Fatigue Durability of Stabilized Recycled Aggregate Base Course Containing Fly Ash and Waste-Plastic Strip Reinforcement

Final Report

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ABSTRACT

The report presented herein describes a laboratory investigation to evaluate the performance of a cement-stabilized pavement base course material consisting of recycled concrete aggregate, ASTM Class C fly ash, and waste plastic (high-density poly ethylene) strips obtained from post-consumer water and milk containers. The primary focus of the study was to systematically characterize the new composite base course under both static and dynamic (fatigue) loading conditions to gain some insights into the long-term durability of the material. To achieve these goals, a coordinated experimental program was undertaken that consisted of the following four Phases: (1) Phase I: Selection of initial mix-design, (2) Phase II: Instrumented split tensile test program, (3) Phase III: Static flexural test program, and (4) Phase IV: Flexural fatigue test program. Since a stabilized layer within a pavement structure is subjected to repeated tensile (flexural) stresses due to dynamic traffic loadings, the experimental program primarily involved material characterization under split tensile or flexural modes. The main objective of utilizing plastic strip reinforcement was to inhibit the propagation of tensile cracks, and thus improve the overall toughness and fatigue resistance of the material. The cement content in all mixes used in this study was either 4% or 8% by total dry weight of the mixture implying that at least 92% of the base course composite consisted of waste or recycled materials. It was found that a mixture containing only 4% cement, 4% fly ash, and 92% recycled aggregate (by weight) achieved a compressive strength of about 5 MPa (725 psi), a split tensile strength of about 0.75 MPa (109 psi), and a flexural strength of about 0.95 MPa (138 psi), indicating a moderately strong stabilized base course material. Flexural fatigue tests conducted on the same mixture reinforced with 1.25% (by weight) of recycled plastic strips (51 mm long and 6.3 mm wide) showed that the performance of the composite base course was comparable to or better than other traditional stabilized material used in pavement construction. Significant results from the repeated load test program include: (a) the relationship between the stress ratio and the number of cycles to failure (S-N curve), (b) the resilient modulus, (c) fatigue endurance limit, and (d) damage accumulation characteristics in the material due to cyclic loading. The study indicates that the new composite base course consisting primarily of waste products holds considerable promise as an alternative material for the construction and rehabilitation of highway pavements.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

An experimental investigation was undertaken to evaluate the performance of a new, composite base course material consisting of the following: (a) recycled crushed concrete aggregate obtained from demolished infrastructure elements, (b) cement and fly ash used as stabilizing agents, and (c) strips of recycled, post-consumer plastics used as reinforcing agents in a brittle, cementitious matrix. The proposed base course material contains low quantities of cement (only 4%-8% by weight), implying that at least 92% of the composite (by weight) is obtained from waste products. The primary motivation for this project was to find innovative reuse of several recyclable materials in highway pavements by conducting systematic characterization studies aimed at providing valuable insights into the long-term performance and durability issues of such composites. Since a stabilized pavement layer is subjected to repeated tensile stresses due to dynamic traffic loads, a primary focus of this project was to assess the durability of the material under flexural fatigue loading. The significant outputs from this research effort includes: (i) mixture proportions of recycled aggregate, cement, and fly ash that satisfy the strength requirements for high quality stabilized base course, (ii) stress-strain-strength behavior under indirect tension, flexure, and fatigue loads, (iii) performance evaluation of recycled plastic fibers in arresting the crack propagation, and (iv) essential material properties and relationships that can be directly used in the current AASHTO and mechanistic based design procedures.

1.2 RECYCLED MATERIALS IN HIGHWAY CONSTRUCTION

Although the use of cement stabilized layers in pavements is not a new idea, developing a cement and fly ash stabilized composite base course with primarily waste materials is certainly timely and innovative. The concept of stabilization and reinforcement, which is achieved in this project with mostly recycled materials, has the potential of producing better performing, longer lasting pavement layers. The stabilization part enhances the strength characteristics of the material, while the inclusion of fiber reinforcement aims at prolonging the formation and propagation of tensile cracks through the pavement layer. This project, therefore, addresses two crucial issues currently encountered by the civil engineering profession: (1) the need for systematic evaluation of candidate waste products that have strong potential for use as a pavement material, and (2) the need for developing innovative, high performance, yet cost effective materials to benefit our decaying infrastructure.

In the recent years, major emphasis has been on the rehabilitation and maintenance of existing highway facilities, rather than building entirely new pavement structures. [1] The increasing availability of reclaimable aggregates from demolished infrastructure elements and the concurrent gradual decline in available landfill spaces for the disposal of construction debris have created a need-driven opportunity for greater use of recycled aggregates in the construction and rehabilitation of pavement systems. Similarly, due to the widespread availability of fly ash as a waste material, and its cementitious characteristics under certain conditions, there is lot of potential for utilizing fly ash as an alternative construction material in highway applications.[2] The current study combines these two waste materials (namely recycled crushed concrete and fly ash) into a stabilized base course with equivalent or superior mechanical properties compared to untreated conventional granular base/subbase materials. The third potential waste material used in this study is shredded reclaimed plastic (high-density poly ethylene or HDPE) obtained from milk and water containers. According to the data published by the EPA (1992), the solid waste stream in the United States in 1988 included 14.4 million tons of plastics which occupied 20% by volume of the available landfill space.[3] Therefore, innovative use of recycled plastics as fiber/strip reinforcement of pavement layers is not only environmentally significant, but has the potential of becoming a new and effective strategy for rehabilitation and maintenance; this will ultimately result in savings to both the highway agency and the user.

1.3 RESEARCH BACKGROUND AND MECHANISTIC ANALYSIS

From a mechanistic standpoint, although a stabilized base course has good load bearing capacity, it is brittle in nature and will undergo failure due to formation and propagation of tensile cracks induced by repeated tensile stresses coming from the traffic. In other words, cementitious stabilization produces a brittle concrete-type material, which is inherently weak in tension. Figure 1 shows the locations of critical stresses and strains in flexible pavements containing either a granular or a stabilized base course. It is found that replacing granular base course with a stabilized base course moves the location of radial tensile stress or strain from the bottom of the asphalt layer to the bottom of the stabilized layer; this redistribution of critical locations completely alters the potential performance of the pavement, and necessitates very different design and construction considerations for pavements with stabilized layers.[4] Since tensile stresses play an important role in the performance of stabilized layers, the current study involved mechanical characterization that primarily focused on split tension and flexural tests.

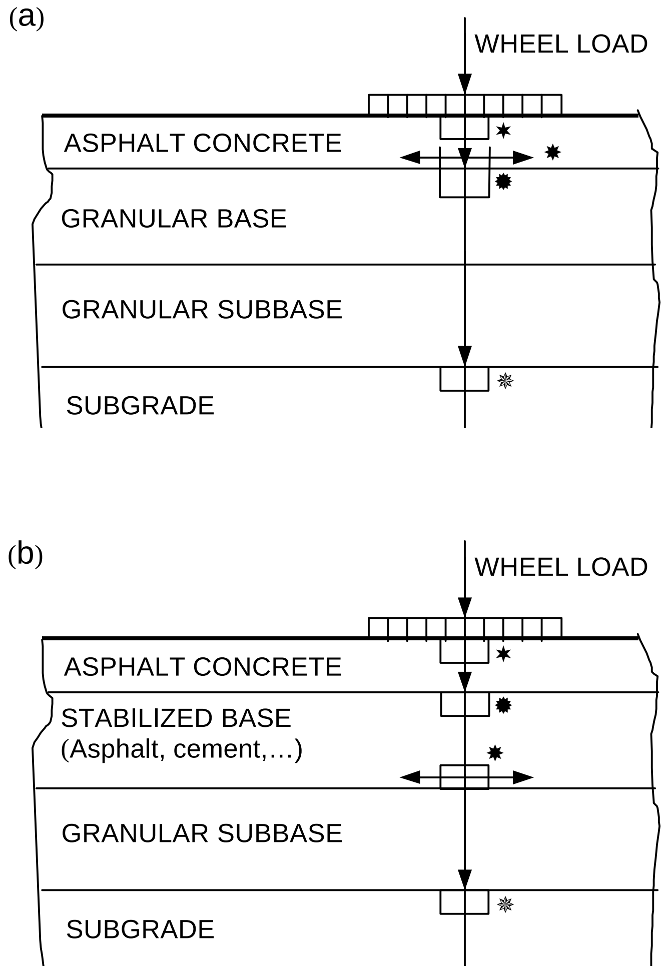

Figure 1. Location of critical stresses and strains in a flexible pavement containing (a) granular and (b) a stabilized base course. Points 1, 3, and 4 are locations of critical vertical stresses or strains. Point 2 represents the location of radial tensile stresses or strains at the bottom of the asphalt layer in (a), and at the bottom of the stabilized layer in (b).

The coordinated experimental program (described later) evaluated fiber toughening mechanisms introduced by the plastic strips to enhance the service life of the pavement layer. It is known that many applications of dynamic traffic loads can cause fatigue failure in the pavement. In the case of a base course containing soil and /or aggregate stabilized with low quantities of cementitious materials, fatigue failure occurs due to the growth and propagation of tensile cracks caused by repeated flexural stresses. Ideally, the inclusion of fibers enhances the energy absorption capacity or toughness of the material and serves to retard the crack propagation process. However, there is some degree of uncertainty as to the effectiveness of fibers in a lean composite containing mostly waste materials (recycled aggregate and fly ash) and low quantities of Portland cement. The coordinated experimental program undertaken in this study, therefore, included repeated load tests under flexural mode, and compared the performance of the new base course with other traditional stabilized base/subbase materials.

1.4 RELEVANT STUDIES

Many studies have been reported on laboratory fatigue characterization and/or design aspects (incorporating fatigue behavior and field performance) of stabilized pavement base course materials (see references 4, 5, 6, and 7). Major findings in References 4, 5, 6, and 7 are (i) the relationship between the stress ratio and number of cycles to failure for soil-cement, lime-fly ash-aggregate, lean-concrete, etc., (ii) design and construction considerations for stabilized pavement layers, and (iii) mechanistic design principles involving stabilized materials. However, little information is available on the fiber reinforcement of such stabilized materials, and none of these studies that involved fiber reinforcements investigated the flexural fatigue behavior of the composite (see references 8, 9, 10, and 11). Studies in References 8, 9, 10, and 11 are primarily on laboratory and field evaluation of soil and soil-cement reinforced with discrete commercial fibers. Although the utilization of waste aggregate in highway construction may be beneficial for reducing the crucial landfill disposal problem, the use of recycled aggregate for a cement stabilized base or subbase has been very limited and largely experimental.(12,13) Information is available in the literature on fatigue and damage accumulation studies on stabilized recycled aggregate reinforced with commercially available hooked-end steel fibers.(14,15) These studies concluded that the use of steel fiber reinforcement significantly improved the fatigue resistance of the composite. However, due to the high cost of steel fibers, it would be impractical to use them in base course materials. It was also suggested in those studies that waste or recycled materials (such as shredded plastics) should be investigated as alternative sources of inexpensive fibers for base course applications. No information was found in the pavement and concrete literature on the flexural fatigue characteristics of a stabilized recycled aggregate base course material reinforced with shredded plastic strips.

1.5 OBJECTIVES

Within this framework, the specific objectives of this study are:

(1) To evaluate the mechanical behavior of a stabilized recycled aggregate base course containing shredded plastic fibers under compression, split tension, flexure and repeated loadings,

(2) To evaluate the effectiveness of shredded recycled plastic fibers in enhancing the performance of the pavement material,

(3) To determine the resilient modulus of the new composite,

(4) To determine the durability of the material in terms of fatigue endurance limits and quantify the gradual damage accumulation process,

(5) To compare the performance (specifically under cyclic loadings) of the proposed new composite with other traditional base/subbase materials.

1.6 METHODOLOGY AND SCOPE

To achieve the above objectives, a coordinated and carefully designed experimental program was undertaken. Details of the methodologies employed will be provided in Chapter 3. Figure 2 provides a flow chart, which summarizes this research program and illustrates the logical sequences involved in the experimental design. The experimental program consisted of the following four phases:

(1) PHASE I: Selection of Initial Mix Design

The objective of this phase was to determine the optimum quantities of recycled aggregate, fly ash, cement, and water, as well as a compactive effort, such that the resultant product satisfies the strength and density requirements for a “high-quality” stabilized base course[7].

(2) PHASE II: Instrumented Split Tension Tests

The objectives of this phase were (i) to determine the optimum amount and geometry of shredded recycled plastic reinforcement that can be accommodated in the test specimens without sacrificing desired density and the strength, and (ii) to evaluate if the inclusion of the above reinforcement produces any enhancement in the mechanical performance in terms of split tensile strength and/or toughness.

(3) PHASE III: Flexural Test Program

The objectives of this phase of the experimental program were to evaluate the flexural load-deformation and strength characteristics of beam specimens made from selected mixes based on the results of split tension tests in Phase I & II.

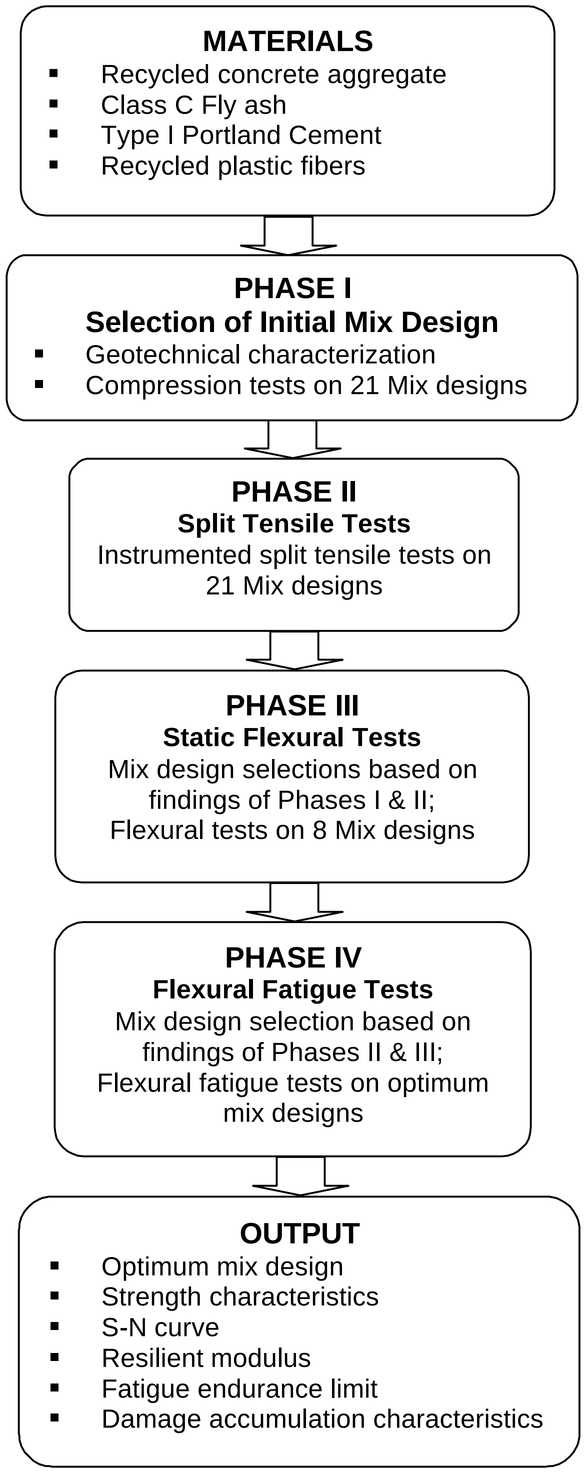

Figure 2. Flow chart of the experimental program.

