

# Strength and Life of Stabilized Pavement Layers Containing Fibrillated Polypropylene

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Laboratory and field results are presented indicating that discrete, fibrillated fibers mixed with chemically stabilized sand or clay soils improve the life of those materials in pavement layers. The improvement can be seen in axial compression stress-strain curves as an increase in both modulus and strength. In some cases, the fibers appear to alter the material response by moving from a strain softening response toward a response analogous to strain hardening.

Flexible pavement base courses, rigid pavement subbase courses, and gravity wall retaining structures that are used in the construction of transportation infrastructure must perform effectively while being subjected to a variety of stresses and a wide range of environmental conditions. Often, a process of improving locally available soils by the use of chemical or mechanical stabilization is used to meet the challenge posed by these conditions. When chemical stabilization is used to decrease the potential for a pavement to rut or pump, or if it is used to help a gravity wall structure resist the undesirable effects of differential movement of the subgrade, a conscious choice is being made to trade flexibility for strength and stiffness. The improvement in stiffness is desirable only to the extent that it can be maintained in service without cracking, eroding, or losing internal friction. This means that the material should not be subjected to any conditions that will cause its strain response to exceed the limit of elastic behavior. Once the elastic limit is exceeded, most chemically stabilized materials enter into the strain-softening portion of their characteristic stress-strain curve. The descending branch for the silty sand tested in this study containing 9 percent portland cement is quite steep, and this softening is often attributed to microcracking and crack coalescence. The same soil has been stabilized with 5 percent portland cement and 0.5 percent fibrillated polypropylene fibers. The fiber material retains approximately the same initial tangent modulus as the material having a higher stabilizer content and containing no fiber, but the descending branch is more gradual, indicating the potential importance of the fibers in controlling cracking.

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## FIBER CHARACTERISTICS

The fibers are constructed from parallel oriented long-chain polypropylene. In the manufacturing process, tapes of the material are caused to split lengthwise in such a way that crossover segments are left intact to connect the coarser stem fibrils. The resulting fiber, when stretched perpendicular to the direction of the long-chain polymer, looks like a miniature mesh with a diamond-shaped pattern. The fibers used in this study were approximately 2.54 cm (1 in.) long, 0.254 cm (0.1 in.) wide, and 1000 denier. Table 1 summarizes other properties of the fibers.

## LABORATORY ASSESSMENT OF COMPOSITE MIXTURE CHARACTERISTICS

Several types of tests were conducted on the materials by different laboratories. Studies included different compaction efforts, confined and unconfined compressive strengths, and basic soil properties of the two soil materials chosen for the study. Basic properties of the clay found at the field site and a select sand material are given in Table 2.

In the laboratory, the mixing procedure was slightly different for the clay and sand materials. The sand was mixed with a wire wisp, whereas the clay required a stiffer mixing blade. The fibers "opened up" from the shape as manufactured to the deformed "grid" shape quickly in the sand mixtures. The clay required a slightly longer mixing time and a fairly gradual addition of water during mixing to minimize the amount of caking on the mixing tools.

Figure 1 shows the variation in maximum dry unit weight and optimum moisture content with fiber content in the unstabilized clay and sand. Apparently, there is an optimum fibers-density curve analogous to the familiar moisture-density curve that can be used in conjunction with other laboratory tests to select fiber content. The reason for this optimum is uncertain. Because the fibers have a lower specific gravity than the soils, one might expect that the introduction of fibers would always decrease the unit weight of soil mixtures. However, the interactions among the soil, the shearing action of the mixer, the compaction technique, volume fractions of the components, and the frictional characteristics of the components of the composite material produce an optimum response as shown in the figure so that unit weight has a peak value (assuming the absence of systematic errors). These curves are the result of testing materials compacted at a nominal com-

TABLE 1 Fiber Properties

PROPERTY	VALUE
Specific gravity	0.91
Tensile strength	552-758 MPa (80-110 ksi)
Modulus	3.5 GPa (508 ksi)
Melting point	162°C (324°F)
Ignition point	593°C (1100°F)
Absorption	Nil
Acid and salt resistance	High
Alkali resistance	High
Electrical conductivity	Low

TABLE 2 Soil Properties

PROPERTY	CLAY	SAND
Classification	CL-CH	SM
Specific gravity	2.694	2.500
Plasticity index	22	nonplastic

paction energy of 2,693 kJ/m<sup>3</sup> (56,250 ft-lb/ft<sup>3</sup>, 100 percent of ASTM D1557).

