Fibre concrete mixes in road pavements: in between plain and reinforced concrete ?

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Abstract
Fibrous concrete has a history in pavements. In the '80-s fibrous concrete became popular thanks to options such as reduced pavement thickness and increased joint distances. Unfortunately, not all promises were kept and the fibrous concrete 'silently' disappeared from the pavement construction scene. However, in industrial floor construction research continued and new concrete mixes containing different types of new steel fibres were developed. Design guidelines were developed to harmonize structural design rules. The track record in industrial floors with steel fibres has become sound. Over the years, the new fibrous concrete returned to the pavements. Several successful projects were constructed and at the instigation of the developers of these mixes a working group for the investigation of fibrous concrete was formed by the Dutch Technology Platform for Transport, Infrastructure and Public Space (CROW). A team of steel fibre producers,

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concrete experts, researchers and contractors had the task to evaluate the performance of recently constructed pavements. The study may lead to recommended practices for the application of fibrous concrete in the Netherlands. The paper elaborates on the fibrous mixes currently in use and presents the results of recently constructed projects.

Key words
Steel fibre concrete / pavement / cracking / plain concrete / continuously reinforced concrete / monitoring / shrinkage joint

Introduction

Concrete is a material widely used in concrete pavements, both plain and provided with reinforcement. In the first case, shrinkage joints are constructed to prevent random cracking; in the latter case the reinforcement should ensure crack width control. Both these measures arise from the relatively low tensile strength of concrete, which is about only 10% of its compressive strength. Tensile stresses should therefore be prevented to occur or cracking should be accepted and controlled by the reinforcement applied, being able to resist the tensile forces generated.

Steel fibres are an alternative for reinforcing steel since they can transfer tensile forces in cracked concrete. The fibres have the advantage that two separate construction phases can be reduced to one phase if the fibres fully replace the reinforcing steel. These phases are (1) the positioning of the reinforcement and (2) the casting / application of the concrete. Fibres are added to the concrete mixture before casting so the casting process itself also comprises applying the reinforcement. This, however, only holds when all the reinforcement can be replaced by steel fibres. This can hardly be the case in concrete pavements since the amount of reinforcement is relatively high (app. 0.66%). In industrial floors on a bedding, however, the reinforcement applied can be almost fully replaced by fibres. When a floor is supported by piles, the peak support moments in the pile region require some additional hogging moment reinforcement. It is noted that these floors are mainly loaded in bending.

The amount of reinforcement applied in continuously reinforced pavements is about 61 kg/m^3. The major part of this (app. 52 kg/m^3) is the 0.66% longitudinal reinforcement. Supports required to position this reinforcement require about 9 kg/m^3. Table 1 gives an overview of the reinforcement traditionally applied in The Netherlands in this type of structure.

The amount of reinforcement is rather high when compared with industrial floors since the pavement is not only loaded by traffic, which causes bending moments, but also by axial forces caused by the restraint of longitudinal deformations. Fully replacing the bar reinforcement by steel fibres will hardly be an option: One should take into account that reinforcing bars can be positioned where they are most effective in transferring forces and reducing crack widths. Since steel fibres are distributed randomly in the mixture, they are (1) also present in concrete’s compression zone, (2) not concentrated at the outer tensile face of a tensile zone (reduced lever arm) and (3) not directed in the direction of the tensile forces, but oriented randomly. These three aspects make that replacing reinforcing steel by steel fibres results in an increase of the amount of steel per volume of concrete. One aspect could be added, namely the absence of the opportunity to inspect the reinforcement before casting takes place: This makes that the application of steel fibres is mostly confronted with questions about their distribution and orientation. Quality control measures, e.g. testing samples taken from the mixture and testing small beams cast on site, should ensure that it can be checked whether the demands are met.

