Properties and Design of Fiber Reinforced Roller Compacted Concrete

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Extensive experimentation in pavement construction has been conducted using steel fiber reinforced concrete (SFRC). Although SFRC has demonstrated outstanding mechanical properties, its commercial application has been limited because of high cost. Cost savings could be realized for paving projects constructed with the emerging roller compacted concrete (RCC) technology. In particular, pavement thickness reduction due to the inclusion of fibers in RCC can allow single-lift construction where two lifts of unreinforced concrete would be required. Alternatively, for two or more lifts, SFRC can be confined to the most stressed layer(s). This paper presents compression and split tension results of laboratory cylinders and field cores reinforced with different types of steel fiber in various percentages. The concrete matrix contained fly ash, either Class F (used as a filler) or Class C (used as a binder). Fiber inclusion disturbed the consolidation of laboratory specimens, whereas field cores did not indicate any loss of density or compressive strength. Post-cracking characteristics were greatly enhanced by fibers with ultimate strength and toughness indexes derived from stress-strain curves for split tension. Sample design calculations compare the preliminary pavement thickness of unreinforced and fiber reinforced RCC with cost estimates for each.

The inclusion of fibrous reinforcement in concrete to produce a better construction material is an important development of concrete technology. Extensive experimentation has been conducted on various types of fiber (such as steel, glass, asbestos, synthetic, and natural), and basic properties of the composite material behavior have been obtained. However, the number of applications of fibrous concrete remains limited as a consequence of side effects, which invariably accompany the use of each fiber and detract from its merits (*1*). Examples are cost (steel), durability (glass), health hazard (asbestos), low modulus (synthetic), and fire resistance (natural).

Steel fiber primarily has been used in highway and airport pavements because it improves the mechanical characteristics of the concrete matrix (*2*), for example, flexural (tensile) strength, toughness, fatigue endurance, post-cracking ductility (pseudo-ductility), and impact resistance. Flat work construction is an attractive research topic for two reasons: large amounts of materials are used with consequent economical implications; and innovative technology can be readily explored, since this type of structure can take a comparatively greater risk than others. In recent years, several publications (*3–7*) have reviewed the performance of steel fiber reinforced concrete (SFRC) pavements constructed during the 1970s and early 1980s. From these evaluations, it is apparent that the overall performance has been satisfactory, though failures have been experienced in four areas (*4*): corner curling and warping, improper jointing, load transfer between adjacent slabs, and exposed fibers.

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Finally, the use of SFRC has not emerged as a viable alternative to conventional plain concrete paving for economical reasons (*1*). Predicted savings have not materialized, and this situation is not likely to change if specifications, such as those presently adopted by the Navy (*7*), do not allow pavement thickness reduction when plain concrete is substituted with SFRC.

NEW DEVELOPMENTS

Roller compacted concrete (RCC) paving (*8*) may represent a new opportunity for using concrete at a competitive cost that inherently contains its own reinforcement. It has been demonstrated that construction of steel fiber reinforced RCC (FRRCC) is feasible (*9*), because steel fibers can be included and randomly distributed in the concrete matrix by a pugmill mixer (i.e., continuous mixing). Furthermore, FRRCC can be laid by a heavy-duty paver without losing compaction efficiency.

The merging of these two technologies produces mutual benefits. A pavement thickness reduction due to the use of fibrous reinforcement is particularly advantageous in multi-lift RCC construction. Not only can the number of lifts be reduced, but when pavement thickness requires more than one lift, the use of fibers can be confined to the lift(s) subjected to the maximum stress (*10*). Plain RCC is currently laid without contraction joints or with saw-cut joints having no load-transfer device. FRRCC pavements without joints would exhibit different cracking behavior from plain RCC. Fewer, and therefore wider, cracks would not be desirable. The fiber micro-dowel action at the saw-cut joints can enhance the aggregate interlock load transfer between adjacent slabs. Fibers bridging the crack will experience corrosion (*11*); therefore, the use of larger diameter fibers is appropriate. Mix constituents and proportions of RCC correct the major defect (i.e., corner warping and curling) encountered in conventional SFRC pavements (*5*). In fact, low cement factor, use of fly ash, and very low mixing water substantially reduce autogenous shrinkage, heat of hydration, and, to a lower extent, dry shrinkage.

