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STEEL FIBRE REINFORCED CONCRETE: REALIZE GREATER ENGINEERING EFFICIENCIES

SEAN PAGE-WOOD[1], DR TIAN SING NG[2]

[1] BOSFA Pty Ltd New Zealand. sean@bosfa.com
[2] BOSFA Pty Ltd Australasia. tian@bosfa.com

ABSTRACT

Steel fibre reinforced concrete (SFRC) has been widely used in New Zealand and worldwide, for slab and pavement construction. The conventional concrete slab and pavement design methodology and that adopted by CCANZ “Concrete Ground Floors & Pavements for Commercial and Industrial use Part Two: Specific Design” guidelines are generally based on elastic theory. The addition of steel fibres to concrete enhances the post crack tensile strength and provides significant ductility. Consequently, SFRC slabs and pavements can be designed using plastic analysis methods, such as yield line theory for ultimate limit state design. Furthermore, the additional post crack tensile strength provided by the SFRC can be used, in combination with conventional reinforcing, for serviceability limit state design to design for nominal crack widths. This paper outlines the design methodology of SFRC slabs and how to specify steel fibres in order to guarantee a minimum level of quality and performance.

INTRODUCTION

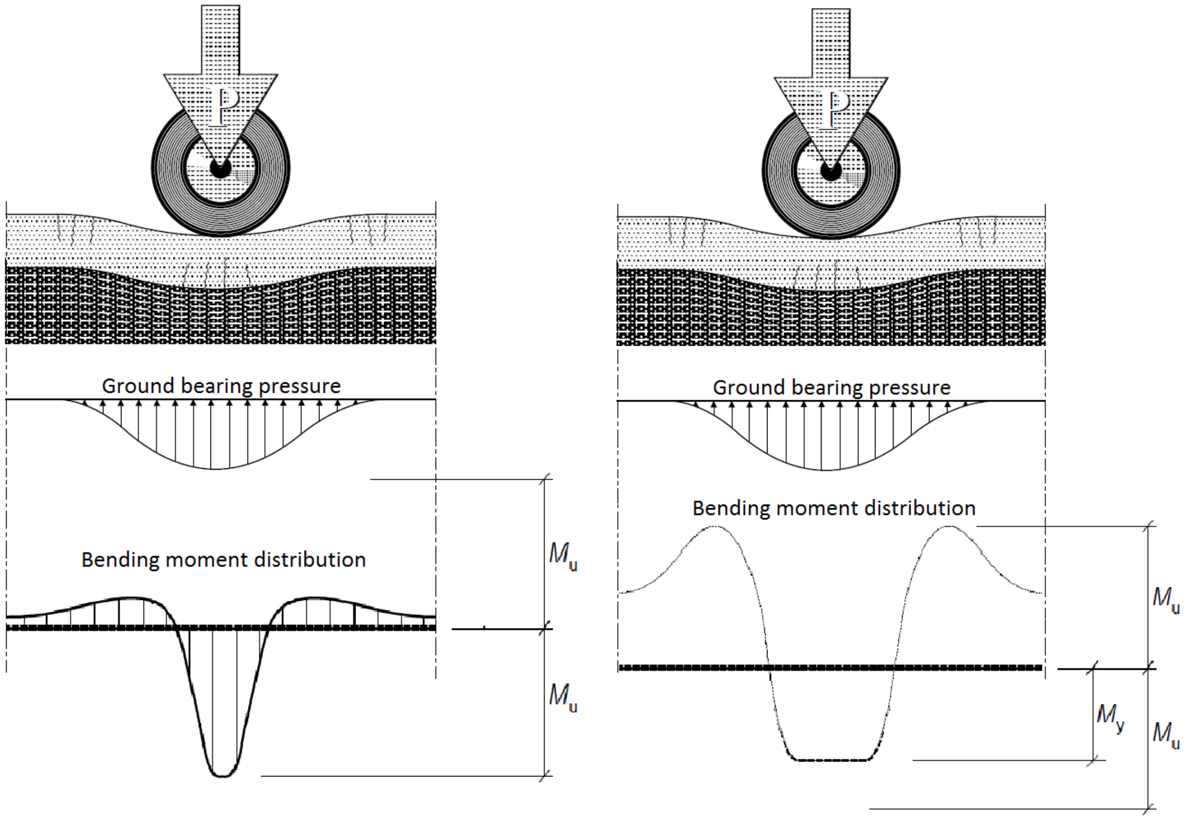
Adding steel fibres to concrete can no longer be considered as new or novel; steel fibre reinforced concrete (SFRC) was pioneered by Romualdi and Batson [1] in the early 1960s where it was demonstrated that tensile strength and crack resistance of concrete can be improved by providing suitably arranged, closed spaced, wire reinforcement. Today, SFRC is included in numerous design guidelines, standards and codes globally. This is due to a steady accumulation of knowledge as well as the research carried out at various Universities and Institutions which have quantified the performance properties of SFRC. The New Zealand Concrete structures standard NZS 3101:2006 [2] was one of the first standards in the world to include SFRC. The Australian Standard for the design of Concrete bridges AS5100.5 [3] was released in March 2017; this is the first standard in Australia to include procedures for the design of SFRC structural elements. The latest AS 3600 Concrete Structures code was released in June 2018 [4] also includes procedures for the design of SFRC structural elements. Even though SFRC is now being used in a wide variety of application including structural raft foundations, liquid tight slabs, heavy structure pile caps and piled supported slabs, its main application is still slab and pavement (pavement) on grade. This paper presents an overview of the SFRC pavement design methodology using plastic analysis method and provides a guidance to practitioners on how to specify steel fibre reinforcing.

