American Journal of Civil Engineering and Architecture, 2016, Vol. 4, No. 6, 189-198
Available online at http://pubs.sciepub.com/ajcea/4/6/1
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DOI:10.12691/ajcea-4-6-1

Quantification of Benefits of Steel Fiber Reinforcement for Rigid Pavement

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Abstract In the present study, strength parameters of steel fibers reinforced concrete (SFRC) were investigated. Their load carrying capacity and deflection characteristics were also evaluated and compared with those of Plain Cement Concrete (PCC). Three different concrete mixes were chosen. One is of PCC and two mixes are of SFRC with fibers content of 4% and 8% of cement weight. Tests on fresh concrete were conducted like, slump test, compaction factor test and Ve. Be. Test. Other tests were conducted on hardened concrete like, compressive strength, flexural strength, modulus of elasticity, indirect tensile strength and ultrasonic pulse velocity. Results leaded to design a SFRC mix with 8% steel fiber content for further tests. Moreover, plate load tests were conducted on pavement model slabs of PCC and SFRC casted and arranged over a prepared subgrade sandy soil in a model tank. Results revealed that the first crack load carrying capacity of SFRC slabs has enhanced by 19%, 15% and 7% for corner, edge and center loading respectively. Also, the failure load has increased for SFRC than for PCC in such a way that it has become 1.13, 1.08 1nd 1.05 for corner, edge and center loadings of the pavement model slabs. Similarly, deflections corresponding to first crack load were also increased for SFRC. A concept was adopted to quantify the benefits of adding steel fibers to PCC in terms of extension of the pavement service life and also in terms of reduction in the concrete thickness for the same service life of both reinforced and unreinforced concrete pavement sections.

Keywords: *Steel Fibers, Concrete Pavements, Service Life Ratio, Layer Thickness Reduction*

Cite This Article: M. A. Kamel, "Quantification of Benefits of Steel Fiber Reinforcement for Rigid Pavement." *American Journal of Civil Engineering and Architecture*, vol. 4, no. 6 (2016): 189-198. doi: 10.12691/ajcea-4-6-1.

1. Introduction

There is an increasing demand for improved load carrying capacity in roads since, road traffic is becoming heavier. In the early days, deep sections were provided for concrete ground slabs. Increased knowledge and experiences in this field had substantially improved the understanding of the behavior of concrete pavements. Considerable interest has been generated in the use of Steel Fiber Reinforced Concrete (SFRC) and other engineered concrete composites. Therefore, SFRC is defined as concrete containing randomly oriented discrete steel fibers. A reduction of design thickness and increasing the maintenance intervals are normally associated with SFRC.

Basically, steel fibers were categorized into four groups depending on the manufacturing process viz: cut wire (cold drawn), slit sheet, melt extract and mill cut. Major efforts have been made in recent years to optimize the shape and size of the steel fibers to achieve improved fiber-matrix bond characteristics and to enhance fiber dispersability, [1]. The use of SFRC revealed many advantages such as the increase of ductility, toughness, strength, fatigue endurance and deformation characteristics. These are the reasons for major saving in time, cost, and materials when using the SFRC, [2,3]. Reference [4] reported that the use of steel fibers reduces the thickness of road pavement by 25% to 30% and subsequently, decreases the overall cost of road construction. Reference [5] studied the use of steel fiber in rigid pavement. M20 Concrete mix was prepared with crimped end steel fibers with 25mm length and 0.5mm diameter. Cube specimens were casted and tested for 0.4 and 0.5% of volume of concrete. The results showed that the compressive strength of steel fiber concrete increased when compared to plain cement concrete. Addition of steel fiber in concrete, the pavement thickness is decreased by 23% and which is economical when compared to plain cement concrete slab. Reference [6] reported that the addition of a combination of 20% marble dust with addition of 0.5%-1% steel fiber is ideal for rigid pavements since, it leads to considerable amount of increase in strength of concrete and gives a higher life expectancy.

Despite of SFRC excellence and superiority, drawbacks exist. Loose fibers at the hardened surface might be blown onto aircraft engines or tire, which leads to unsafe operation. Injury to personnel being scraped or cut by an exposed fiber while working on the concrete surface is also possible, however, no accident has been reported regarding any of the above two scares, [7]. There are many data available on the mechanical properties of SFRC, [8,9] and [10]. All of them show that steel fibers significantly improve most mechanical properties of concrete. The behaviour of SFRC started to be well known in the case of a first short-term loading; the durability of their vital character in the structural applications remains still largely to be explored. The long-term behaviour of operational structures reinforced with steel fiber in the cracked mod depends on their capacity of effort taken by the fiber between the two lips of cracks. This is conditioned, on the one hand, with mechanical creep and fatigue effect, on the other hand, with corrosion of fibers, [11].

Despite of the wide range of the available lab. information, the information is fragmented and research concentrate on SFRC as material rather than its applications. Some full-scale tests are more realistic and give a broad idea about the tested elements. They are also more relevant to the field of pavements. Few tests are conducted to clarify and address issue such as load capacity and deformation characteristics for the SFRC. Reference [12] observed that slabs reinforced with steel fibers produce smaller deflections than the plain concrete at equal number of impact. Reference [13] observed 25% increase in impact strength of concrete every 0.5% increase in fiber content. Reference [14] investigated the load carrying capacity of thin SFRC pavements over WBM base. They revealed that 60mm thin SFRC pavement placed over WBM base exhibits satisfactory performance under central, edge and corner loading conditions.