EXPERIMENTAL PROGRAM

Series A (South-Florida Limestone, Class F Fly Ash)

The matrix constituents for this series were portland cement Type I, Class F fly ash, and crushed South-Florida limestone

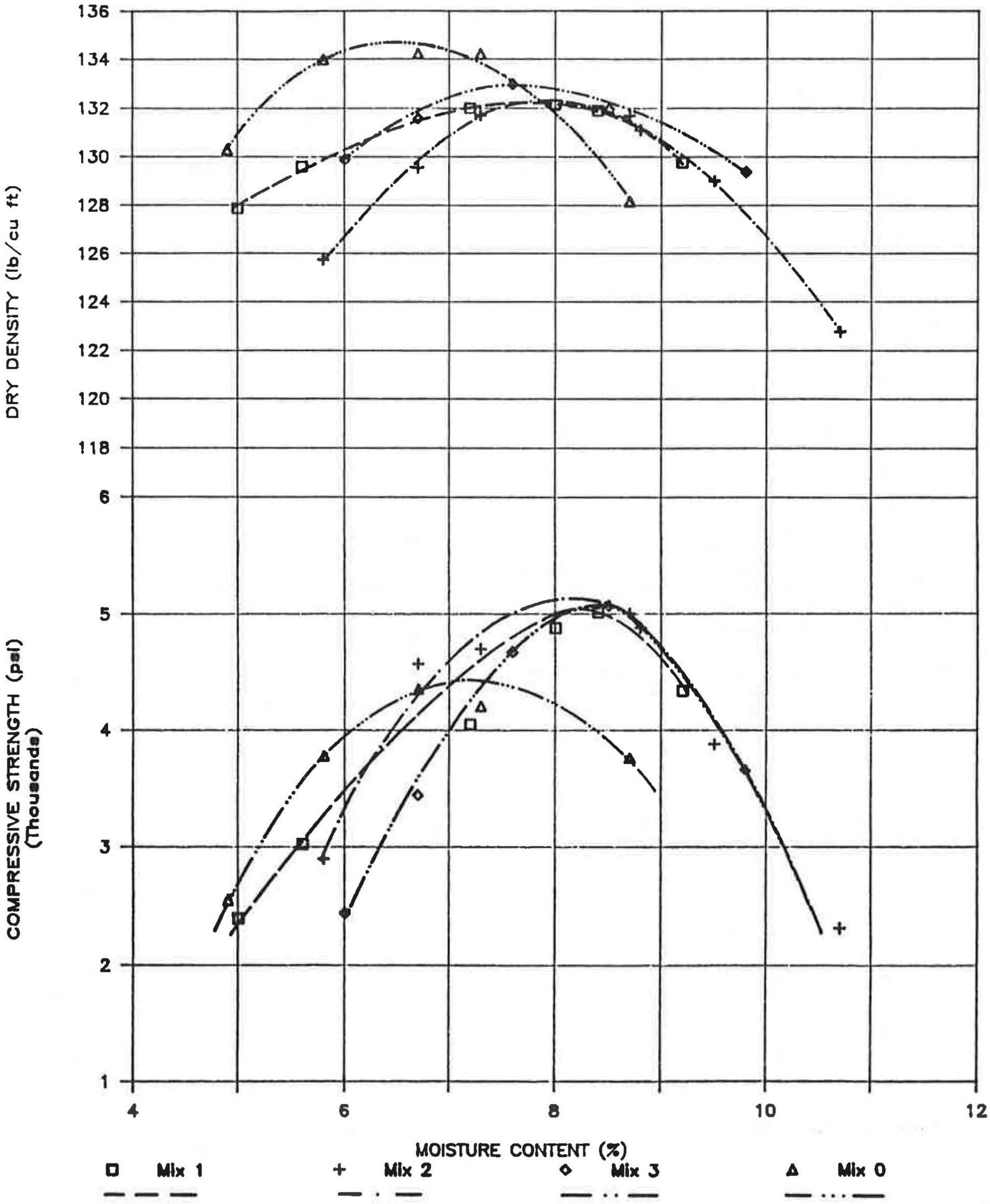

FIGURE 1 28-day compressive strength and initial dry density vs. moisture content (series A, 12 percent cement).

aggregate. The fine and coarse aggregate complied with ASTM D-448 sizes 10 and 57, respectively.

Selection of Matrix Proportions

Several combinations of mix constituents were investigated to empirically determine the proportions that would optimize density and compressive strength. In this instance, Class F fly ash was used as a filler. The objective was to improve mix compactability, since pozzolanic reaction of low calcium ash is negligible at 28 days. Each selected mix was compacted according to the modified Proctor method (ASTM D-1557, 4 in. × 4.5 in. mold) at five different moisture contents. Figure 1 shows the results obtained for some of the mixes with 12 percent by dry weight of cement. Both 28-day compressive strength and dry density at fabrication are plotted as a function of the initial water content. The properties relative to the

TABLE 1 MATRIX PROPORTIONS, DENSITY, AND STRENGTH (SERIES A)