Specimens of the materials were compacted for strength testing using approximately 44 percent of ASTM D1557 nominal compaction effort with a cylindrical mold 15.24 cm (6 in.) in diameter by 20.32 cm (8 in.) tall. This compaction effort

is similar to the effort used in Texas and lies between modified (ASTM D1557) and standard Proctor efforts (ASTM D698, which is approximately 22 percent of modified effort). Various combinations of the components with and without stabilizers and fibers and with varying percentages of the stabilizers and fibers were tried. The stabilizer selected for the sand was portland cement, and that selected for the clay was hydrated lime. Cement-stabilized sand was cured for 7 days at 22.8°C (73°F), whereas the lime-stabilized clay was subjected to an accelerated curing process using a temperature of 48.9°C (120°F) for 48 hr followed by cooling at 22.8°C (73°F) for 24 hr before testing. The strength tests were conducted in a Texas triaxial cell using a 34.5-kPa (5-psi) confining pressure and a controlled displacement rate of 0.006 cm/sec (0.135 in./min). (The Texas cell uses a thick rubber membrane and applies pressure only to the curved surface of the specimen. Therefore, the applied axial stress is the major principal stress, not the deviatoric stress.) Figure 2 shows results for clay and sand. For both materials, the fibers increased the modulus of elasticity, the strength, and the strain energy density (which is basically the area under the stress-strain curve). (The analysis performed in this paper assumes that integration of the full tensor is not required and that the area under the stress-strain curve yields a value for strain energy density that is adequate for use in the study.) Implications are that simultaneously increasing the modulus and the strength may delay the onset of failure, whereas an increase in strain energy may help slow down the failure process once it has started.

Interesting indications of the effects of the various mix components on the measured strain energy density (*W*, computed between strain levels of 0 and 0.05) from the strength tests are shown in Figure 3. In Figure 3a, it appears that the addition of fibers to the soils with no stabilizers results in a recognizable trend in the strain energy density with fiber content. However, the directions of the trends are opposite for the two types of soil. The increasing trend with increasing fiber content in the sand might be expected on the basis of speculation. The decreasing trend seen in the clay may be a manifestation of the characteristics of the mixing or compaction equipment and procedures. Alternatively, a phenomenon similar to bulking may be at work. In Figure 3b, it is seen that strain energy density can be related linearly to the port-

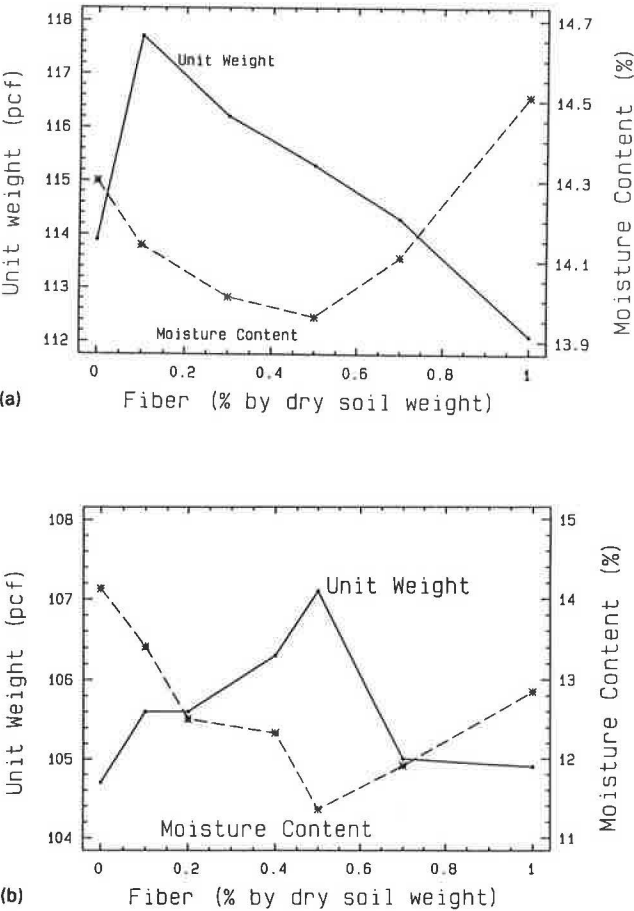


FIGURE 1 Optimum fibers-density (solid) and fibers-moisture (dashed) curve for (a) clay material [115 pcf (18.1 kN/m<sup>3</sup>)] and (b) sand [106 pcf (16.7 kN/m<sup>3</sup>)].