(4) PHASE IV: Flexural Fatigue Test Program

The selected, most efficient mix based on results from Phases II and III is utilized to prepare several fiber-reinforced and control beam specimens for repeated load flexural tests. The primary objectives of this phase are to (i) determine the S-N (Stress ratio versus the number of cycles to failure) relationships, fatigue endurance limits, and resilient modulus for the selected mix, and (ii) quantify the damage accumulation process during cyclic loading. Evaluating the durability of the composite against fatigue failure is the primary focus of this research endeavor.

1.7 RESEARCH SIGNIFICANCE

The current research evaluates the performance of several candidate waste materials for use in highway construction. Moreover, the experimental program is designed such that the materials properties determined in this study can be directly used in conjunction with an appropriate mechanistic-empirical design procedure. These properties include the resilient modulus, flexural strength, the stress ratio versus the number of cycles relationships (S-N curves), and the damage accumulation characteristics. For example, a mechanistic-empirical design procedure may involve utilization of a structural model (such as a layered elastic theory) to predict stresses and strains in the stabilized layer. Material properties such as the resilient modulus will be an input to this structural model. The calculated stresses can then be used to predict the performance (cycles to failure) of the stabilized layer by using a transfer function (S-N relationships) developed from a flexural fatigue test program. The current study also provides a useful correlation between static flexural strength and resilient modulus (which is a dynamic property), thus eliminating the need for conducting expensive and time consuming repeated-load tests to evaluate this essential material property for use in mechanistic design. It is to be noted that the upcoming AASHTO 2002 Design Manual NCHRP 1-37 [16] will be mechanistic-empirical in nature. Therefore, the results of this investigation will be useful in implementing the future AASHTO pavement design procedures. In addition, the current study demonstrates a systematic procedure for characterizing similar potential recycled materials (as they become available) for possible use in highway applications.

CHAPTER 2: MATERIALS

2.1 INTRODUCTION

The primary materials used in this study included recycled crushed concrete aggregate, Type I Portland cement, fly ash, and recycled high-density poly-ethylene (HDPE) plastic strips. Brief descriptions for each of these materials are provided in this chapter.

2.2 RECYCLED AGGREGATE

Recycled crushed concrete aggregate was obtained from Jobe Concrete Products located in El Paso, Texas. The source of this aggregate was primarily demolished building and infrastructure elements originating in the southwestern United States. Grain size distribution tests were conducted on six random samples obtained from the recycled aggregate pile. These results are shown in Figure 3. A representative average curve is selected from this figure and is superimposed on Figure 4, which contains the grain size distribution characteristics of recycled crushed aggregate from two other sources located in Maryland and Illinois.[17] It is concluded that (i) the crushed recycled aggregate selected for this study (representing the western United States) have very similar gradations compared to those found in the Eastern (Maryland), and the Midwest (Illinois) regions of the country, and (ii) all three sources of recycled aggregate conform approximately to the gradations of standard base course materials used for highway construction as shown in Table 1.

2.3 FLY ASH

Fly ash was obtained from Pleasant Prairie power plant and was supplied by Mineral Solutions located in Naperville, Illinois. The physical and chemical properties of this fly ash are provided in Table 2. The fly ash had a dull yellow color and conformed to both ASTM and AASHTO Class C specifications.

2.4 PORTLAND CEMENT

Type I Portland cement was used as a stabilizing agent throughout this investigation.

2.5 WATER

Regular potable water was used throughout this investigation.

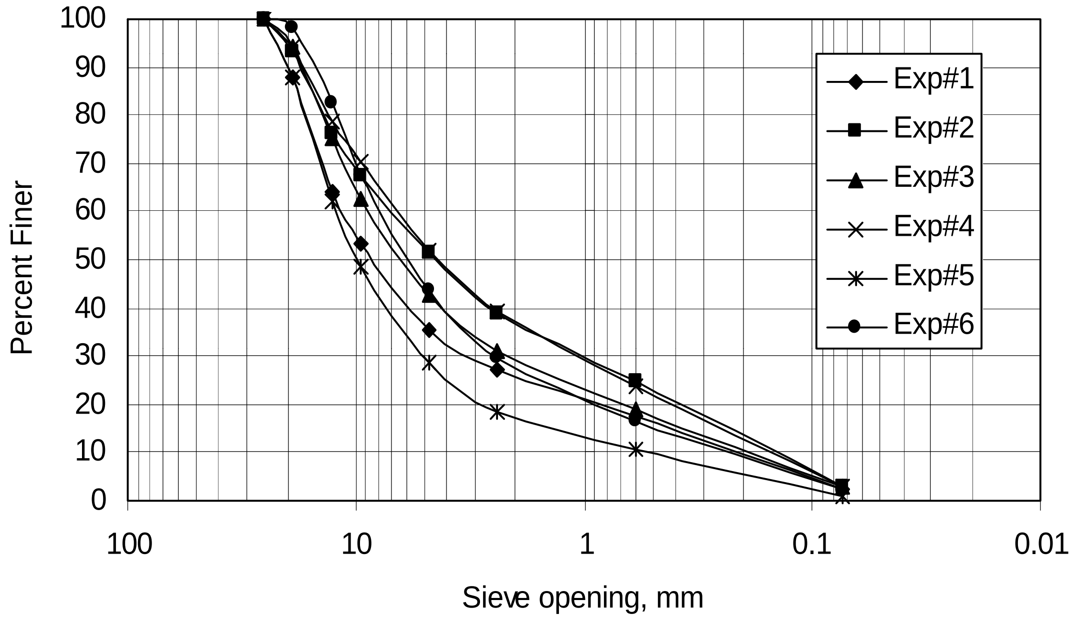

Figure 3. Grain size distribution by sieve analysis of 6 random samples collected from aggregate used in Research.

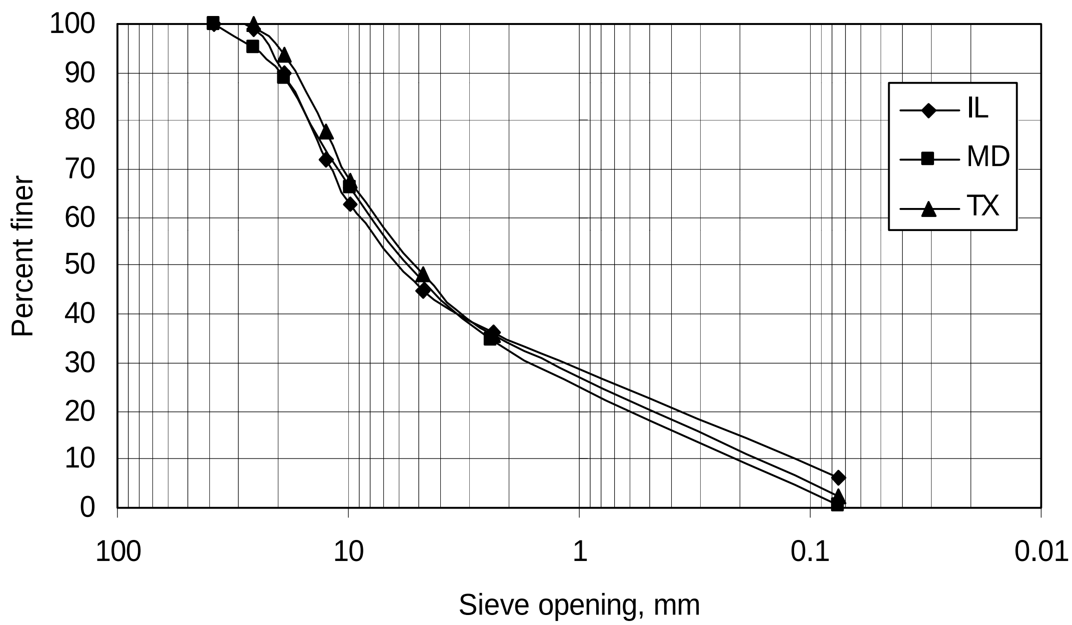

Figure 4. Combined average grain size distribution of aggregate used in Research study (TX) compared to material sampled elsewhere in US (IL: Illinois; MD: Maryland)[17].

Table 1. Comparison of gradation for various base aggregates (numbers indicate % passing each sieve size).

Sieve Size	Sieve Size (mm)	Crushed Stone	Dense Graded	AASHTO 67'	AASHTO 57'	Recycled Materials		
						IL	MD	TX
1-1/2"	38.00	100			100	100	100	
1"	25.40		100	100	95-100	99	95	100
3/4"	19.00			90-100		90	89	94
1/2"	12.50				25-60	72		78
3/8"	9.70	40-75		20-55		63	66	68
No. 4	4.75	25-60	35-70	0-10	0-10	45		48
No. 8	2.36			0-5	0-5	36		36
No. 10	2.40	15-45					35	
No. 200	75µ	3-12 µ	3-10			6.3	0.5	2.4

2.6 RECYCLED PLASTIC FIBERS

Recycled plastic strips used in this study were high-density poly ethylene (HDPE) obtained from shredding post-consumer milk and water containers using a band saw. Recycled HDPE strips from milk jugs are reported to have an average tensile strength of 16.4 MPa and Young's modulus of 900 MPa.[18] The strips were cut such that the width was 6.35 mm (0.25-inch), and the lengths were 19 mm (0.75-inch), 50.8 mm (2-inch), and 76.2 mm (3-inch), implying aspect ratios (length/width) of 3, 8, and 12 respectively. Typical thickness of the strips was 0.50 mm (0.02-inch).

Table 2. Physical and chemical properties of Pleasant Prairie Fly Ash

Properties			ASTM C 618 CLASS C	AASHTO M 295 CLASS C
Chemical Properties				
▪ Silica (SiO_2),%	=	35.80		
▪ Iron Oxide (Fe_2O_3),%	=	5.29		
▪ Alumina (Al_2O_3),%	=	19.20		
SiO_2 +Fe_2O_3 +Al_2O_3	=	60.3	50.0 min	50.0 min
▪ Calcium Oxide (CaO),%	=	27.50		40.0 max
▪ Magnesium Oxide (MgO),%	=	5.43		
▪ (SO_3),%	=	2.07	5.0 max	5.0 max
▪ Moisture content, %	=	0.15	3.0 max	3.0 max
▪ Loss of ignition, %	=	0.43	6.0 max	5.0 max
Variation	=	0.08		
Total Alkalies				
▪ Sodium Oxide (Na_2O), %	=	1.83		
▪ Potassium Oxide (K_2O), %	=	0.30		
▪ Equivalent Na_2O, %	=	2.03		
Analysis total		97.5		
Available Alkalies				
▪ Na_2O	=	1.06		
▪ K_2O	=	0.14		
▪ Na_2O	=	1.15	1.5 max	1.5 max
Physical Properties				
▪ Fineness, # 325 Sieve residue				
Variation	=	12.6	34 max	34 max
	=	1.9	5 max	5 max
▪ Density, g/cm^3				
Variation	=	2.68		
	=	1.90	5 max	5 max
▪ Strength activity index with Portland cement				
at 7 days, % of control				
at 28 days, % of control	=	97.9	75 min	75 min
	=	NA	75 min	75 min
▪ Water requirement, % of control				
▪ Soundness, autoclave expansion or contraction	=	95.0	105 max	100 max
	=	0.10	0.8 max	0.8 max

CHAPTER 3: EXPERIMENtal program

3.1 INTRODUCTION

The experimental program consists of the following four phases (i) Selection of initial mix design, (ii) Instrumented split tension tests, (iii) Static flexural tests and, and (iv) Flexural fatigue tests. The primary focus of the experimental program was to evaluate the resistance and durability of the material against fatigue type of failure due to repeated or cyclic loading. Systematic series of materials characterization studies were performed in Phases I, II and III, and the conclusions drawn from these phases were utilized to identify a target mix design for the Phase IV repeated load tests. This procedure helped optimize the time and cost involved in the whole experimental test program.

3.2 PHASE I: SELECTION OF INITIAL MIX DESIGN

3.2.1 Objectives and scope

The objectives of the Phase I activities were (i) to conduct preliminary geotechnical tests including the grain size distribution and the moisture density relationships, (ii) to prepare cylindrical specimens for compressive and split tensile tests, (iii) to determine the compressive strengths for different mixes with varying amount of cement, fly ash, and recycled plastics as the reinforcing material, and (iv) to identify mix designs which produce desired strength levels necessary for a high-quality stabilized base course.

3.2.2 Modified proctor tests

Modified Proctor tests (ASTM D 1557-91) [(19)] were conducted to determine moisture-density relationships of four different mixtures: aggregate only, aggregate with 4% by weight of cement, aggregate with 8% by weight of cement, and aggregate with 4% by weight of cement and 4% by weight of fly ash. These results are shown in Figure 5 from which it can be concluded that the maximum dry unit weight for all mixes varied between 20 to 21 kN/m^3 while the optimum moisture content varied between 7% to 9%. For meaningful comparison of mechanical performance of various mixes, it was decided that for all subsequent specimens used in this study, the dry unit weight will be held constant at about 19.2 kN/m^3 (120 pcf) (representing about 95% of the maximum modified Proctor density), with a molding water content of 9 %.

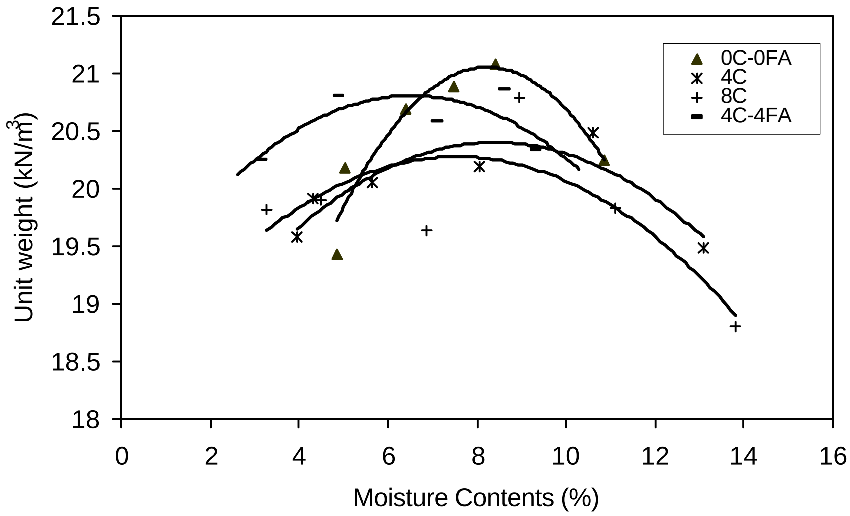

Figure 5. Modified Procter compaction characteristics (C = cement, and FA = fly ash).

