

Chapter 3

Steel Fiber Reinforced Concrete Ground Slabs

3.1 Synopsis

The improved engineering properties of SFRC have implications for concrete pavement design criterion, as SFRC has improved fatigue performance and flexural strength. Apart from technical aspects, economy is usually the core aim that designs strive to. SFRC is found to have a significant impact on the economy of the pavements mainly due to the possibility of providing less thickness, longer joint spacing, less maintenance cost and longer useful life if compared to the plain concrete pavements.

In this section, published information on SFRC pavements is discussed and conclusions are drawn.

3.2 Design methods

Most of the accepted methods for conventional concrete pavement design have been used to design SFRC slabs^[56]. The main difference in designing for SFRC is the factor applied to the concrete flexural strength or slab thickness to take account for the improved ability of the SFRC to withstand impact and repetitive flexural loading^[30]. Generally, Westergaard formulas and its derivatives have been commonly used^[57]. Supporting design charts and formulas are available^{[11] [30] [39] [58]} for determining the thickness of SFRC warehouse floors. Airfield slab thickness for new designs can be obtained from charts developed for SFRC by the Corps of Engineers U.S.A.^{[56] [59]}. Heavy-duty port pavement design procedures and specifications are found in the manual developed by the British Ports and American Association of port authorities entitled "The Structural Design of Heavy Duty Pavements for Ports and other Industries", in which SFRC was considered^[9]. The plain concrete design criterion can be used to determine the design thickness for highways, but attention should be given to the failure criterion associated with SFRC as discussed later in this section.

The design parameters for SFRC are similar to those of plain concrete. Traffic loading, sub-grade reaction and static flexural strength and fatigue properties of the concrete are the design inputs to design charts. The required slab thickness is

determined as that necessary to limit the tensile stress in the slab to a such level that fatigue cracking will not occur until after the pavement have received the design number of stress repetitions ^[56]. Since the SFRC slabs are expected to yield thinner design thickness, it is necessary to ensure that the stress and strains induced in the foundation material do not exceed the strength of the sub grade, and that the deflection is within tolerable limits. Computer programs based on layered system theory and finite element analysis technique can be used to ensure that all criteria are met ^[58]. Data from plain and reinforced concrete was used to develop relationships between the elastic deflection and pavement performance using the available SFRC data a curve was drawn parallel to that of plain and conventionally reinforced concrete pavements, and this relationship was used to provide maximum acceptable deflections for entire pavement rather than providing limiting deflections ^[59].

Criticism has been leveled at some early and recent design procedures. Although SFRC has different fatigue and strength development characteristics, criterion in many cases was not altered to compensate for this difference and the fatigue properties of SFRC were considered to be similar to the fatigue properties of plain concrete ^[4]. The after crack flexural strength of the SFRC was not considered or considered indirectly, while, the first crack strength was used through Westergaard formulas (either directly on the formulas or proceeding through it's simplified design charts). In addition to that, these procedures lack or give little information regarding correlation between steel fiber parameters and the flexural strength and fatigue performance of SFRC in a design environment ^[27]. Some SFRC constrain the designer to a certain mix designs ^[30], which in many cases are not suitable for the required application. With the vast increase in use of SFRC, better experience is gained, and more refined design catalogues become available with time (for instance the steel fibers manufacturer design catalogues which considers the after cracking strength and clarify the correlation between fiber parameters and the flexural strength) ^[11].

3.3 Ground Slabs Distresses

Since pavement performance is a time dependant, the behaviour of materials cannot be predicted from stress analysis. It becomes evident that the structural performance involves more than stress analysis.

It is prudent to consider material related distresses at design stages in order to ensure better performance for the intended pavement. As discussed in previous sections, alteration on mechanical and physical properties brought to concrete by addition of steel fibers is seen to improve pavement performance.

Break-off and spalling of corners, edges, and joints usually results from excessive stresses, loss of support and curling^[60]. Investigations on SFRC airfield pavements in the U.S.A., found that although break-off is found in many locations, its effect on performance is minimal because the pieces remain held together with the rest of the slab and it was concluded that the normal routine maintenance could tackle the problem^[4]. As far as the spalling of concrete is concerned, laboratory tests and field investigation have shown that SFRC has much higher spalling endurance than the plain concrete^[29]. As a qualitative measure, results from dynamic and explosive test are used and it was found that SFRC does not disintegrate upon load application^[9]. To minimize the possible corner and edge break off, it was recommended that staggered transverse joints could be used resulting in two corners created instead of four corners^[61].