STRUCTURAL THICKNESS DESIGN OF SFRC PAVEMENT

Design Guidelines

A concrete pavement must be thick enough to be able to withstand various types of loads. These loads range from dynamic wheel loads to distributed loads from stacked materials. The thickness of the pavement is to ensure satisfactory performance of the pavement under all the applied loads, by preventing the occurrence of excessive flexural, fatigue and bearing stresses. The CCANZ TM38 guide "Concrete Ground Floor & Pavements for Commercial and Industrial Use, Part Two: Specific Design" [5] is commonly used in New Zealand for concrete pavement design. The design method is fundamentally based on the theoretical studies of pavement slab behaviour by Westergaard [6-10]. The Westergaard thickness design approach uses the elasticity theory by assuming that the concrete section is uncracked. The design is more or less done based on plain concrete. The calculated maximum bending moment is compared to the maximum flexural capacity of the concrete, i.e. the cracking moment.

As an example, Figure 1(a) shows a concrete pavement loaded to the point of flexural rupture. The maximum bending moment occurs at the bottom of the slab and the positive bending moment governs the design. It is important to note that when the maximum capacity is reached for positive bending moment, the negative bending moment is still far below maximum.



(a) Plain concrete pavement (b) SFRC pavement

Figure 1. Concrete pavement subjected to a concentrated load at point of flexural rupture.

SFRC behaves very differently to plain concrete. The addition of steel fibres to concrete enhance the post crack tensile strength and provides significant ductility to the concrete composite. Arguably SFRC pavement can be designed using the Westergaard elastic analysis approach but it under-estimates the load carrying capacity of the SFRC pavements, as it doesn't take the ductile behaviour of the SFRC into account.

SFRC Pavement Design Concept

Figure 2 shows a typical relationship between load (moment or stress) and deflection of a SFRC pavement loaded to the point of flexural rupture observed in many studies including Skarendahl and Westerberg [11], Beckett and Humphreys [12] and Falkner et al [13]. The pavement behaves linear-elastically up to the proportional limit (F_R). This is equal to a plain concrete pavement flexural capacity where the maximum bending moment has occurred at the bottom of the slab. As the elastic limit is exceeded, crack begins to form at the bottom of the pavement. With SFRC, the fibres bridge the crack and provide post cracking strength and, hence, a bending moment can be determined even after the pavement is cracked. The load can be increased beyond the cracking moment if there is room for a sufficient increase of the negative moment to compensate for the decrease of positive moment. This is illustrated in Figure 3 by the reduced gradient of the curve between points F_R and F_R'. As the load is increased beyond F_R', more redistribution of stresses and energy absorption occur. The ultimate capacity of the pavement is reached when the negative moment reaches the maximum capacity as shown in Figure 3. Using the earlier explanatory diagram, Figure 1(b) illustrates the SFRC pavement bending moment re-distribution.