Optimizing the strength and fatigue characteristics, which is possible by using various steel fiber dosages, can minimize the cost. On the other hand, rational design and evaluation of pavements require determination of fundamental properties of various materials. This fundamental property includes modulus of elasticity (E), Poisson's ratio (μ) strength and fatigue characteristics. In order to use SFRC in road applications, the above stated properties are to be estimated accurately. In the present study, the fundamental properties of SFRC are determined by using both destructive and non-destructive test methods. Moreover, a discussion of the behavioral properties of the SFRC and the possible effects of these properties on the performance of ground slabs constructed with the material is also presented.

2. Materials Selection

Materials used in production of the selected concrete mixes are locally available. The used cement (C) is ordinary Portland Cement. The physical and mechanical properties of each cement type are shown in Table 1.

Table 1. Physical and Mechanical Properties of the Used Cement

Property	OPC	
	Test Results	ASTM-C150 (ACI-318M-08)
Specific gravity	3.15	-
Consistency %	25.0	20-30%
Fineness %	2.00	-
Setting Time		
Initial	100 min	> 45 min
Final	4.0 hrs	< 10 hrs
Compressive strength (MPa)		
3 days	18.7	18 MPa
7 days	27.0	27 MPa

The used coarse aggregate (CA) was natural gravel while, the used fine aggregate (FA) was natural coarse sand. The main properties of different aggregates are shown in Table 2.

Table 2. Main properties of aggregates

Type	Specific Gravity	Unit Weight (kg/m^3)	Void %	Fineness Modulus	Maximum Nominal Size (mm)
FA (Sand)	2.65	1675	36.8	2.92	-
CA (Gravel)	2.62	1635	37.6	7.11	20

The used water (W) was clean and did not contain any deleterious materials like oil, salt, acid & vegetables etc. A super plasticizer (SP) is used as it has a powerful dispersing effect on the cement particles. The facility with which high performance concrete can be made depends essentially on the behavior of the binder in the presence of the super plasticizers. In addition, silica fume (micro silica) (MS) with content of 10% of cement content in all investigated mixes for both SFRC and PCC was used. The steel fibers used (SF) are high strength cold – drawn wires, supplied freely by the manufacture. They present anchor hooks at both fiber ends for improvement of anchorage in concrete and are supplied in plates of 40 to 44 fibers glued together with a water soluble material. Table 3 shows the properties of the used steel fibers as collected from the supplier.

Table 3. Properties of Steel Fibers

Length	Diameter	Aspect Ratio L/d	Specific Gravity	Tensile strength (MPa)	Elastic Modulus (Gpa)	Number of fibers per kg	Length (m) of fibers/kg
35 mm	0.55 mm	64	8.5	1100	210	14500	508

2.1. Design of Mixes for PCC and SFRC

The mixes were designed by ACI-211 method for good degree of control and low workability. The maximum size of coarse aggregate was kept as 20 mm. The designed mix has given a designation of M1 for further tests and analysis in the present study. Similarly, two mixes were chosen for SFRC which are given the designation M2 and M3 respectively. The fiber content was taken as 4% and 8% by weight of cement for both mixes M1 and M2 respectively. The ratio between sand and gravel was adopted as 40/60. The used w/c ratio was taken as 0.4. The details of all mixes including all quantities required for mixes constituents are given in Table 4.

2.2. Tests for Fresh Concrete

There are many control tests conducted for fresh concrete to control its workability and to satisfy the design requirements. Many test methods are available for measuring concrete workability. The procedure for measuring such workability is varying from free flow, confined flow and vibration test methods. Slump test, compaction factor test and vebe test are examples of such tests respectively, [18].

Table 4. Investigated Mixes Constituents and Materials Weight Per Cubic Meter of Concrete

Type of Mix	Mix Designation	Weight of materials per cu. m. of concrete						
		C (Kg)	F A (Kg)	C A (Kg)	W (Kg)	S P (kg)	M S (Kg)	S.F (Kg)
PCC	M1	550	609	914	220	5.5	55	___
SFRC-1	M2	550	606	910	220	5.5	55	22
SFRC-2	M3	550	604	906	220	5.5	55	44

2.2.1. Slump Test

The slump test is the most well-known and widely used test method to characterize the workability of fresh concrete. It is inexpensive test, which measures consistency and used on job sites to determine rapidly whether a concrete batch should be accepted or rejected. The test method is widely standardized throughout the world, including in ASTM C143 in the United States and EN 12350-2 in Europe. In the present study, three samples for each investigated concrete mix were tested and the average slump value was determined.

2.2.2. Compaction Factor Test

The compaction factor test measures the degree of compaction resulting from the application of a standard amount of work. The test was conducted as per EN 12350-4. The compaction factor is defined as the ratio of the mass of the concrete compacted in the compaction factor apparatus to the mass of the fully compacted concrete. Similar to the slump test, each considered concrete mix was investigated through three specimens and the average result was determined.

2.2.3. Ve Be Test

The vebe consistometer was used to measure the remolding ability of concrete under vibration. The time for the concrete to remold from the slump cone shape to the shape of the outer cylindrical container is recorded for three specimens for each concrete mix. The average time values were computed and presented.

2.3. Tests for Hardened Concrete

There are many control tests conducted on hardened concrete to ensure its mechanical and physical properties. These test are categorized either destructive or non-destructive tests, [18].

2.3.1. Compressive Strength Test

The compressive strength test was conducted on cubes of dimensions 150 x150 x 150 mm. Nine specimens were prepared for each mix to determine 7, 28 and 56 days compressive strengths. The compressive strength “fc” was calculated for all tested samples concerning control samples as well as SFR samples.

