Waste Fibers in Cement-Stabilized Recycled Aggregate Base Course Material

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A coordinated laboratory and field study was undertaken to assess the suitability of producing an economically suitable pavement base course material by reinforcing cement-stabilized recycled concrete aggregate with strips of reclaimed plastic or tire wires and tire chunks from recycled scrap tires. The field program included constructing 12 test sections using different proportions of various waste materials. It was found that the addition of fibers exerted no measurable effect on field compaction, but the in-place mixing technique used was unsuccessful in distributing the fibers homogeneously throughout the full depth of the slab. Laboratory split tensile tests and beam flexural tests showed that reinforced specimens exhibited lower tensile and flexural strengths and no improvement in toughness compared with unreinforced specimens. The same basic recycled aggregate mix, when reinforced with a commercially available hooked-end steel fiber, showed that 28-day specimens with 4 percent fiber reinforcement exhibited a pseudo strain hardening behavior after the peak, accompanied by a modest increase in tensile strength and almost doubling in toughness. Notwithstanding the generally recognized benefits to be realized in a pavement system by an increase in toughness in one or more layers, the results of this study suggest that caution and careful investigation should be exercised when contemplating the incorporation of waste products in the component layers. Failure to do so may result in false economy whereby initial cost is reduced somewhat at the expense of increased life-cycle costs because the anticipated performance was not achieved.

In an effort to address growing national concerns for mitigating the solid waste disposal problem and conserving available landfill space, a number of studies have been conducted to identify waste products that can be effectively recycled and used in highway construction (*1,2*). One recent survey, which elicited responses from 44 state Departments of Transportation (DOTs) on current practice in the use of waste materials in highway construction, identified only 11 waste products (including recycled asphalt and portland cement concrete paving materials; building rubble; and other demolition debris, scrap tires, waste glass, recycled plastics, and various kinds of slags and ashes) that are being used by more than 7 percent (approximately three states) of the respondents (*2*). However, the use of most of these materials was reported to be still in the experimental stage.

Section 1038(b) of the Intermodal Surface Transportation Efficiency Act of 1991 requires the Secretary of Transportation and the Environmental Protection Agency to conduct studies to evaluate the economic, technical, and environmental factors associated with using recycled materials in highway construction. Although the concept of recycling is timely and desirable, caution must be exercised when incorporating recycled materials with unknown or questionable properties into a highway pavement system. Of particular concern is the use of materials for which there is limited knowledge about their long-term performance characteristics. The idealized goal of incorporating waste materials in highway pavements must not be satisfied at the expense of building an inferior (and ultimately uneconomical) pavement system, which will eventually contribute to the nation's already overwhelming infrastructure problems. Alternatively one must not aggravate the infrastructure problem by using highways as "linear landfills" to help solve the waste disposal problem. The use of recycled materials in highway construction can be justified only if it results in a pavement system that is at least as serviceable and economical (with all factors considered) as the ones being built.

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OBJECTIVE AND SCOPE

The objective of this study was to evaluate, through laboratory and field testing programs, the performance of a cement-stabilized base course material consisting of recycled concrete aggregate reinforced with either strips of reclaimed plastic or wires from old tires. In some cases, pieces of shredded tires were included in the mix. The primary motivations for this research were that (a) a fiber-reinforced, aggregate-cement composite has characteristic engineering properties that offer advantages for a pavement structure and (b) such a base course material is composed entirely of waste materials (except for a nominal cement content). The study is concerned mainly with (a) the mechanical characterization of the selected base course materials, (b) the benefits derived from incorporating waste fibers, and (c) the experience gathered from field mixing and the construction of test slabs. Evaluations of the environmental acceptability, economic feasibility, and frost susceptibility are beyond the scope of this investigation.

BACKGROUND OF CANDIDATE WASTE PRODUCTS

Although several studies indicate that recycled crushed concrete aggregate is being used to construct or reconstruct various components of a pavement structure, only a limited number of successful field projects (many of which were experimental pavements) have been completed to date (*1,3–5*). Of the 30 state highway agencies that reported their experience with the use of waste tires in highway pavement systems (*2*), 50 percent considered their use uneconomical, 30 percent reported poor performance, and 9 percent were not confident about their future environmental acceptance. However, varying degrees of success have been claimed in several

experimental projects using tire products in geotechnical-related applications (*2,6,7*). Recycled plastics have been used in hot mix asphalt concrete (*3*), in fence line and guardrail posts (*8*), as lightweight reinforcing inclusions in concrete (*9*), and as reinforcement in granular soils (*10*). Efforts to use recycled fibers include waste nylon fibers (*11*) and recycled carpet fibers (*12*) in portland cement concrete and recycled cellulose fibers as an asphalt modifier (*13*). No information was found in the literature on the mechanical behavior (toughness, in particular) of a material composed of a cement-stabilized, recycled aggregate and waste fiber, where shredded plastic bottles or reinforcing wires from scrap tires were used as fibers. Therefore, an evaluation of this particular composite material constitutes the focus of this study, which was conducted in three stages:

- Construction of test slabs and field testing,
- Concurrent laboratory test program on field-prepared specimens, and
- Series of controlled laboratory tests and a comparison study.