Edge punching is typical distress of continuously reinforced concrete pavements. The mechanism involves that, two adjacent cracks (about 1.2m apart) at the edge of the pavement, start to fault and spall slightly, which cause that portion of the slab to act as a cantilever beam. By that time more cracks are induced and pieces of concrete punch downward under load into the sub-base^[60]. Once again steel fibers can minimize this punching, because for the piece of concrete to punch fibers should either break down or pull out of concrete, which needs higher energy to be exerted.

Longitudinal cracks occurring parallel to the centerline of pavement slab are either due to loss of support or to the fatigue of concrete. SFRC can result in a reduction in the formation of fatigue related cracks, as the fatigue endurance of SFRC is better than that of plain concrete. Also if cracks are supposed to occur, it will be much narrower in SFRC preventing the ingress of water and deleterious material onto the underlying layers, thus reducing pumping.

Transverse cracks are usually caused by friction stresses between slab and sub-base, which causes tensile stresses on the slab. At some stage, these tensile stresses exceed the tensile strength of the slab and eventually transverse cracks occur ^[62]. Steel fibers in SFRC acts as discontinuous reinforcement, which to some extent restrain the drying shrinkage and expansion caused by moisture, in other words it reduces the action of the slab movement. As a result of this reduction, micro cracks are distributed through the slab instead of having one macro crack at approximately equal distances. Transverse crack spacing for SFRC pavements is expected to increase, which imply that savings could be achieved on transverse joints.

Curling stresses are the stresses caused by the temperature differential through the depth of the pavement. Downward curling occurs during the day due to the rise of temperature. The top of the slab tends to expand with respect to the neutral axis while the bottom tends to contract. However the weight of the slab restrains it from expansion and contraction, thus compressive stresses are induced at the top while tensile stresses occur at the bottom. At night the picture is reverse and upward curling has to occur ^[60]. Curling can be a serious impediment to satisfactory serviceability and thus the influence of steel fibers on curl must be established. The severity of curling on SFRC pavements is due to the fact that thinner section could possibly be provided, moreover, SFRC mixes have higher cement content which has a negative influence to the curling characteristics of the concrete ^[4]. Airfield investigation carried out in the U.S.A. concluded that, although some curling has occurred in SFRC pavement projects, distress associated with this curling has been minimal (in the form of corner cracking) and there has been very little need for maintenance. The investigation further recommended that curling and its effect should be minimized by adjusting the concrete mix through provision of lower cement content, use of water reducing admixtures, and use of retarding admixtures ^[61].

3.4 Insight Through Previous Projects

SFRC pavements have now been in use for about three decades. Question on how these pavements performed and the lesson learned is important for the future of the use of the steel fibers in this field.

Field investigation in 1982 ^[12] in the U.S.A. on SFRC pavements, reported that few of these pavements performed well and many developed defects in early stages

of their service life. The investigation concluded that additional research is needed in the areas of joint design and spacing, load transfer at joints, fiber content and thickness.

Another field study in 1989 ^[63] conducted in Belgium on overlays with SFRC stated that fairly good results are gained by using steel fibers in concrete. It was found that the bond condition between the old pavement and the overlay is fundamental. Further more direct resurfacing on concrete should only be considered when the condition of the old pavement is still relatively good. Suggestion was made for further research to address the problem of reflective cracks that were encountered at many locations in the project.

The decision was made to use SFRC to overlay two aprons at McCarran *International Airport /Las Vegas /USA* in 1976 and 1979 ^[64]. The first one is 152 mm deep built over an existing asphalt pavement to serve transient cargo aircraft. The SFRC mixture contained 95 kg/m³ of (0.25x0.56x25mm) straight steel fibers. Problems existed in overlaying the existing pavement, as the existing cargo building was already 0.6 to 0.9 m below the level of the ramp. Using conventional concrete would have added 381 to 406 mm to this difference, while SFRC allowed this thickness to be reduced to 152mm. In this project, transverse joints are spaced 15 m apart, longitudinal joints were spaced 7.6 m apart and keyway or tie bars were used (no dowels). A number of corner breaks was found and some of them were faulted and developed spalling, also some tight longitudinal cracks near the panel centerline were observed.