Since, the relationship between cube and cylinder strengths for PCC is varying due to many factors like, targeted concrete strength and nominal maximum size of aggregates, cylindrical specimens of 150mm diameter and 300 mm height were also prepared and cured for 28 days only. This was considered to investigate this relationship for SFR concrete.

2.3.2. Flexural Strength Test

The flexural strength tests were carried out on beams of 100 mm x 100 mm x 500 mm, according to EN 12390-5. Two beams were cast for each mix to determine 28 days flexural strength. The beams were simply supported with 450 mm clear span, and subjected to two-point loads. The distance between the two loads was 150 mm. The maximum flexural load of PCC, SFRC-1 and SFRC-2 beams under static loading was calculated.

2.3.3. Modulus of Elasticity (E. VALUE)

E-value is a fundamental property which has to be determined for the concrete mixes and also required for concrete pavements design. Since, the modulus of elasticity of concrete is closely related to properties of cement paste, the stiffness of the selected aggregate, and also the method of determining the modulus, values of static modulus of elasticity (E-value) in compression were determined according to ASTM C469/C469M-14 for all considered concrete mixes. Three cylindrical specimens of 150 mm diameter with 300 mm height were prepared for each mix. Three Loading/unloading cycles were applied up to stress level of about one third of the ultimate compressive strength. The average displacements were recorded at each load increment. The stress-strain curves are plotted and the slope of the last loading cycle was taken as a measure for the modulus of elasticity.

2.3.4. Bond Strength Test

The bond strength between a reinforcing bar and the surrounding concrete in cylindrical specimens of 150 mm diameter and 300 mm height was determined by using the pull out test. Testing was carried out using a universal machine with a capacity of 30 tons and an accuracy of 0.1 ton. The test was carried out according to BS 1881: part 207:1992. The bond, strength “f_b” in N/mm^2

2.3.5. Splitting Tensile Strength Test

It is well known that, the tensi1e splitting test of cylindrical specimens gives a more reasonable tensile strength estimation than the direct tensile test or the modulus of rupture test, [25]. The tensile splitting test was carried out on cylindrical specimens of diameter 150 mm and height 300 mm in a hydraulic testing machine of 200 tons’ capacity. The test was carried out according to EN 12390-6. The tensile splitting strength was calculated.

2.3.6. Ultrasonic Pulse Velocity Test

This test is a non-destructive test which was conducted on all types of samples i.e. cylinders, cubes and beams. The main principle involved in this method is that the velocity of pulse traveling in a media is dependent on density and elastic properties of material, [27]. Grease was applied on the probes and on two opposite faces of samples and the initial readings was adjusted to zero by sensitivity control and making the probes touching to each other. Then two probes were pressed uniformly against at the centre of faces axially and the corresponding transit time in microseconds was noted. The distance between faces noted. After knowing the pulse time or transit time

"T", the velocity "V" could be computed. The dynamic modulus of elasticity E_d can be computed by using Equation 1.

$$E_d = \frac{(1+\mu)(1-2\mu)}{(1-\mu)} V^2 \frac{d}{g} \quad (1)$$

where:

E_d is the dynamic modulus of elasticity.
μ is Poisson's Ratio (taken 0.2 for all mixes).
V is the pulse velocity in cm/sec.
d is the unit weight of mix.
g is acceleration due to gravity (981 cm/sec^2).

2.4. Plate Load Tests on Pavement Model Slabs

Plate load tests were conducted on pavement model slabs. These slabs have to be casted over a prepared subgrade. For this issue, a subgrade soil is prepared and also the slabs have to be constructed.

2.4.1. Preparation of Sub-grade

A setup was fabricated to assess the load carrying capacity of SFRC slabs and also PCC slabs. This set up consists of a cubical steel tank of size 150 × 150× 65 cm with 3.0 mm thickness. The size of the tank was selected such that its side walls do not affect the test result and also to be relative with the diameter of loading area. This tank was filled with a soil mass as a homogenous material to simulate the subgrade soil of a pavement structure. The concrete slabs were laid over this subgrade soil. The loading area was achieved by placing a circular plate on the top surface of the soil mass filled the tank. Sandy soil was selected as a subgrade material. Simple routine laboratory tests were firstly carried out to find out the physical and mechanical properties of the tested material such as, grain size distribution, liquid limits and plasticity index for classification. Table 5 introduces the properties of the tested soil.

Table 5. Properties of The Tested Soil

Property	AASHTO Designation	Result
O.M.C %	T 99 -74	12 %
CBR %	T193 -72	12 %
Max. dry density (MDD) (t/m³)	T99 -74	1.75
Liquid limit %	T 89 – 76	-
Plastic limit %	T 90 – 70	-
Plasticity index %	T 90 – 70	No plastic
Soil Classification (AASHTO)	T 88-78	A – 3

For placing the sandy soil in the tank and obtaining a uniform dense sand model, the model tank was filled into six layers where each layer has thickness of 10.0 cm. To obtain a uniform density within the whole soil mass in the tank, the side walls of the tank were marked at intervals of 10 cm each. The weight of each layer was calculated by using the volume of this layer and the MDD determined earlier. It was mixed with water at the O.M.C. The mixed soil belongs to each layer was compacted till the mark of the specified layer. Furthermore, initially many trials were conducted in order to achieve the required number of blows to compact the mixed soil of each layer.