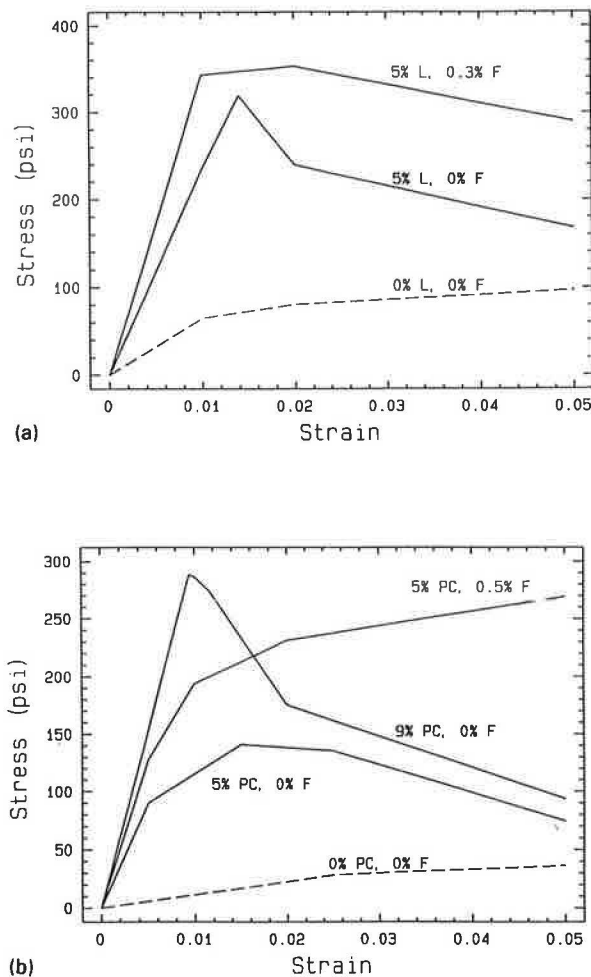


FIGURE 2 Stress-strain curves for (a) clay [300 psi (2.1 MPa)] and (b) sand [200 psi (1.4 MPa)].

land cement content of the stabilized sand mixtures used in this study. However, the clay appears to show a peak at approximately 5 percent lime content. Finally, Figure 3c shows that both sand and clay containing 5 percent chemical stabilizer have a peak in strain energy density (at 0.5 and 0.3 percent content, respectively).

On the basis of the location of the peaks in Figure 1 coupled with the strain energy density results of laboratory strength testing shown in Figure 3c, 0.3 percent fibers by dry weight of the clay and 0.5 percent by dry weight of the sand appeared to be appropriate choices for optimum fiber contents. The choice of the optimum fiber content for the clay was a compromise between unit weight and strain energy density, but the strain energy density results were considered to be the most important factor. In addition to the compromise value of 0.3 percent for the optimum fiber content with clay, a lower fiber content of 0.1 percent, which was closer to the maximum observed unit weight, was included in the field study treatments. Lime content for the clay material was selected using the procedure suggested by Eades and Grim (1). Strain energy density results for Figure 3b showed a maximum value at 5 percent lime, which supports the selection of lime content on the basis of pH. With regard to the sand materials, Figure 3b