3.2.3 Specimen preparation and curing

Twenty one different mix designs were selected for preparing 152.4 mm x 304.8 mm (6x12-inch) cylindrical specimens to evaluate the strength characteristics under unconfined compression and split tension modes. Split tensile specimens were prepared for Phase II of the experimental program. Table 3 shows details of all these mixes, which included recycled crushed aggregate and various combinations of cement, fly ash, and shredded recycled plastic fibers. Mixes were numbered 1 through 21. Mixes 1 through 3 were unreinforced; these were tested as the control samples. Fiber reinforced specimens contained either 0.25% or 0.5% (by total dry weight of the mix) of plastic strips having lengths of 19 mm, 50.8 mm and 76.2 mm. Three specimens were prepared from each mix.

The cement, aggregate, fly ash, and fibers were first dry mixed in a rotary-type concrete mixer as shown in Figure 6. After this step, predetermined amount of water was added gradually to the materials, which was mixed for an additional 5 minutes. The resultant mix resembled a zero-slump concrete-type mixture. The specimens were prepared in split-type steel molds by empirically determined impact compaction techniques such that a target dry unit weight of 19.2 kN/m^3 (120 pcf) was achieved. The specimens were sealed cured in the laboratory environment for about 24 hours after which they were demolded and transported to a 100% humidity room for curing.

Table 3. Summary of compressive and split tensile test program (C: Unconfined Compression Tests, T: Split Tensile Tests).

Mixes	Mix Design	Type of Tests
Mix-1	8% Cement	C,T
Mix-2	4% Cement + 4% Fly Ash	C,T
Mix-3	8% Cement + 8% Fly Ash	C,T
Mix-4	8% Cement + 0.25%, 50.8 mm Fibers	C,T
Mix-5	4% Cement + 4% Fly Ash + 0.25%, 50.8 mm Fibers	C,T
Mix-6	8% Cement + 8% Fly Ash + 0.25%, 50.8 mm Fibers	C,T
Mix-7	8% Cement + 0.50%, 50.8 mm Fibers	C,T
Mix-8	4% Cement + 4% Fly Ash + 0.50%, 50.8 mm Fibers	C,T
Mix-9	8% Cement + 8% Fly Ash + 0.50%, 50.8 mm Fibers	C,T
Mix-10	8% Cement + 0.25%, 76.2 mm Fibers	C,T
Mix-11	4% Cement + 4% Fly Ash + 0.25%, 76.2 mm Fibers	C,T
Mix-12	8% Cement + 8% Fly Ash + 0.25%, 76.2 mm Fibers	C,T
Mix-13	8% Cement + 0.50%, 76.2 mm Fibers	C,T
Mix-14	4% Cement + 4% Fly Ash + 0.50%, 76.2 mm Fibers	C,T
Mix-15	8% Cement + 8% Fly Ash + 0.50%, 76.2 mm Fibers	C,T
Mix-16	8% Cement + 0.25%, 19 mm Fibers	C,T
Mix-17	4% Cement + 4% Fly Ash + 0.25%,19 mm Fibers	C,T
Mix-18	8% Cement + 8% Fly Ash + 0.25%,19 mm Fibers	C,T
Mix-19	8% Cement + 0.50%,19 mm Fibers	C,T
Mix-20	4% Cement + 4% Fly Ash + 0.50%,19 mm Fibers	C,T
Mix-21	8% Cement + 8% Fly Ash + 0.50%,19 mm Fibers	C,T

Figure 6. Materials were mixed in a rotary concrete mixer.

3.2.4 Test procedures and equipment

Unconfined compressive strength tests were performed approximately in accordance with ASTM C39[20] procedures using a 400-kip hydraulic universal-testing machine. Tests were conducted under load control; no deformation measurements were taken. Test results will be presented in Chapter 4.

3.3 PHASE II: INSTRUMENTED SPLIT TENSION TESTS

3.3.1 Objectives and scope

The objectives of the split tensile test program were: (i) to determine the split tensile strength of different mixes due to the variation of cement, fly ash, and reinforcing fibers, and (ii) to determine the post peak load carrying capacity and toughness characteristics of fiber reinforced specimens relative to unreinforced specimens.

3.3.2 Specimen preparation and curing

Specimens for this phase were prepared in Phase I of the test program as described in Section 3.2.3.

3.3.3 Test procedures and equipment

The split tensile tests were conducted approximately according to the procedures outlined in ASTM C 496[21]. This standard test method can be used to determine the split tensile strength only; no information is obtained on the load deformation behavior of the material. As an extension to this method, two horizontal linear variable differential transformers (LVDT) were attached at the longitudinal and vertical mid height of the specimens to measure the lateral or tensile deformation of the horizontal diameter due to compressive loading in an orthogonal direction. This method permitted an evaluation of the toughness characteristics of the composite, which is a measure of the effectiveness of the recycled plastic fibers in retarding the propagation of the tensile cracks. A schematic of the test setup is shown in Figure 7. The instrumented split tensile tests were performed using a 20-kip INSTRON servo-hydraulic testing machine equipped with automated test control and external high-speed data acquisition system. All tests were conducted under deformation control at a rate of 0.5 mm/min. In order to capture the post-peak load deformation characteristics, one data point was recorded per second; each data point included information from the load cell, and two horizontal LVDTs. Results of this section are reported in Chapter 4.

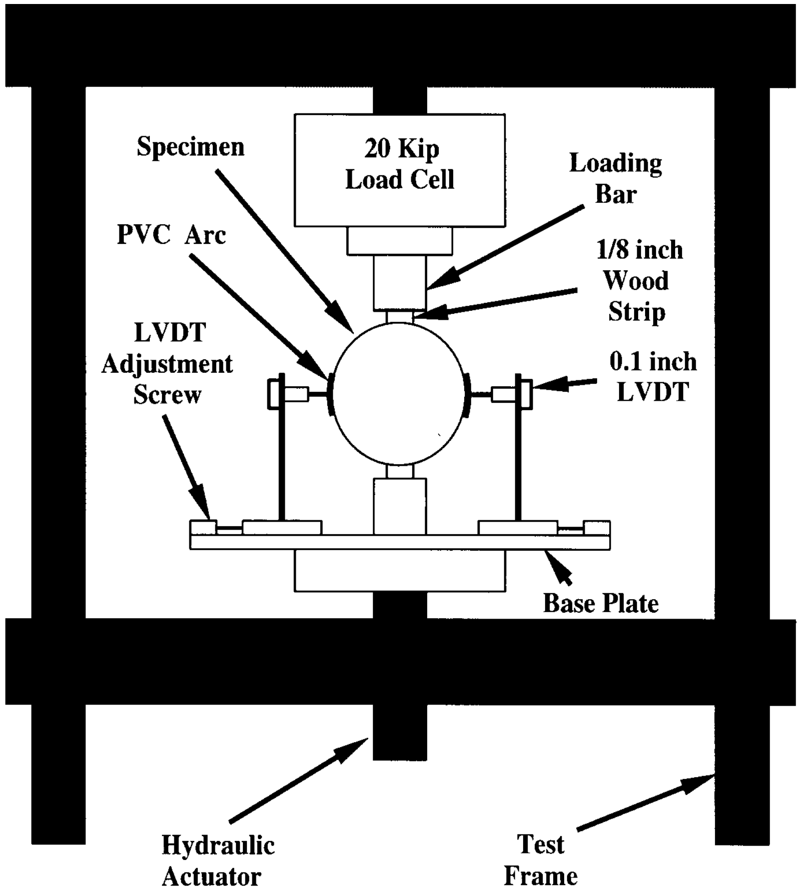

Figure 7. Schematics of split tension test setup.

3.4 PHASE III: FLEXURAL TEST PROGRAM

3.4.1 Objectives and scope

Based on the results of Phases I & II, different mix designs were selected for evaluating the static flexural characteristics of the composite. Specific objectives include: (i) determining the flexural strengths of selected mixes, (ii) determining the flexural load-deformation characteristics to evaluate the effects of fiber inclusions, and (iii) selecting the final mix design for dynamic flexural tests.

3.4.2 Specimen preparation and curing

The size of each prismatic beam prepared for this study was 76.2x15.24x15.24-cm (30x6x6-in). The procedure for mixing the materials was the same as described in Section 3.2.3. The beams were prepared by compacting the mix in detachable steel molds in 3 equal layers. Each layer was scarified for proper bonding with the next layer. Predetermined amount of mix was compacted in the molds using an empirically determined compactive effort so that a target dry unit weight of 19.2 kN/m^3 (120 pcf) was achieved. The beams were sealed cured for 24 hours in the laboratory environment, and then were demolded and carried to the 100% humidity room (Figure 8). Average curing period was 28 days. Specimens were prepared from eight different mix designs (Mixes 1B through 8B) as shown in Table 4. During specimen preparation it was found empirically that 1.25% by weight of plastic fibers was approximately the maximum amount that could be accommodated into the mixes without sacrificing the workability.

Figure 8. Preparation of beam specimens (left) and curing in humidity room (right).

Table 4. Mix designs selected for static flexural tests.

Mixes	Mix Design
Mix-1B	4% Cement + 4% Fly Ash
Mix-2B	4% Cement + 4% Fly Ash + 0.50%, 50.8 mm Fibers
Mix-3B	4% Cement + 4% Fly Ash + 1.00%, 50.8 mm Fibers
Mix-4B	4% Cement + 4% Fly Ash + 1.25%, 50.8 mm Fibers
Mix-5B	8% Cement + 8% Fly Ash
Mix-6B	8% Cement + 8% Fly Ash + 0.50%, 50.8 mm Fibers
Mix-7B	8% Cement + 8% Fly Ash + 1.00%, 50.8 mm Fibers
Mix-8B	8% Cement + 8% Fly Ash + 1.25%, 50.8 mm Fibers

3.4.3 Procedure and equipment

The beams were tested approximately according to the ASTM C1084[22] specification. Beams were tested by a 20-kip INSTRON servo hydraulic testing machine as used in the split tensile test programs. Each beam was simply supported with a span length of 686 mm (27 in). The loading was accomplished with a 3rd point configuration through a flexible collar; the collar could move parallel to the longitudinal axis of the beam in case the surface of the beam was not properly flat. This mechanism ensured uniform loading through the two loading bars of the collar. In order to record the vertical deformation of the beam, an LVDT was attached to the beam at the midspan. The loading and deformation were recorded at every second by the data acquisition system; the loading configuration and the instrument setup are shown in Figure 9.

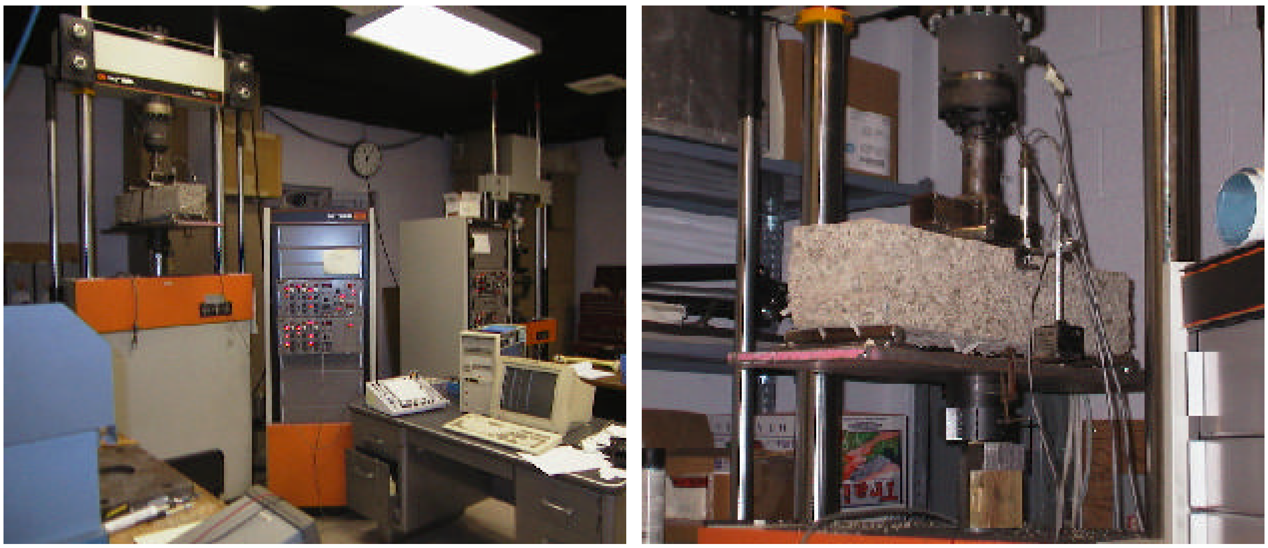

Figure 9. Instrument setup for flexural tests (left) and close-up of a beam and LVDT arrangements (right).

3.5 PHASE IV: FLEXURAL FATIGUE TEST PROGRAM

3.5.1 Objectives and scope

A repeated load flexural test program was undertaken to evaluate the durability of the proposed recycled aggregate base course against fatigue loading conditions. A total of twelve prismatic beams were tested in repeated flexure until failure; three were unreinforced, and nine were reinforced with recycled plastic strips. As shown in the flowchart of Figure 1, the mix design for the repeated load tests was determined from the results of Phases II, III, and IV experimental programs. These results will be discussed later in Chapter 4. The specific objectives of this final phase of the research program were as follows:

1. Establish the traditional S-N (stress ratio versus the number of cycles to failure) relationship for the proposed new composite base course, and compare its performance with other traditional stabilized pavement materials.
2. Determine the fatigue endurance limit for this new composite.

3. Quantify the accumulation of fatigue damage with applied loading cycles, and propose relationships to predict permanent deformation at any stage of the fatigue life.
4. Determine the resilient modulus of the composite.

3.5.2 Specimen preparation and curing

Each of the twelve beams having dimensions of 152.4 mm x 152.4 mm x 762 mm (6 in. x 6 in. x 30 in.) consisted of 92% recycled aggregate, 4% cement, and 4% fly ash by weight; the fiber-reinforced specimens contained recycled HDPE strips at a dosage of 1% to 1.25% by total dry weight of the mix. All specimens were prepared at a target dry unit weight of 19.2 kN/m^3 (120 pcf) as described previously for Phases I through III. Specimens were covered with wet burlap and plastic and left in the mold for 48 hours at room temperature. The beams were then demolded and transferred to a 100% relative humidity room, where they were cured between 28 to 35 days. Afterwards they were removed from the curing room and stored in the laboratory until they were tested. Since some of the fatigue experiments took several days to complete, and since the time required to reach failure could not be predicted beforehand, not all specimens could be tested immediately after the curing period; however, the maximum delay in testing any given specimen did not exceed one week.

