.

Slab load-carrying capacity

Figure 4 shows that although the SFRC slab is 16,6 % thinner than the plain concrete slab, the load-carrying capacity of the SFRC slab was about 11% less and not equal as expected in the experimental design. The shape of the two curves are similar, which suggests that the support stiffness plays a major role, and that the effect of the steel fibres in producing ductile behaviour is not as marked as when the support is weak.

The deflection at off-set points along the width of the slab at distances of 500, 1 000 and 1 500 mm from the loading point were similar, as shown in figure 5. From this figure it can be seen that both slabs curve upward at approximately the same distance from the loading point. Recalling the concept of the radius of relative stiffness as in equation 6 (refer to the appendix), a thinner slab should result in a lower radius, which means that the presence of the steel fibres have caused the SFRC slab to distribute the effect of the loading to a larger area. This suggests that the ductility of the SFRC has played a role in distributing the effect of loading to a larger area. Indeed, it has been stated that the load-carrying capacity in bending depends not only on the tensile strength and the thickness of slab, but also on the post-cracking ductility (Henrik & Vinding 1990).

The fact that the plain concrete slab load-carrying capacity was about 11 % higher than that of the SFRC slab is due to the over-estimation of the post-cracking ductility used at the design stage. Since the measured equivalent flexural strength of the SFRC ($R_{e,3}$ = 35 %) was lower than the magnitude given by the steel fibre manufacturer ($R_{e,3}$= 42 %), this indicates that the SFRC slab thickness (125 mm) should be such that the SFRC slab fails at a lower load than the plain concrete slab. Theoretically the 125 mm SFRC slab should fail at a load 6,25 % lower than the failure load of the 150 mm plain concrete slab. Therefore, a marginally thicker SFRC slab should have been cast if this actual tested value ($R_{e,3}$ = 35 %) was used. Using $R_{e,3}$ = 35 %, the appropriate thickness for a SFRC slab with load-carrying capacity equivalent to the 150 mm thick plain concrete slab would be 129 mm.

Deflection

Apart from the load-carrying capacity, deflection is also a crucial factor in concrete pavement design. Thinner slabs are likely to yield higher deflection. Although the SFRC slab was thinner than plain concrete slab, it was found to deflect similarly to the thicker plain concrete slab.

Beneath the loading point, the two slabs yielded the same deflections up to a load of about 400 kN (refer to figure 4). As the load increased (beyond 400 kN), the SFRC had higher deflections compared with the plain concrete slab at equal load. Field ground slabs, such as concrete roads, are usually designed for much lower load values. For instance, at a dual wheel load of 50 kN, the deflection read off the figure is about 0,28 mm. Thus, the deflection of the thinner SFRC slabs is comparable to deflection appropriate for field applications, as long as the adequate thickness for required application is provided.

Figure 5 suggests that the deflection within the immediate loaded area was dictated by the thickness of the slabs, but further away, at offset points along the width of the slab, other factors play a major role. These factors could be the ductility of the material, support characteristics or membrane action of the slab.

Using steel fibre contents in excess of 15 kg/m³ would have yielded a SFRC slab that is thinner than 125 mm according to the design method. The deflection in this case is then expected to be more critical unless the stiffening effect of the steel fibre content can contribute to reduce the deflection. Studies on flexural deflection of beam specimens containing steel fibre contents ranging between 0 and 120 kg/m³ have proven that deflection decreases with an increase in the fibre content (Alsayed 1993).

Additional slab tests with greater fibre contents are therefore needed to investigate suitable steel fibre contents that are appropriate to increase the load-carrying capacity (reducing the thickness) with acceptable deflection for applications where this is critical.

General

The values of post-cracking ductility derived, using beam specimens, correlates well with the increase in load-carrying capacity of the SFRC slab. The $R_{e,3}$ values given by foreign steel fibre manufacturers should be adjusted to take the effect of local concrete materials into account.