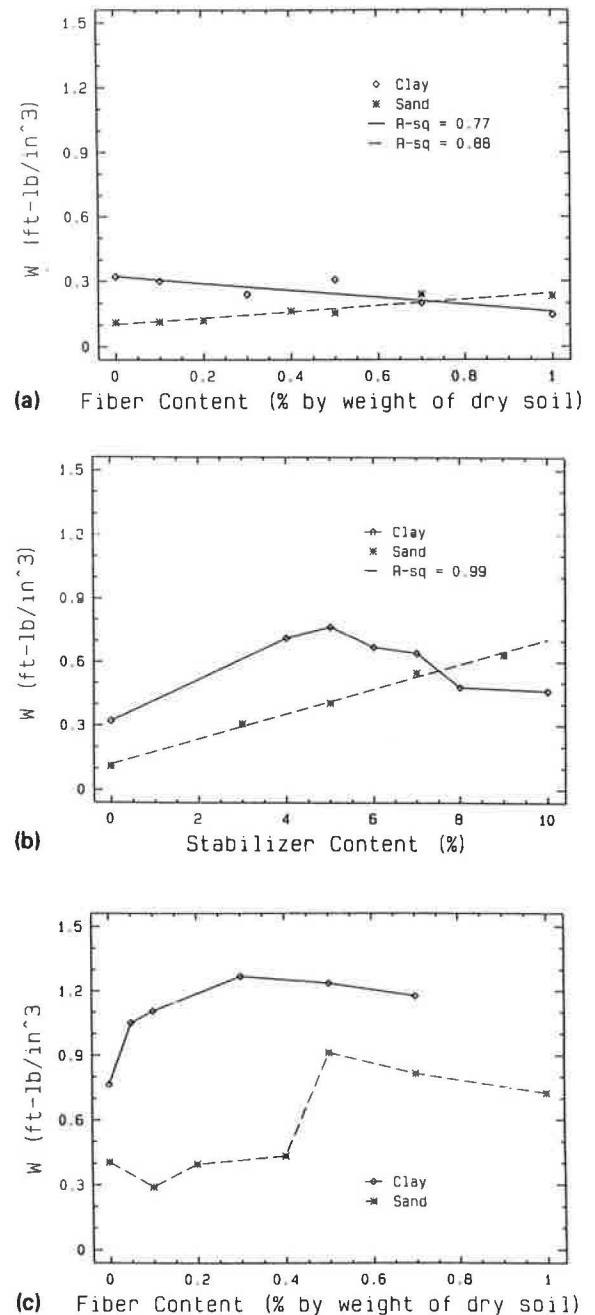


FIGURE 3 Effects on strain energy density: (a) fibers, no chemical stabilizer; (b) chemical stabilizer, no fibers (lime with clay, portland cement with sand); and (c) combined effect, 5 percent chemical stabilizer with fibers.

shows that the strain energy density continues to increase with cement contents up to 9 percent, which approaches a mix that is not economical to produce. Even at 9 percent cement, this material would not meet the Texas specification for cement-stabilized base. However, this study did not purport to meet such a specification. Therefore, the cement content for the sand was selected somewhat more qualitatively than the lime content for clay and was based substantially on soil classification (2).

FIELD TEST SECTION

Design

The design was a racetrack pattern with a lane width of 4.9 m (16 ft). The straightaway section on each side of the oval was 67 m (220 ft). Each of the 14 sections was 9.4 m (31 ft) long with the four sections at the ends of the straightaways being slightly longer to provide a transition to the turning operation in the curve. The geometric design, section numbering scheme, and the different mixtures planned for the experimental treatments are shown in Figure 4. The site was selected to ensure a relatively homogeneous subgrade with a very low California bearing ratio (CBR). The CBR at the top of the subgrade on the test track immediately before traffic averaged 4.5. The track had no surface course or seal coat and was designed so that it would fail within approximately 5,000 passes of the loading vehicle. Sections 4, 5, 9, and 10 had not failed at the time traffic was suspended.