MATERIALS USED

Aggregates

The recycled concrete aggregate was obtained from two sources. For the Maryland field and laboratory study, the aggregate was obtained from the E.L. Gardner Concrete Company in Crofton, Maryland, and for the Illinois laboratory study, it was obtained from the R. I. Busse Corporation in Elk Grove, Illinois. The aggregate used met the CA–6 specifications for recycled concrete. The grain size distributions for four samples taken from different locations in the aggregate stockpiles of each of the sources are shown in Figure 1.

Stabilizing Materials

Type II portland cement and several different types of waste materials were used to stabilize the aggregate. Three kinds of waste products from scrap tires were used. The first, termed "tire wire," is a waste product of the tire shredding process and consists of several strands of wire, generally 50 to 75 mm (2 to 3 in.) long, connected by small portions of rubber. The second, called "tire chips," was pieces of a tire 50 to 100 mm (2 to 4 in.) in width and length and about 13 mm (0.5 in.) thick containing wires. "Tire straps," the third type, were portions of a tire cross section 25 to 60 cm (10 to 24 in.) long. The recycled tire products were obtained from Sawyer Environmental Recycling Company in Hampden, Maine. The shredded plastic strips were derived from recycled soda bottles and were about 6 mm (0.25 in.) wide, 2.5 mm (0.1 in.) thick, and 50 to 100 mm (2 to 4 in.) long. The recycled plastic strips were supplied by Nikon Plastics in New York City. In addition, 75-mm (3-in.) long, 24-gauge galvanized steel wires were used to simulate the tire wires. To evaluate the performance of recycled fibers, a comparison study was conducted by reinforcing the cement-stabilized recycled aggregate with 60-mm (2.36-in.) long Dramix hooked-end steel fibers manufactured by the Bekeart Corporation.

FIELD CONSTRUCTABILITY TESTS

Using conventional construction techniques and equipment, a test pad consisting of 12 different test sections (each modeling a typical stabilized base course in a pavement section) was built in Crofton, Maryland, to (a) evaluate the effectiveness of in-place mixing of the stabilizing materials and the recycled aggregate, (b) determine the distribution of the fibers in the slab, and (c) quantify the effect of the fibers on the density of the roller-compacted test pads. The excavation and construction equipment included a Bobcat loader/dozer,

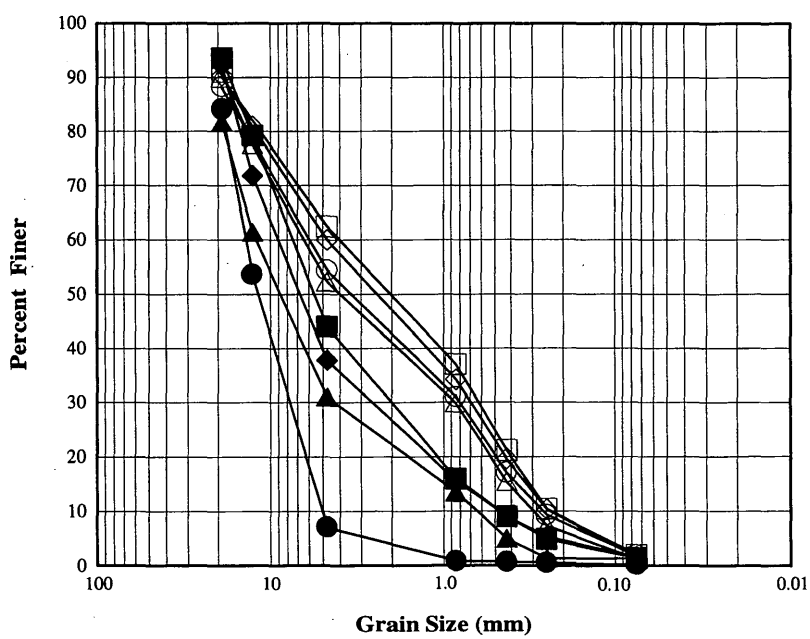


FIGURE 1 Grain size distribution curves for recycled aggregate (solid symbols represent samples from Elk Grove, Ill.; open symbols, Crofton, Md.).

