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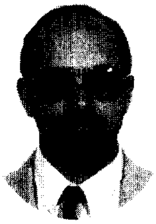
CONCRETE DESIGN USING STEEL FIBRES



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1. ABSTRACT

Steel fibres have been recognized to increase concrete's physical properties. The combination of high tensile strength, modulus of elasticity, stiffness modulus, and mechanical deformations provides concrete with increased ductility.

SFRC can be used in applications of high impact and fatigue without the fear of brittle concrete failures. The costs of SFRC and SFRS are very often under evaluated. Design methodology and cost comparisons have been prepared for the readers. The values in this article may not be applicable to all different kinds of steel fibers and thus it is recommended that the SFRC mix be fully tested in order to verify the necessary material properties needed in the construction field before application.

2. CHOOSING THE RIGHT TYPE OF FIBRE

Choosing the right fibre type, length and concentration is as critical as making an adequate stress analysis. Choosing the wrong fibre can lead to failure, exposed fibres, difficulties in pumping and placing. It is essential for design engineers to understand the design concepts of steel fibres and to recognize the differences between the performance, workability and finishability obtained by using different types of fibre and different fibre concentrations.

Factors influencing the choice of the fibre length are: equipment (pump, vibratory screed or hand screed), experience, concrete

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mix, pavement or overlay thickness and the environment.

3. COMPARING STEEL FIBRES

There are several types of steel fibres available on the world market. Some fibres are more expensive than others and some appear to be more efficient than others. Low carbon steel fibres are manufactured by several methods and are available in a variety of configurations, diameters, lengths, and alloys. ASTM identifies four (4) different classifications of steel fibres in their Standard Specification for Fibre Reinforced Concrete, A 820 - 90. The classifications are:

Type I, Cold Drawn Wire.

- Type II, Cut Sheet
- Type III, Melt Extracted
- Type IV, Other Fibres

All steel fibres do not provide the same degree of effectiveness in reinforcing concrete. Designers must rely on recognized test results as well as on existing references when specifying the concentration and type of fibres to use.

In many applications, long steel fibres meeting ASTM A-820 type 1 may require a lower concentration than a fibre meeting ASTM A-820 type 2 and 4.

3.1 Aspect Ratio

The aspect ratio is a numerical parameter used to describe the geometry of a given fibre design. It is calculated by dividing the fibre length by the fibre's diameter (or equivalent diameter). Because of the different shapes and anchorage mechanisms of the steel fibres currently available, the aspect ratio should only be used as a guide to qualify fibres of similar ASTM A 820-90 classifications rather than as a value to compare fibres for design purposes.

Typically, aspect ratios range from 30 to 150 for fibre lengths of 6 to 63mm.

At first glance, it would appear that the designer should specify a fibre with the highest aspect ratio. This, however, is not realistic. As the aspect ratio of a fibre increases, the mixing, placing and finishing problems are compounded. Therefore, the industry has adjusted production techniques and material compositions to manufacture more rigid, lower aspect ratio fibres with mechanical deformations that produce the same results of small diameter fibres with higher aspect ratios. Fibre lengths of 38 to 60mm with aspect ratio of 40 to 75 produce excellent results in as optimized mix design for pavements(3, 14).

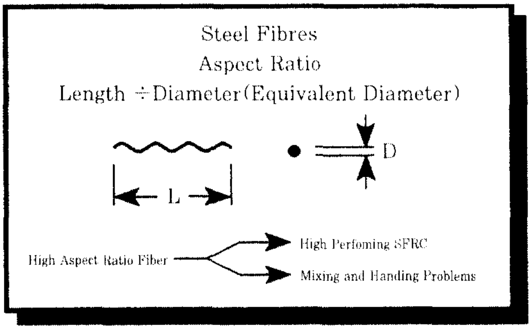


Fig. 1

3.2 Critical Length and Deformation

Figure 2 shows the results of tests performed to determine the influence of steel fibre length on the flexural properties of concrete. There is a significant difference in the performance of the 25, 38, 50, and 63 mm fibres in the post crack behavior of the concrete at a same volume fraction.