2.4.2. Casting of Slabs

The concrete mixes contain steel fibers were optimized based up on the results of the above mentioned tests. Slabs with dimensions of 500mm x 500mm x 50mm were cast for the control concrete mix (PCC) and also the mix that contains the better fiber content. This fiber content was decided based upon the results of conducted mechanical tests like, compressive, flexural and split tensile. The material required for casting the slab was taken in predetermined proportions by weight. After weighting various constituents, they were mixed thoroughly in dry as well as wet condition by spade till a uniform color was achieved. Then the material was transformed immediately into the formwork and compacted by a vibrator. After 48 hours, slabs were cured for 28 days by placing wet sand around the slab and sprinkling the water.

2.4.3. Testing

Model slabs were arranged on the top of the compacted subgrade soil in a manner that simulates the actual field conditions. Plate load tests were conducted at the center, edge and corner of the center slab to be confined with other slabs. The slabs were first cleaned and the position of the dial gauges and studs were then fixed on the slabs with the help of an adhesive and left for drying for about 4 hours. The loading was done by a hydraulic jack. The plate size was scaled down in order to be proportioning to the slab dimensions. Reference [28] adopted that the effect of load is going to be neglected within a distance of “4a” from the axis of symmetry and at a depth of “5a” where “a” is the radius of loaded area. Therefore, plate of diameter of 10 cm was selected for carrying out such test. Deflection of pavement slabs was measured and load-deflection curves were plotted for different loading positions above casted slabs of considered mixes. Figure 1 illustrates different stages of the conducted loading test on model slabs like, preparation of subgrade, arrangement of slabs, loading and support conditions.

a) Fixing the model tank under the loading frame. b) Preparation of the subgrade under slabs c) Slabs arrangement over the compacted subgrade. d) Loading on slabs through a hydraulic jack.

Figure 1. Stages of the Conducted Loading Test on Model Slabs

2.5. Results and Discussions

2.5.1. Fresh State Tests

Table 6 shows the results of slump test conducted on fresh concrete for all mixes. It is clear that the presence of fibers in concrete reduces the consistency of the fresh concrete and subsequently, the workability of the concrete mix. This is achieved since slump reduced by about 14% with the addition of 4% fibers by weight of cement (SFRC-1). Moreover, the addition of 8% fibers by weight of cement has reduced the slump value by 50%. This is also showing that addition of steel fiber has a minimum effect for low dosage while it has a significant effect for higher dosages.

Table 6. Results of Tests Conducted for Fresh Concrete for Different Mixtures

Mix Designation	M1	M2	M3
Mix Type	PCC	SFRC-1	SFRC-2
Slump (cm)	21	18	10.5
Mix Consistency (ASTM-C143)	Sloppy	Wet or Sloppy	Wet or Plastic

On the other hand, results of the compaction factor test are somewhat similar to the slump test results. Figure 2 shows the revealed compaction factors for different specified mixes. It is clear that the inclusion of fibers in concrete mixes reduces its workability. This is quite expected since the presence of steel fibers may cause some segregation during the free falling of concrete during the test. This is obvious since the compaction factor of the PCC mix (M1) was equal 0.96 which represents a high level of workability. This level has decreased with M2 (SFRC-1) which includes 4% of fibers by cement weight. The resulted compaction factor of such mix was 0.91 which represents a medium level of workability. The addition of more dosage of fibers decreased the compaction factor to 0.84 with 8% steel fiber content. This is representing a low level of workability.

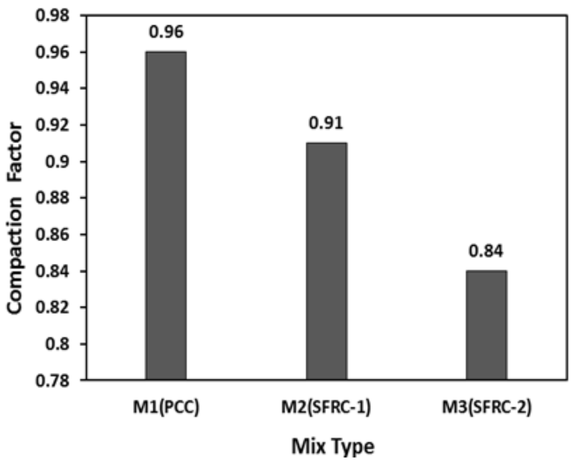

Figure 2. Compaction Factors for Different Investigated Mixes

In addition, the time for the concrete to remold from the slump cone shape to the shape of the outer cylindrical container was recorded through the ve be test. The results revealed a time of 8 seconds required for the PCC mix (M1). This time has increased to 10.5 seconds with the inclusion of fibers with 4% content by cement weight. This time has further increased with 8% fiber content. Figure 3 illustrates the relationship between the recorded time and steel fiber dosage. The dotted line shows the general trend for the effect of steel fiber content on the time for the concrete to remold. The increase in time with the increase in fiber content conveys the loss of workability with addition of steel fibers to the PCC mixes. In general, it can be concluded that consistency as well as workability of fresh concrete affected negatively with the inclusion of steel fibers to PCC mixes.