The second project was the new construction of 178 mm deep SFRC placed over 51 mm of new asphaltic concrete, which was on top of 305 mm of conventional concrete. The SFRC mixture had a cement content of 385 kg/ m³, a pozzolan content of 149 kg/m³, and fiber content of 50 kg/ m³ of (0.51x0.51mm) deformed steel fibers. Transverse joints (sawn 75 mm deep) were 15.2 m apart and longitudinal joints of 7.6 m apart were enhanced. Almost 10% of the panels had corner breaks and it was stated to be somewhat less than those of the 1976 apron. About half of the transverse contraction joints had not functioned resulting in wide-open joints at those that have functioned.

It was stated by Packard et al ^[12] that the problems associated with this project were:

- (a) Lack of load transfer to adjacent slab that was due the thinner SFRC slabs at which load transfer devices such as dowels had to be omitted.
- (b) Curling stresses influenced the edges and corners and.
- (c) Large amount of movement in some joints resulted in failures of the joint seal, therefore, water and debris filtered to the bottom layers causing more damage.

An old pavement at *J.F. Kennedy Airport /New York /USA* had a serious problem of “shoving” caused by aircrafts turning off the taxiway onto the runway ^{[56][64]}. Construction consisted of the removal of the old asphalt concrete wearing course, construction of 51 mm asphalt leveling course, placement of a double thickness of 0.15 mm thick polythene, and then construction of the SFRC overlay. The overlay was 140 mm thick, and used both keyway and doweled construction joints. The concrete mixture had a cement content of 445 kg/m³ and 104 kg/m³ of (0.64x64mm) straight steel fibers. One year later (1975) a survey indicated satisfactory performance and the repaired area were enlarged. Performance evaluation in 1984 stated that the paved area was still in service although there was some cracking and shattered corners at intersections.

Packard et al ^[12] stated that small apron areas in the same project were placed over asphalt where fuel spillage was causing serious “shoving” and rutting. These areas continue to settle badly. Some of the SFRC that was not jointed is cracking badly.

At *Ashland ramp /Ohio/USA* ^[64], an entrance to a truck weighing station was built as an experimental project to evaluate the use of SFRC in new pavement construction. Construction was completed in 1971 and opened to the estimated daily traffic of about 2400 to 3600 truck per day in the year 1973.

The ramp was 152 m long and 4.9 m wide having a depth of 102 mm and placed on top of an asphaltic concrete base. Ends were tapered to 229 mm over a 2.1m length. Doweled expansion joints were installed at either end. The concrete had a cement content of 500 kg/m³ and fiber content of 157 kg/m³ of (0.25x0.56x25mm) straight steel fibers. The maximum aggregate size was 9.5 mm.

The day following the placement, transverse cracks occurred approximately at midpoint of the slabs. The cracks varied in width from 3.2 to 12.7 mm. Four months

later a second transverse crack occurred 50 m from the first crack and 30m from one end. In 1973 a third transverse crack was found 30 m from the other end. An irregular longitudinal crack, hairline in nature, was also observed over a 12 m length at the center of the pavement beginning approximately 30m from the end of the pavement.

After it was opened to the traffic, spalling at areas of the transverse cracks occurred and these areas were resurfaced to full depth again. In 1976 the entire project was resurfaced.

An evaluation carried out by Packard et al ^[12], suggest that the problem was caused by a lack of load transfer through the transverse cracks, excessive deflection as a result of the thin section used and the heavy type of traffic was encountered. The ramp had corners break-off and slabs shattered.

A series of trails was conducted during 1970s on *bus lanes in Calgary /Canada* ^[65] to evaluate the usage of SFRC in new pavement construction. University bus route sections of conventional un-reinforced concrete were compared to similar thicknesses of SFRC containing 80 kg/m³ steel fibers. Pavement thicknesses of 76 mm, 102 mm, 152 mm, and 178mm were tested.

The result of this study showed that after four years and over 200 000 bus passed, the SFRC either greatly reduced the cracking for similar thicknesses or only 50 to 60% of the plain concrete thickness was required for equivalent performance. It was also stated that damage in conventional concrete slabs with thicknesses of 76 mm, 102 mm and 127 mm necessitate its replacement after just four weeks of trafficking whilst SFRC sections performed adequately over the four years.