These initial tests indicate that the Japanese Concrete Institute (JCI-SF4 1983) method for calculating the post-cracking ductility seems to give a satisfactory estimation of the contribution of the steel fibres to the strength of the SFRC ground slabs.

The results from this full-scale slab test in conjunction with table 1 prove that incorporation of steel fibre into plain concrete increases the load-carrying capacity of ground slabs for all ranges of support stiffness used.

CONCLUSIONS

Based on the results of this investigation the following can be concluded:

- The post-cracking ductility enhanced by steel fibre reinforced concrete is found to increase the load-carrying capacity of the SFRC ground slabs. The increase in load-carrying capacity of SFRC slabs on a very stiff support is not as marked as in SFRC on a softer support.
- The design strength (f_d), as a sum of the post-cracking strength ($f_{e,3}$) and the flexural strength (f_{ct}), seems to be applicable to thickness design of SFRC slabs. Further slab testing is required to develop the influence of the underlying support.
- The addition of the steel fibres to concrete (for steel fibre content as low as 15 kg/m³) was found to increase the load-carrying capacity of concrete slabs on a stiff support. Therefore, the SFRC slab thickness can be reduced to withstand loads equal to a plain concrete slab.
- The derived $R_{e,3}$ value from a third-point loading beam test correlates well with the strength increase for the SFRC slab. Therefore, the procedure of the Japanese Concrete Institute for assessing the magnitude of post-cracking ductility is deemed to be valid.
- In comparison to plain concrete slabs, thinner SFRC slabs yield higher deflection values. When SFRC slabs are used, deflection must be limited to acceptable values. For use as road slabs, this aspect did not appear to be critical.
- The results of this investigation, together with published data by other researchers, indicate that nominal steel fibre contents in concrete ground slabs (significantly) improve the load-carrying capacity regardless of the support stiffness.
- The $R_{e,3}$ values given by foreign steel fibre manufacturers should be validated to take the effect of local concrete materials into account.

Appendix

Slab interior load-carrying capacity, as given by the Meyerhof formula, is indicated in equation 5.

$$P_i = 6\left[1 + \frac{2a}{l}\right]M_o \qquad (5)$$

Where:
P_i = Interior load-carrying capacity
a = The radius of the loading plate (equivalent radius is used when using square plate)
l = The radius of relative stiffness – it can be calculated using equation 6
M_o = The moment-carrying capacity

$$l = \left[\frac{Eh^3}{12\left(1-\mu^2\right)K}\right]^{0.25} \qquad (6)$$

Where:
E = The modulus of elasticity
h = The slab thickness
μ = Poisson's ratio
K = The support stiffness (modulus of subgrade reaction)

Assuming that the plain concrete and the SFRC slabs have equal modulus of elasticity, Poisson's ratio and support stiffness, as well as using similar size for loading plate, the term $\left[1+\frac{2a}{l}\right]$ can be assumed to be equal for both slabs (the effect of the thickness value in this term is negligible). Therefore, the difference between the plain concrete slab and the SFRC slab can be attributed to the moment-carrying capacity term M_o . For the plain concrete slab, the moment-carrying capacity is limited by the maximum stress derived from a third-point flexural test as indicated in equation 7.

$$M_o = f_{ct}\frac{bh_p^2}{6} \qquad (7)$$

For the SFRC slab, the post-cracking strength is assumed to contribute to the load-carrying capacity and the moment-carrying capacity is then given as in equation 8.

$$M_o = \left[1 + \frac{R_{e,3}}{100}\right]f_{ct}\frac{bh_f^2}{6} \qquad (8)$$

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

$$f_{ct}\frac{h_p^2 b}{6} = \left[1 + \frac{R_{e,3}}{100}\right]f_{ct}\frac{h_f^2 b}{6} \qquad (9)$$

According to the steel fibre manufacturers, 42 additional structural strength will be obtained by dispersing 15 kg/m³ of steel fibre in the concrete. By setting h_p and $R_{e,3}$ equal to 150 mm and 42 respectively and cancelling equal terms in euation 9, the magnitude of h_f was calculated to be 125,8 mm.

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