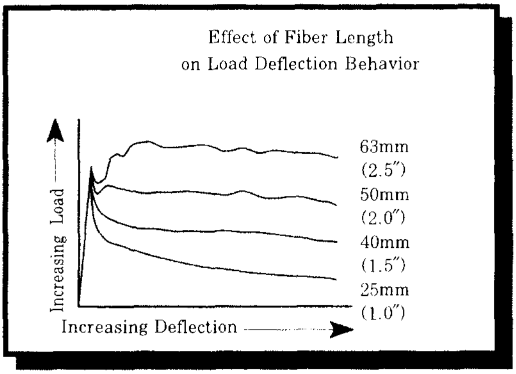


Fig. 2

3.3 Typical Fibre Concentration

The choice of fibre concentration is guided by the type of application where the fibre will be used and the ability of the fibres to perform under a given loading condition. The length of the fibre, the deformation, and the critical length are all important factors to consider. Typical concentrations of steel fibres, 50mm in length are presented in Table 1.

Table 1 Fibre concentration guideline for 50 mm continuously deformed ASTM type 1 steel fibres,(kg/m^3)

Shrinkage control	10 to 20
Light dynamic loading	20 to 30
Medium dynamic loading	20 to 40
Severe dynamic loading	40 to 75
High impacts	50 to 150

3.4 Flexural Properties

3.4.1 Modulus of Rupture (MOR)

The MOR is primarily influenced by the concrete mix and is dependent on the interaction between the aggregates, the sand, the cement and all other components.

The following table shows comparative values that could be expected for concrete mixes in areas where good quality aggregates and cements are available. These valuse will reflect the improvement in the MOR values because of the usage of better quality mixes.

Table 2 Typical MOR of SFRC Fibre

Concentration of Steel Fibres	MOR for a 25 MPa matrix (MPA)	MOR for a 25 MPa matrix (MPA)
10	3.75	4.10
20	4.15	4.60
25	4.50	4.80
30	4.65	5.10
50	-	5.90
60	-	6.55

3.4.2 Flexural Toughness, Residual Strength and Toughness Performance Levels

These values are representative of the post crack carrying capacity of a given composite. Toughness indices are identified by: I_5, I_{10}, ⋯, I_{50} and the Residual Strength by R(I, ii). These values will be dependant of the flexural strength of the mix, the concentration and type of fibre and the first crack deflection point determined during the analysis of the flexural test results.

ASTM C-1018 defines Toughness Indices and Residual Strength as a function of the first crack deflection "δ" which varies between

Table 3:Toughness Indices

Indices	Calculated*	Ideal
I_5	3δ	5
I_{10}	5.5δ	10
I_{20}	10.5δ	20
I_{30}	15.5δ	30
Indices	Calculated	Ideal
I_{40}	20.5δ	40
I_{50}	25.5δ	50
I_{60}	30.5δ	60

* δ=First Crack Deflection

0.031 to 0.052mm.

Residual Strength can be calculated with:

$$R_{x,y} = \frac{100}{y - x}(I_Y - I_X)$$

A great deal of confusion exists when toughness and residual strength of various fibres are compared. For this reason test results must be compared only if flexural beams were prepared at the same time, if fibres were tested with the same concrete mix, if tests were done on the same machine and the interpretation of the first crack deflection was done by the same engineer and are consistent from one test to another.

3.4.3 Toughness Performance Level

Figure 3 graphically demonstrates toughness performance level for a design flexural strength of 5 MPa concrete mix. These performance levels are commonly used in specifying classes of performance for shotcrete.

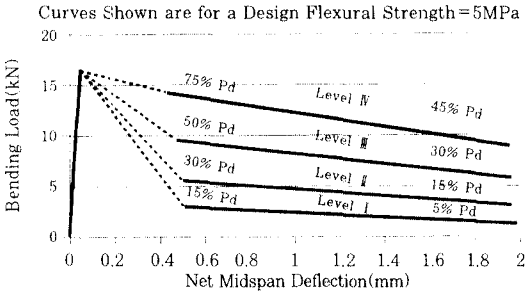


Fig. 3

4. DESIGN METHODOLOGY OUTLINE

4.1 Design Criteria

While designing a Steel Fibre Reinforced Concrete (SFRC) structure or slab, several aspects are taken into consideration. These typically are flexural stresses due to positive or negative moments, flexural fatigue, impact, punch and shear stresses, etc. The following table gives an outline of the information needed to make a suitable design using SFRC.