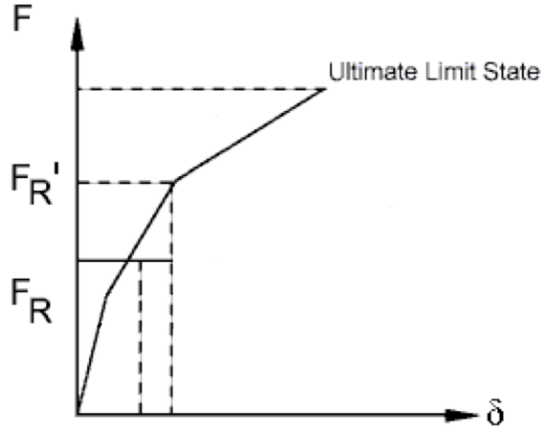


Figure 2. Typical load-deflection relationship for SFRC pavement.

Designing SFRC Pavement Thickness using Plastic Analysis Method

Plastic analysis method such as yield line theory provides an appropriate design tool for SFRC pavement on elastic sub-base. Some of the yield line theory design approaches include those proposed by Losberg [14,15], Meyerhof [16], Baumann and Weigerber [17]and Rao and Singh [18].

Space in this paper prohibits an extensive review of the literature on the yield line theory design approaches but more information on the topic can be found in the literature including Beckett [19], Meyerhof [16], Baumann and Weigerber [17] and Rao and Singh [18].

Losberg's Yield Line Theory for SFRC Pavement Thickness Design

Yield line analysis of the concrete pavement was proposed by Losberg [14,15]. The pavement thickness design method covers both serviceability and ultimate limit states.

In the serviceability limit state, the pavement is designed to carry external mechanical loads. The influence of shrinkage and temperature variations are also taken into account. In practice, the shrinkage and/or temperature restrained stresses are handled by means of crack control jointing. The desire for less jointing has led to the development of combined reinforcement solutions, which consist of both steel fibres and conventional steel reinforcement, to create a seamless pavement. The design methodology for seamless pavement are covered off in section 3.

The ultimate limit state design for external mechanical loading can be determined by assuming that the pavement is in cracked state and using the yield line theory. The following condition apply:

$$F_d \leq g(m, m') \qquad (1)$$

where F_d is the design load, $g()$ is a function for relevant yield line pattern, while m and m' are the bending moment capacities for positive (bottom of the pavement) and negative (top of the pavement) yield lines and can be determined as:

$$m = m' = \frac{f_{fl} h^2}{6} \qquad (2)$$

where f_{fl} is the SFRC design flexural strength according to Table 1 and h is the slab thickness. Solutions for $g()$ for various loading cases can be found in Losberg [14,15].

Table 1 presents the adopted design values for the SFRC flexural strength, f_{fl}, based on the current state of practice. In general, the post crack flexural strength of SFRC is used to carry the positive moment while the negative moment capacity is commonly determined from the flexural strength of the plain concrete or first crack flexural strength, $f_{ct,f}$, so as to prevent the formation of crack on top of the pavement.

	Ultimate Limit State	Serviceability Limit State
Positive bending moment, m	$f_{R,3}$	$f_{R,1}$
Negative bending moment, m'	$f_{ct,f}$	$f_{ct,f}$

where $f_{R,1}$, $f_{R,3}$ and $f_{R,4}$ are the residual flexural strengths at 0.5 mm, 2.5 mm and 3.5 mm crack mouth opening displacements, respectively, measured from the EN14651 [20] notched bending test.