3.5.3 Test configuration and design of experiments

Beams were tested in bending under a third-point loading configuration over a span length of 686-mm (27 inches); this implies that the load points were 229 mm (9 in) apart. All beams were loaded with an INSTRON closed-loop servo-hydraulic testing system equipped with a function generator, which is capable of producing cyclic waveforms at a wide range of frequencies. The number of cycles to failure during a fatigue test was recorded by a counter panel attached to the machine. All fatigue tests were conducted under load control using a sinusoidal load pulse with a constant amplitude at a frequency of 2 Hz (120 cycles/minute). It is generally known that, for concrete-type materials, the rate of loading does not have a significant effect on the fatigue life for frequencies between 1 and 15 Hz(23). In an actual situation, an axle load traveling at 88.5 km/hour (55 miles/hour) would traverse two 6.1-meter (20-foot) long slabs in 0.00826 minutes, which implies that the frequency of loading on that pavement section is 121 cycles/minute or approximately 2 Hz. The amplitude (which was different for each specimen) was selected such that the magnitude of the load varied between a maximum and a minimum load, the latter of which was about 10% of the maximum load for all tests. The minimum load was used so that the specimen would be loaded without any shock or impact at each cycle.

In a typical fatigue experiment, the repeated load is usually expressed in terms of a stress ratio, which is the ratio of the applied flexural stress to the static flexural strength or the modulus of rupture of the material. A traditional practice is to conduct three or more static flexural tests and consider the average flexural strength to be representative of the material. Notwithstanding the well-known heterogeneity inherent to concrete-type materials, this procedure was used in this study to obtain an initial estimate of stress ratio. However, in order to determine the "actual" static strength of the specimens with a higher degree of confidence, a separate series of tests was conducted on the broken pieces obtained from the failed static (Phase III) and fatigue (Phase IV) specimens; these results will be discussed later. Due to the uncertainty inherent in estimating the initial stress level, the following procedure was followed for most of the tests:

1. A stress level (for example 80% of the ultimate strength) was selected, from which the corresponding load on the beam was determined by using the estimated strength of the specimen.
2. Using the function generator of the testing machine, a single cycle of loading and unloading was applied at a rate such that the maximum load (determined in step one) was reached in about 10 minutes.
3. If the beam survived the first cycle, its actual strength was obviously higher than the applied stress and the repeated load test was carried out.
4. If the beam failed before reaching the intended maximum load in the first cycle, the load at failure is recorded to calculate the ultimate flexural strength of the specimen, and this information was combined with that from the other static flexural tests.

In addition to recording the number of cycles to failure for each experiment, a linear variable differential transformer (LVDT) was attached to measure the midpoint cyclic deformation of the specimens. The LVDT and the load cell of the testing machine were attached to a high-speed external data acquisition system for continuously recording the cyclic load deformation response. This information was necessary to monitor and quantify the gradual accumulation of fatigue damage in the material with progress of loading cycles. The data acquisition software was programmed so that it recorded two complete load-deformation cycles at every 10-cycle interval.

3.6 STRENGTH CORRELATION STUDIES

In order to develop a correlation between the compressive strength and flexural strength, the procedure suggested in ASTM C116[24] was approximately followed. After the static flexural tests were completed, prismatic specimens having dimensions of 152.4 mm x 152.4 mm x 304.8 mm (6 in. x 6 in. x 12 in.) were saw-cut from the beams for compression testing. The results of this study produced a correlation between the compressive and flexural strengths. Several data points were also used from the literature on soil-cement and stabilized recycled aggregate to develop this correlation. [14,25] The objective was to utilize the correlation to predict the “actual” flexural strength of beams broken in fatigue tests; this would produce a more accurate calculation of the applied stress ratio. These results are presented in Chapter 4.

CHAPTER 4: RESULTS And Analysis

4.1 RESULTS OF PHASES I & II

4.1.1 Compressive and split tensile strengths

As shown in Table 5 there are six groups of specimens (Group A through Group G) with each group consisting of three basic mix designs. For example, Mixes 1 through 3 represent a group (Group A) which consists of specimens from the following 3 mixes: (1) 8% cement and no fly ash, (2) 4% cement and 4% fly ash, and (3) 8% cement and 8% fly ash. Similarly Mixes 4 through 6 represent the second group of specimens (Group B), and so on. Each group contains either no fiber or a different length or amount of fibers. Table 5 shows the average compressive and split tensile strengths for all mixes. The strength data are also plotted in Figure 10 for easy comparison. The split tensile strength is computed according to ASTM C 496-96[21] as follows:

$$s_t = \frac{2P}{p\, l\, d} \qquad (1)$$

where s_t is the split tensile strength, *P* is the applied maximum load, and *l* and *d* are respectively the length and diameter of the specimen.

For the mix designs tested in this experimental program, the specimens with 8% cement and 8% fly ash achieved the highest 28-day compressive and split tensile strengths; these values are approximately 14 MPa (2000 psi) and 1.5 MPa (232 psi) respectively. These strength levels (which are almost 50% of the strength of regular concrete) indicate a remarkably strong stabilized base course material similar to lean concrete despite the fact that 92% of this composite contains recycled materials. The average compressive and split tensile strength of unreinforced specimens are 8.3 MPa and 1.0 MPa respectively, indicating that the split tensile strength is about 12% of the compressive strength. This observation is in agreement with the general assumption often made in case of concrete-type materials that the tensile strength is approximately 10% of the compressive strength. It is found that the compressive strength drops when 50% of the cement is replaced by fly ash (comparing Mixes 1 and 2), and significantly increases when the amount of cementitious material is doubled by adding fly ash to the composite (comparing Mixes 1 and 3). This trend is similar for all other groups. In the case of split tensile tests, it is found that for all groups of specimens, the mix with 4% cement and 4% fly ash performed equivalent or better compared to the mix containing 8% cement and no fly ash. For all mixes, the inclusion of fibers had a detrimental effect on compressive strength compared to a corresponding unreinforced mix (such as Mixes 1,4,7,10 and 13). However, a similar comparison reveals that for most mixes, the split tensile strength remained approximately same or showed noticeable improvement due to the inclusion of fibers. Improvement in tensile strength due to fiber addition is encouraging, since it is known that stabilized materials are generally weak in tension.

Table 5. Summary of 28-day unconfined compressive and split tensile strengths.

Mixes	Mix Design	Compressive Strength (MPa)	Tensile Strength (MPa)
Mix-1	8% Cement	6.22	0.65
Mix-2	4% Cement + 4% Fly Ash	5.05	0.77
Mix-3	8% Cement + 8% Fly Ash	13.63	1.56
Mix-4	8% Cement + 0.25%, 50.8 mm Fibers	4.73	0.84
Mix-5	4% Cement + 4% Fly Ash + 0.25%, 50.8 mm Fibers	4.01	1.12
Mix-6	8% Cement + 8% Fly Ash + 0.25%, 50.8 mm Fibers	9.28	1.70
Mix-7	8% Cement + 0.50%, 50.8 mm Fibers	4.73	0.98
Mix-8	4% Cement + 4% Fly Ash + 0.50%, 50.8 mm Fibers	3.29	0.96
Mix-9	8% Cement + 8% Fly Ash + 0.50%, 50.8 mm Fibers	10.72	1.51
Mix-10	8% Cement + 0.25%, 76.2 mm Fibers	4.01	0.56
Mix-11	4% Cement + 4% Fly Ash + 0.25%, 76.2 mm Fibers	2.69	0.77
Mix-12	8% Cement + 8% Fly Ash + 0.25%, 76.2 mm Fibers	7.36	0.92
Mix-13	8% Cement + 0.50%, 76.2 mm Fibers	2.90	0.65
Mix-14	4% Cement + 4% Fly Ash + 0.50%, 76.2 mm Fibers	2.90	0.66
Mix-15	8% Cement + 8% Fly Ash + 0.50%, 76.2 mm Fibers	7.72	1.25
Mix-16	8% Cement + 0.25%, 19 mm Fibers	3.90	0.77
Mix-17	4% Cement + 4% Fly Ash + 0.25%,19 mm Fibers	3.65	0.66
Mix-18	8% Cement + 8% Fly Ash + 0.25%,19 mm Fibers	6.40	1.18
Mix-19	8% Cement + 0.50%,19 mm Fibers	2.92	0.79
Mix-20	4% Cement + 4% Fly Ash + 0.50%,19 mm Fibers	2.68	0.47
Mix-21	8% Cement + 8% Fly Ash + 0.50%,19 mm Fibers	4.87	0.45

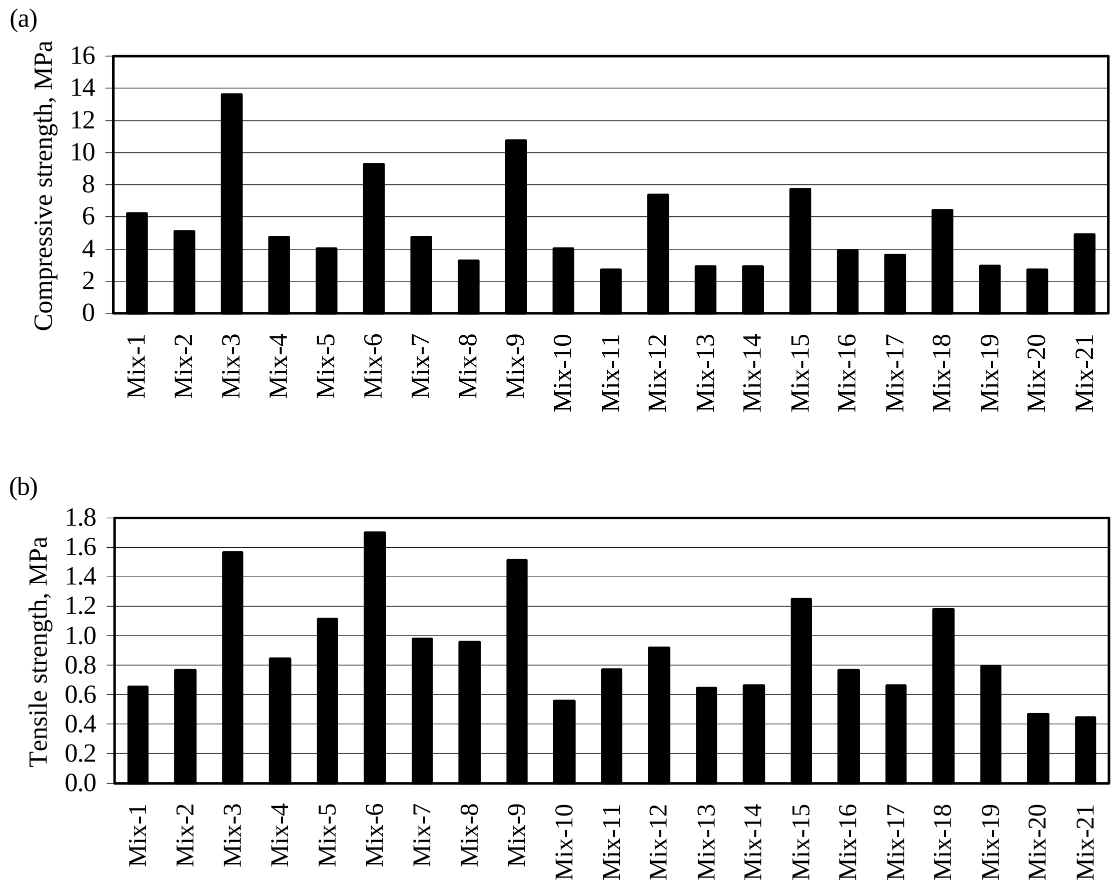

Figure 10. 28-day compressive and split tensile strengths of various mixes.

4.1.2 Load deformation behavior and toughness characteristics

Figures 11,12 and 13 show the load versus tensile deformation for all three mixes: (i) 8% cement and no fly ash, (ii) 4% cement and 4% fly ash, and (iii) 8% Cement and 8% fly ash. The lateral deformations recorded by the two LVDTs were added to obtain the total tensile deformation. It is found that the load-deformation behavior is linear up to the first-crack strength. In order to evaluate the effectiveness of the fibers in improving the post-peak load bearing capacity, the area under the load-deflection curve was calculated up to a deflection of 0.002 m. This quantity is termed as the absolute toughness and is a measure of the energy absorption capacity of the material. The toughness calculated in this manner incorporates the enhancement in both strength and ductility due to fiber inclusion. These toughness values are plotted in Figure 14 which shows that for all three mixes the specimens with 50.8-mm fiber (Mixes 4 through 9, except Mix 5), in general, produced the higher toughness values, and clearly showed the beneficial effects (improvement in toughness) of fiber inclusions. For all other mixes the effect of fiber inclusion on toughness values could not be clearly ascertained.