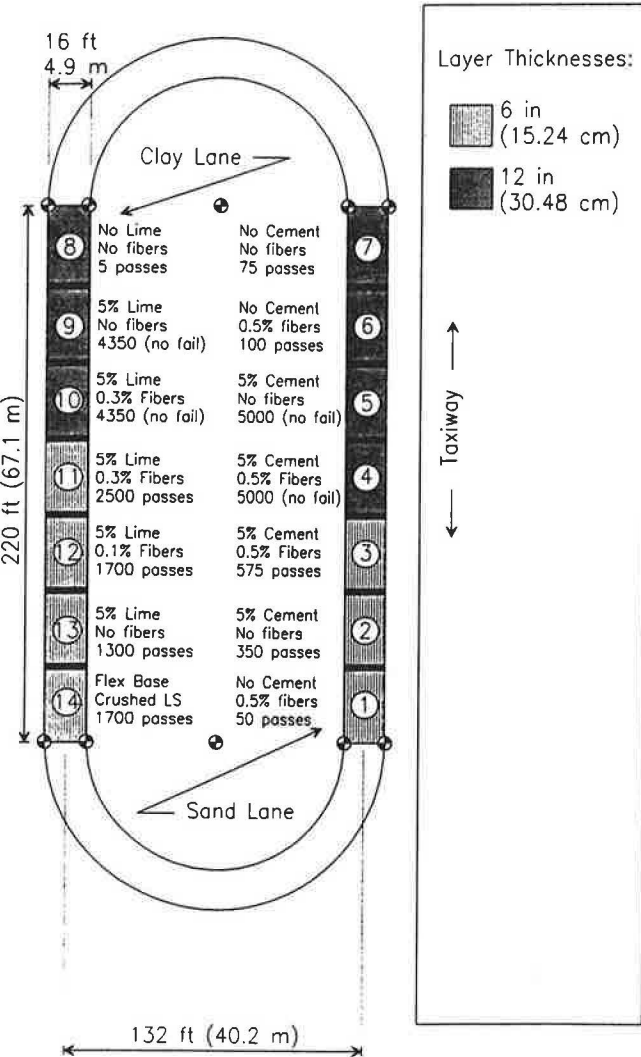


FIGURE 4 Test section design, numbering scheme, and number of passes to failure.

Construction

After initially surveying the track, the surface root zone was removed and an attempt was made to achieve a uniform density and moisture content at least 15.24 cm (6 in.) into the subgrade throughout the test track. A borrow pit was excavated in the infield of the track, and the material from this pit was used for the experimental stabilized materials on the clay lane. When sufficient material was in place, the construction of the different material treatments began.

On the basis of a knowledge of existing construction practice and the laboratory results, the following construction procedures were selected. All materials were mixed in place using a rotary mixer with the exception of sand-cement, which was mixed in a central pugmill plant. After mixing at the pugmill, the sand-cement was delivered to the site and fibers were mixed with the material in place.

The lime was mixed in place with the clay, followed by mixing the fibers in place. Visually, it appeared that the fibers opened up better in the clay than in the sand sections during field operations. This was opposite to the experience in the laboratory and is attributed to differences in the shearing mechanisms of the various agitators. In the clay lane, two passes of the mixer were used to mix in the lime. The mixing blades were raised at the transitions between each section. An additional five passes (three sets of five passes each were required to cover the width of the lane) were applied to the sections after the fiber was added. Two compaction passes without vibration and three passes with vibration were then applied using a padfoot roller. Four passes with a pneumatic roller were applied followed by finish rolling with a steel wheel roller. The desired density was not obtained in all of the sections. Therefore, additional scarification and compaction were performed (approximately eight passes with a vibrating padfoot roller, four with a light pneumatic roller, three with a steel wheel roller, five with a loaded track loader, and final passes with a heavy pneumatic roller). The large number of passes with the various compactors was applied in an attempt to reach a specified density. However, the consensus was that it was almost impossible to obtain laboratory densities in the field because the subgrade was so soft and therefore provided little support to compact against.

In the sand lane, the fibers were mixed with the pugmill mixed sand and cement. Approximately seven passes with the mixer were applied to these sections. Compaction was accomplished with five passes of a vibrating steel wheel roller, one pass without vibration, and two passes with a heavy pneumatic roller. This sand material seemed to be easier to compact to the desired density than the clay material.

Approximately 3 weeks was planned for curing of the stabilized material. Drainage was lacking at the site, a relatively low-lying flat area. In a normal year in College Station, Texas, this lack of drainage probably would not have been a problem if the section had been constructed on schedule. However, shortly after construction, an abnormally high-rainfall rainy season ensued from December 1991 through April 1992. There was never a long-enough time between rainfall events for the clay to return to a reasonable moisture content during this period. Two of the implications of this rain delay were that the stabilized sections cured for a much longer time period than planned and the surface of the track was exposed to

more severe environmental conditioning than had been anticipated. The sections were covered with plastic during many of the rainfall events and uncovered during many of the drying periods, but this activity was only partially successful in reducing the effects of the environmental conditions.