Table 4:Loading Conditions

Loading Conditions	Loading Characteristics		
Unformly Distributed Load	Static	Frequency and Magnitude	Operation or Maintenance or Construction Loads
Lift Truck	Dynamic		
Tractor Trailer	Impact		
Other Types of Vehicles	Fatigue		
Point Loads(racks, conveyors)	Seismic		
Hydraulic	Explosion		
Mining tunnel or Chimney	Shrinkage		

4.2 Calculation Methods

Standard and accepted designing methods are normally used when designing with SFRC. In most cases, a computer analysis of slab on grade stresses should be performed by using reliable computer software. Using these types of design software will calculate stresses more accurately and faster than standard hand or graphical calculations.

4.3 Safety Factors

The following safety factors are typical for SFRC applications.

Table 5 Safety Factors

Static Loading	1.4
Uniform Loading	1.4
Low Dynamic Loading	1.5
Medium Dynamic Loading***	1.5 to 2.0
Severe Dynamic Loading or Impact***	1.8 to 3.0

*** In cases of dynamic loadings, the fatigue endurance limit theory can be used in order to take full advantage of the enhanced flexural fatigue resistance of steel fibre reinforced concrete composite(Section 4.6).

4.4 Surface of Contact Load Dispersion

Dr. Beckett's study (Ref. 11), suggests that the uni-axial resistance of a beam can be correlated with the bi-axial load distribution of a slab on grade. This can be done by taking into account load dispersion through the thickness of the concrete slab using an angle of 45 degrees. It has to be understood that while using the load dispersion theory, the built in safety factor that is normally inclueded with "no load dispersion" is considerably reduced.

For point loads, the surface of contact can be calculated as follows:

l_i Plate side dimension
t Slab thickness
S_1 No dispersion $l_1 \times l_2$
S_2 Mid-depth dispersion $(t+l_1)(t+l_2)$
S_3 Full-depth dispersion $(2t+l_1)(2t+l_2)$

Note that dimensional units must be compatible.

4.5 Contact Pressure

For racks or solid tires, the pressure applied to the slab on grade is $P = LOAD/S_i$.

In case of a pneumatic vehicle, the pressure is equal to the tire pressure.

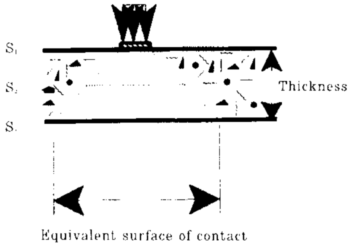


Fig. 4 Post Load Layout

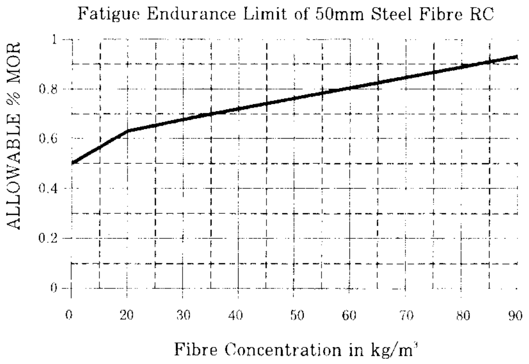


Fig. 5 Design Methodology Using the Fatigue Endurance Limit

4.6 Fatigue Endurance Limit of SFRC and Dynamic loads

Fatigue Endurance Limit of SFRC

Figure 6 can be used to determine the allowable working stress of an SFRC composite using 50 mm fibres in various concentrations(Note : The shape of curve may depend on the type of steel fibers in application).

a- Determine the loading parameters:
  1- Soil conditions and preparation, section
  2- Magnitude of load, section
  3- Frequency of load
  4- The geometry of the load pattern section
  5- Safety factor required
  6- Concrete flexural strength
  7- Assume a thickness

b- Determine your allowable working stress.