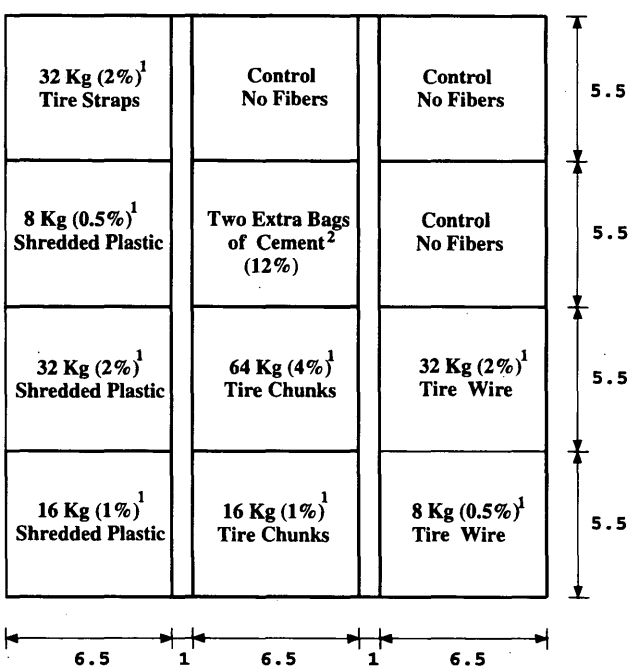
a BOMAG vibratory roller, and a REX in-place soil mixer. A nuclear density gauge was used for in-place density determinations.

Test Pad Construction

Each section of the test pad was approximately 2 m (6.5 ft) wide and 1.7 m (5.5 ft) long. The arrangement and numbering of the test sections, as well as the type and amount of reinforcement used in each section, are shown in Figure 2. The aggregate was transported with a Bobcat. Thirty-six bags of portland cement were distributed evenly on the surface of the test pad to provide an 8 percent cement mix. One test section was prepared with 12 percent cement. The cement was mixed dry to a depth of about 0.25 m (10 in.) using the REX mixer. A measured amount of water was added to the test pad and the designated fibers were placed on the wet pad in the proportions shown in Figure 2. The REX mixer then made a second pass, and the material was compacted with a vibratory roller, after which nuclear density gauge readings were taken at several locations in the compacted test pad. Seven days after construction, coring was attempted at 19 locations, but usable samples were obtained at only 6 locations. These cores were 100 mm (4 in.) in diameter and 100 to 150 mm (4 to 6 in.) long. Beam samples were sawed from the test pad after 14 days, but the quality of the resulting samples was poor. After 28 days, the test pad was broken into several pieces with a backhoe to evaluate the mixing of the cement and the distribution of the fibers in the aggregate-cement matrix.

Density Measurements

Nuclear gauge density determinations on a companion test pad consisting of only recycled aggregate showed that the average dry density at a depth of about 0.3 m (12 in.) was 1786 kg/m^3 (111.5 pcf) with a variation of $\pm$59 kg/m^3 (3.7 pcf) and the average moisture content was 12.1 percent with a variation of $\pm$2.5 percent. Density measurements at the center of each test section to a depth of about 0.2 m (8 in.) indicated that at least 90 percent compaction (based on the laboratory-determined maximum Proctor dry density without cement or fibers) was achieved in all of the test sections. The average dry density was about 1800 kg/m^3 (112.6 pcf) with a variation of $\pm$48 kg/m^3 (3.0 pcf), and the average moisture content was 13.7 percent with a variation of $\pm$1.7 percent. The measured densities indicate that the inclusion of fibers did not affect the densities attained in field compaction.



All dimensions are in feet

Notes: [1]Indicated percentages of inclusions are by weight
[2]All sections had 8% cement by weight, except this one

FIGURE 2 Composition of individual field test sections.

Distribution of Cement and Fibers

Based on visual observations of the cores (both successful and unsuccessful ones) and the broken pieces of the test pad, it was determined that the top 75 to 100 mm (3 to 4 in.) resembled concrete and the underlying aggregate-cement layer was granular with almost no cohesion. In addition, the plastic fibers, tire wires, and tire chunks were also located primarily near the surface in the top 50 to 100 mm (2 to 4 in.). Frequently the tire wires and chunks were observed to form clusters, thus preventing a more even distribution.

Lesson Learned

In this limited field exercise it was learned that the field mixing method employed did not produce an acceptably homogeneous mixture of the recycled aggregate, cement, and waste fibers or chunks used. Consequently, a satisfactory performance by the composite material could not be expected.

CONCEPT OF TOUGHNESS

Although a stabilized base course in a highway pavement is designed so that working stresses in the layer are generally lower than its ultimate tensile strength, many applications of traffic loads will cause fatigue cracking and eventually lead to failure. However, a properly designed fiber-reinforced layer will tend to resist the propagation of fatigue cracks under working stress levels because of its superior capacity for energy absorption. This capacity for energy absorption is termed toughness, and it is normally defined with reference to the post-peak responses associated with a single-load cycle going to failure. Because toughness is also a desirable property for enhancing material performance under conditions of repeated loading (fatigue) at applied stresses less than the peak strength, such as would be experienced by a highway base course material, it was a key material property measured in this study.

LABORATORY TESTS

As stated previously, two series of laboratory tests (denoted as the Maryland tests and the Illinois tests, the latter of which includes a program of comparison tests) were conducted to

- Identify candidate materials, fibers, and optimum mix proportions suitable for use in pavement base courses;

- Evaluate the effect of fiber type and proportion on the ultimate split tensile strength of specimens; and
- Determine the toughness characteristics and post-peak increase in ductility due to fiber inclusions.