Table 1 Characteristics of continuously reinforced concrete pavements (steel FeB 500; characteristic yield strength = 500 N/mm^2).

concrete strength class (cylinder/cube)	C 35/45	
steel bar diameter [mm]	16	20
reinforcement ratio (% of the cross-section) required for maximum crack width 0.40 mm	0.62	0.66
specified thickness of the concrete layer		
230 mm - minimum reinforcement amount [mm^2/m] - max. centre-to-centre spacing bars [mm]	 1438 140	 1518 207
250 mm - minimum reinforcement amount [mm^2/m] - max. centre-to-centre spacing bars [mm]	 1547 130	 1650 190
270 mm - minimum reinforcement amount [mm^2/m] - max. centre-to-centre spacing bars [mm]	 1674 120	 1782 176
overlap length longitudinal bars [mm]	370	450

Design aspects

Jointed Plain Concrete Pavements (JPCP) Pavements are designed using theories for slabs and beams on elastic foundations. When no reinforcement is provided, the tensile stresses must not exceed the concrete tensile strength. This implies that shrinkage joints must be applied to reduce the stresses generated by restrained shrinkage of the concrete. These joints are formed as soon as possible after casting by sawing the pavement over at least 1/3 of its height.

Not only horizontally but also vertically oriented reaction forces will be generated because the frictional forces act on the pavement – foundation interface, which is below the centre of gravity of the concrete. Moreover, the imposed deformation can also partly be an imposed curvature. Extensive research on this subject has been carried out by Petterson (1998).

Stresses from external loads (e.g. wheel loads) are calculated using standard expressions for stresses in a slab on an elastic bedding (see, among others, Westergaard, 1926 & 1948). These linear-elastic stage calculations are the basis when designing plain concrete pavements: the thickness of the pavement and the distance between shrinkage joints is such that the maximum concrete tensile stress does not exceed the flexural tensile strength of the concrete (cracking criterion).

Results from theory and practice have learned that cracking of the concrete is not to be expected at a shrinkage joint spacing of 4.2 m in longitudinal direction (transverse joints) and approximately 5 m in transverse direction (longitudinal joints). The individual concrete slabs are connected by means of steel dowels to control unequal vertical deformations and/or tie-bars to control crack width and horizontal movements. The following amount of steel bars is characteristic:

- transverse joint:
  dowels; steel FeB 220 bars ϕ 25 mm, length 500 mm, fully coated; spaced at 250 mm
- longitudinal joint:
  tie-bars; steel FeB 500 bars ϕ 20 mm, length 800 mm, mid 200 mm coated; spaced at 1.67 m

The total amount of steel required for dowels and tie-bars is about 8 kg/m^3 when related to the concrete. By reducing the spacing between the transverse joints the total amount of steel required in the transverse joints can be reduced considerably. This is the most effective measure since about 90% of the steel required for dowels or tie-bars is applied in the transverse joints.

Continuously Reinforced Concrete Pavements (CRCP) The design of continuously reinforced concrete is based on load transfer across a cracked cross-section; the tensile strength of the concrete is assumed to be zero and the reinforcing steel is designed such as to meet ultimate limit state (ULS) and serviceability limit state (SLS) demands.

The design procedure differs from the one described for plain concrete in two respects. First, in SLS the structure is assumed to crack, which results in a considerable reduction of its stiffness, and, as a result, in a reduction of the forces caused by restrained deformations: Contrary to an external load, forces induced by restrained deformations depend on both the magnitude of the deformation itself and on the structure’s stiffness. Exact calculations require an iterative procedure since structural stiffness itself depends on the total load level, vice versa. Engineering models were developed to calculate by hand relatively accurate upper bound values for the forces from restrained deformations. The total load level is the sum of these loads and the external loading. Crack widths are calculated using theories traditionally used in concrete structures. An important aspect in crack width calculation is the combination of forces that is assumed to cause cracking: pure tension is unfavourable from the point of view of crack width control. In the ULS structural stiffness is reduced that much, that restrained deformations induce hardly any forces. Their action is, therefore, most often neglected in this state.