Mix	Type I Cement (%)*	Class F Fly-ash (%)*	Fine Aggregate (%)*	Coarse Aggregate (%)*	Total Water (%)*	Initial Dry-Density (lb/cu.ft)	Cement Factor (lb/cu.yd)	W/C** Ratio	28-Day Compressive Strength (psi)
0	12	0	40	48	6.7	134.3	435	0.29	4356
1	12	6	46	36	8.4	131.9	427	0.45	5013
2	12	6	37	45	8.7	131.7	427	0.47	5005
3	12	6	32	50	8.5	132.0	428	0.46	5071
5	12	12	35	41	8.0	129.4	419	0.43	4151
8	12	18	32	38	8.9	125.3	406	0.52	3841
11	12	24	29	35	9.0	125.7	407	0.55	3572

* Percent of Total Dry Weight

** Aggregate Water Absorption: Fine=3.4%, Coarse=3.9%

mixes with the highest compressive strength are presented in Table 1 under mix denominations 0, 1, 2, and 3. From this data, it is evident that: (a) varying the coarse to fine aggregate ratio between 0.8 and 1.6 (Mixes 1, 2, and 3) does not significantly affect strength or density, and (b) including 6 percent by dry weight of Class F fly ash improves compactability, and therefore strength, despite a higher water to cement ratio.

Compressive strength results of other mixes (i.e., mixes 5, 8, and 11) reported in Table 1 indicate that addition of fines in the form of fly ash is not beneficial at a cement content of 12 percent.

Properties of Laboratory FRRCC

Mix 2 was selected as the matrix for fiber reinforced specimens. Three types of steel fibers were used: straight slit sheet (SS), hooked-end wire (HE), and mill cut bar (MC). The fiber length was limited to 1 in. because of the overall cylinder dimensions (4 in. × 4.5 in.). The aspect ratio (L/D) of the three fibers was 60, 60, and 30, respectively. The fiber content by volume (V) varied between 0 and 1.64 percent (i.e., 0 and 6 percent by weight). Test results of specimens compacted according to the modified Proctor method at an average moisture content of 7.6 percent (standard deviation = 0.3 for 90 specimens) are shown in Figure 2. The lower part of the diagram indicates that the matrix dry density at fabrication decreases with fiber dosage expressed in terms of the VL/D factor (volume percentage × aspect ratio). The 28-day compressive strength as plotted in the central part of the diagram reveals the same trend. This is a clear indication that the presence of fibers disturbs laboratory consolidation. Even though the quality of the matrix is lowered, the ultimate split tensile strength at 28 days increases with the VL/D factor, as shown in the upper part of the diagram.

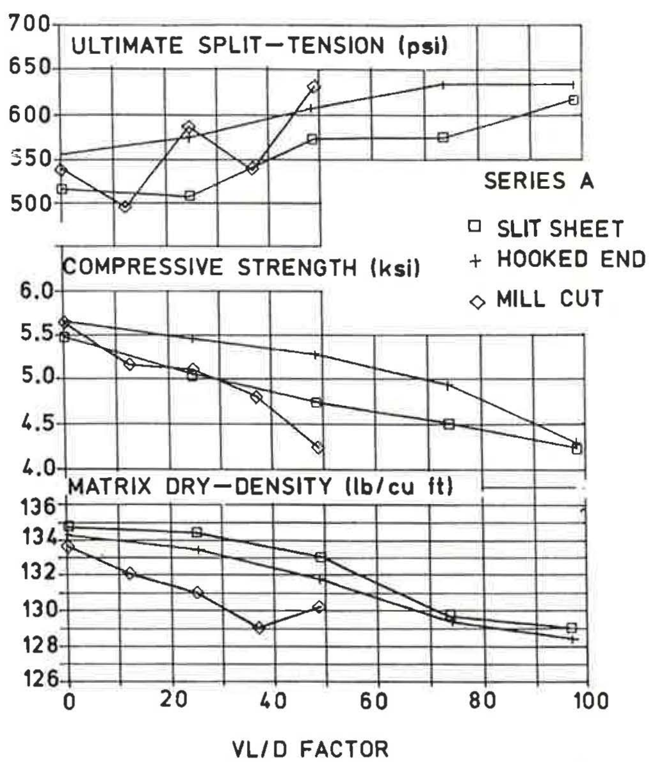

FIGURE 2 Dry density, compression strength and ultimate split tension vs. VL/D factor (series A).