The Maryland tests were performed on field-prepared specimens using the same materials and mixes incorporated in the various sections of the test pad. The Illinois test program included more sophisticated tests on specimens prepared with greater control. In addition, a different recycled aggregate and some different fibers were used.

Maryland Laboratory Tests

Simultaneous with constructing the field test pad, test cylinders 152 mm (6 in.) in diameter and 305 mm (12 in.) in length were prepared in the field for conducting laboratory split tensile (Brazilian) tests in accordance with ASTM C496. Four cylinders were prepared by conventional compaction techniques for each of the 12 sections; two were tested after 7 days and two after 28 days. The fiber types and quantities (measured by the weight percentage of the total dry weight) included tire wires (1, 4, and 8 percent), tire chunks (1 and 4 percent), and shredded plastic (0.5, 1, and 4 percent). Ten of the 12 sets had 8 percent cement, and the remaining two sets had 12 percent cement; the water-to-cement ratio was maintained at approximately 0.5. The inclusion of fibers affected the laboratory compaction and a constant density could not be achieved. The samples were stripped from their molds after 48 hr, wrapped in wet burlap, and cured at approximately 23°C (73°F).

Results

The ultimate tensile strengths for the 28-day specimens are plotted versus dry density in Figure 3 (although not shown, the 7-day results show the same pattern). These data show that the split tensile strength strongly depends on density; the 28-day tensile strength increased from 190 KPa (28 psi) at a dry density of 1712 kg/m^3 (107 pcf) to almost 1335 KPa (194 psi) at a dry density of 2010 kg/m^3 (125 pcf). For the same type and amount of fiber, the strength generally increased with an increase in density. These data indicate that there is a slight increase in strength as a result of an increase in cement for specimens with no fibers. In general, however, there was a decrease in the tensile strength of specimens with fibers relative to the control specimens (no fibers).

Lesson Learned

Based on the experience gained during this phase of the study, it was learned that

- A procedure must be developed to prepare specimens with a controlled density,
- Fiber length should be controlled to reduce the number of variables, and
- Lateral deformation measurements should be incorporated into the test program to evaluate the post-peak response and the overall toughness of the material.

Illinois Laboratory Tests

The Illinois test program was undertaken in response to the foregoing dictates. The recycled aggregate used in this program was obtained from R. I. Busse Corporation in Elk Grove, Illinois. Shredded plastic fibers were used, but the lengths were cut to approxi-

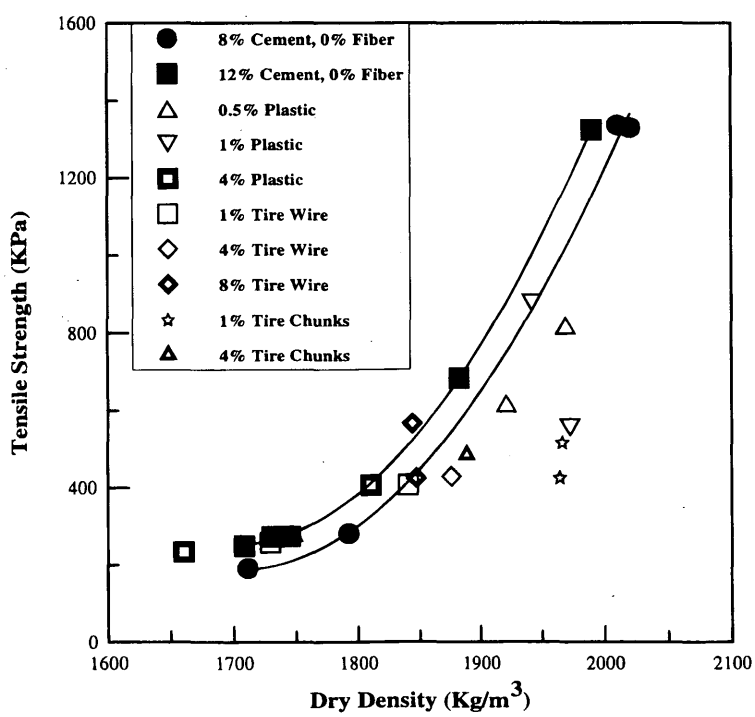


FIGURE 3 Split tensile strength versus dry density for 28-day specimens.

mately 75 mm (3 in.). Instead of tire wires, a galvanized smooth steel wire (cut into approximately 75-mm lengths) was used to simulate the tire wires. The test program included split tensile tests with lateral deformation measurements and flexural beam tests under third-point loading. To control the density, a simple static compactor consisting of a load frame and a hydraulic pump was developed. This apparatus worked well, and it was found that the desired density could be achieved consistently.