SFRC slabs were used instead of double reinforced concrete slabs in *Burnssum Warehouse /Holland* ^[4]. This eliminated the conventional concrete and reduced the slab thickness from 200 mm to 180 mm. A concrete mixture containing 340 kg/m³ cement, 30 kg/m³ of hook-ended high tensile steel fibers, and a maximum aggregate size of 32 mm. Plasticisers were used to achieve low water content.

Although no mention was made regarding performance, it was stated that cost and shrinkage cracks were reduced; SFRC warehouse flooring became more common in other subsequent projects.

An experimental project was constructed during 1982 in *Maldegem /Belgium* ^[63] on a badly deteriorated concrete road, where pumping and stepping had taken place. The road was subjected to heavy traffic load.

Two overlay sections were constructed. The first section (1250 m long) had contraction joints 15 m apart following the pattern of the previous road, while the second section (500 m long) was constructed without contraction joints. The overlay thickness was between 100 and 120 mm. An asphalt separation course was used to prepare the surface.

The concrete mix had a cement content of 400 kg/m³, and 50 kg/m³ of hook-ended 50 mm long and 0.5 mm thick steel fibers. A water cement ratio of 0.55 was used.

An evaluation in 1988 revealed that, in the 500 m section (without joints), cracks developed at an early age at distances between 10 and 60 m and they present slowly evolving distress for the entire overlay. On the other hand the section with contraction joints was not damaged at all, however, approximately 50% of the neoprene profiles utilized to fill the joints were loosened and 10% of the joints needed to be resealed.

In 1983 a concrete road in *Gent /Belgium* ^[63] that was heavily scaled but in good structural condition was overlaid. The old road was constructed on a crushed stone base and it had doweled contraction joints. It was serving a very heavy industrial type of traffic.

To ensure fully bonded overlay, surface preparations such as grouting, cleaning and milling to the old surface were performed prior the overlaying. A 100 mm deep layer with joints 10 m apart (coincide to the old pavement joints) was constructed. The mixture had a cement content of 400 kg/m³, water cement ratio of 0.53 and 40 kg/m³ of hook-ended 0.5 mm diameter by 50 mm long steel fibers.

In 1988 the project was evaluated. The left lane exhibits relatively little damage, as the intense traffic utilize essentially the right lane. On that right lane, cracks developed at joints, indicating de-bonding at the interface. Obviously grouting had no positive effect especially at the high temperature reported during construction. The evaluation recommended that the right lane had to be resurfaced in the near future.

In some of these selected projects, the cement content was relatively high. The reason might be the additional paste required to coat the steel fibers. High cement content is normally associated with higher potential for curling and shrinkage ^[4]. Fly ash was used in the second project at Mccarran International Airport and it seems to work better as there was relatively less damage reported on the SFRC in that project. This agrees with the facts that fly ash does not only reduce the plastic shrinkage through the reduction of the heat of hydration at early curing ages, but it also improves workability and cost effectiveness ^[66].

High steel fiber content were used in some of the projects, for instance 157 kg/m³ straight steel fibers, was used in the Ashland ramp. The aim of that was probably to get very high flexural strength, thus very thin section was obtained. With the technology of to day, hook-ended steel fibers with high tensile strength have proven to yield better results and a reduction in the fiber content have become possible. Literature shows that fiber content of between 15 - 50 kg/m³ is satisfactory and more economical.

Performance evaluation stated that efforts to obtain the maximum economy had resulted in some designs that were on the un-conservative side, therewith, inadequate thicknesses were obtained and failure had taken place ^[12]. Pavement thickness should be considered for the deflection and curling of the slab as both these factors can cause edge breaking and shattering which was evident in some projects such as the Ashland ramp for the case of deflection and Maldegem overlay.

Joints spacing and load transfer devices were seen to cause major distresses in some projects. Inappropriate joint spacing caused cracks in middle of slab; moreover, these cracks are relatively wide. Transverse joint spacing of 15 m is found to perform well which agrees with the recommended spacing by some research corporations ^[56]. Inappropriate load transfer methods have contributed to the cause of damage in many SFRC pavements ^[4]. Thin slabs have led to the omission of keyways and dowels causing reduced joint efficiency and thus resulting in damage ^[12]. With better joint spacing and proper load transfer devices, middle crack effects could be reduced if not eliminated. In the case of narrow cracks the steel fibers could possibly acts as mini-dowels thus better load transfer could be achieved through cracks.