The average 28-day split tension stress-strain curves for cylinders reinforced with fiber type HE are given in Figure 3. Deformation is measured along the diameter perpendicular to the load plane, and stress is computed according to ASTM C-496. The diagram illustrates the lack of improvement in first crack strength. This is due to fiber inclusion,

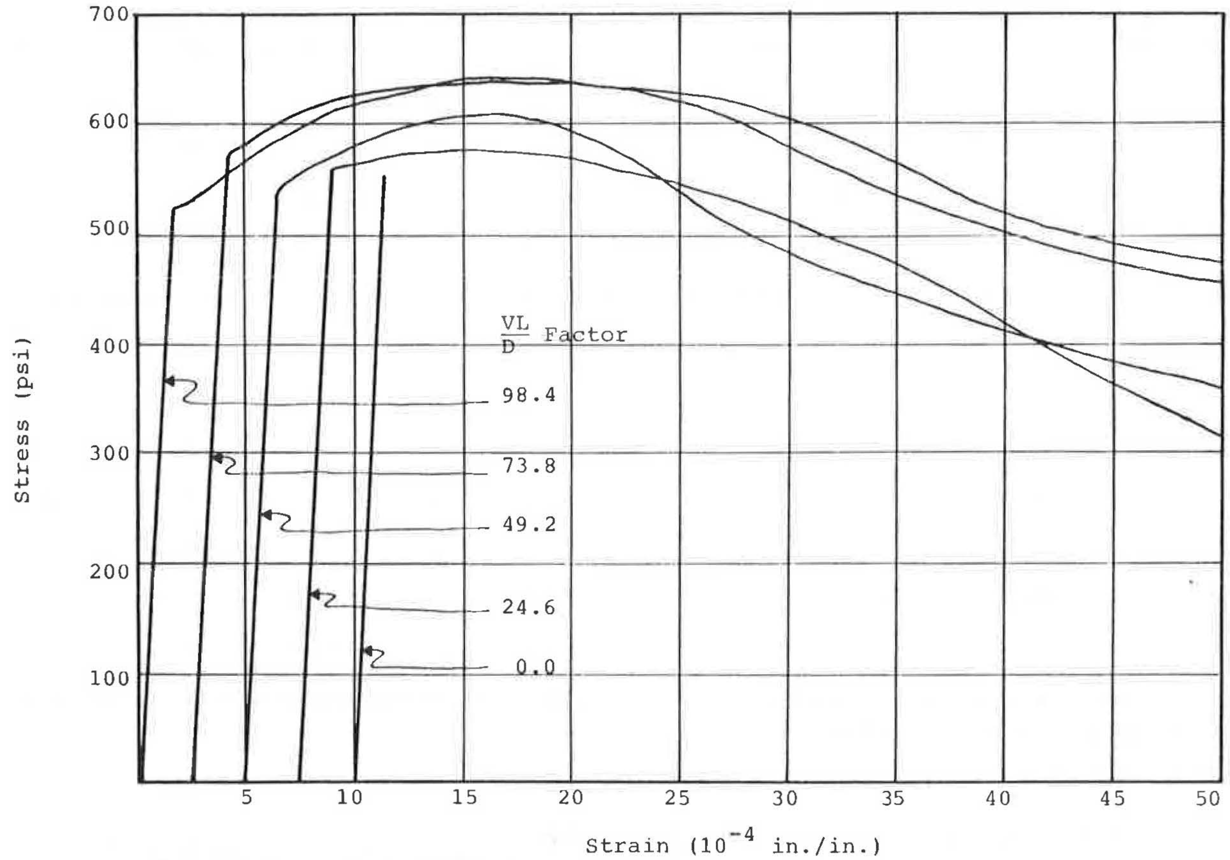

FIGURE 3 Stress-strain curves for split tension (series A, fiber HE).

since the matrix has become less dense. However, the post-cracking behavior is significantly affected by the presence of fibers in terms of ultimate strength and pseudo-ductility. The same conclusion can be reached by considering Figure 4, where the toughness indexes I_5, I_{10}, and I_{30} are computed for the flexural test (ASTM C-1018) and plotted as a function of the VL/D factor.

Series B (Texas Limestone, Class C Fly Ash)

The matrix constituents and proportions were selected based on a successful field project (*12*, p. 14). Portland cement Type I and Class C fly ash were used in equal amounts of 260 lb/yd^3 and fine and coarse aggregates in equal amounts of 1,610 lb/yd^3. The total water content was 5.9 percent by dry weight (standard deviation = 0.25 for 63 samples).

Properties of Laboratory FRRCC

Three types of steel fiber were used in this series. Two types were previously described as SS and HE, whereas the third type was a crimped slit sheet fiber (CR), 1 in. long and with an aspect ratio of 60. Test results on laboratory-fabricated specimens are given in Figure 5 as a function of fiber dosage. These data confirm what is presented in Figure 2 for Series A. In particular,

- The matrix dry density decreases as the VL/D factor increases,
- The first crack split tensile strength remains practically unchanged, and
- The ultimate split tensile strength is directly proportional to the VL/D factor.