Steel Fibre Reinforced Concrete Pavements (SFRCP) The design of steel fibre reinforced concrete (SFRC) was first based on linear-elastic theories used for plain concrete. More suitable design methods have become available. Vitt (2003) (Fig. 1) proposed a design approach in which use is made of the yield line theory as presented by Losberg (1961). When using this approach, the actual post-cracking material properties and resistance can be taken into account. In this way a more realistic ultimate load can be determined.

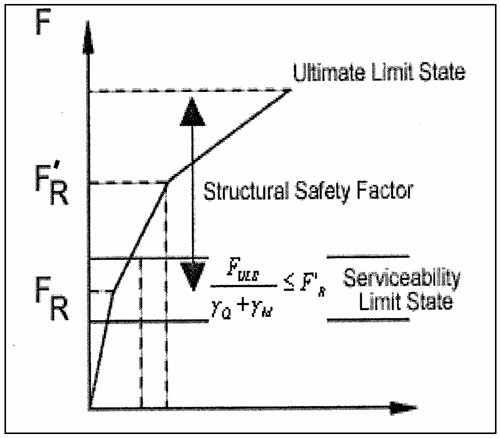

Figure 1 Design based on ultimate limit state & yield line theory (Vitt, 2003)

In The Netherlands, design was often linear-elastic, using a fictitious concrete flexural tensile strength. This fictitious strength was the actual flexural strength of plain concrete multiplied by a factor that represents the influence of the steel fibres. This factor was calculated using the output from bending tests on small SFRC beams [NEN, 2005; Bouquet *et al*., 2008]. Post-cracking strengths at predefined deformations were used to calculate a factor (> 1) by which the flexural tensile strength can be multiplied [CUR, 1994a]. The major advantage of this procedure is, as stated before, that the calculation remains unaltered compared with the one used for plain concrete [CUR, 1994b]. A major drawback is, however, that the design procedure for plain concrete pavements is based on rather small (e.g. 4-5 m) shrinkage joint distances. It might be discussed whether these procedures still apply when the shrinkage joint distance increases. Moreover, using post-cracking strengths to define a strength to be used in an uncracked stage calculations raises the question whether the pavement actually remains uncracked or is only uncracked from a theoretical point of view.

New insights and further developments have resulted in calculation procedures in which SFRC structures are designed in the same way as reinforced concrete structures [CUR, 2007]. Actual cracking and crack width calculations were incorporated.

Steel fibre concrete with reinforcement The use of reinforced concrete design theories also for SFRC opened the opportunity to calculate combinations of steel fibres and rebars without having to introduce much alterations to the theory. Now, all applications ranging from SFRC to reinforced concrete and intermediate alternatives are covered [CUR, 2007].

Synthetic fibre concrete Synthetic fibres are added primarily to control plastic shrinkage cracking. This type of cracking can occur when the concrete surface is subjected to premature drying and, as a result, is subjected to tensile stresses caused by drying of pores. In that stage, synthetic fibres can bridge cracks and, thus, reduce crack widths. The fibres don't increase the structural bearing capacity and, as a result, are considered as being a secondary reinforcement. The fibre content should be about 0.1 to 0.2 vol-% to ensure their functioning. The synthetic fibres should never be considered as a primary reinforcement.

SFRC applied in demonstration projects

At the instigation of the concrete producers a working group for the investigation of fibrous concrete was formed at the Dutch Technology Platform for Transport, Infrastructure and Public Space (CROW). The project was started in 2005 and is expected to be finished mid 2008.

Scope of the working group The CROW project had several objectives:

- to prepare a state-of-the-art survey on SFRC including design aspects, construction practices, type of mixes, test methods etc.;
- to evaluate projects constructed earlier by means of a questionnaire to be developed. The questionnaire must be based on a monitoring scheme to be used when monitoring projects during construction;
- to indicate how to adjust a design tool for plain and continuously reinforced concrete road pavements, namely the so-called VENCON 2.0 tool (CROW, 2004). The capabilities and models incorporated in this standard design tool often used in The Netherlands are discussed by Stet *et al*. (2006). The design of SFRC pavements can then become part of an upgrade of this design tool;
- to monitor the design and construction of some construction projects. The monitoring scheme was executed on two projects;
- to prepare recommendations for the design and construction of SFRC road pavements in the Netherlands and to present a CROW-report with recommended practices.