Split Tensile Tests

A closed-loop, servo-hydraulic testing machine (manufactured by MTS) was used to conduct the split tensile tests with lateral deformation measurements to capture the post-peak response of the specimens. As illustrated in Figure 4, two linear variable differential transformers (LVDTs) were attached to the specimen to measure the change in the horizontal diameter due to compression loading in the vertical direction. Sixteen cylinders with dimensions similar to those in the Maryland program were tested. The fiber percentages were 1 and 0.5 percent plastic and 1 percent steel, and four samples were made without fibers. The dry cement, aggregate, and fibers were mixed for 3 to 4 min in a concrete mixer, followed by another 5 min of mixing after the addition of water. The amount of water corresponded to approximately the optimum moisture content (in this case about 14 percent). The samples were cured for 7 or 28 days inside sealed containers. A relatively constant dry density of approximately 1715 kg/m^3 (107 pcf) with a variation of ± 32 kg/m^3 (2 pcf) was achieved for all of the test specimens.

Beam Tests

Six beams [152 mm (6 in.) wide, 230 mm (9 in.) deep, and 915 mm (36 in.) long] were prepared (two with no fibers, two with 1 percent plastic fibers, and two with 1 percent steel fibers) at a predetermined dry density of approximately 1680 kg/m^3 (105 pcf) by compaction with a modified Proctor hammer. The beams were removed from their mold after 7 days, wrapped with moist burlap, and cured for 28 days in the same room as the cylinders. They were tested in flexure by loading at the third points (as specified in ASTM C78–84) using a 220-kip capacity MTS hydraulic test machine. The midpoint deflection of the beams was measured with an LVDT as they were loaded with displacement control at a displacement rate of 0.05 mm/min (0.002 in./min).

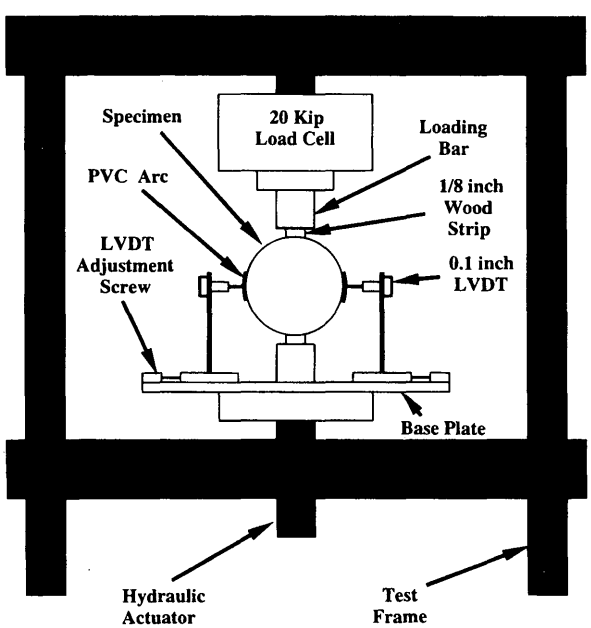


FIGURE 4 Apparatus for splitting tensile test with lateral deformation measurement.

Results

The results of 7- and 28-day split tensile tests and 28-day beam flexural tests are shown in Table 1. Figure 5 shows the tensile stress versus strain curves for the 28-day split tensile tests, and Figure 6 shows the load-deformation curves for 28-day beam flexural tests. For split tensile tests, the plotted symbols represent every 25th and 60th data point for unreinforced and fiber-reinforced specimens, respectively, whereas for unreinforced and fiber-reinforced specimens subjected to beam tests, symbols are shown for every 60th and 100th data point, respectively. The split tensile strength of a specimen is calculated in accordance with ASTM C496 and is given by

$$T = \frac{2P}{\pi l d} \tag{1}$$

where

T = split tensile strength,
P = vertical compression load,
l = specimen length, and
d = specimen diameter.

In this study, the energy absorption capacity or toughness of a split tensile test specimen is estimated from the area under the entire stress-strain curve up to a strain of 0.025 m/m. A ratio termed the toughness index is calculated by dividing the areas for fiber-reinforced specimens by the area of the no-fiber specimen, and the values are summarized in Table 1. A toughness index value greater than unity indicates an overall increase in toughness or energy absorbing capacity, with resulting higher ductility in the post-peak region, relative to that of an unreinforced specimen. The data indicate that the average tensile strength of 7-day and 28-day specimens with plastic fibers (0.5 and 1 percent) decreased by approximately 40 and 20 percent, respectively, relative to the average strength of corresponding unreinforced specimens. In the case of the steel-wire fiber (1 percent) reinforced specimens, the decreases for the 7- and 28-day specimens were 19 and 4 percent respectively. There was a slight improvement in the toughness of the 7-day specimens with steel fibers, but the toughness decreased in all other cases involving the addition of fibers.