Table 1. Design values for SFRC flexural strength, f_{fl}

Yield line theory considers the equilibrium between the total occurring moments to the total moment capacities. Hence, by relating equation (2) and f_{fl} values in Table 1, the overall design formula can be written as:

Ultimate limit state:

$$f_{R,3} = \left(\frac{6(m+m')}{h^2} - f_{ct,f} \right) \qquad (3)$$

Serviceability limit state:

$$f_{R,1} = \left(\frac{6[(m+m') + M_S + M_T]}{h^2} - f_{ct,f} \right) \qquad (4)$$

where M_S and M_T are restraining moment due to shrinkage and temperature variation, respectively.

It is important to note that when using the above equations for design, engineers have to apply appropriate factors to account for the variation in SFRC strength and properties.

Example of Plain Concrete and SFRC Pavement Thickness Design

A concrete pavement is to be designed with the critical load case being a 20 ton front axle forklift, with dual tyres. The axle width is 1.75m, the wheel spacing is 0.3m and the tyre pressure is 700 kPa. The number of load repetitions over the design life is estimated to be 100,000. The geotechnical engineer has determined a CBR of 10%. The concrete strength is 35 MPa. Estimate the thickness of the pavement:

- Conventionally Reinforced Pavement Thickness Design:

This design example is extracted from the CCANZ Chapter 6, Design Example 6.1. Based on the guideline, the minimum pavement thickness required is 200mm when the forklift is trafficked within the interior section of the pavement. The 200mm thick slab will be overstressed at the edges and corners.

- SFRC Pavement Thickness Design using the Losberg's yield line theory:

Step 1: Define material reduction factor and load factor

The material reduction factor for SFRC, both in compression and tension, is taken as 1/1.5 = 0.67 as per the recommendation of the fib Mode Code 2010 [21].

The load factor is taken to be 1.5, in line with the recommendation of CCANZ guidelines.

Further, the dynamic load factor, α, is taken to be 20% to account for the 100,000 load repetition. Effectively, the total load factor used in the design is $1.5 \times (1+\alpha) = 1.8$

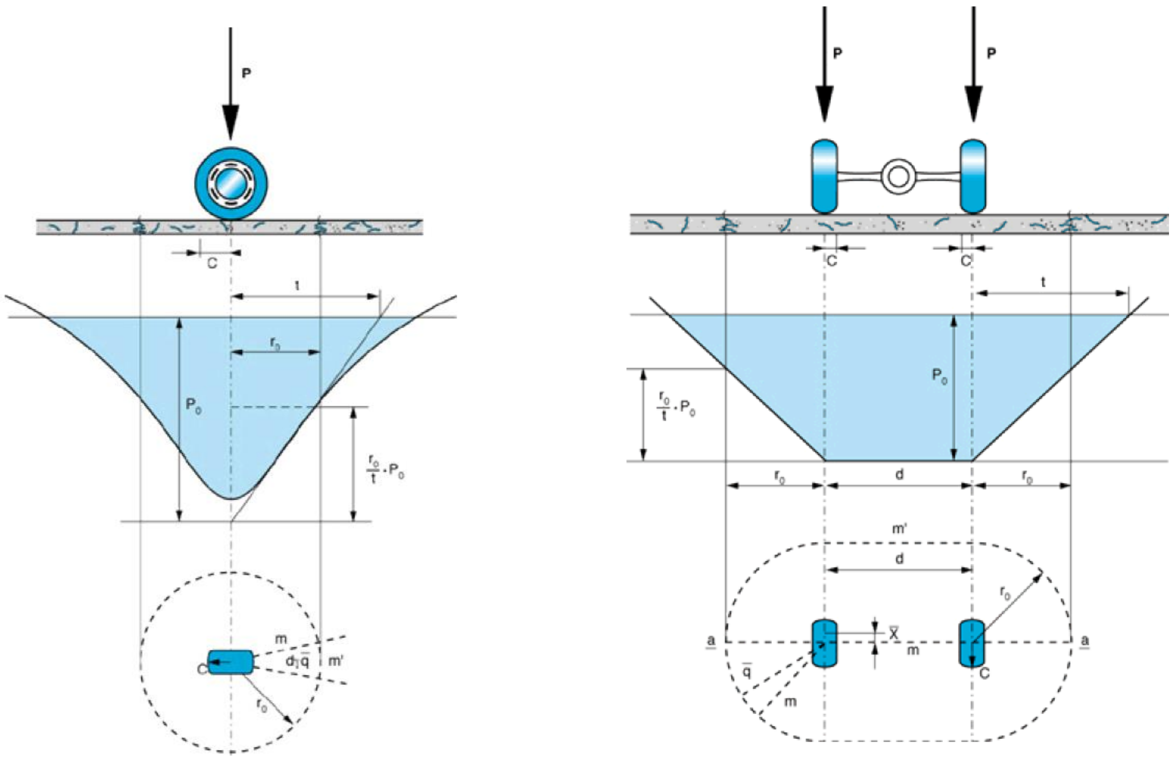
Step 2: Determine the critical yield line pattern:

The axle load consists of 4 wheels. As it is not known beforehand which yield line pattern is the most critical one, all possible load combinations, i.e. a single wheel load (Figure 3(a)) or 2 or more wheels load (Figure 3(b)), have to be considered.

Assume initially that the SFRC pavement is 150 mm thick, Table 2 below summarises the occurring moments from the two load combinations. In this design, the single axle dual wheels load case generates the most critical yield line pattern.

Load Combination	**m + m'**
	Ultimate Limit State
single wheel load ●○ ○○	9.4 kNm/m
2 wheels ●● ○○	16.0 kNm/m
Single axle single wheel ○● ●○	9.8 kNm/m
Single axle dual wheels ●● ●●	17.3 kNm/m

Table 2. Occurring moments from the possible load combinations



$$m + m' = \frac{P.\gamma_Q.\gamma_{Q,d}}{2\pi}\left\{1 - \pi\gamma\left(\frac{r_0}{l}\right)^2\left[1 - \frac{2r_0}{3t} + \frac{2d}{\pi r_0}\left(1 - \frac{r_0}{2t}\right)\right]\right\}$$

$$\frac{r_0}{l} = \sqrt{\frac{1 + \frac{\pi\bar{x}}{d}}{2\pi\gamma\left[\left(1 - \frac{2r_0}{3t}\right) + \frac{d}{\pi r_0}\left(1 - \frac{r_0}{2t}\right) + \frac{2r_0}{3d}\left(1 - \frac{3r_0}{4t}\right)\right]}}$$

$$m + m' = \frac{2.P.\gamma_Q.\gamma_{Q,d}}{2\pi}\left\{1 - \pi\gamma\left(\frac{r_0}{l}\right)^2\left[1 - \frac{2r_0}{3t} + \frac{2d}{\pi r_0}\left(1 - \frac{r_0}{2t}\right)\right]\right\}$$

$$\frac{r_0}{l} = \sqrt{\frac{1 + \frac{\pi\bar{x}}{d}}{2\pi\gamma\left[\left(1 - \frac{2r_0}{3t}\right) + \frac{d}{\pi r_0}\left(1 - \frac{r_0}{2t}\right) + \frac{2r_0}{3d}\left(1 - \frac{3r_0}{4t}\right)\right]}}$$

(a) Yield line pattern & moments single wheel. (b) Yield line pattern & moments 2 or more wheels.

Figure 3. Possible load combinations resulting in critical yield line pattern.

Step 3: Determine the required SFRC design flexural strength*:*

The plain flexural strength of a 35 MPa concrete, $f_{ct,f}$, is 3.5 MPa, determined from NZS 3101.

For ultimate limit state, the required SFRC design flexural strength is determined using Equation (3):

$$f_{R,3} = 1.5\left(\frac{6(17.3 \times 10^3)}{140^2} - 0.67 \times 3.5\right) = 3.4\ MPa$$

Step 4: Choose the steel fibre type and dosage:

Based on the above design criteria and assumption 30 kg/m^3 of a commercially available Dramix® 3D 65/60BG steel fibres has an $f_{R,3}$ value in excess of the required 3.4 MPa.