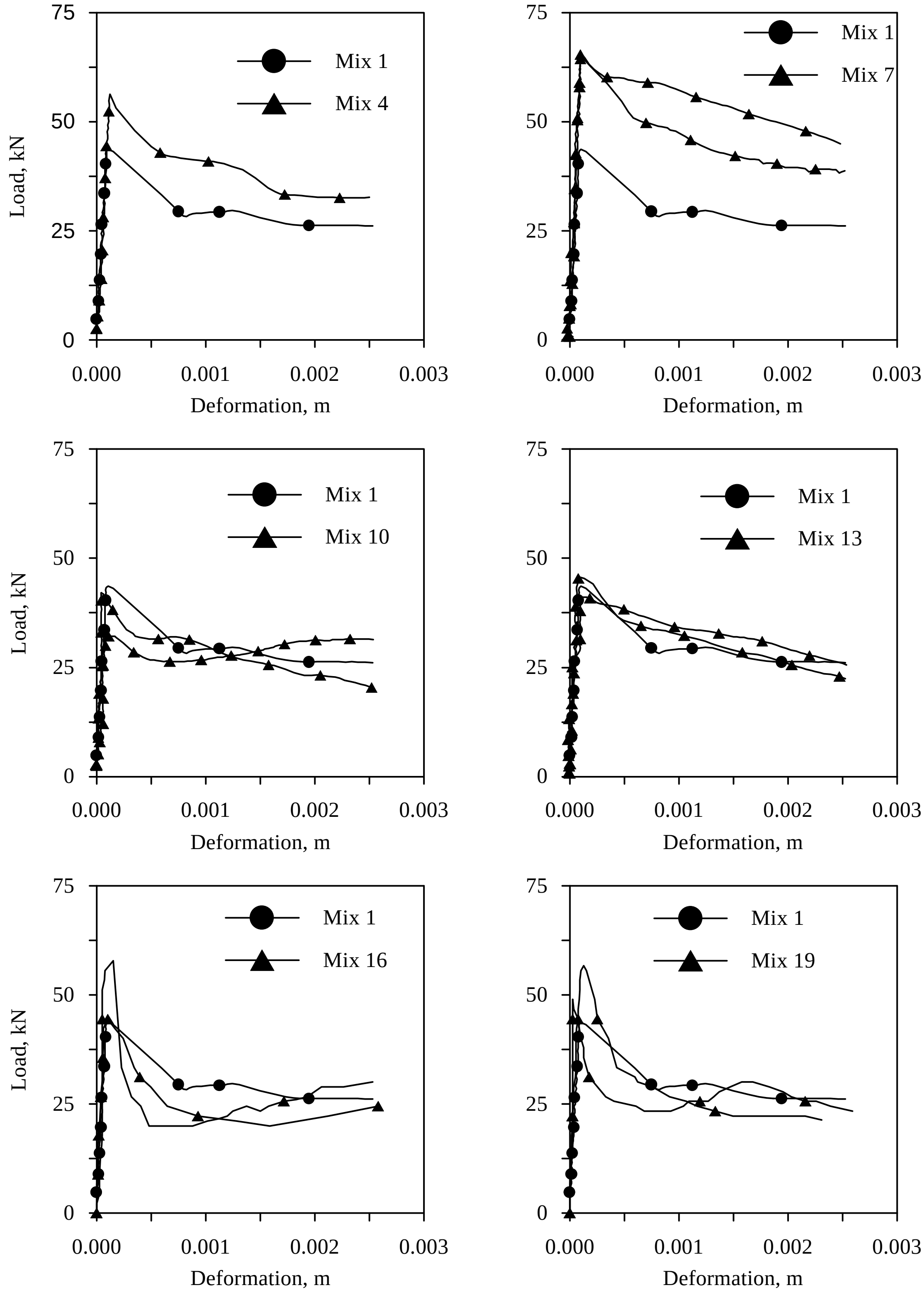

Figure 11. Split tensile load deformation curves for mixes with 8% Cement and no Fly Ash.

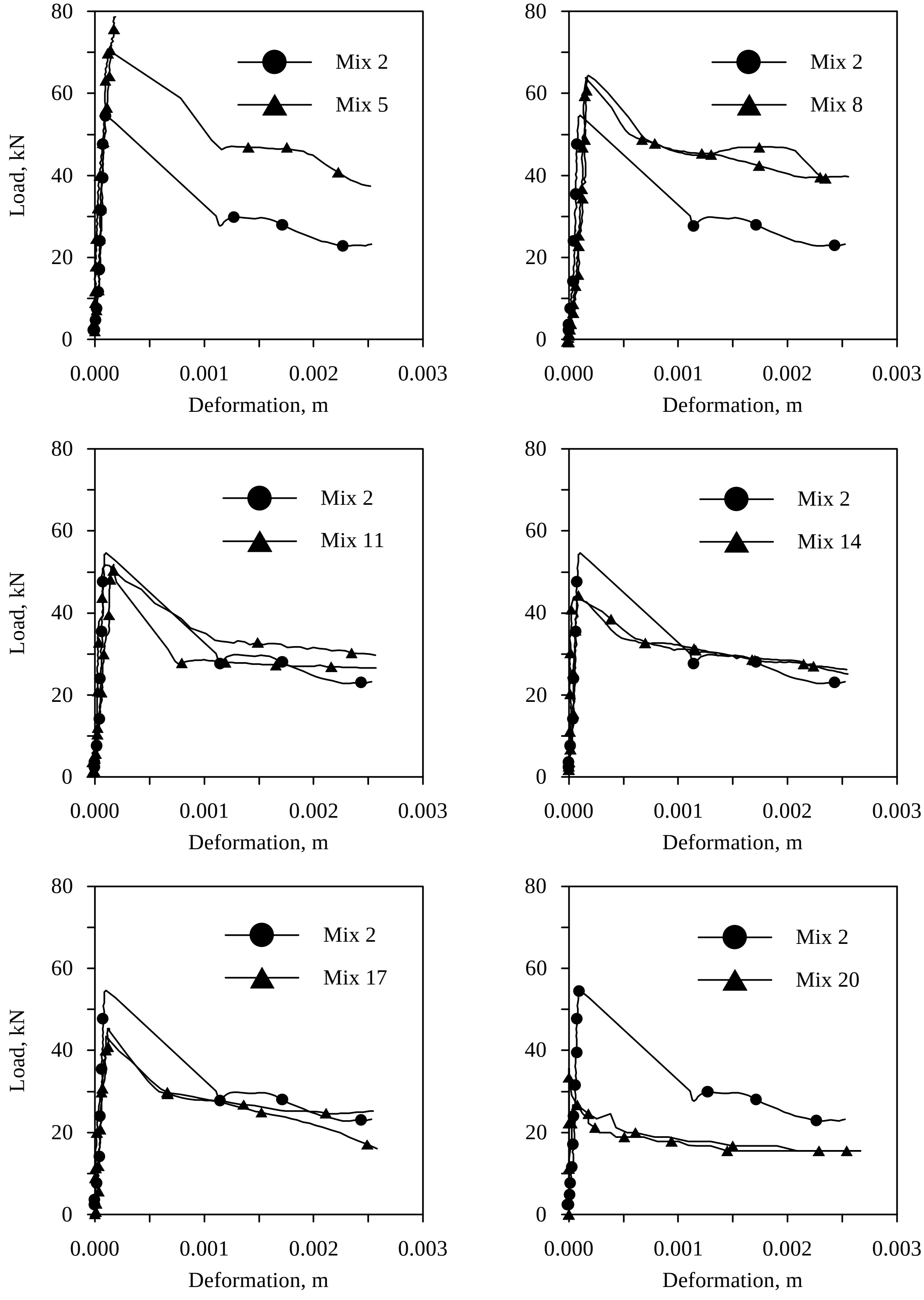

Figure 12. Split tensile load deformation curves for mixes with 4% Cement and 4% Fly Ash.

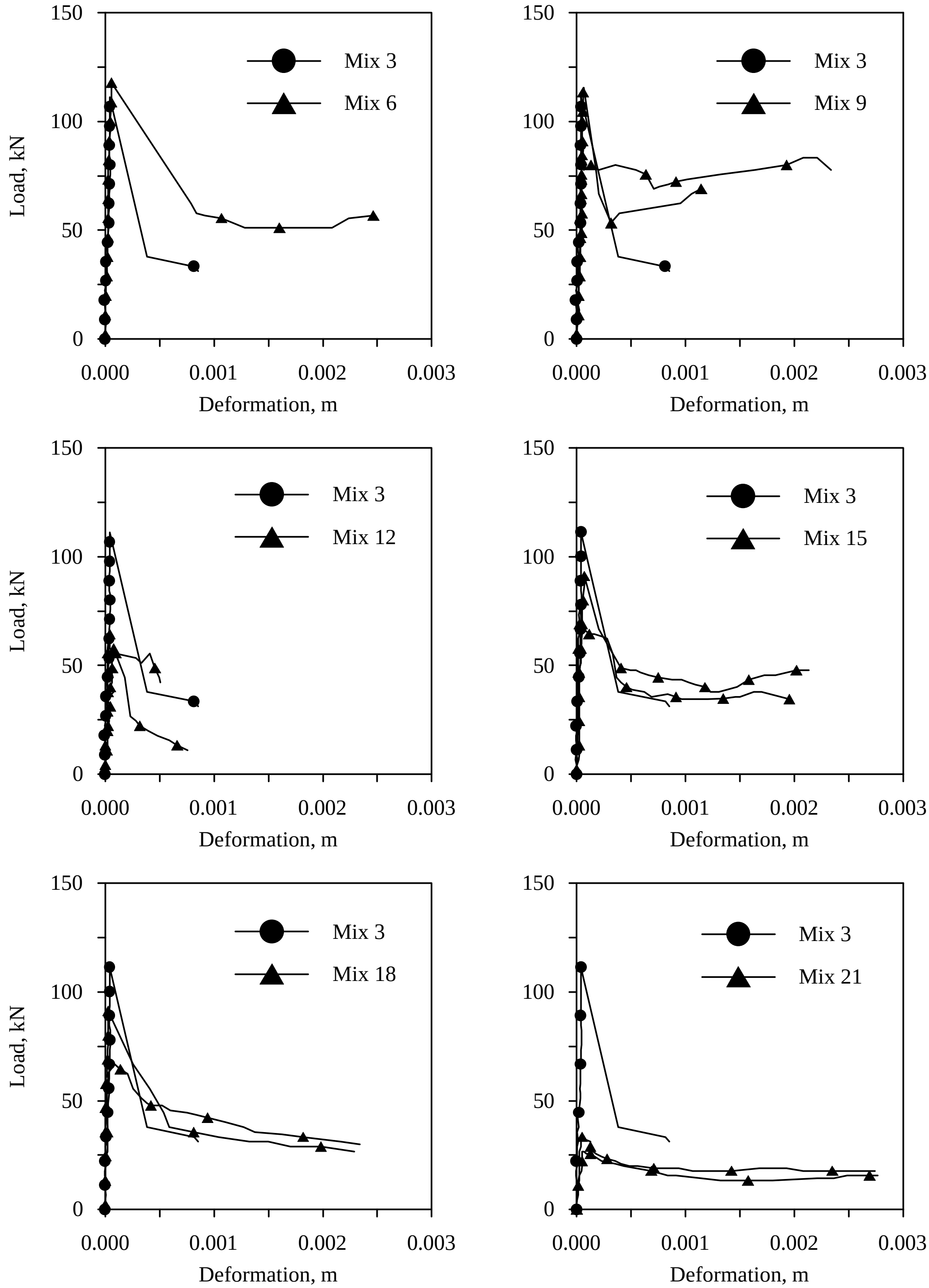

Figure 13. Split tensile load deformation curves for mixes with 8% Cement and 8% Fly Ash.

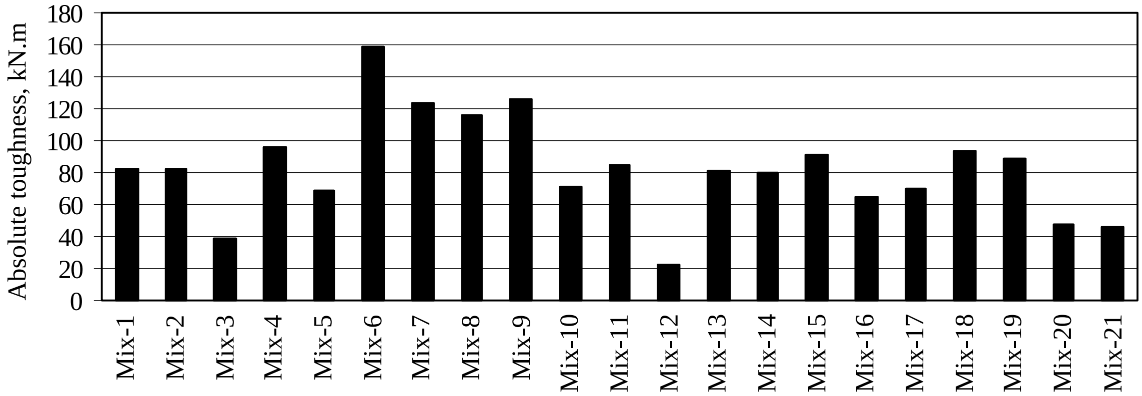

Figure 14. Toughness of various mixes.

4.1.3 Effect of fiber length

In order to clearly determine an optimum fiber length based on performance, the strength and toughness values were plotted against the fiber length for all mixes as shown in Figure 15. It is found that for both 0.25% and 0.50% fiber contents, the best performance was achieved with the 50.8-mm fiber.

4.1.4 Significant findings

The most important conclusion from this segment of the experimental program is that the recycled plastic fibers, when mixed at appropriate lengths and amount, can enhance the performance of the composite. Also, the fibers are most effective when the mix contains 8% fly ash in addition to 8% cement. The Class C fly ash used in this project has cementitious properties in conjunction with cement, and helps improve the bonding between the recycled plastic strips and the matrix. The resultant product containing 92% waste materials is a "high performance" composite base course in terms of both strength and toughness. Based on these observations it was decided that the flexural test specimens would be prepared from mixes with both 4% cement and 4% fly ash, and 8% cement and 8% fly ash, and also the fiber specimen will contain 50.8-mm long fibers. The optimum amount of fibers for use in subsequent fatigue experiments was determined from the observed performance of beam specimens as described in the following section.

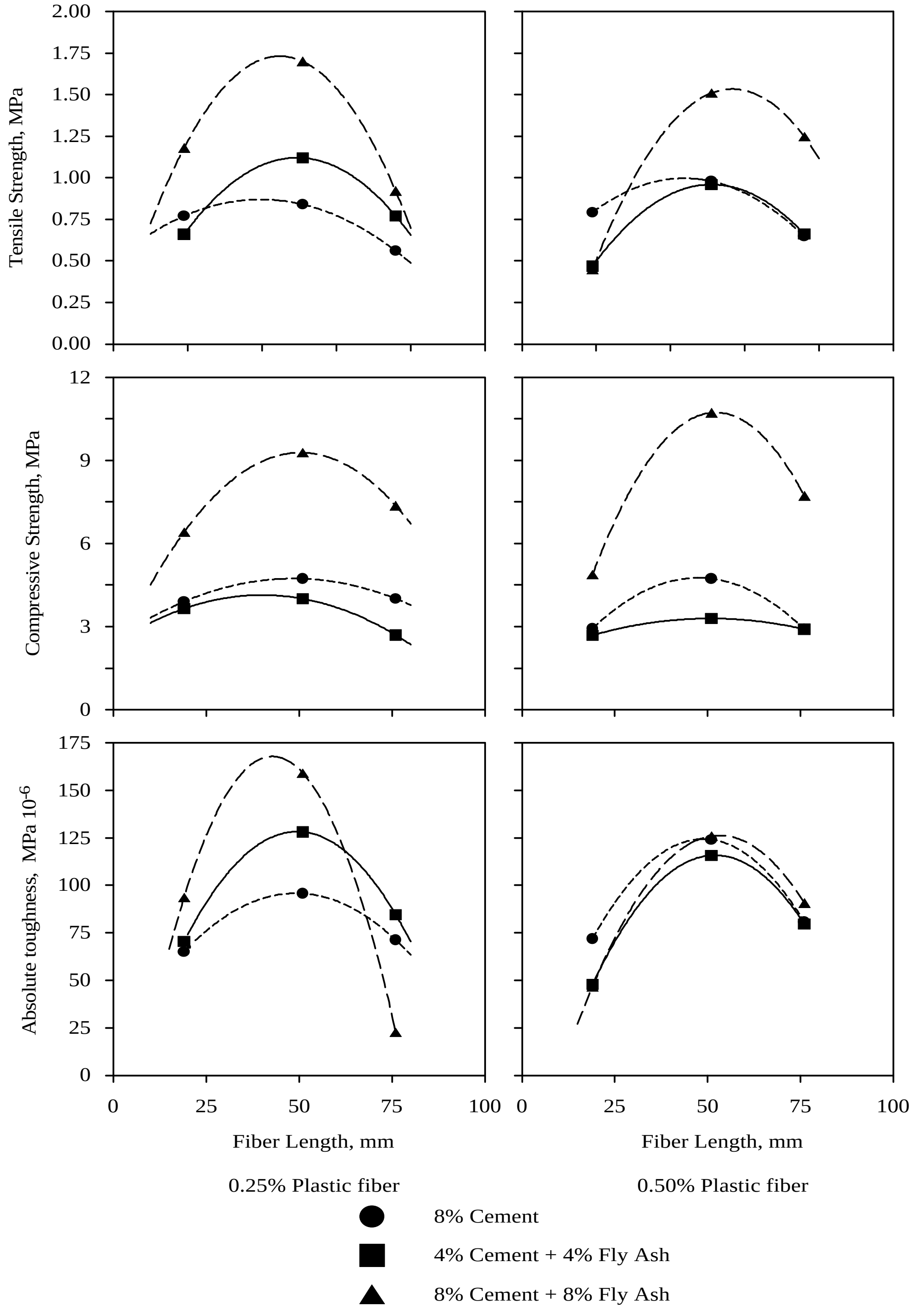

Figure 15. Effect of fiber length on strength and toughness.