### Traffic

The traffic was applied only in one direction (counterclockwise when viewed from above) with a nonarticulated, single-axle, dual wheel, flatbed truck between mid-May and mid-June. The rear tires were Summit Duro-mile Lug Regroovable 9.00-20 E, and the steering axle tires were Firestone 9.00-20 Transport 1. Concrete median barriers were used to load the truck. Primarily because of time limitations, the load on the rear axle was increased at Pass 1,100 to 77.4 kN (17.4 kip) from 56.27 kN (12.65 kip). The heavier rear load actually decreased the steering axle load from 22.6 kN (5.09 kip) to 21.5 kN (4.84 kip).

### FIELD RESULTS

The results given herein are based primarily on measurements taken perpendicular to the centerline. These cross section measurement locations were spaced at 1.2-m (4-ft) intervals along the centerline and included only the central 3.7 m (12 ft) of each test section longitudinally. The measurements extended the full width of the lane, 4.9 m (16 ft). "Failure" was determined by average rut depths of 7.62 cm (3 in.) and is recorded in Figure 4. In Table 3, the moisture contents just below the surface and at the top of the subgrade are presented for each experimental section as measured before the traffic was applied and at the time each section failed.

Figures 5 and 6 show a more continuous measure of the progression of the failure over the period of the test and include data on Sections 4, 5, 9, and 10. The ordinate on these plots is termed the strain index. This terminology is used to emphasize that the value is nondimensional (i.e., a strain) but

does not meet the mathematical definition of strain (hence the use of the term "index"). It is computed as follows:

$$\text{Strain index} = \sum_{i=0}^{16} \left| \frac{\Delta h}{h} \right| \quad (1)$$

where  $h$  is the elevation (relative to an arbitrary datum) before traffic and the relatively small  $\Delta h$  is the change as traffic is applied. The absolute value of the "strain" is taken at each of the measurement points along the cross section (0–16) and then summed and averaged over the four cross sections in each experimental section. Therefore, the strain index gives a measure of the total vertical movement (both up and down) of the surface about the original location of that surface. On these plots, the lower strain index values at large pass numbers indicate longer life. In each case shown in the figures, the fibers appear to improve the life over the comparable materials and thicknesses without fibers. For instance, Figures 5b and 6b show that the sections without fibers were approaching failure more rapidly than the sections with fibers at the time traffic was suspended.

### CONCLUSIONS

Laboratory mix design was relatively straightforward for the materials tested in this study. It appears possible to design the mix on the basis of curves from laboratory testing: the stabilizer-strain energy density curve (e.g., Figure 3b), the fibers-strain energy density curve for the optimum stabilizer content (e.g., Figure 3c), and the optimum fibers-density curve (e.g., Figure 1).

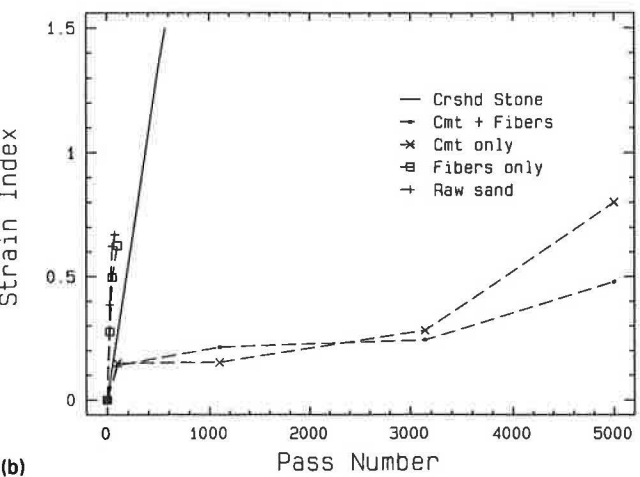
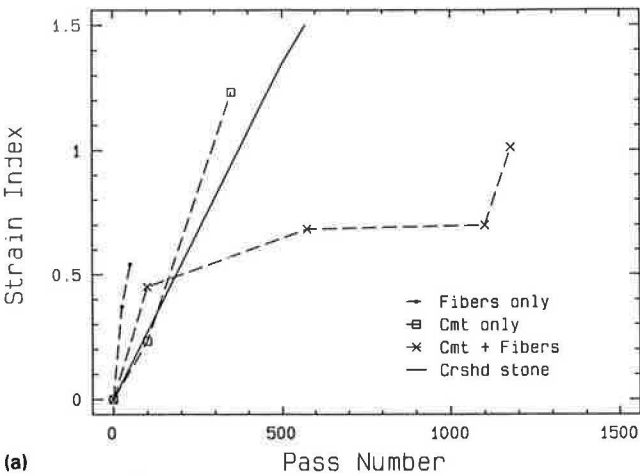
Qualitative as well as quantitative observations suggest that fibers alone can not completely replace chemical stabilizers in certain relatively high-stress pavement applications. However, it is apparent that the fibers tested in this study enhance the performance of chemically stabilized materials. The fibers increased the modulus, strength, and strain energy of the sand and clay materials as tested in this study. In certain situations, the use of fibers may allow for a reduction in chemical sta-