Literature survey An inquiry learned that SFRC pavements should be regarded as being an alternative for plain concrete. It might also compete with continuously reinforced concrete pavements provided that shrinkage joint spacing can be increased to 100-150 m. As stated before, the amount of reinforcement required in continuously reinforced pavements (app. 61 kg/m^3) can hardly be replaced by an equivalent amount of steel fibres. Compared with plain concrete pavements with dowels (app. 8 kg/m^3), the improved flexural tensile strength and the post-cracking strength capacity of SFRC (app. 40 kg/m^3) enables the reduction of the number of transverse shrinkage joints. As a result, the amount of steel required for dowels can be reduced.

Unit prices per m^2 by 250 mm thickness of concrete pavement structure are 115% for CRCP (including bituminous interlayer) and 130% for SFRC pavements if the investment for JPCP is 100%. This implies that SFRC pavement thickness has to be reduced to about 77% (190 mm) of the jointed plain concrete pavement thickness to require the same investment.

Monitoring scheme The CROW working group examined a limited number of projects. Because the working group merely monitored the construction of SFRC-projects and did not participate, its influence was rather limited. However, in order to make sure that all relevant topics were addressed, the monitoring scheme was used. The two projects monitored from their start are presented briefly. Results can only be presented over a short period following execution; the structural performance under actual loading will be monitored the coming years.

Pilot project Tilburg

Materials and methods In April 2007, approximately 500 m of a 6.6 m wide road pavement near Tilburg (NL) was constructed in fibre reinforced concrete (Fig. 2). The concrete (h = 180 mm) was applied by a slipform paver. The concrete was mixed at a concrete plant. Steel fibres were manually added using a small conveyer belt to gradually add the fibres in the mixing plant. The mixture was then transported by open trucks.

The concrete strength class was C35/45 (28-day characteristic cylinder/cube compressive strength). Use was made of portland fly ash cement (CEM II BV 32,5; 350 kg/m^3) to improve the scaling resistance (freeze-thaw de-icing salt cycles). The water-cement ratio was 0.45. Fibre content was 40 kg/m^3 (Twincone 1.0 by the Arcelor Group). The fibre content was chosen such to enable crack free section lengths of up to 30 m.

As a reference the pavement was also designed in jointed plain concrete (h = 250 mm) at a shrinkage transverse joint spacing of 4.5 m. The construction costs of the SFRC alternative were estimated to be about the same as for the traditional plain concrete structure

Transverse saw cuts (to initiate shrinkage joints) were provided at intervals of 267 m, 46 m, 48 m, 56 m, 26 m, 30 m and 30 m. This wide range of interval length enabled checking whether the foreseen 30 m crack free section length could be reached. The seven sections were inspected on their cracking behaviour up to 62 d after construction.

The concrete compressive strength was measured at several ages, both using cubes (150 mm rib length) from the producer (stored under water) and drilled cores (100 mm diameter) taken from the pavement.

Figure 2 The Tilburg pavement during (left) and after construction (right).

Results and discussion Table 2 presents the results of the compressive strength measurements. The results are close to the requirements of strength class C35/45 since in practice the 28-day characteristic cube compressive strength is about the mean value minus 8 N/mm^2 (Eurocode, 2004).

Table 2 Mean concrete compressive strength [N/mm^2]

concrete age [days]	7	14	21	28	56
cube (150 mm)	40.0	48.4	50.9	52.4	64.0
cylinder (d = 100 mm)		35.7		44.2	

Inspection up to 62 days after construction resulted in the number of transverse cracks in specific sections as presented in Table 3. The mean crack spacing was in the range of 25-30 m. Unfortunately, some of the cracks were generated near manholes of a sewage system that passed underneath the pavement. The concrete manholes acted as crack initiators and possibly partly prevented the longitudinal pavement to freely deform. About 1/3 of the cracks that had appeared were located near a manhole. Taking this onto account, it appears that, with regard to crack-free lengths, the pavement behaved as expected.