4.2 RESULTS OF PHASE III

4.2.1 Flexural strength

Table 6 shows the average flexural strengths for all mixes. These data are also plotted in Figure 16 for easy comparison. The flexural strength is computed using the elastic beam theory as follows:

$$s_f = \frac{PL}{b\,d^2} \tag{2}$$

where s_f is the flexural strength, P is the applied maximum load, L is the span, b is the width, and d is the depth of the beam. There are two groups of specimens: First Group (Mixes 1B through 4B) contains 4% cement and 4% fly ash, whereas, the second group (Mixes 5B through 8B) contains 8% cement and 8% fly ash. All fiber reinforced specimens contained 50.8 mm fibers. The highest flexural strength achieved was 1.64 MPa (238 psi) by Mix 7B containing 8% cement, 8% fly ash, and reinforced with 1% fibers. Its counterpart, Mix 2B containing the 4% cement, 4% fly ash and 0.5% fibers achieved the highest strength in its group with a value of 1.06 MPa (154 psi). These strength levels are promising and make this new composite very suitable for use as a good quality stabilized base course for highway pavements. Addition of fibers improved the flexural strengths of the second group compared to corresponding unreinforced specimens.

4.2.2 Load deformation behavior

In order to determine the best performing Mix, both the strength and the post peak load bearing capacity or toughness values must be evaluated. Figure 17 shows the load deformation behavior for both groups of beams. The curves for the reinforced beams have been shifted along the X-axis for clarity. It is found that the unreinforced beams failed in a typical brittle manner characteristic of concrete-type materials. On the other hand, all fiber reinforced specimens demonstrated a post-peak load bearing capacity after the sharp drop following the first-crack indicating that the recycled plastic fibers were able to bridge some of the tensile cracks and delay the failure process. To isolate and better understand the post-peak behavior, the curves are normalized with respect to the peak load as shown in Figure 18. It is found that for both groups, the specimens with 1.25% fiber content showed the highest post-peak load bearing capacity. Although these mixes with 1.25% fibers did not show the highest strengths, they had similar or slightly better strengths compared to corresponding unreinforced specimens, coupled with much superior toughness. Improved toughness is considered to be a desirable

Table 6. Mix designs and 28-day flexural strengths.

Mixes	Mix Design	Flexural Strength (MPa)
Mix-1B	4% Cement + 4% Fly Ash	0.94
Mix-2B	4% Cement + 4% Fly Ash + 0.50%,50.8 mm Fibers	1.06
Mix-3B	4% Cement + 4% Fly Ash + 1.00%,50.8 mm Fibers	0.90
Mix-4B	4% Cement + 4% Fly Ash + 1.25%,50.8 mm Fibers	0.82
Mix-5B	8% Cement + 8% Fly Ash	0.91
Mix-6B	8% Cement + 8% Fly Ash + 0.50%,50.8 mm Fibers	1.44
Mix-7B	8% Cement + 8% Fly Ash + 1.00%,50.8 mm Fibers	1.64
Mix-8B	8% Cement + 8% Fly Ash + 1.25%,50.8 mm Fibers	1.10

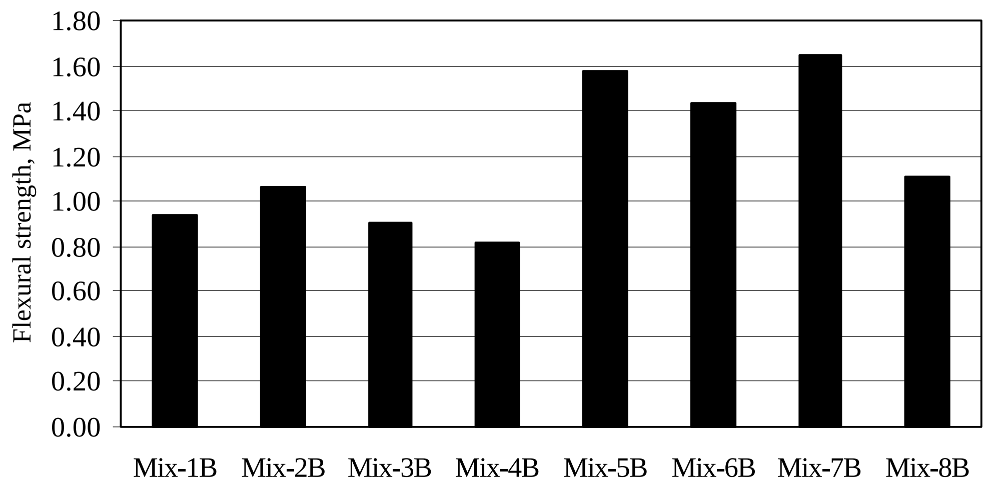

Figure 16. Average flexural strengths of various mixes.

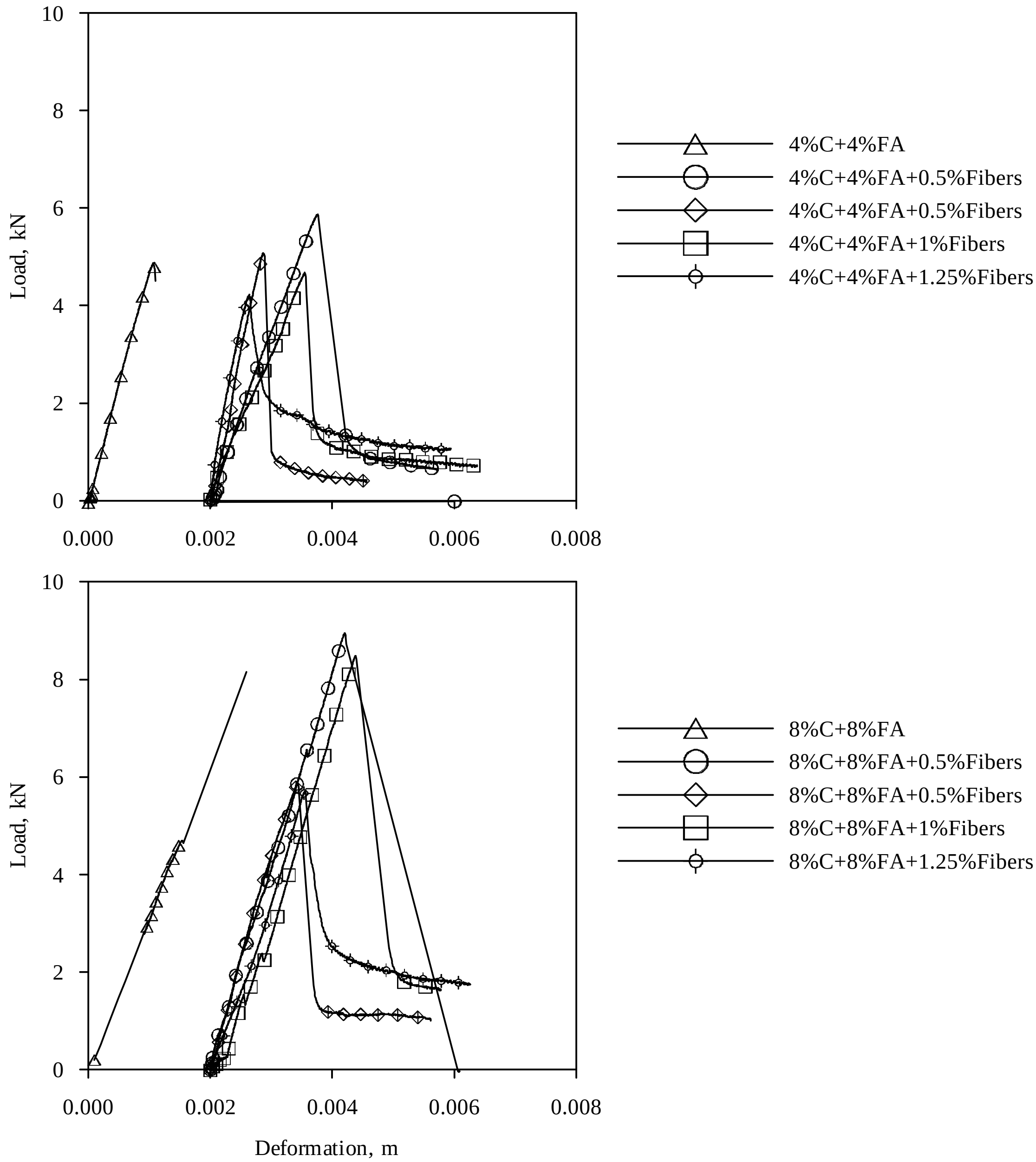

Figure 17. Load-deformation behavior in flexure.

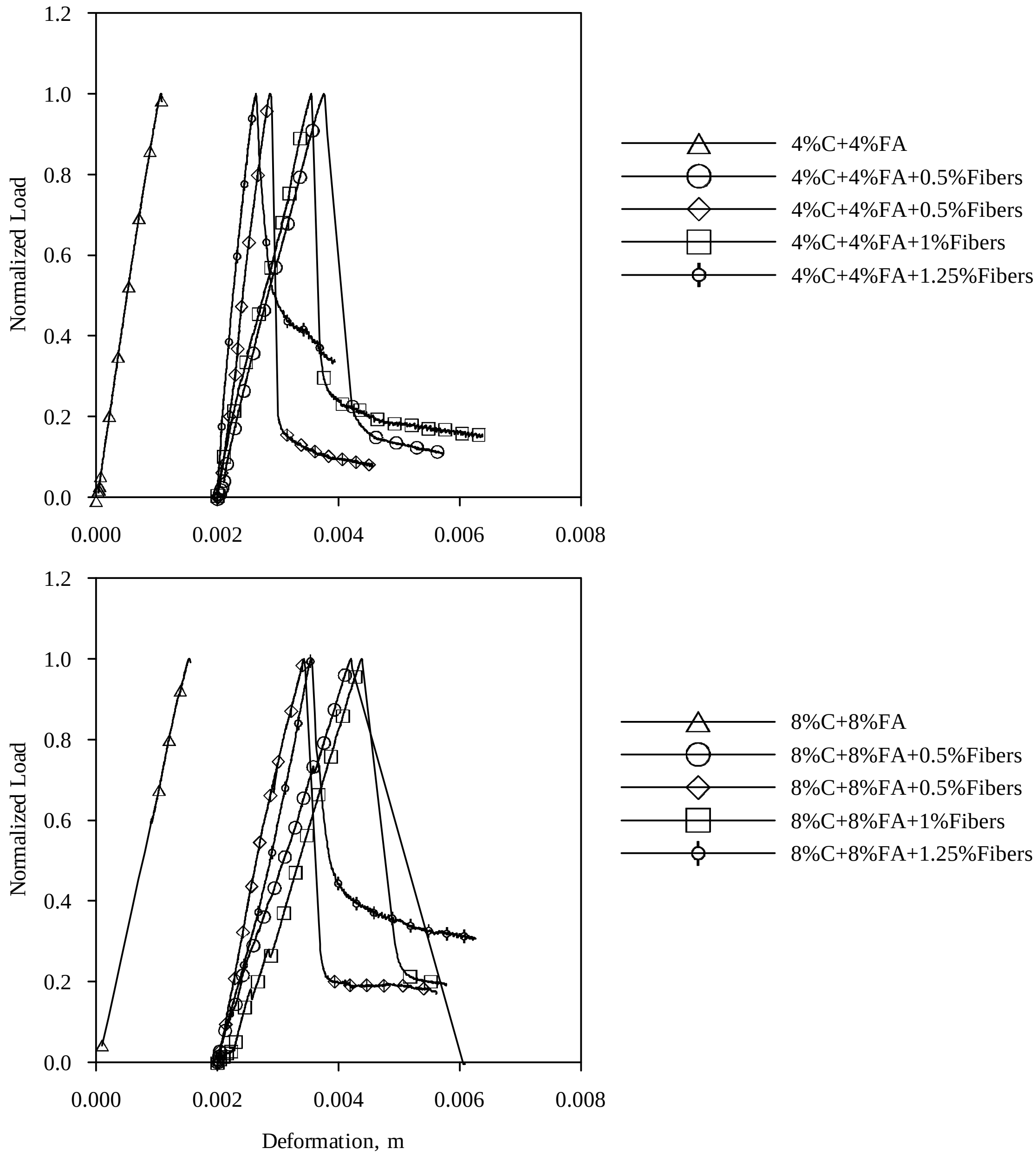

Figure 18. Normalized load-deformation behavior in flexure.

characteristic for cementitious materials (especially in highway applications) because the higher energy absorption capacity of the material corresponds to increased resistance to fatigue failure due to dynamic loading. Therefore, from considerations of both strength and toughness, the Mixes with 1.25% fiber content performed the best, and shows promise of improved resistance to fatigue failure.

It was mentioned previously that 1.25% plastic fiber was found to be an upper bound of fiber content in order to ensure workability of the mixes. With the maximum fiber content selected and held constant at 1.25%, the first group with 4% cement and 4% fly ash is likely to demonstrate better toughness than the second group with 8% cement and 8% fly ash because the latter would be a more brittle mix due to higher cementitious materials. Therefore, considering the fact that the mix with 4% cement and 4% fly ash also has sufficient compressive, split tensile and flexural strengths (as described in previous sections) to be classified as a high quality base course, this mix was selected as the best choice for further investigation under flexural fatigue loading.