The ultimate flexural strength or the modulus of rupture of a beam specimen is calculated in accordance with ASTM C78–84 and is given by

$$\sigma = \frac{Ps}{bh^2} \tag{2}$$

TABLE 1. Results of 7- and 28-Day Split Tensile Test Specimens and 28-Day Flexural Test Specimens

Fiber Content (by weight)	7-Day Split Tensile Tests			28-Day Split Tensile Tests			28-Day Flexural Tests	
	Strength (Kpa)	Area[1] (KPa)	Toughness[3] Index	Strength (KPa)	Area (KPa)	Toughness Index	Modulus of Rupture (KPa)	Area[2] (10^{-4}KN-m)
0%	551	6.58	NA[4]	586	8.29	NA[4]	765	21.50
0%	593	6.58	NA[4]	579	8.92	NA[4]	1117	36.16
1% P	310	6.70	1.01	531	7.92	0.92	482	15.82
1% P	338	6.46	0.98	372	6.58	0.76	751	27.12
0.5% P	462	6.70	1.01	538	8.17	0.95	NA[6]	NA[6]
0.5% P	241	4.63	0.70	338	4.63	0.54	NA[6]	NA[6]
1% S	489	7.68	1.17	600	8.43	0.98	772	32.77
1% S	434	7.92	1.20	510	NA[5]	NA[5]	800	29.38

[1]Area under the stress-strain curve up to strain 0.025 m/m
[2]Area under the load deformation curve up to 6×10^{-4} m deformation
[3]Ratio of the areas under the stress-strain curves for fiber reinforced specimens to unreinforced specimens
[4]Not applicable for unreinforced specimens
[5]Test was interrupted prematurely
[6]Not investigated for beam specimens
P = Shredded plastic fibers
S = Hooked-end steel fibers

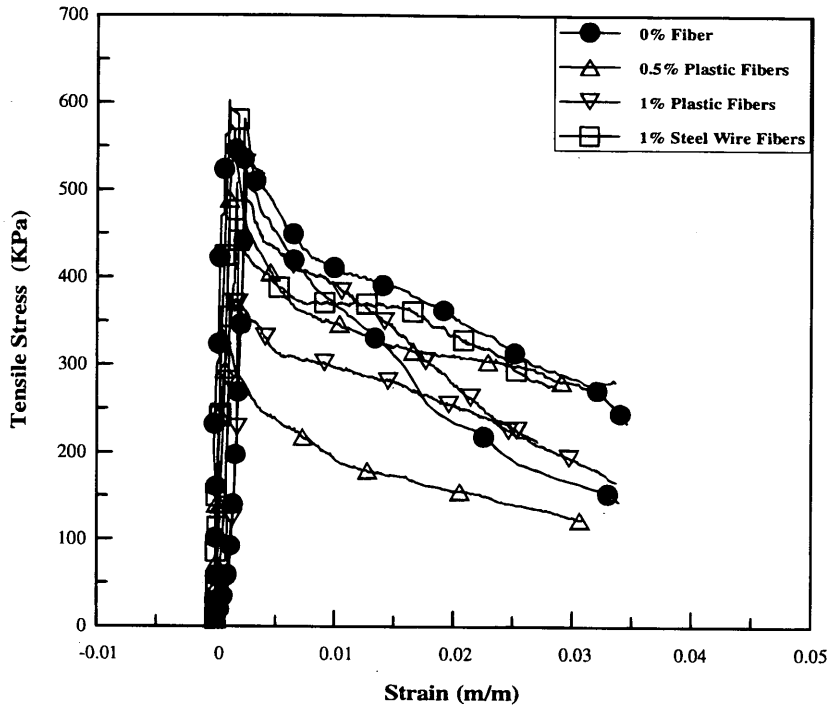


FIGURE 5 Stress-strain curves for 28-day split tensile test specimens.

where

σ = modulus of rupture,
P = maximum applied load,
s = length of span,
b = average width of beam, and
h = average depth of beam.

The results from the flexural tests show that one beam with no fibers, one with 1 percent plastic fibers, and the two with 1 percent steel fibers had approximately the same ultimate flexural strength or modulus of rupture [average of 772 KPa (112 psi)]; one beam containing no fibers had the highest modulus of rupture [1117 KPa (162 psi)], and one of the beams containing 1 percent plastic fibers had the lowest modulus of rupture [482 KPa (70 psi)]. Relative to Beam 2 (the

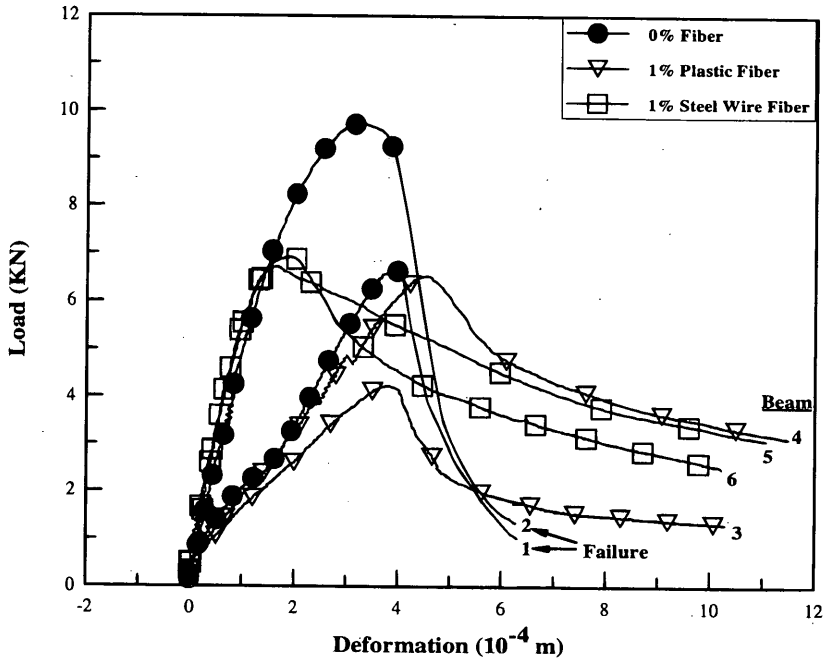


FIGURE 6 Load-deformation curves for 28-day flexural test specimens.