The average 28-day split tension stress-strain curves for cylinders reinforced with fiber type SS are reported in Figure 6.

FRRCC Field Cores

Test results under split tension of field cores with identical matrixes and reinforced with 0.49 percent by volume of fiber type SS are reported in Figure 7. These results emphasize the primary difference between field cores and laboratory-fabricated specimens. Testing was conducted between 28 and 39 days from construction. Field inclusion of fibers in RCC neither disturbed consolidation nor compromised the resulting density and compressive strength (*9*). As a consequence, the first crack strength of FRRCC cores (Figure 7, curves a and c) is appreciably higher than that of corresponding unreinforced RCC (Figure 7, curve e). Also, two curves (b and d) relative to specimens cored from the bottom half of the pavement lift, which had a dry density 4 to 5 percent lower than that of the top half (*9*), are reported in the figure. This condition is common in plain RCC pavements constructed with double-screed double-tamping bar pavers (*13*). Based on these results, it was concluded that compaction of fibrous concrete obtained in the laboratory using the Proctor hammer is representative of the lower portion of the pavement lift.

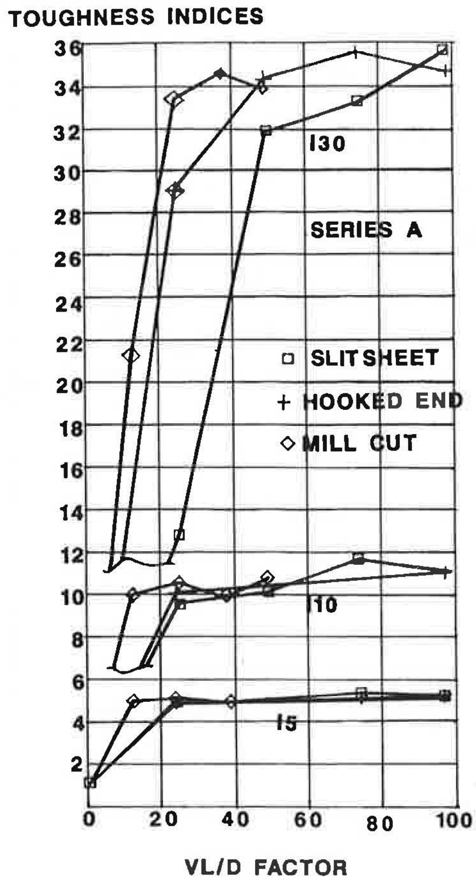

FIGURE 4 Split tension toughness indexes (series A).

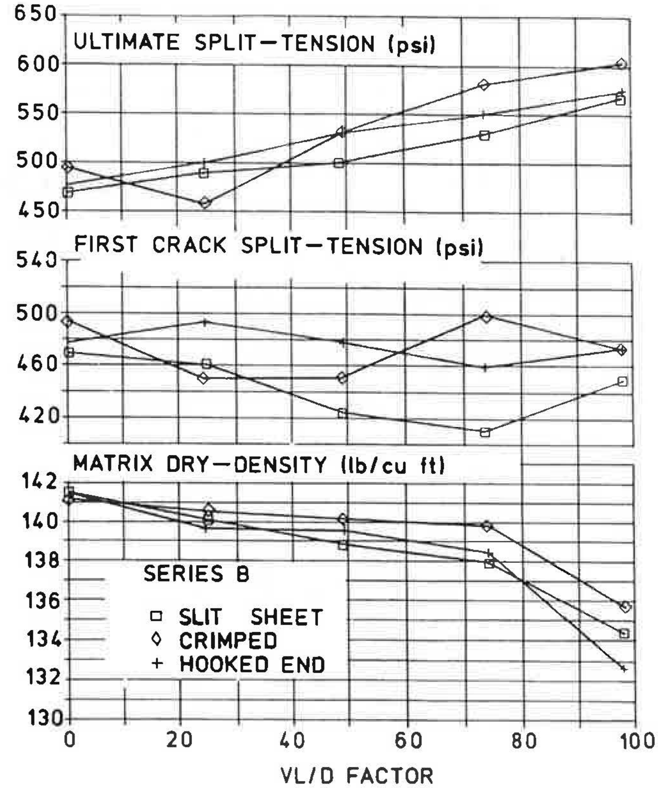

FIGURE 5 Dry density, first crack split tension, and ultimate split tension vs. VL/D factor (series B).