W_{SF} = MOR / Safety Factor

and W_{EE} = X% MOR

Where x = Allowable working stress (Figure 5)

Example:

x = 72% for 1.5% vol fr.(40 kg/m^3 of 50 mm Continuously deformed steel fibres)

x = 80% for 0.8% vol fr.(60 kg/m^3 of 50 mm Continuously deformed steel fibres)

x = 85% for 1.0% vol fr.(75 kg/m^3 of 50 mm Continuously deformed steel fibres)

c- Estimate pavement thickness and input values in computer program or hand calculation.

$W_S < W_{SF}$ and $W_S < W_{FE}$

4.7 Cross Sectional of Steel Area of Steel in Slab Section

It is often required to compare the steel content between an existing rebar or mesh design and a steel fibre concentration. In such case, the equivalent cross sectional area of steel reinforcement can be used to calculate the concentration of steel fibres that will give an equivalent area of steel (Soroushian and Lee, ref: 12).

Methodology

i. Calculate the unit cross section of steel reinforcement

$$A_i = A_{SR} / A_C$$

A_i = Unit area of steel for a given section

A_{SR} = Area of steel reinforcement per meter wide section, (mm^2)

A_C = Area of concrete per meter wide section, (mm^2)
i.e. 1000 (mm) x thickness, (mm)

Note : Approximate values of A_{SR} are listed in table 6.

ii. Concentration of steel fibers for an equal thickness of concrete.

$$\delta = \frac{A_i \times 7830}{\alpha}$$

δ = Concentration of steel fibres,(kg/m^3)

A_i = Unit area of steel for a given section

α = Orientation factor of the steel fibre
= 0.519 for $t/l > 3$
= 0.617 for $t/l \leq 3$

where:

l = fibre length (mm)

t = concrete thickness (mm)

Figure 6 was generated for welded wire mesh 150×150mm(6″×6″) using the above equations.

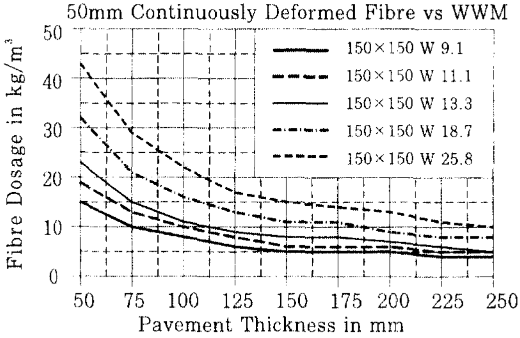


Fig. 6 Cross Section area of Steel

Table 6 Approximate Cross Section Area of Rebar Reinforcements

Mesh Type	Area of Steel mm^2/m	Reinforcing Bar	AREA (mm^2)
150×150-MW 9.1	60	#3	70
150×150-MW11.1	75	#4	130
150×150-MW13.3	90	#5	200
150×150-MW18.7	125	#6	284
150×150-MA25.8	170	#7	390
102×102-MW 9.1	90		
102×102-MW11.1	110		
102×102-MW13.3	130		
102×102-MW18.7	185		
102×102-MW25.8	255		

5. COMPOSITE STEEL DECK

On composite steel decks where the loading is static, the fibre quantity can range from 12 to 20kg/m^3 of 38mm long continuously deformed fibres. In cases where the decks will be subjected with dynamic loads, the concrete should be reinforced with 25 to 50 kg/m^3 of 38mm long continuously deformed fibres(Fig. 8).

In some casee, it may be required to use bar or a band of WWM over the main beams.

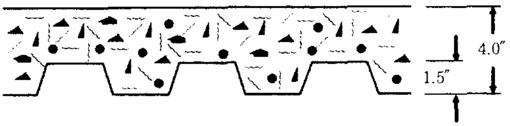


Fig. 7

6. OVERLAYS

Mesh and bar reinforcements are very difficult to install in thin overlays. Non-reinforced concrete overlays have a tendency to crack, debond and form potholes. Steel fibres will incerease the integrity of the overlay and provide a mean of reinforcing the overlay in all possible directions reducing the formation of cracks and potholes.