Design engineers should be aware that not all fibres perform equally. The design engineer has a responsibility and duty of care to confirm that the specified steel fibre and fibre dosage can satisfy the design properties; This can be achieved by requesting a CE certification and Declaration of Performance (DoP) from the steel fibre supplier.

From the above example, we can see that SFRC reduces the required pavement thickness from 200mm to 150mm. It represents 25% reduction in pavement thickness. This design is not only a cost saving solution but it also allows faster and more efficient installation, and more sustainable by reducing the amount of concrete used. Equally important, it does not compromise the safety and quality.

SFRC FOR SERVICEABILITY LIMIT STATE DESIGN

The strain softening behaviour of SFRC is problematic in terms of calculating crack widths. The tensile strength of the uncracked fibre reinforced concrete is higher than the tensile strength of the cracked fibre reinforced concrete. This means that for a concrete element where the full section is in tension, for example due to restraint of shrinkage stresses in slab on grade, the cracked section is the weakest section and it's not possible to determine accurately if and where the concrete section will crack again i.e. it is impossible to determine a theoretical spacing between cracks and without a crack spacing it is also impossible to determine a crack width using current crack width calculation theory.

When conventional and steel fibre reinforcement are combined the strain softening behaviour of SFRC does not change. However, the post cracking tensile capacity of the SFRC can be taken into account when calculating crack widths for the conventional reinforcement. The basic principle is that due to increasing post crack strength of the SFRC the released force at crack formation decreases: The fibres provide some capacity through the cracked section carry a part of the released force. As a consequence, the reinforcing steel needs to transfer only a reduced force back into the concrete. Therefore the strain in the reinforcing steel, as well as the required transfer length, is directly reduced. For a given crack width, the use of steel fibres can therefore significantly decrease the required amount of conventional reinforcement required.

The crack width design approach corresponds with the method for reinforced concrete introduced in Eurocode 2 [22]. Following the DAfStb Guidelines for SFRC [23], the rules of Eurocode 2 [22] are amended by the post crack tensile strength provided by the steel fibre concrete. This is done by introducing α_f as the ratio of the post crack tensile strength over the first crack tensile strength.
As a simplification of this concept the crack width w_k may be seen as a function of the concrete tensile strength, f_{ct}, in the case of reinforced concrete and a function of the concrete tensile strength minus the cracked tensile strength of SFRC, $f_{ct,SFRC}$, in the case of combined reinforcement, this is shown in equation (5):

$$w_k = s_{r,max}\left(\varepsilon^f_{sm} - \varepsilon_{cm}\right) \tag{5}$$

where: $S_{r,max}$ = maximum crack spacing in a combined steel fibres and conventional reinforced concrete

$\left(\varepsilon^f_{sm} - \varepsilon_{cm}\right)$ = the difference between the mean strain in the reinforcement and the mean strain in the SFRC

Space in this paper prohibits an extensive review of the literature on the crack width design approaches but more information on the topic can be found in the literature including DAfStb Guidelines for SFRC [23], Eurocode 2 [22], Ross [24] and Ng [25].

SPECIFYING STEEL FIBRES

SFRC pavement design using plastic analysis method may be required to undergo significant moment redistribution. Therefore it is critical to specify steel fibres that can guarantee a minimum level of quality and performance so as to achieve a significant level of ductility.

Steel Fibre Performance and Dosage

The performance of SFRC generally increases with increasing fibre dosage. However, it is not practical, not economical and not sustainable to specify an excessive high dosage of fibre in a concrete for which the extra dosage is not structurally required.

An over-dosage of steel fibres will also result in decrease in SFRC workability, increase the risk of fibre balling and, more importantly, up to a certain fibre dosage, the addition of fibre dosage does not further improve the SFRC performance due to the weaker cementitious matrix and crack paths find ways of minimum resistance and are likely to divert around fibre ends [26].