DESIGN EXAMPLES

Pavement Thickness

The two pavement thickness design examples reported below illustrate a comparison between conventional and FRRCC. The following assumptions are common to both examples:

	RCC	*FRRCC*
Design flexural strength (psi)	660	660
Modulus of elasticity (10^6 psi)	3.80	3.80
Steel fiber content (lb/yd^3)	—	100
Fatigue life	Figure 8	Figure 8
Modulus of subgrade reaction (Subgrade + 6 in granular base) (pci)	140	140

Both unreinforced and fiber reinforced RCC are assumed to have the same first crack strength, which is equal to 660 psi. Since the first crack strength of SFRC is higher than that of the corresponding unreinforced matrix (*9, 16, 17*), this assumption is conservative for the FRRCC alternative. A major benefit of fiber inclusion in concrete is the improved fatigue life. Design data for the two alternatives were derived from the literature as presented below. RCC flexural fatigue performance is reported to be quite similar to that of conventional concrete (*14*). This evaluation by the Portland Cement Association (PCA) was based on field beams of four different RCC mixes. Values of the stress ratio (load stress modulus of rupture) as a function of allowable load repetitions were derived according to the design procedure used by PCA for conventional airport and highway concrete pavements (see Figure 8).

Figure 8 also shows the derived design data from tests conducted at the South Australian Institute of Technology (*15*) on SFRC with 125 lb/yd^3 of fibers. This stress ratio to load repetition relationship is considered appropriate even if derived for conventionally cast SFRC; more recent research (*17*) indicates higher endurance values for smaller amounts of fibers with mechanical anchorage.

The pavement thickness is determined by stress values computed with the PCA microcomputer program (*18*), which is based on Westergaard's modified analysis for loads at the interior of a slab. Similar pavement thickness values for unreinforced RCC are determined using the modified Corps of Engineers design method for airports (*19*). For the purpose of this comparison, no consideration has been given to the problem of load transfer at construction joints and natural or saw-cut contraction joints (*20*) or to the case of vehicles traveling close to the pavement edge (*14*).

Heavy-Duty Freight Yard (20-Year Life)

For heavy-duty freight yards, the problem data are as follows:

Vehicle type	*Piggypacker loader*
Single wheel load (kip)	110
Tire inflation pressure (psi)	100
Tire contact area (in^2)	1,090
Total wheel load applications	20,000