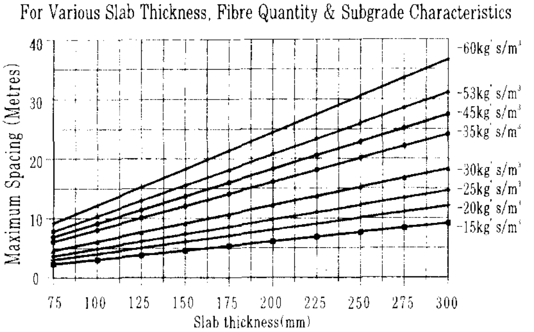
Steel fibres have been used with great success in industrial overlays, bridge decks and exterior pavement overlays. The concentration of steel fibre can be determined by calculating the steel cross section equivalent or by using the following table.

Table 7 SFRC in Overlay

Application	Thickness (mm)	Concentration (kg/m^3)
Resurfacing of Commercial	50-75mm	12 to 20
Light Industrial Floors	50-100mm	15 to 25
Heavy Industrial Floors	75-100mm	25 to 60
Bridge and Highway Overlays	75-150mm	30 to 60
High Impact	100-150mm	50 to 90

7. JOINTS, EDGES & CURING

Figure 9 was generated as a guide to determine the joint spacing of slab on ground reinforced with ASTM Type 1 Steel Fibres.



Reduce by 5-20% depending on subgrade friction.

Fig. 8 Optimum Control Joint Spacing

8. COST COMPARISON

The cost of an SFRC slab on ground will be determined by the labor cost as well as by the material cost. In several cases, SFRC design offers solutions where the slab on ground would be reduced in thickness compared to a design which would have been done with mesh or rebar. Because of the large number of possible design cases, it is not possible to give a cost comparison that would cover them all. Table 8 lists steel fibre cost in place without considering the cost of concrete. These cost can easily be compared to the cost of conventional reinforcement converted to a square meter base.

9. CONCLUSION

Steel Fibre have been used for the last 30 years and have been proven successful and

Table 8 Steel Fibre and Placement Costs Per Square Meter
Note that the cost of concrete is not considered in this table

1	=Assumed In Place Cost of Steel Filbres Per 1000 Won.										
Slab Depth (mm)	Steel Fiber Concentration (kg/m^3)										
	15	20	25	30	35	40	45	50	55	60	65
125	1.875	2.500	3.125	3.750	4.375	5.000	5.625	6.250	6.875	7.500	8.125
150	2.250	3.000	3.750	4.500	5.250	6.000	6.750	7.500	8.250	9.000	9.750
200	3.000	4.000	5.000	6.000	7.000	8.000	9.000	10.000	11.000	12.000	13.000
250	3.750	5.00	6.250	7.500	8.750	10.000	11.250	12.500	13.750	15.000	16.250
300	45.000	6.000	7.500	9.000	10.500	12.000	13.500	15.000	16.500	18.000	19.500
350	5.250	7.000	8.750	10.500	12.250	14.000	15.750	17.500	19.250	21.000	22.750
400	6.000	8.000	10.000	12.000	14.000	16.000	18.000	20.000	22.000	24.000	26.000
450	6.750	9.000	11.250	13.500	15.750	18.000	20.250	22.500	24.750	27.000	29.250

cost effective for the construction of slab on ground, pavements, overlays, shotcrete, pre-cast, etc. Designing with SFRC and SFRS uses standard design methods or methodologies that have been updated to take into consideration the increased impact, fatigue, toughness and shrinkage resistance when using steel fibre.

SFRC and SFRS are cost effective solutions when compared to standard reinforcements. These systems offer the possibility of building concrete structures with better quality concrete and with considerable improvements in the construction process. In most cases, the use of SFRC and SFRS will also allow contractors to be more efficient which will translate into a reduction in material costs, construction costs and construction time.

The fibre type, the length and concentration as well as the quality of the concrete matrix will all work together to make SFRC or SFRS design a successful solution.

Engineers and contractors should work closely with the fibre supplier in order to get the proper technical support required to optimize the design with SFRC and SFRS.

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