TABLE 3 Field Moisture Contents (percent, by Oven Drying)

Section	Surface		Top of Subgrade†	
	Start	Final	Start	Final
1	19.0	14.8	21.4	14.0
2	18.7	5.2	20.5	20.6
3	20.2	10.0	23.0	21.2
4	15.7	4.7	21.2	17.7
5	13.4	11.8	22.7	24.8*
6	14.8	14.9	23.0	23.8
7	19.3	12.1	25.6	23.3
8	28.5	31.2	27.0	27.8
9	25.9	31.3	26.2	36.9
10	23.2	39.0	28.2	37.6
11	21.8	16.1	27.3	25.4
12	20.5	18.2	28.9	27.8
13	25.4*	20.2*	28.8	26.9
14	9.4	1.5	25.9	26.0

\*by nuclear gage measurement.  
†measurement taken in clay subgrade, depth depends on layer thickness (see Figure 6 for thicknesses).





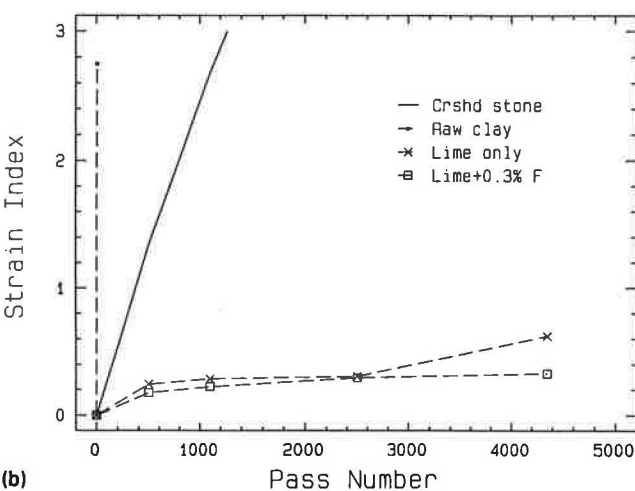
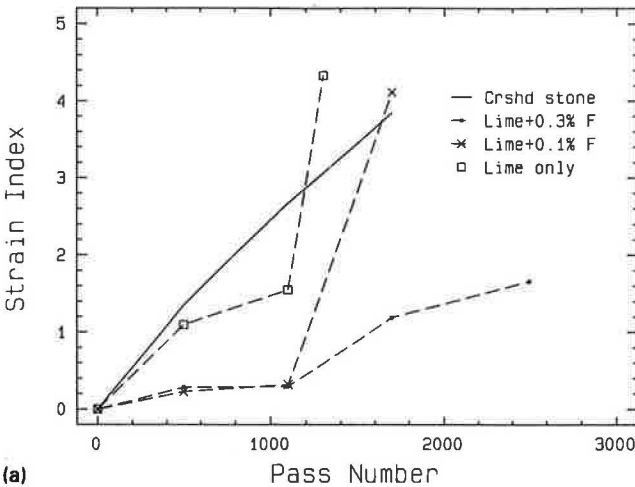
**FIGURE 5** Strain index—sand (vehicle load increased at 1,100 passes): (a) 6-in.-thick sections and (b) 12-in.-thick sections (1 in. = 2.54 cm).

bilizer content. Alternatively, the use of fibers may allow reduction in the thickness of the layer in which they are used. Sangineni (3) computed thickness reductions on the order of 5 to 16 percent using data for chemically stabilized materials incorporating fibers in an AASHTO analysis (4) of a fictional pavement structure with a 5-cm (2-in.) hot mix asphalt surface course.