strongest unreinforced beam), there was a significant reduction (approximately 30 percent) in the average ultimate flexural strength due to the inclusion of fibers; this is consistent with the previous results obtained from split tensile tests. The areas under the load-deflection curves up to 0.6 mm (0.024 in.) deflection were calculated to estimate toughness (this method is typical for determining the toughness of a material subjected to a beam flexure test, in contrast to the strain criterion that was used for split tensile specimens). Although there was no meaningful change in toughness for any of the beams relative to that for Beam 2, there was a sharp drop in the load-carrying capacity of the unreinforced beams immediately after the peak load was reached. It is significant that these unreinforced beams manifested some modest level of post-peak load-carrying capacity, as represented by the recorded curves that are shown, until a brittle-type, catastrophic failure was encountered. On the other hand, the fiber-reinforced beams showed a relatively gradual decrease in their load-carrying capacity after the peak load was reached. These beams also sustained higher deformations than the unreinforced specimens, representing a more ductile type of failure.

Lesson Learned

Although the Illinois test program was conducted under reasonably well-controlled conditions (especially dry density and fiber length), the performance of the fiber-reinforced specimens suggests that the waste fibers used in this study are more likely to reduce, instead of enhance, the structural integrity and functional performance of a pavement system. Whereas the concept of toughness as a desirable attribute in a pavement system remains valid, the means to achieve it economically remains a challenge.

Comparison Study

To address the foregoing issue, a separate series of laboratory split tensile tests was conducted on specimens with the same basic mix design, except that they were reinforced with a commercially available regular steel fiber commonly used in the concrete industry. The objective of this test program was to compare the performance of recycled fibers with that of a regular fiber and thereby attempt to explain the unsatisfactory performance of the recycled fibers, as observed during the field and laboratory tests. The fiber used in this study was a 60-mm (2.36-in.) long Bekeart Dramix hooked-end steel fiber with an aspect ratio of 75. Split tensile tests with lateral deformation measurements were performed on specimens with a dry density of approximately 1712 kg/m^3 (107 pcf) and containing 1 and 4 percent steel fibers.

Results

The results of split tensile tests on 7-day and 28-day specimens are presented in Table 2. These data show that the average strength for 7-day specimens either remained the same (1 percent fiber) or decreased by approximately 10 percent (4 percent fiber) compared with that for unreinforced specimens, and the tensile strength of the 28-day specimens increased by approximately 15 percent (1 percent fiber) and 24 percent (4 percent fiber). The areas under the stress-strain curves up to a strain of 0.025 m/m showed a noticeable increase in toughness for most of the specimens (with the exception of the 28-day specimens with 1 percent fibers). Figure 7 compares the performance of unreinforced specimens with those containing 4 percent fiber reinforcement, and a significant difference in behavior is observed; specifically, the toughness of a 28-day specimen with 4 percent fibers doubled relative to one with no fibers and a pseudo-hardening behavior was observed in the post-peak region. These specimens continued to carry load even when the lateral LVDTs reached their ultimate range and the tests were terminated (i.e., the specimens did not fail). This type of behavior is very desirable in a highway pavement system.

Lesson Learned

Significant improvement in the mechanical behavior (especially toughness) of a recycled aggregate mix can be achieved by incor-

TABLE 2. Results of 7- and 28-Day Split Tensile Test Specimens with Hooked-End Steel Fibers

Fiber Content (by weight)	7-Day Split Tensile Tests			28-Day Split Tensile Tests		
	Strength (KPa)	Area[1] (KPa)	Toughness[3] Index	Strength (KPa)	Area (KPa)	Toughness Index
0%	545	6.58	NA[2]	586	8.29	NA[2]
0%	593	6.53	NA[2]	579	8.90	NA[2]
1%	627	8.63	1.29	689	8.52	1.00
1%	496	8.3	1.26	648	8.10	0.94
4%	462	7.65	1.16	834	17.67	2.05
4%	558	10.28	1.57	614	13.44	1.56

[1]Area under the stress-strain curve up to strain 0.025 m/m
[2]Not applicable for unreinforced specimens
[3]Ratio of the areas under the stress-strain curves for fiber reinforced specimens to unreinforced specimens