4.2.3 Significant findings

Flexural tests for stabilized materials can be considered as "performance-based" laboratory tests. Performance-based tests are those which have the potential for simulating the field conditions for better prediction of actual performance. Since the stabilized pavement slab is subjected to tensile (flexural) stresses in the field, the flexural test programs (both static and fatigue) are better indicators of real-life performance of the pavement. The choice of final mix design (for fatigue test program) based primarily on the flexural tests is therefore justified. The selected mix with 4% cement, 4% fly ash and 1.25% of 50.8 mm fiber did not demonstrate significant improvement over an unreinforced mix, but it is definitely many times superior in terms of load-bearing capacity compared to conventional granular base course materials obtained from natural resources. Moreover, this new composite has more than 92% by weight of waste materials, which makes it a potential alternative construction material from both environmental and economical standpoints.

4.3 RESULTS OF PHASE IV

4.3.1 Experimental results

The magnitude of the repeated flexural stress and the number of loading cycles to failure for each fatigue specimen are summarized in Table 7, where the unreinforced beams are designated as FU1 through FU3, and the fiber-reinforced beams are designated as FR4 through FR10. Two beams failed prematurely due to equipment malfunction, and therefore, the repeated load test results for these two specimens are excluded from the following discussions. The results include the repeated flexural stress, the number of cycles to failure, the computation of stress ratios, and the resilient modulus. These results are discussed in the following sections.

Table 7. Prediction of flexural strength and stress ratio.

Beam (1)	Repeated flexural stress (MPa) (2)	Cycles to failure N_f (3)	Compressive strength from broken fatigue beams (MPa) (4)	Predicted flexural strength from Eq.3 (MPa) (5)	Initial estimated strength (Mpa) (6)	Flexural strength of fatigue beams (MPa) (7)	Stress Ratio SR (8)	Resilient modulus (MPa) (9)
FU1	0.97	40	6.28	0.94	0.96	0.95	1.02	0.69
FU2	0.52	696411	6.00	0.92	0.96	0.94	0.55	0.79
FU3	0.90	4	4.23	0.78	0.96	0.87	1.03	-[§]
FR4	0.69	38493	5.55	0.88	0.96	0.92	0.75	1.09
FR5	0.52	138578	5.36	0.87	0.96	0.91	0.57	0.91
FR6	0.52	28468	6.25	0.94	0.96	0.95	0.54	0.69
FR7	0.45	996700	5.36	0.87	0.96	0.91	0.49	0.97
FR8	0.63	24409	7.13	1.01	0.96	0.98	0.64	0.80
FR9	0.50	994001	4.96	0.84	0.96	0.90	0.56	0.74
FR10	0.65	9987	4.87	0.83	0.96	0.90	0.73	0.84

[§] Calculation for resilient modulus could not be done.

4.3.2 Results of correlation studies

The results of the strength correlation studies described in this section were used to predict the original static flexural strength of beams, which were broken in fatigue. Table 8 presents the results of the unconfined compression tests conducted on portions of broken beams failed in static flexure as described previously in Section 3.6. These values are plotted in Figure 19 against the flexural strength of the original beam. Also included in this figure are results from similar tests conducted on soil-cements and stabilized recycled aggregate[14,25]. The best-fit curve through all points can be represented by the following equation:

$$S_f = .0777 * S_c + 0.452 \quad (3)$$

Where S_f = flexural strength in MPa and S_c = unconfined compressive strength in MPa. Equation 3 is used in the following section to obtain a better estimate of the “actual” flexural strength of the failed fatigue specimens.

Table 8. Results of correlation studies from static flexural tests.

Beam (1)	Fiber (Weight %) (2)	Flexural strength (MPa) (3)	Compressive strength from broken static beams (MPa) (4)
U1	4%C+4%FA	0.94	5.49
U2	8%C+ 8%FA	1.58	12.20
R1	4%C+4%FA+0.50%, 50.8 mm Fibers	0.98	5.35
R2	4%C+4%FA+0.50%, 50.8 mm Fibers	1.14	9.29
R3	4%C+4%FA+1.00%, 50.8 mm Fibers	0.90	5.25
R4	4%C+4%FA+1.25%, 50.8 mm Fibers	0.82	6.36
R5	8%C+8%FA+0.50%, 50.8 mm Fibers	1.14	11.30
R6	8%C+8%FA+0.50%, 50.8 mm Fibers	1.73	11.88
R7	8%C+8%FA+1.00%, 50.8 mm Fibers	1.64	14.37
R8	8%C+8%FA+1.25%, 50.8 mm Fibers	1.10	10.00

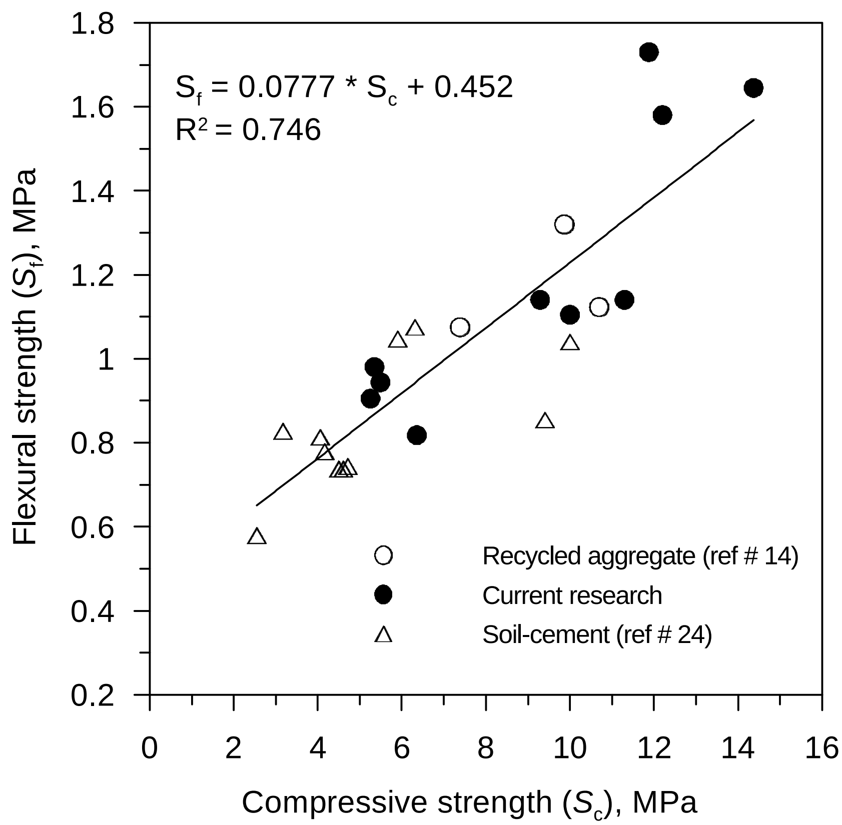

Figure 19. Correlation between compressive strength and flexural strength.

4.3.3 Prediction of "Actual" flexural strength

After the fatigue tests were completed, prismatic specimens were saw-cut from the ends of the failed beams, and unconfined compression tests were conducted on these specimens in a manner similar to the correlation studies described earlier. The results of these unconfined compression tests are given in Table 7 (column 4), together with the computed strengths using Equations 3. The initial estimated strength of 0.96 MPa, which represents the mean flexural strengths from static tests, is also given in Table 7 (column 6). Both unreinforced and fiber reinforced specimens were used to calculate the mean strength, since it is known that at this fiber dosage there is no meaningful improvement in flexural strength. Since the objective of this endeavor was to "predict" the strength of the specimens prior to the repeated load tests, the initial mean strength was included in the final prediction process. Accordingly, the "best" estimate of the actual flexural strength of the original beam was considered to be the average of the strengths predicted by both methods; these values are simply called the flexural strengths of fatigue beams and are shown in Table 7 (column 7). Finally, the repeated flexural stresses are divided by the flexural strengths to determine the final stress ratio for each beam, and these values are shown in Table 7.

4.3.4 The S-N curves and comparison studies

It is customary to express fatigue behavior in terms of a so-called S-N curve, which is the relationship between the stress ratio and the corresponding number of cycles to failure. The concept of stress ratio, which is obtained by normalizing the applied repeated stress with the respective ultimate strength, minimizes the effect of variations in individual specimen strengths on the fatigue relationships. The data for the recycled aggregate specimens are plotted in Figure 20, and a solid curve is drawn through the fiber-reinforced specimens. Since the focus of this research was to evaluate the performance of fiber reinforced stabilized recycled aggregate, only three unreinforced specimens were prepared and tested in fatigue. These three data points are also plotted in the S-N space, but no attempt was made to draw a trend line through these points. It is found that these unreinforced specimens performed as good as the fiber-reinforced specimens, but due to insufficient number of tests, no conclusion can be drawn on such specimens.

One of the objectives of the fatigue experiments was to compare the performance of the recycled aggregate base course with those of similar stabilized base course materials typically used in pavement construction. Five such materials were chosen for this purpose: (1) high

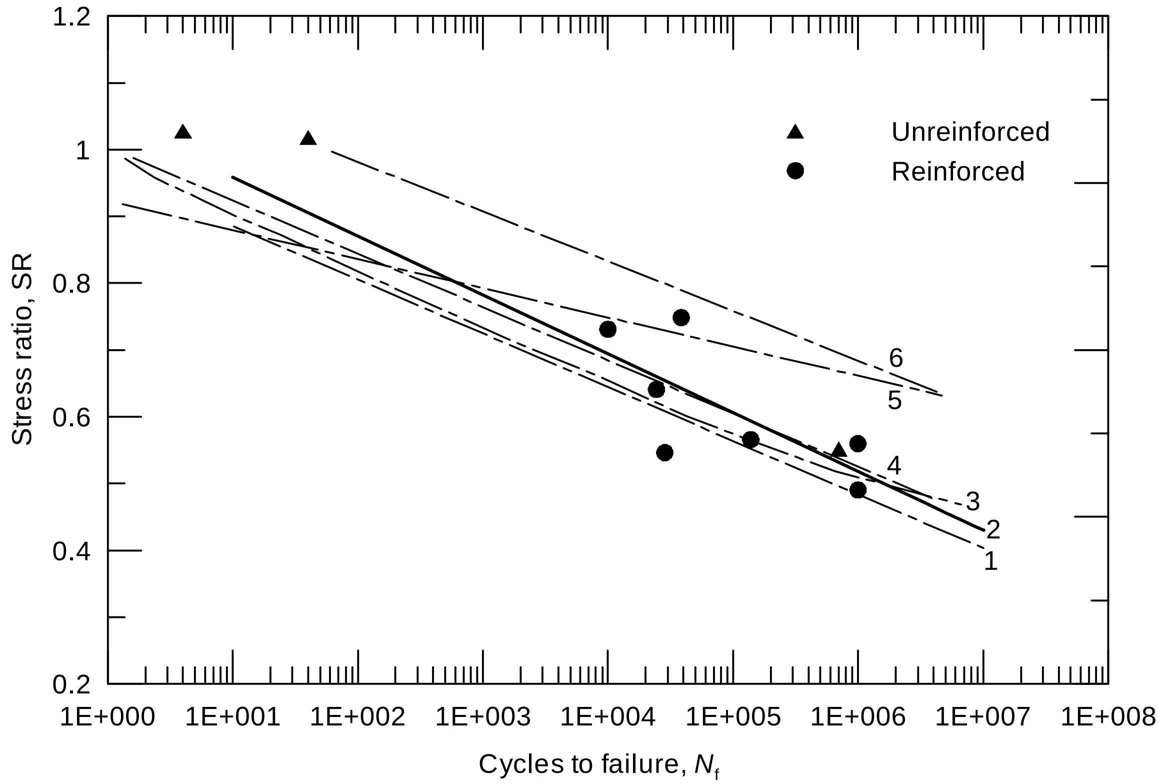

Figure 20. Stress ratio versus number of cycles to failure for various stabilized pavement materials: 1.HSSB materials, 2. Fiber reinforced recycled aggregates, 3.Concrete, 4.Lime-fly ash, 5.Soil-cement, and 6.Lean-concrete.

strength stabilized base (HSSB) materials,[7] (2) concrete, (3) lime-fly ash-aggregate, (4) soil-cement, and (5) lean concrete. Typical S-N relationships for these materials were retrieved from the literature,[4] and superimposed on Figure 20 with dashed lines. These comparisons show that the performance of stabilized fiber reinforced recycled aggregate is quite similar to soil-cement, HSSB, and concrete. It is also seen that the lean concrete base course outperforms all other materials in fatigue. A nonlinear regression analysis on the data for recycled aggregate specimens gives the following relationships between the stress ratio, SR, and the fatigue life, N:

$$SR = -0.038 * \ln(N) + 1.047 \tag{4}$$

Equation 4 can be directly used as a transfer function in mechanistic pavement design methods involving the new stabilized recycled aggregate composite.

4.3.5 Endurance limit

Fatigue strength is generally defined as the maximum flexural stress at which a beam can withstand 2 million cycles of non-reversed fatigue loading. Fatigue strength, expressed as a percentage of the modulus of rupture or flexural strength, is called the endurance limit, which idealistically refers to a stress level at which the beam will never fail in fatigue. Although it can be argued that plain concrete does not show any definite endurance limit, it is often taken as 55% of the static modulus of rupture. As reported in the literature,[26] the endurance limit of plain concrete varies between 50% and 57% of the static modulus of rupture. In the current study, the 2-million cycle endurance limit for the fiber-reinforced specimens computed from Equations 4 was 50%. These results suggest that a relatively inexpensive base course containing recycled aggregate with low quantities of cement and shredded plastic as fiber reinforcement is a promising material in terms of fatigue strength and endurance limit.

4.3.6 Damage accumulation studies

As mentioned previously, the load-deformation cycles were continuously recorded for all specimens until failure. This data was necessary to determine the gradual damage process within the material as the loading cycles progressed. The loading and unloading process generated a hysteresis loop for each cycle; this is shown schematically in Figure 21. As can be seen, the total vertical deformation, Δ_T is the summation of a recoverable deformation, Δ_R and a plastic deformation, Δ_P :

$$\Delta_T = \Delta_R + \Delta_P \qquad (5)$$

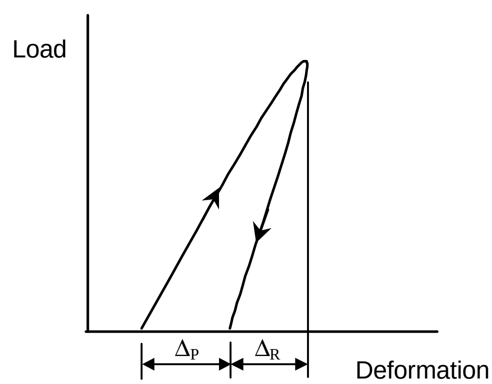

Figure 21. Schematic of loading-unloading process.