**RECOMMENDATIONS**

Our experience with the in-place mixing and grading operations was that the test sections shown in Figure 4 were almost too short. Future experiments should use longer individual test sections. Adjacent sections of dissimilar materials require that the rotary mixing operation be started and stopped frequently by lifting up the tines. This process adversely affects the material uniformity in the area of the lifting operation and becomes a more significant problem as the sections become shorter.

There has been some speculation and limited experience with the use of concrete ready mix trucks to mix the material



**FIGURE 6** Strain index—clay: (a) 6-in.-thick sections and (b) 12-in.-thick sections (1 in. = 2.54 cm).

and cause the fibers to open up. There is a need to explore this approach further, since it is very attractive in terms of cost, efficiency, and potential quality of the final product. The idea has the potential to deliver a homogeneous product at minimum cost. The primary use for this type of approach is in applications that use select, cement-stabilized, fiber-reinforced, cohesionless (or low-cohesion) soils.

It should be possible to develop a simple procedure for estimating life on the basis of the stress-strain curves from the mix design process. Standard techniques are available in the literature that use strength or modulus from the stress-strain curves (4). However, strain energy density might be useful as well. An example of the potential of this approach is shown in Figure 7, wherein there appears to be an identifiable relationship between strain energy and the number of passes to failure. The strain energy presented in this figure is the result of multiplying the strain energy density from the mix design strength tests by a volume of material. In this case, a cylindrical volume with a unit radius and a height equal to the thickness of the pavement layer in the field was used. The technique might be improved by taking the volume as that of a frustum of a right circular cone defined by the contact area

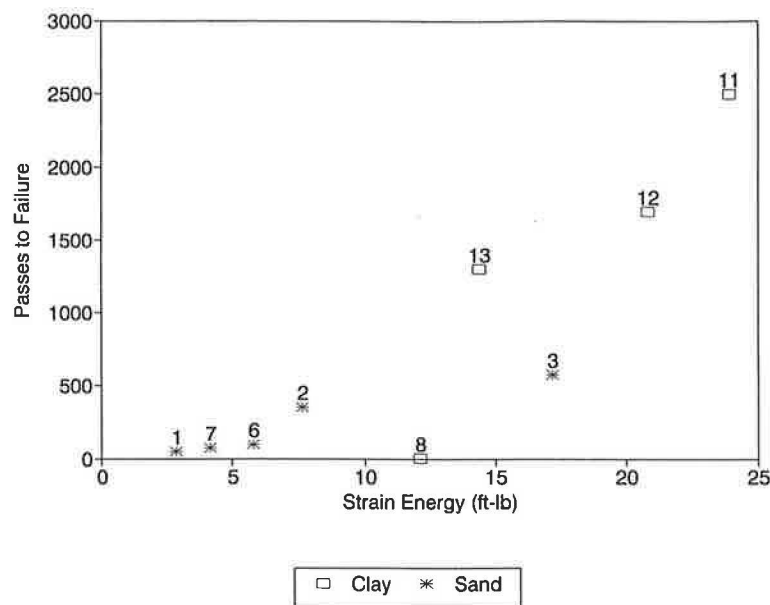


FIGURE 7 Potential relationship between strain energy and number of passes to failure (1 ft-lb  $\approx$  1.36 J). Numbers above symbols indicate experimental section numbers.

of the tire, the depth of the layer, and the stress distribution within the layer. The approach is a simplistic form of energy approaches that have been used in the past (5) and that are being used currently by at least two of the major contractors in the Strategic Highway Research Program.

The surface of pavement layer materials containing fibers should be sealed in some fashion (e.g., with an emulsion). Although no quantitative measurements were taken, visual indications were that the fibers can provide a path for capillary absorption of water into the shallow layer of soil near the surface, which can result in weak support in that area. This weakness could lead to other problems such as rutting and slippage of asphalt pavements and pumping under portland cement concrete pavements. It is anticipated that correct application of sealing or tacking material at the fiber-stabilized layer interfaces will eliminate these potential problems.

The mix design procedure should be validated by an independent laboratory. Studies of drainage characteristics such as permeability and critical shear stress should be conducted. Life cycle cost analyses should be accomplished. Accelerated tests simulating combined distresses from traffic and environmental conditions, coupled with full-scale test sections on

public or private roads, would be useful. Laboratory fracture testing is being conducted.

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