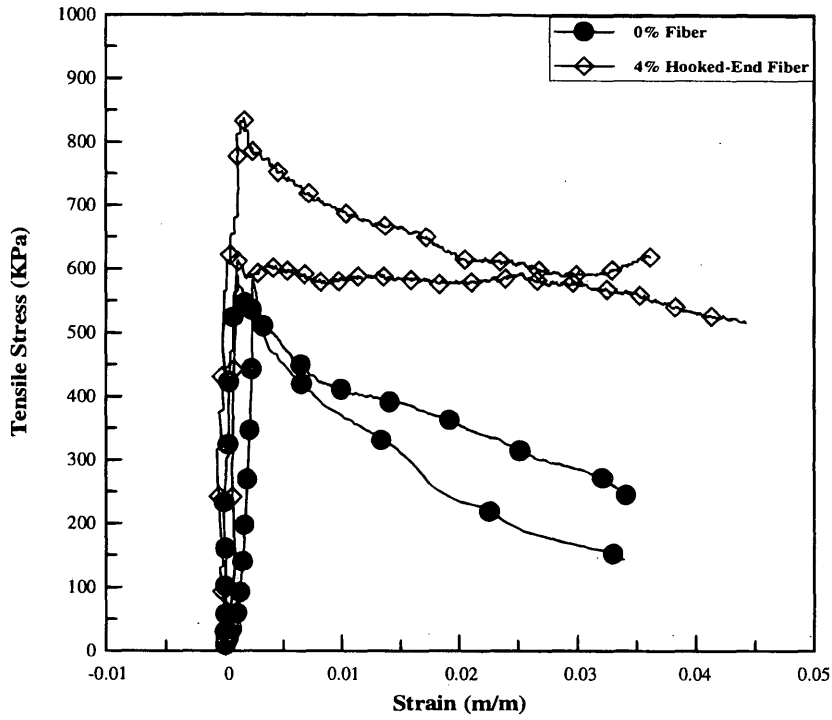


FIGURE 7 Stress-strain curves for 28-day split tensile tests with hooked-end steel fibers.

porating the correct amount of an appropriate fiber. It follows that the basic idea of fiber-reinforcement appears to have merit, and the unsatisfactory performance of the composite materials in the Maryland and Illinois studies was due to the inclusion of unsuitable waste fibers. Hence, careful evaluation is essential before using any waste product in highway construction, and studies are required to identify suitable candidate fibers and their optimum proportions within economical limits.

DISCUSSION OF RESULTS

The primary benefit obtained by adding fibers to a cement-based composite is to increase the energy absorption capacity or toughness (*14*). Higher toughness means higher fatigue strength and greater resistance to crack formation and propagation. A cement-stabilized pavement layer is typically subjected to flexural (tensile) stresses in the slab, and this eventually leads to crack formation, crack propagation, and failure. If suitable fibers are incorporated in the pavement system in correct proportions, they can slow down the process of failure by effectively bridging the cracks and imparting a higher degree of tensile resistance to the material. Toughness is a measure of the effectiveness of the fibers in a composite; therefore, it is logical to expect that an improvement in this material property will enhance the flexural fatigue performance of a pavement system consisting of at least one layer of a fiber-reinforced composite. Accordingly, the material evaluations in this study were based primarily on the measured values of toughness.

Although there is perhaps little disagreement with the foregoing general concepts, incorporating fibers into pavement systems is limited by the cost of the fibers and the uncertainty of the benefit to be achieved for this added cost. It follows that the economics would be significantly improved if low-cost or no-cost waste products could be used advantageously, and this is the principal motivating factor behind this study. Unfortunately, the recycled plastics and tire products in the forms and sizes described in this study not only afforded little or no improvement in material behavior, but also generally affected both the strength and toughness of the composite material adversely. Tire chunks, strands of tire wires, and strips of plastics acted more as defects in the composite system, instead of as beneficial additives. The unsatisfactory performance of the steel wires (which closely resemble "idealized" tire wires) suggests that, even if the tire wires could be economically separated from companion strands or tire chunks by complete removal of the rubber, they would still offer little benefit as fibers in a stabilized base course containing recycled concrete aggregate. The results of the comparison study indicated that recycled concrete aggregate would probably be suitable for use in a fiber-reinforced stabilized base course pavement system, provided the correct amount of an appropriate fiber is used. This use of recycled concrete aggregate would, of course, affect the economics and perhaps render the implementation unfeasible or unacceptable.

CONCLUSIONS

Although the basic concept of incorporating fiber-reinforcement in a highway base course to enhance the desirable property of toughness is generally accepted and appears achievable with a proper proportion of an appropriate fiber (even for the relatively low cement content of an economical cement-stabilized recycled concrete aggregate mix), the use of fibers from reclaimed waste products (shredded

plastic bottles and wires from scrap tires) did not produce the desired benefits. Instead, using fibers from waste products degraded the material properties relative to those of similar unreinforced mixes. Accordingly, notwithstanding the attractiveness of using waste materials from an environmental standpoint and from initial cost considerations, a careful evaluation of performance characteristics and life-cycle costs must be performed before any particular waste product is incorporated into a highway pavement system.

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