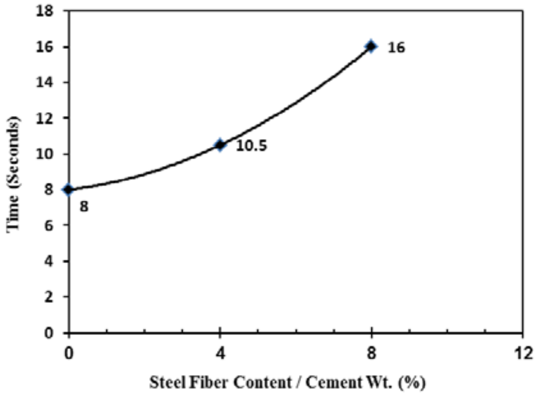

Figure 3. Relationship between Steel Fiber Content by Cement Weight to the Time Required to Remold from Slump Cone to Cylindrical Shape

2.5.2. Compressive Strength Test

All prepared cubic and cylindrical specimens were tested until failure. The results revealed that the inclusion of fibers in concrete enhanced the compressive strength. Table 7 proofs this enhancement where compressive strength was considerably increased for SFRC mixes rather than the PCC mix.

Table 7. Compressive Strengths for Cubes of All Considered Mixes

Curing Time (days)	7	28	56
Mix Designation	Average Compressive Strength (MPa)		
M1(PCC)	24.13	32.08	43.85
M2(SFRC-1)	30.02	36.29	48.36
M3(SFRC-2)	34.92	43.46	51.01

For example, the compressive strength after 7 days has increased from 246 kg/cm2 for PCC mix to 306 kg/cm2 for mix SFRC-1 (4% fiber by cement wt.) and to 356 kg/cm2 for mix SFRC-2 (8% fiber by wt.). Another example, after 28 days, the compressive strength increased by 13% for mix SFRC-1 (4% fiber by wt.) and 35% for mix SFRC-2(8% fiber by cement wt.). It is also obvious through the previous table that the compressive strength for all mixtures increase with the curing period. The same trend has been obtained for cylinder specimens tested for compressive strength and cured for 28 days as illustrated in Figure 4.

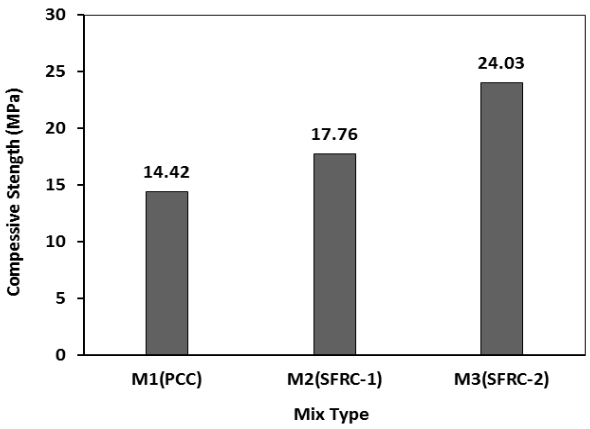

Figure 4. Compressive Strength Results after 28 days for Cylindrical Specimens for Different Investigated Mixes

It is clear that for SFR mixes, the compressive strength for cylinders is about 50% that for cubes which is a similar trend to PCC.

2.5.3. Flexural Strength Test

The maximum flexural load of PCC, SFRC-1 and SFRC-2 beams under static loading was determined. Flexural strength of the specimens was calculated on the basis of elastic theory. Table 8 shows the results of the flexural strength test conducted for all mixes with and without steel fibers. It is clear that the flexural strength has increased by 30% for the mix (M2 = 4% steel fiber content) with respect to PCC. Moreover, the Flexural Strength Ratio w. r. t PCC has become 1.6 for the mix (M3 = 8% steel fiber content). Therefore, the inclusion of steel fibers in PCC is beneficial in increasing the flexural strength which is an important factor in design of concrete pavements.

Table 8. Results of Flexural Strength Test Conducted for All Mixes

Mix Designation	M1	M2	M3
Average Flexural Strength (MPa)	49.05	63.765	78.48
Flexural Strength Ratio w. r. t PCC	1.0	1.3	1.6

2.5.4. Modulus of Elasticity (E-value)

The modulus of elasticity was calculated by dividing the stress corresponding to 33% of maximum cube strength from the stress-strain plot for each mix. The cube strength after 28 days curing was used to determine the E-value for each mix. Table 9 shows the variation of E-values for all mixes (average of the tested three specimens for each mix) where the effect of inclusion of steel fibers to PCC is significantly enhancing the E-value of the mix up to about two times the E-value of PCC. This enhancement can be beneficial in concrete pavement design. It can be expressed as extension in service life if the same thickness of PCC slabs will be used with reinforcement of steel fibers. On the other hand, it can be beneficial in reduction of the thickness of PCC slabs for the same service life.

Table 9. Variation of E-value for All Mixes

Mix Designation	M1	M2	M3
E-Value (GPa)	20	37	48
E-Value Ratio w. r. t PCC	1.0	1.85	2.4

2.5.5. Bond Test Results

The results revealed that the bond strength in pullout test was higher for SFRC than for plain concrete within the limited scope of the investigation. The pullout test revealed that the bond strength has increased from 0.7 N/mm^2 for PCC to o.88 N/mm2 for SFRC-1. Moreover, the steel bars embedded in tested specimens concerning SFRC-2 (8% steel fiber content) have broken while the concrete specimens did not fail. The latter behavior can be explained by the fibers capability to arrest the splitting cracks formed along the embedded length of the steel bar, thereby delayed splitting bond failure. Table 10 summarized the obtained results through pullout test.