On the other hand, an absolute minimum fibre dosage shall be specified to ensure minimum overlap between fibres and provide consistency network of fibres in the concrete just like the minimum lap splice requirement for conventional reinforcement. Therefore, the fibre dosage of SFRC are governed by the maximum of:

(i) Minimum fibre dosage for ensuring the required SFRC performance; and
(ii) Minimum fibre dosage based on minimum overlap.

Minimum fibre dosage for ensuring the required SFRC performance

The minimum fibre dosage is to satisfy the limit states design requirements as discussed in Section 2 above. SFRC performance can be determined by either undertaking the EN 14651 [20] three point notched beam bending test and/or, if available, using the credible steel fibre manufacturers and suppliers data sheet.

Minimum fibre dosage based on minimum overlap

Based on fibre spacing theory (Figure 7), McKee [27] suggested that the average distance between fibres, *s*, can be estimated as:

$$s = \sqrt[3]{\frac{\pi \times d_f^2 \times l_f}{4\rho_f}} \tag{6}$$

where l_f is the length of the fibre, d_f is the diameter of the fibre and ρ_f is the percentage of fibre by volume.

Steel Fibre Material Quality

Ensuring the steel fibres are manufactured in a quality controlled environment should be seen as a minimum requirement for any steel fibre reinforced concrete (SFRC) specification; just as AS/NZS 4671 [28] is specified as a minimum requirement for reinforcing steel.

How to Specify:

- Steel fibres should be manufactured in accordance with EN 14889-1,[29] system 1 for structural use or, ISO 13270 [30]Class A.
- A Declaration of Performance (DoP) should be supplied to the project engineer or interested party and will be used to check against the CE label attached to delivered pallets of fibre.
- Fibres without a DoP and corresponding CE label attached to delivered product do not comply with that ISO or EN standard but they may comply with a different framework.

Presently, no New Zealand based manufacturing standard for steel fibre quality control exists. Both EN14889-1 and ISO 13270 are cited in AS 5100.5 [3] and AS 3600[4] as a minimum requirement for steel fibres.

CONCLUSION

SFRC has been around for a long time and has been widely used in the construction of concrete slabs and pavements. Generally a conventionally reinforced concrete pavement design uses the elasticity theory by assuming that the concrete section is uncracked whereas a SFRC design uses the plastic analysis and design approach. This allowing for the material properties of the SFRC to be taken into account and therefore a more realistic load bearing capacity can be estimated. Consequently SFRC pavement thickness can be significantly reduced and the distance between the crack control joint spacing can be increased when compared to conventional pavements.

There is an increasing trend to realize greater engineering efficiencies by reduce or remove crack control jointing through combining SFRC with conventional reinforcing. The thickness of a combined SFRC and conventional reinforced pavement is still determined by the plastic analysis and design approach of the SFRC. Nevertheless the potential to remove all crack control joints would potentially provide an opportunity to further reduce the thickness of the pavement because often the critical load case which determines the thickness of the slab is modelled on a joint.