It was evident that steel fibers cannot be used as an alternative for the normal steel bars thus continuous road overlays cannot be constructed using SFRC even if much

high fiber content was used. Gent overlay and Ashland ramp were examples of failure of this application.

SFRC applications in warehouse floors have proven to result in massive savings and good performance. Many of the problems encountered with other pavements were not found in warehouse slabs and the probable reason for that is the exposure to weather condition for those floors are different to that of other mentioned pavements. The curling stresses and joint movement for warehouse floors are thus limited.

SFRC have proven good performance in many other applications such as bridge-decks, pipes, hydraulic structures, pre-cast elements and some others, which lies out of the scope of this research.

3.5 Economic Evaluation

Traditionally the decision between various alternative solutions to the problem of providing a pavement has been made on the basis of initial costs. This approach has some disadvantages in the way that the useful life span for different options and the maintenance cost are not considered. The concept of life cycle costs is found to be better in determining the most cost-effective option because the maintenance cost and useful life span are included ^[67].

Any new technology should, at the same level of performance, be cheaper than the one it substitutes; otherwise it will stay in the laboratory stage. SFRC is not cheaper than traditional techniques in many applications. Therefore it is very important to select and develop these applications where sufficient economics are guaranteed. Initial cost saving could be achieved in many cases where less thickness and longer joint spaces could be provided.

It was established by many researchers that saving could be made in different pavement components. Longer joints spacing could be used, 15 m for transverse joints and 7.5 m for longitudinal are applicable, thus massive saving could be attained due to the reduction of the number of joints to be used ^[56]. Saving in material is also possible and it's dependant on the type of application as presented in section 3.4. Also it has been established that in some projects, the SFRC shorten the construction period once again an indirect saving is made due to the earlier opening to the traffic ^[10].

Experience gained from previous projects has shown that massive initial cost saving could be made if SFRC is to be used. Saving was greatly recognized in airfield pavements, for instance, at Denver airport in the U.S.A., a saving of \$1.0 million (15.5% saving) was attained by using SFRC slabs having a depth of 203 mm instead of using 381 mm of plain concrete to with-stand the same load ^[68]. Saving was also acknowledged at container terminals where tremendous load growth has been experienced during the last two decades. SFRC is not only economical but it was also found to work perfectly and interruption caused by shorter maintenance intervals is no longer encountered. For the overlay at Ghent port in Belgium a saving of 40% in thickness and 50% of joint spacing was achieved in comparison to if conventional concrete was used ^[9]. SFRC roads in the past have been found not to be cost-effective when compared to plain concrete ^[69], as the small reduction in thickness on these pavements will probably not make SFRC economically feasible ^[12]. During projects constructed in the early 70s fiber supply capabilities and manufacturer were unable to meet the demand for any major projects, which could have been a fairer evaluator for such pavements ^[4]. On the other hand SFRC overlays and inlays have proven to be very cost-effective and reducing thickness by about 40% could make initial saving. SFRC have been widely used in industrial building floor with an economical advantage (saving in material and joints) of about 5 to 10 % initially gained and much of the concentrated heavy loads could be handled ^[70].

Where much thicker pavements are required for the heavier loads and higher tire pressure, SFRC may be more feasible ^[12].

The extra cost of adding fibers to the concrete mix and other additional cost is usually offset by the savings in cost of supplying and placing materials ^[10].

3.6 Conclusions

- Design methods for plain concrete pavements can be used for the SFRC pavements. Alteration to these methods is required to consider for the higher deflection values usually associated with the SFRC slabs due to the thinner sections.
- Distresses associated with wearing course are either be eliminated or reduced by the addition of steel fibers to concrete. Therefore, SFRC can have a performance superior to that of plain concrete pavements taking



into account all considerations of good applications, design and construction.

- The majority of the previous SFRC pavements are found not to perform as perfect as anticipated. The reasons for that are found to pivot around the inadequate designs, for instance, the thickness and the joints spacing.
- The SFRC for pavements is economically viable when compared to the plain concrete. A minimum of 10% to a maximum of 40% saving could be achieved in warehouse and overlay pavements respectively. It was further found that more saving could be perceived if the life cycle performance is considered for the evaluation of different pavement alternatives.
- Apart from the economy, SFRC could play the role to solve several technical problems, for example, the less required thickness can be beneficial in cases where headroom restrictions are found. Designers should however bear in mind that with reduced thickness, more curling stresses occur.