Table 10. Bond Strength Values for All Mixes

Mix Designation	M1	M2	M3
Bond Strength (MPa)	7	8.8	Undetermined Since the steel bar has broken without concrete failure
Ratio w. r. t PCC	1.0	1.26	

2.5.6. Indirect Tensile Test Results

The results of the indirect tension test results show an improvement in the indirect tensile strength. Table 11 introduces the obtained results which proofs such improvement. It is clear that the indirect tensile strength increased to 117% with the use of 4% steel fiber content by cement weight of the mix. This increase was doubled with 8% steel fiber content in mix (M3).

Table 11. Results of Indirect Tensile Strength Test Conducted for All Mixes

Mix Designation	M1	M2	M3
Indirect Tensile Strength (MPa)	3.19	3.75	4.31
Indirect Tensile Strength Ratio w. r. t PCC	1.0	1.17	1.35

2.5.7. Ultrasonic Pulse Velocity Test Results

The test was conducted on all types of specimens for both PCC mix and SFRC mixes. It was observed for all specimens that the recorded pulse travel time through PCC specimens is more than the same time recorded for SFRC mixes. This will subsequently, leads to higher pulse velocities with SFRC mixes. This is quite reasonable and expected due to the presence of steel fibers in the concrete mix. The dynamic moduli were computed through Equation 1 where Poisson's ratio was taken equal to 0.2, the unit weight of PCC is 2.2 t/m^3 while, it is 2.5 t/m^3 for reinforced concrete. Therefore, the unit weight of PCC specimens was taken as 2.2 t/m^3. However, it was assumed as 2.3 t/m^3 for specimens of SFRC-1(4% fiber content) and was assumed as 2.4 t/m^3 for specimens of SFRC-2(8% fiber content). The recorded transit times and the computed dynamic moduli are given in Table 12 which shows higher values of dynamic modulus with SFRC-2 than that for SFRC-1and PCC mixes. This is also quite expected since the computed pulse velocity attains same trend. This is also matching with the observed trends of predetermined strength parameters through the previous tests.

Table 12. Recorded Pulse Transit Times, Velocities and Dynamic Moduli for All Tested Specimens for All Mixes

Mix Type	Type of Sample	Length of Specimen (cm)	Transit Time (Micro Sec.)	Velocity (cm/sec.)	Average Dynamic Modulus (E_d)*10^6 kg/m^2	Average (E_d)*10^6 kg/m^2 of All Specimens
PCC	Cubes	15	14	1071428.57	2.32	2.11
	Beams	50	52	961538.46	1.87	
	Cylinders	30	29	1034482.759	2.16	
SFRC-1	Cubes	15	13.6	1102941.18	2.57	2.37
	Beams	50	50.8	984251.97	2.04	
	Cylinders	30	27.6	1086956.52	2.49	
SFRC-2	Cubes	15	13.1	1145038.17	2.89	2.60
	Beams	50	49.4	1012145.75	2.26	
	Cylinders	30	27.3	1098901.1	2.66	

2.6. Effect of Fiber Content

To incorporate SFRC as an alternative for concrete pavements, the effect of fiber content on mechanical properties of concrete should be studied. For the focus of the present study, the results of all conducted tests on all mixes indicated that for maximum benefit, a fiber content of 8% by cement weight shows maximum benefit. This is valid through the enhancement of compressive strength, flexural strength, static E-value, dynamic E-value obtained through ultrasound test, bond strength and indirect tensile strength. Therefore, the steel fiber content of 8% of cement weight was adopted for SFRC specimens used for further tests. It should be reported that, the inclusion of steel fibers of 8% by cement weight shows low workability compared to lower steel fiber content and PCC mixes. This is the only drawback observed with SFRC of 8% fiber content. However, the designer may choose a lower dose of steel fibers such as 4% by cement weight to compromise between workability and strength parameters considerations.

3. Pavement Performance

As illustrated earlier, the concrete pavement slabs were prepared with fiber content of 8% based upon the conducted mechanical tests on all considered mixes. Subsequently, the performance of a pavement slab is evaluated in terms of deflection and load carrying capacity under static plate load tests conducted on three different cases of loading. The cases of loading are considered to simulate the probable positions of wheel loads on a pavement slab. Load-deflection curves were plotted for the different cases of loadings for both PCC mix and the 8% SFRC mix. The load at which first crack started and the failure load are also recorded. These loads as well as corresponding deflections are presented through Table 13.

Table 13. First Crack and Failure Loads and Deflections Recorded through Plate Loading on Pavement Model Slabs

Mix Type	Loading Position	First Crack		Failure	
		Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)
PCC	Corner	102	2.75	119	3.5
	Edge	110	2.25	128	2.75
	Center	150	1.75	160	2.0
SFRC-2	Corner	122	3.25	135	4
	Edge	127	2.5	138	3
	Center	161	2.0	169	2.25

3.1. Load Capacity

Results presented in Table 13 show that SFRC slabs have greater values for both first crack strength as well as failure strength at different loading conditions. It is obvious that the first crack load enhanced by 19%, 15% and 7% for corner, edge and center loading with the use of steel fibers. Similarly, the failure load has also increased with the addition of steel fibers to PCC in such a way that it has become 1.13, 1.08 and 1.05 for corner, edge and center loadings of the pavement model slabs. It should be reported that the observed difference between first crack and failure loads may refer to the localized fiber orientation which cause the slabs to sustain higher maximum load before its load capacity drops down.