Table 3 Number of transverse cracks

section	length [m]	number of days after construction					
		2	4	6	14	27	62
1	267	1	4	6	7	9	13
2	46					2	3
3	48			2	2	2	3
4	56				2	3	3
5	26						1
6	30						
7	30						

Pilot project Roermond

Materials and methods Along the motorway A73 close to Roermond (NL) two parking lots for trucks were constructed with SFRC pavement, 85×24 m^2 each. Each parking lot was applied in December 2007 in two runs, 12 m of width being applied in one run by a slipformpaver. The 12 m wide pavements were not mutually connected, so each parking was regarded as consisting of two individual slabs, each 85 m long and 12 m wide. One of the four slabs was not provided with transverse shrinkage joints, whereas the three other slabs had only one shrinkage joint in the middle (i.e. at 42 m).
The concrete contained 40 kg/m^3 of a steel fibre mix. The mix consisted of twisted 32 mm long (20 kg/m^3) and 50 mm long, 1 mm diameter (20 kg/m^3) steel fibres (Fig. 3). Both types of fibres had deformed ends to improve anchorage / bond behaviour. Also 0.6 kg/m^3 of polypropylene fibres was added to reduce possible cracking caused by plastic shrinkage.

Figure 3 The fibres used in the Roermond pilot project. From left to right: long and short steel fibres and synthetic fibres.

The thickness of the pavement was calculated using the VENCON2.0 software (CROW, 2004 & Stet *et al.*, 2006), taking into account both traffic loads and frictional forces from shrinkage deformation and temperature loads. Since continuously steel fibre reinforced concrete is yet not implemented in the package, the pavement was calculated as being a plain concrete slab on a bedding, provided with shrinkage joints. Transverse joints were assumed to be spaced at 5 m. A longitudinal joint was assumed, providing a 4 m slab width in transverse direction. The calculation for this 5×4 m^2 slab on a bedding resulted in a required thickness of at least 253 mm. This thickness had to be corrected for two aspects: First, the use of steel fibre reinforced concrete, a material not brittle but having a post-cracking tensile strength. Second, the increase of longitudinal tensile forces from bedding friction when shrinkage joint spacing increases. The designers aimed at a joint spacing of 40-50 m. Taking these two aspects into account, it was decided to reduce the pavement thickness to 230 mm, combined with a shrinkage joint spacing of 42 m (Fig. 4). Therefore, three slabs 85 m in length were provided with one transverse joint (Fig. 5). To investigate the behaviour at further increased joint spacing, one slab was not provided with a transverse joint.

Figure 4   The Roermond pavement during construction and the mix in detail.

Figure 5   Placing the dowels at the predefined location of a transverse shrinkage joint.

Inspection was carried out 4, 7, 24 and 36 days after applying the pavements. Apart from expected transverse cracks beneath the shrinkage joints (figure 6), no other cracks were found. Only one out of the three slabs provided with a shrinkage joint demonstrated cracking at this joint. The 85 m long slab not provided with a shrinkage joint demonstrated no cracking up to the most recent inspection date (March 2008).

Figure 6 Shrinkage crack formed beneath a transverse shrinkage joint sawn after application of the pavement.

Closure

This paper has addressed a practical approach and monitoring program to assess the performance of steel fibre reinforced concrete applied to construct pavements. The work program was first theoretically executed in 2006, followed by monitoring of practical application in 2007 and 2008. Pavements to be traditionally constructed in plain concrete provided with transverse shrinkage joints, were constructed in SFRC. Joint spacing could be increased from 5 m to up to about 25 m, whereas even 80 m seems to be an option. It appeared that SFRC could keep its promise and can result in a good serviceable road pavement provided that it is produced under strict quality control. Its application will become more popular as soon as cost will be acceptable compared to JPCP and when SFRC will be incorporated in the design tools and codes of practice used in the Netherlands.

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