REFERENCES

1. Romualdi, J.P., Batson, GB., "Behavior of reinforced concrete beams with closely spaced reinforcement", ACI Journal Proceedings, Vol. 60(6) 1963, pp:775-790.
2. The New Zealand Concrete structures standard NZS 3101:2006
3. AS 5100.5, Bridge Design Part 5: Concrete, Standards Australia, Sydney, 2017.
4. AS 3600, Draft for Public Comment Australian Standard - Concrete structures (Revision of AS 3600-2009), Standards Australia, Sydney, 2017.
5. CCANZ TM38 guide "Concrete Ground Floor & Pavements for Commercial and Industrial Use, Part Two: Specific Design"
6. Westergaard, H. M., Computation of stresses in concrete roads, Highway Research Board Proceedings, Fifth Annual Meeting, Part 1, 1925, pp. 90-112.
7. Westergaard, H. M., Stresses in Concrete Pavements Computed by theoretical analysis, Public Roads, Vol. 7, No. 2, 1926, pp. 25-35.
8. Westergaard, H. M., Analysis of stresses in concrete roads caused by variations in temperature, Public Roads, Vol. 8, No. 3, 1927a, pp. 201-215.
9. Westergaard, H. M., Theory of concrete pavement design. Highway Research Board Proceedings, Seventh Annual Meeting, Part 1, 1927b, pp. 175-181.
10. Westergaard, H. M., Analytical tools for judging results of structural tests of concrete pavements, Public Roads, Vol. 14 No. 10, 1933, pp. 185-188,
11. Skarendahl, A. and Westerberg, B., Guide for designing fibre concrete floors. CBI report, Vol. 1, No. 89, 1989, p.15.
12. Beckett, D. and Humphreys, J., Comparative Tests on Plain, Fabric Reinforced and Steel Fibre Reinforced Concrete Ground Slabs, Report No. TP/B/1, Thames Polytechnic School of Civil Engineering, Dartford, 1989, 33 pp.
13. Falkner, H., Huang, Z., and Teutsch, M., Comparative Study of Plain and Steel Fibre Reinforced Concrete Ground Slabs, Concrete International, Vol. 17 No. 1, 1995, pp. 45-51.
14. Losberg, A., Design methods for structurally reinforced concrete pavements, Bulletin No. 250, Chalmers University of Technology, Gothenberg, Sweden. 1961.
15. Losberg, A., Pavements and slabs on grade with structurally active reinforcement, ACI Journal Proceedings, 75 (12), 1978, pp.647-657.
16. Meyerhof, G.G., Load carrying capacity of concrete pavement, Journal of Soil Mechanics & Foundations Div, 1962.
17. Baumann, R.A. and Weisgerber, F.E., Yield-line analysis of slabs-on-grade, Journal of Structural Engineering, Vol. 109, No. 7, 1983, pp. 1553-1568.
18. Rao, K.S.S. and Singh, S., Concentrated load-carrying capacity of concrete slabs on ground, Journal of Structural Engineering, Vol. 112, No. 12, 1986, pp. 2628-2645.

19. Beckett, D., Concrete industrial ground slabs. Chapter 1 - Design Applications of Raft Foundations, 2000, p. 1-38.
20. EN 14651, Test method for metallic fibre concrete. Measuring the flexural tensile strength (limit of proportionality (LOP), residual). British Standards institution, London, 2005.
21. Fédération internationale du béton (fib), fib model code for concrete structures 2010. Berlin, Germany, 2013.
22. Eurocode 2, Design of Concrete Structures – Part 1-1: General Rules and Rules for Buildings, European-Commission, 2004
23. Deutscher Ausschuß für Stahlbeton (DAfStb), Commentary on the DAfStb Guideline "Steel Fibre Reinforced Concrete" DAfStb-Heft 614, Berlin, Germany, 2015.
24. Ross, A., Joint free restrained slabs: SFRC combined with mesh, Australian Society for Concrete Pavements (ASCP), 2015, Coffs Harbour.
25. Ng, T. S., Structural Application of Steel Fibres Reinforced Concrete with and without Conventional Reinforcement, Proceedings of the 28th Biennial Conference of the Concrete Institute of Australia, October, 2017, Adelaide.
26. Foster, S.J., Htut, T.N.S., and Ng, T.S., High performance fibre reinforced concrete: fundamental behaviour and modelling, Proceedings of the 8th International Conference on Fracture Mechanics Concrete and Concrete Structures (FraMCoS-8), Toledo, Spain, 2013, pp. 69-78.
27. McKee, D.C., The Properties of an Expansive Cement Mortar Reinforced with Random Wire Fibers, Doctoral dissertation, University of Illinois at Urbana-Champaign, 1969.
28. AS/NZS 4671, Steel reinforcing materials, Standards Australia/Standards New Zealand, Sydney, 2001.
29. EN 14889-1, Fibres for concrete - Part 1: Steel fibres - Definitions, specifications and conformity, European Committee for Standardization, 2006.
30. ISO 13270, Steel fibres for concrete - Definitions and specifications, International Organization for Standardization, 2013.