3.2. Deflection Characteristics

The corner, edge and center deflection on SFRC slabs was found to have 18%, 11% and 14% respectively, greater than same positions on PCC slabs. This is introduced in Figures 5 and 6. Moreover, the increase in failure deflection with steel fibers was 14%, 9% and 12% for corner, edge and center loading respectively. It should be reported that the deflection of SFRC slabs must be less than or equal to that of plain concrete. The excessive deflection values especially at corners may be associated with the free corners of slabs which usually dowelled to the next corner. Furthermore, shearing of the underlying layers may took place, therefore, one should check the resulting deflection must not exceed the underlying materials vertical strain capacity for all critical load conditions.

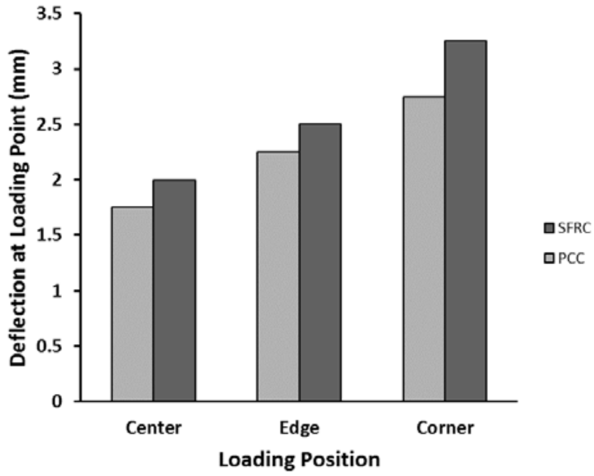

Figure 5. Deflection at Loading Point (at First Crack Load)

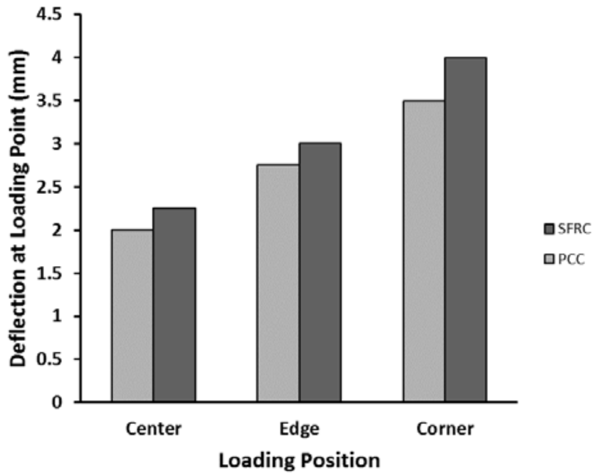

Figure 6. Deflection at Loading Point (at Failure Load)

4. Quantification of Steel Fiber Reinforcement in Rigid Pavements

4.1. Proposed Concept

The load carrying capacity of the SFRC pavements was studied where they are found to be superior to PCC pavements in terms of load carrying capacity or deflection characteristics. The reason for considering steel fibers concrete as potentially advantageous for pavements are attributed mainly to increase in their flexural strength and its association with established relationships for plain concrete with increased service life or reduced thickness.

In the AASHO Road Test Program, service life of a pavement (N) to a serviceability index of 2.5, was related to flexural strength (S_f), and slab thickness (h) by Equation 2.

$$N_{2.5} \alpha\ S_f^4 h^5. \quad (2)$$

Thus, for a given loading condition, increased flexural strength can be used to extend pavement life for a constant thickness or to permit equivalent life to be achieved with reduced thickness. The former tends to increase initial capital cost but reduced subsequently, maintenance costs. The latter offers the possibility of capital cost saving if the reduction in thickness offsets the extra costs associated with the fibers. For this concern, two terminologies are adopted to quantify the benefits of steel fibers reinforcement for concrete pavement systems. The first terminology is the Service Life Ratio (SLR) which may be defined in different terms to represent the gained benefit in specified design element like service life of a SFRC pavement as compared to an equivalent unreinforced pavement (PCC pavement). The SLR can be written in equation form as given by Equation 3.

$$SLR = \frac{N_R}{N_U} \quad (3)$$

where: -N is the pavement service life
-the symbols R and U denote reinforced and unreinforced pavement

The SLR in the above equation is expressed as an extension in service life of the pavement section. By substitution from Equation 2, a direct definition of SLR is deduced based on the flexural strength for both PCC pavement as well as SFRC pavement. Therefore, the SLR can be expressed as given in Equation 4.

$$SLR = \left(\frac{S_{f(R)}}{S_{f(u)}} \right)^4 \quad (4)$$

where: $-S_f(R)$ is the flexural strength of a SFRC section
$-S_f(u)$ is the flexural strength of an unreinforced section (PCC)

The above equation can be used for calculating the extension of the pavement service life when the designer decides to keep the same thickness of the concrete slabs and add the steel fiber to the plain concrete slabs. The second terminology is the Thickness Reduction Ratio (TRR) that defines the reduction in slab thickness for equivalent service life.

$$TRR = 100 \frac{h_U - h_R}{h_U} \quad (5)$$

where: h_U and h_R are the concrete slab thickness of the unreinforced and reinforced pavements, respectively.

To find out the slab thickness for the reinforced section, Equation 2 may be used where the service life of reinforced and unreinforced sections is equal therefore,

$$S_{f(u)}^4 h_{(u)}^5 = S_{f(R)}^4 h_{(R)}^5 \quad (6)$$

The above equation can be used to estimate the slab thickness for reinforced section and subsequently, the TRR can be determined through Equation 5.

4.2. Worked Example

To apply the proposed concept for quantification of steel fibers enhancement to concrete pavements, the following example is worked out for illustrations.