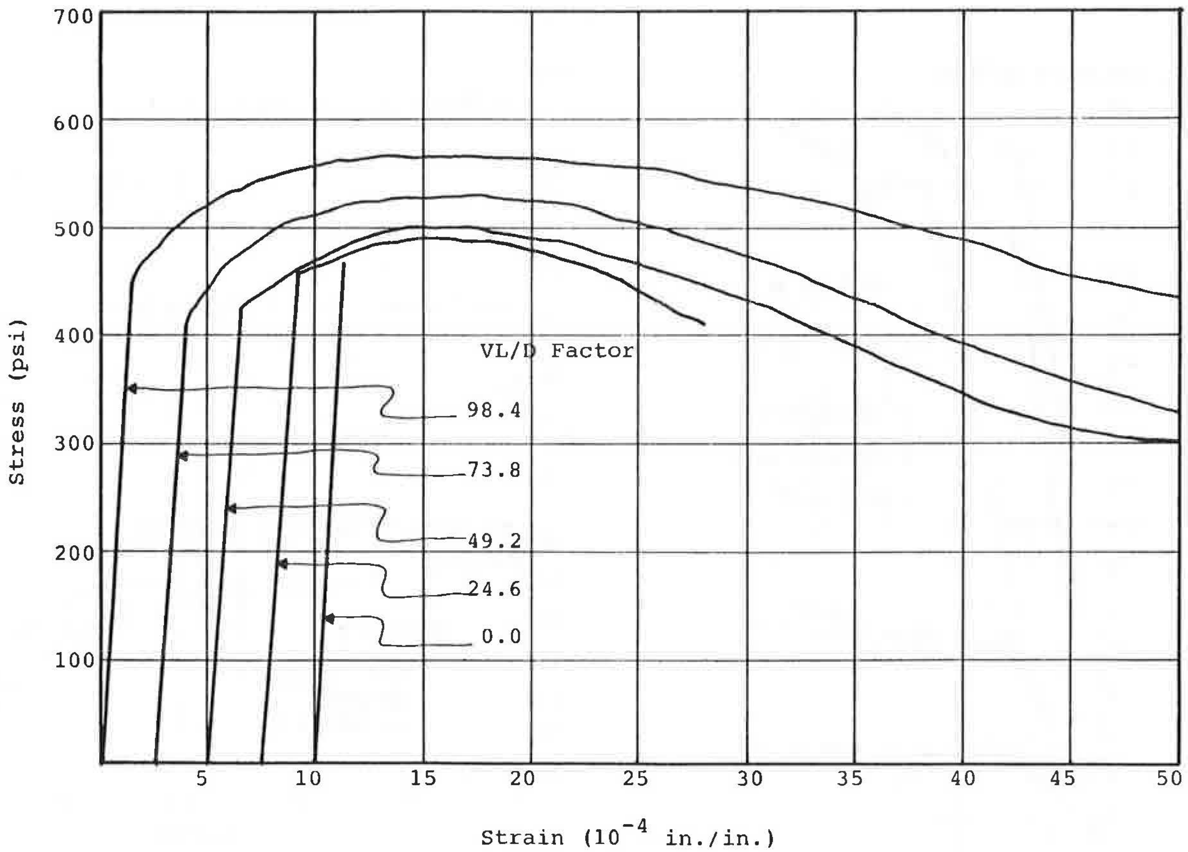

FIGURE 6 Stress-strain curves for split tension (series B, fiber SS).

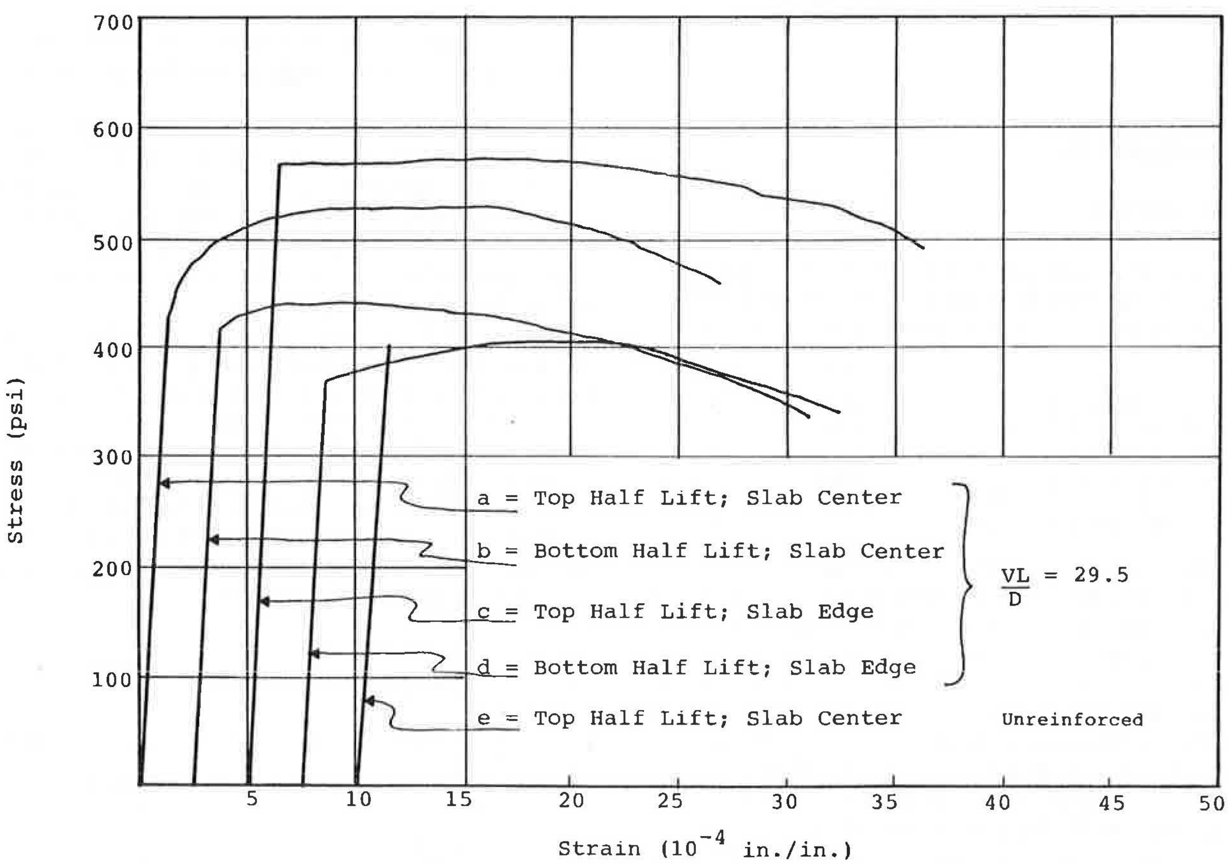

FIGURE 7 Stress-strain curves for split tension (field cores, fiber SS).