Assume a stretch in a road of 1 Kilometer length and 7.0 m width was constructed of a concrete pavement. If the PCC slab thickness was designed to be 35 cm with a flexural strength of that obtained through the present experimental work which equals to 49.05 MPa. This value was enhanced to 78.48 MPa with the addition of 8% steel fibers by cement content of the concrete mix.

A cost estimation for all constituents of one cubic meter of concrete for both PCC and SFRC (8% Fiber content) was adopted based upon the Egyptian schedule of rates [cost in Egyptian Ponds (E.P)]. These costs were as follows:

- Cost of one cubic meter of concrete required for the unreinforced section = 500 E.P.
- Cost of one cubic meter of concrete required for the unreinforced section = 725 E.P.

There are two strategies in quantification of reinforcement benefits.

Srategy-1: If the designer decides to have an increase in the pavement service life

Equation 4 was used to estimate the SLR which will equal 6.5. This means that the design life of such concrete pavement section has increased to 6.5 times with the inclusion of 8% steel fiber content to the unreinforced section. This is an impressive enhancement.

In terms of cost considerations, the cost of one cubic meter for both reinforced and unreinforced concrete slabs was used to estimate the initial cost of concrete slabs for the proposed example as follows:

- Total cubic meters required for the pavement section (reinforced or unreinforced) = 2450 m^3.
- Cost of concrete required for the unreinforced pavement section = 1.2 Million E.P.
- Cost of concrete required for the reinforced pavement section = 1.7 Million E.P.

It is clear that the initial cost increased by 41% with the inclusion of steel fibers to the plain concrete. This is a considerable increase in the initial cost but the pavement service life at the same time doubled multi times.

In terms of saving in the natural resources, this strategy keeps the same pavement section for both reinforced and unreinforced cases which means there will no saving in the natural resources especially for aggregates.

Srategy-2: If the designer decides to keep the same pavement service life

Equation 6 was used to estimate the concrete slab thickness for reinforced section. By substitution, h(u) equals to 35 cm, Sf(u) and Sf(R) equal to 49.05 MPa and 78.48 MPa respectively. Therefore, the resulted slab thickness for the reinforced concrete pavement section with 8% steel fiber content was 17cm. This can be quantified through the term TRR as given in Equation 5 leading to TRR equals to 51.4%. This means that for the same pavement service life, there was a reduction in the pavement thickness and subsequently, the initial cost of near about 50% with steel fiber reinforcement of 8% fiber content by weight of cement.

Considering the initial cost estimation, the Cost of concrete required for the unreinforced pavement section was the same as calculated in strategy-1 (1.2 Million E.P).

- Total cubic meters required for the reinforced pavement section = 1190 m^3.

- Cost of concrete required for the reinforced pavement section = 0.86 Million E.P.

It is obvious that the initial cost decreased by 28% with the steel fiber reinforcement of concrete slabs which considered as a good economical contribution.

Moreover, the saving in virgin materials collected form natural resources like, aggregates required for the concrete used in the pavement section was also quantified as follows:

- Difference in cubic meters of concrete required for both reinforced and unreinforced sections = 1260 m^3.

- Saving in coarse aggregates required for concrete of the unreinforced pavement section = 491.4 m^3

- Saving in coarse aggregates required for concrete of the unreinforced pavement section = 315 m^3

This means each one kilometer of the road can save the illustrated amounts of natural aggregates. This is considered as a double benefit since the initial cost has rustically decreased. Moreover, it is also beneficial in terms of saving of the natural resources.

It should be emphasized that the proposed technique gives the designer two alternatives and he has to optimize the best alternative based on his priorities. If the service life is considered, he will choose the first alternative despite its high initial cost. If the funds are not available and initial cost is controlling, he has to choose the second alternative.

5. Conclusions

- The workability of SFRC is less sensitive to low steel fiber dosage and the sensitivity increases with the increase of the dosage.
- The incorporation of steel fibers to PCC results in an appreciable increase in compressive strength for different curing times. The increase has ranged from 10% to 45%. Moreover, the increase was less with low steel fiber dosage and was more with the increase of the dosage.
- The inclusion of steel fibers in PCC is beneficial in increasing the flexural strength which is an important factor in design of concrete pavements. Flexural strength has improved up to 60% as compared to PCC.
- A tremendous enhancement was achieved in static E-values which can be beneficial in concrete pavement design. E-values have almost doubled with steel fiber reinforcement.
- Indirect tensile and bond strengths have also followed the same resulted trend in which a considerable increase has achieved with the increase of steel fiber dosage.
- The dynamic modulus of elasticity determined through ultrasonic testing on different concrete specimens has also got an increase of 25% with a steel fiber content of 8% by cement weight.
- A fiber content of 8% of cement content was selected for reinforcement of the model slabs since it has given the highest values with different strength parameters of concrete.
- SFRC pavement slabs had a gradual or slow failure mechanism compared to plain concrete slabs.
- The gain of strength for the SFRC is higher than that for plain concrete since, the first crack load had enhanced by 19%, 15% and 7% for corner, edge and center loading respectively, with the use of steel fibers.
- The failure load has also increased with the addition of steel fibers to PCC in such a way that it has increased by 13%, 8% and 5% for corner, edge and center loading of the pavement model slabs respectively.
- The pavement service life of the SFR section increased to 6.5 times rather than the unreinforced section.
- For the same pavement service life, the thickness of SFR section reduced by about 50% of thickness of the unreinforced section.
- The reinforcement of concrete pavements with steel fibers may be considered as a good economical alternative. Not only, is the reduction of the construction costs expected but also, in terms of saving of natural resources.

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