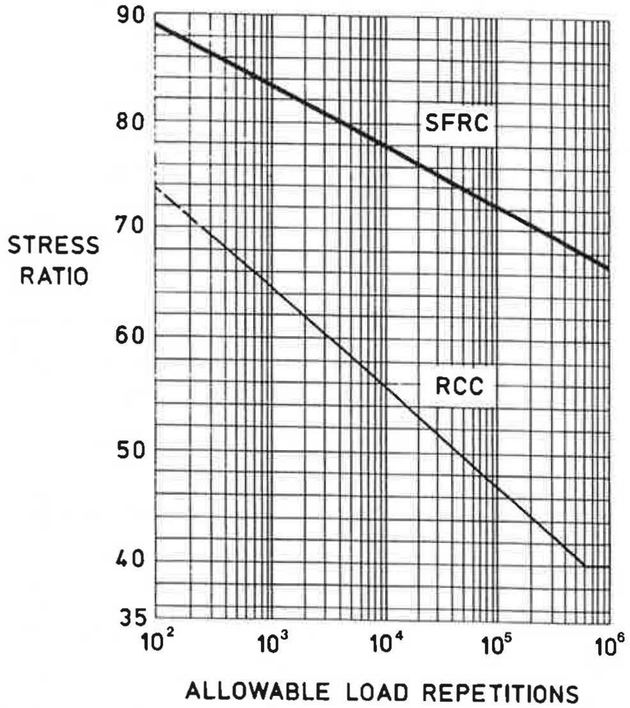

FIGURE 8 Stress ratio vs. allowable load repetitions.

The design results are:

	RCC	*FRRCC*
Pavement thickness (in.)	18.0	14.0
Maximum stress (psi)	343	511
Allowable stress (psi)	660 × 0.53 = 350	660 × 0.77 = 508

The reduction in pavement thickness due to the inclusion of fibers is 22 percent.

Industrial Pavement (20-Year Life)

For industrial pavement, the problem data are:

Vehicle type	*Straddle carrier*
Single wheel load (kip)	26
Tire inflation pressure (psi)	100
Tire contact area (in^2)	260
Total wheel load applications	200,000

The design results are

	RCC	*FRRCC*
Pavement thickness (in.)	10.5	7.5
Maximum stress (psi)	281	486
Allowable stress (psi)	660 × 0.44 = 290	660 × 0.72 = 475

The reduction in pavement thickness due to the inclusion of fibers is 29 percent.

Cost Analysis

The following costs have been estimated for paving projects of approximately 20,000 yd^2 of surface. Based on field experience with heavy-duty pavers, the lift depth range for acceptable compaction is between 4 and 8 in (*21*). Listed below are the unit costs per square yard of paved surface:

Concrete	\$1.50/in. of lift depth
Fibers (@ 100 lb/yd^3)	\$1.10/in. of lift depth
Mixing/placing/curing	\$3.00 + \$0.25/in. of lift depth

Heavy-Duty Freight Yard

Due to required pavement thickness, the unreinforced RCC pavement is constructed in three lifts (8, 5, and 5 in.) and the FRRCC in two lifts (8 and 6 in.), the top of which is plain RCC. In the latter case, the use of two types of mix in the same project is not necessarily impractical even when pugmill mixers are used. In fact, the addition of fibers does not require a modification of mix proportions or plant recalibration. Costs are as follows:

RCC

8.0 × \$1.50 + \$5.00 = \$17.00
5.0 × \$1.50 + \$4.25 = \$11.75
5.0 × \$1.50 + \$4.25 = \$11.75
\$40.50

FRRCC

8.0 × (\$1.50 + \$1.10) + \$5.00 = \$25.80
6.0 × \$1.50 + \$4.50 = \$13.50
\$39.30

The FRRCC alternative is 3 percent cheaper.

Industrial Pavement

Due to required pavement thickness, the unreinforced RCC pavement is constructed in two lifts (6 and 4.5 in.) and the FRRCC in one lift (7.5 in.). Costs are as follows:

RCC

6.0 × \$1.50 + \$4.50 = \$13.50
4.5 × \$1.50 + \$4.12 = \$10.87
\$24.37

FRRCC

7.5 × (\$1.50 + \$1.10) + \$4.87 = \$24.37
\$24.37

As shown, the two alternatives have identical costs.

CONCLUSIONS

In this paper, the existence of post-cracking strength and pseudo-ductility of RCC resulting from the inclusion of steel fiber reinforcement is shown. All fibers tested indicated that post-cracking performance is directly proportional to fiber content. This study was limited to one length of steel fiber; longer and thicker fibers should be included for a more complete coverage of the cost-performance ratio. The performance of field cores was better than that of equivalent laboratory-fabricated samples because fiber presence does not disturb the consolidation efforts of both paver and roller.

Based on improved fatigue life, inclusion of fibers in RCC results in pavement thickness reduction. Savings in material and construction costs compensate for the additional cost of fibers. In the given examples, improvement in first crack strength due to the presence of fibers was not considered. Fiber content may be lowered depending on the type of fiber.

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