The plastic or permanent deformation in the pavement foundation layer contributes to the total rutting of a flexible pavement. The observed values of the permanent deformations were added at every 10th cycle to compute the total accumulated deformation up to that cycle. Since deformations were not measured at every cycle (due to large size of the data files), the sum of the permanent deformations at any stage represents the minimum accumulated damage sustained by the specimen up to that point. The Δ_P values were normalized with respect to the maximum or total accumulated permanent deformation at failure, Δ_{PF}, and plotted in Figure 22 against the cycles ratio defined as the ratio of the applied number of cycles at any stage to the total number of cycles at failure. The significance of these curves is that at any stage of the fatigue life as expressed by the cycles ratio, the expected permanent deformation (expressed as a percent of total permanent deformation at failure) can be determined. This will provide an estimation as to what percent of the total damage has already accumulated in the material. Since plastic deformation is related to rutting, this information will help in formulating a pavement rehabilitation strategy, or this can be an input to a pavement management system. As shown in these figures, the accumulated damage for most specimens closely follows the 45^0 line. This line is a representation of linear damage accumulation law known as Miner's Rule(27) which is often used in pavement engineering. Therefore, the damage accumulation in the stabilized recycled aggregate base course used in this study can be reasonably estimated using Miner's hypothesis (27).

4.3.7 Resilient modulus

A mechanistic pavement design method requires the input of an elastic modulus determined from repeated load tests. Generally, the elastic modulus is computed after a certain number of loading cycles have been applied and is called the resilient modulus. The standard methods for determining the resilient modulus involve (a) dynamic triaxial tests proposed by AASHTO(28) for granular and fine grained soils, and (b) dynamic indirect tension tests proposed by ASTM(29) for stabilized pavement materials. The majority of the early work (prior to 1970) on resilient modulus testing in the United States was performed on beam specimens subjected to repeated flexural loading.(30) The general equation for calculating the resilient modulus, M_R, from flexural tests is as follows: (30)

$$M_R = K \frac{P}{I.\Delta} \tag{6}$$

where *K* = constant depending on load, end constraint, and specimen geometry, *P* = magnitude of repeated load, *I* = moment of inertia of cross section, and *Ä* = dynamic midspan deflection. For the purpose of calculating the resilient modulus, *Ä* refers to the recoverable deformation. In the standard method,(28) the recoverable strain at the 200th cycle (following the"sample conditioning" steps, which involve the application of repeated loads of various specified magnitudes) is used to calculate the resilient modulus. Mitchell and Shen,(6) who studied the resilient properties of soil-cement by performing dynamic triaxial compression and flexural tests, calculated the resilient modulus after 1000 load repetitions. Previous research on stabilized recycled aggregate indicated that the deformations are mostly elastic (i.e. the rate of accumulation of permanent deformation is stabilized) after the specimen had completed about 5% of its fatigue life.[15] If the resilient deformation at 5% fatigue life is denoted by Ä5, using a K value appropriate for a four-point bending configuration leads to a resilient modulus of the form:

$$M_R = \frac{Pa\,(3\,L^2 - 4\,a^2)}{48\,I\,\Delta_5} \qquad (7)$$

where M_R is the resilient modulus, P is the applied repeated load, L is the span length, I is the moment of inertia of the beam cross section, and $a = L/3$. The resilient moduli calculated in this fashion are provided in Table 7 (column 9).

It is found that the resilient modulus for the proposed base course composite varies between 0.70 to 1.1 GPa. Since a cement stabilized base course will be subjected primarily to repeated tensile stresses, it is logical to determine the resilient modulus for these materials from flexural or indirect tensile tests. Mitchell and Shen[6] determined the resilient modulus of soil-cement in flexure by using a silty clay stabilized with 3% and 13% cement and a sand stabilized with 7% cement. In that study, the authors presented a relationship between the flexural strength and the resilient modulus for these three soil-cements in a log-log plot similar to that shown in Figure 23. Superimposed on their results are the values determined from the recycled aggregate beam specimens in this study, and several points from an earlier study on stabilized recycled aggregate.[15] A best fit regression curve through all of the points has the following form ($R^2 = 0.95$):

$$\ln(R_M) = 1.808\,S_f + 5.64 \qquad (8)$$

where R_M = resilient modulus and S_f = flexural strength. Since the recycled aggregate specimens had almost similar strengths, they form a cluster about the best-fit curve. It is concluded that the resilient modulus (which is necessary for implementing a mechanistic-empirical design) of this new composite can be reasonably estimated from its static flexural strength using Figure 23 or Equation 8, thus eliminating the need for undertaking a more expensive and time consuming dynamic repeated load test program.

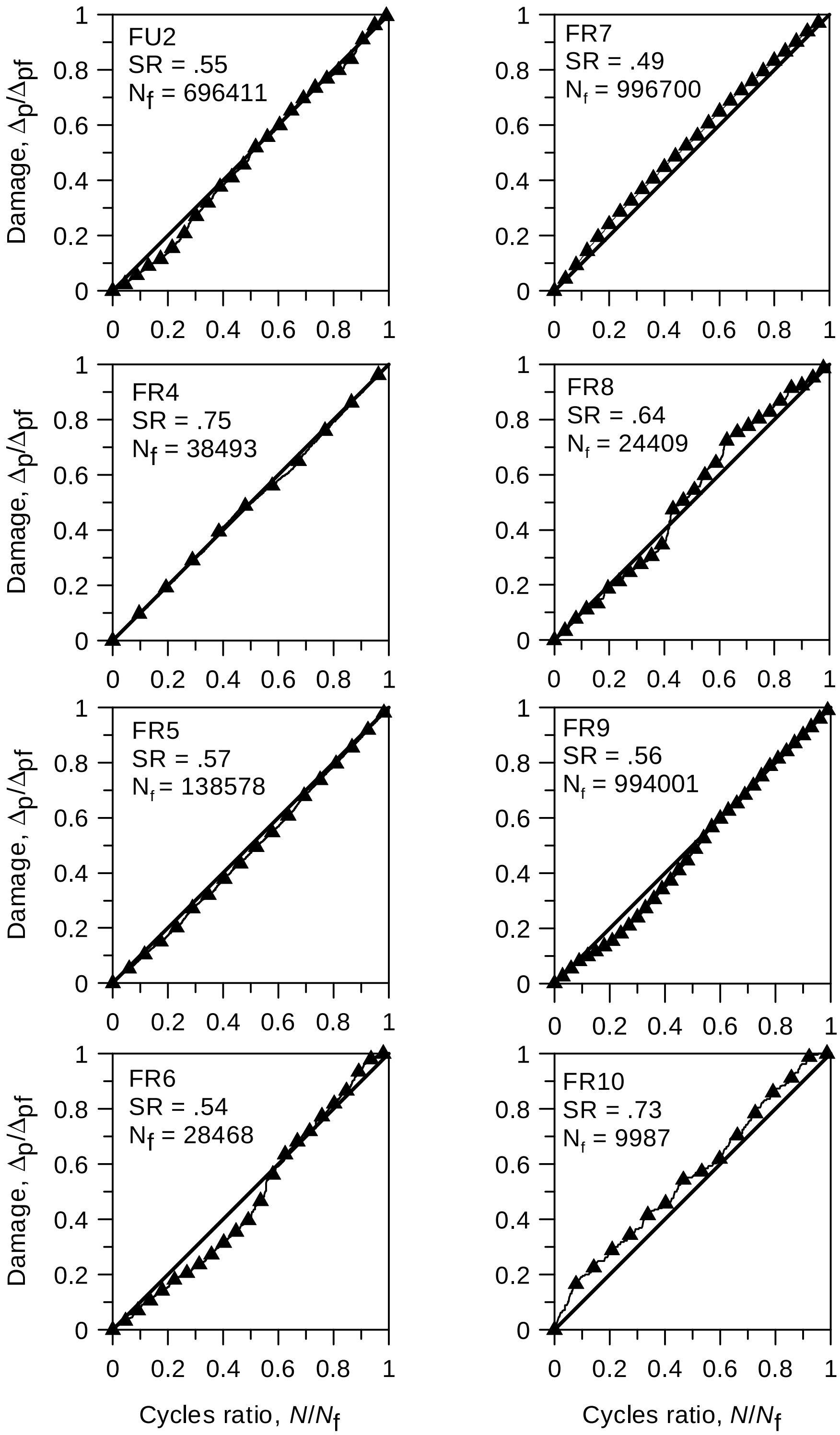

Figure 22. Damage accumulation due to cyclic loading. (the 45^0 line represents Miner's rule[27])

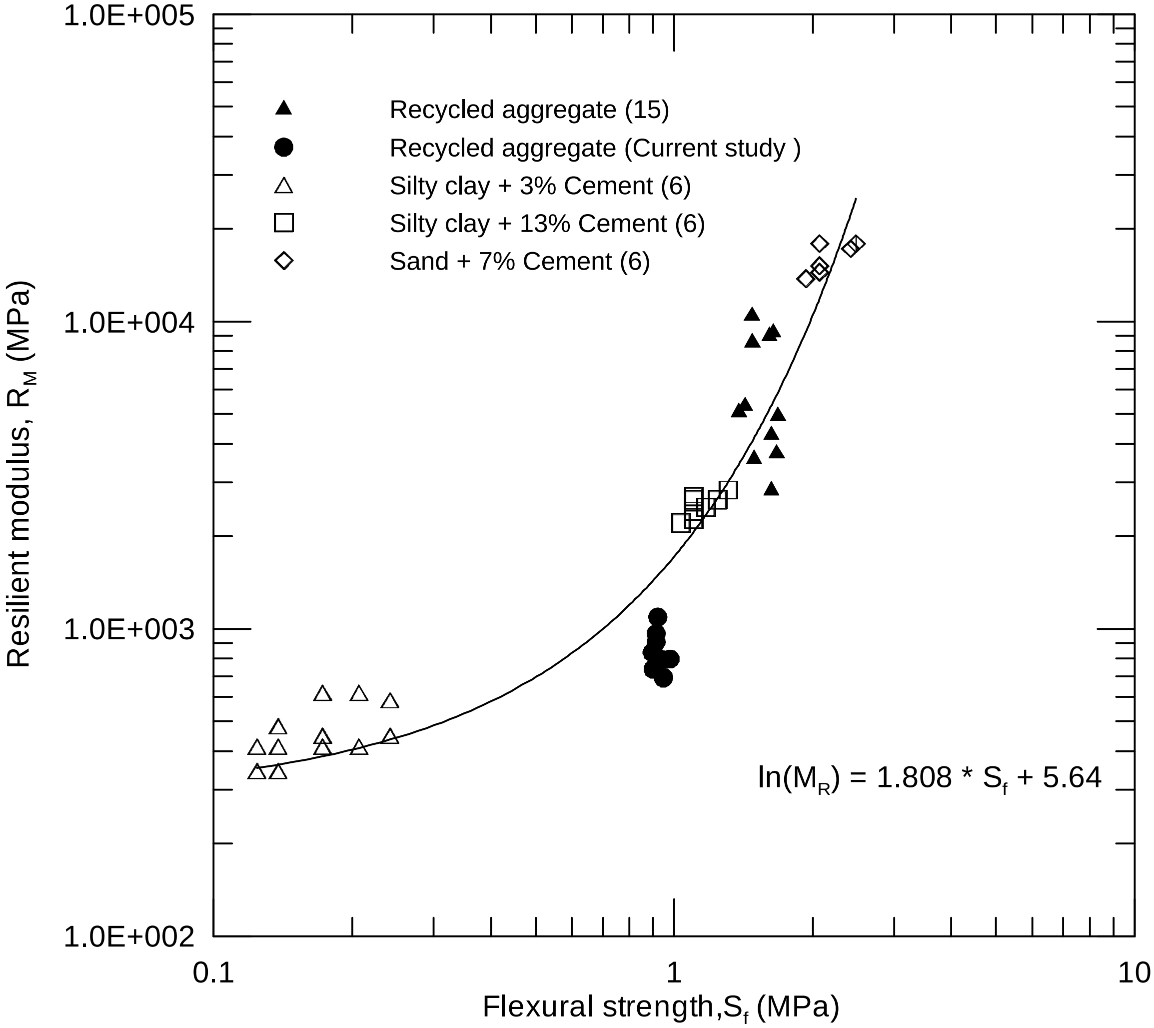

Figure 23. Relationship between flexural strength and resilient modulus.

CHAPTER 5: CONCLUSIONS

5.1 SUMMARY AND CONCLUSIONS

It is generally recognized that the utilization of waste materials in highway construction is a timely and desirable concept. However, caution must be exercised when incorporating recycled materials with unknown or questionable properties or for which there is limited knowledge about their long-term durability and performance characteristics. The idealized goal of incorporating waste materials in highway pavement 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. Therefore, a careful evaluation of all candidate waste materials should be performed before incorporating them into the pavement structure. Accordingly, the current study was undertaken to evaluate an unconventional stabilized base course material consisting of recycled concrete aggregate, fly ash, cement, and strips of reclaimed plastics. The primary focus of the experimental program was to gain some insights into the long-term durability of this new composite base course by performing short-term laboratory tests which included a flexural fatigue test program. A systematic materials characterization process involving unconfined compression, split tension and static flexural tests was used in this study to evaluate the new material and identify a performance-based mix-designs for the repeated load tests. This final mixture consisted of 92% by weight of recycled aggregate stabilized with 4% Class C fly ash, 4% Portland cement, and an additional 1.25% by weight of shredded reclaimed plastics, implying that at least 92% (by weight) of the composite base course contained waste materials. The durability of this material against fatigue failure, its relative performance compared to traditional stabilized pavement materials, and the gradual accumulation of fatigue damage in the material were determined from the repeated flexural tests. Due to stabilization and reinforcement (achieved mostly with recycled materials), the selected mix with 4% cement, 4% fly ash and 1.25% of 50.8-mm fiber is likely to outperform conventional granular pavement foundation materials obtained from natural resources. This new composite, therefore, has the potential for becoming an attractive alternative construction material not only from environmental and economical standpoints, but also from performance considerations. Following are the significant conclusions derived from this experimental investigation:

- The unreinforced mixture containing 92% recycled aggragate (by weight), 4% fly ash, and only 4% cement achieved a compressive strength of about 5 MPa (725 psi), a split tensile strength of about 0.75 MPa (109 psi), and a flexural strength of about 0.95 MPa (138 psi), indicating a moderately strong stabilized base course material.

- For the ranges in mix-designs used in this study, the use of fiber reinforcement had a detrimental effect on compressive strength. However, specimens reinforced with 50.8 mm fibers in general showed noticeable improvement in both split tensile strength and absolute toughness compared to unreinforced specimens.

- Among the fiber reinforced specimens, the optimum or best performance in terms of compressive strength, split tensile strength, and absolute toughness was observed in specimens reinforced with 50.8 mm long fibers.

- The performance of the proposed stabilized base course under flexural fatigue loading as depicted by the S-N relationships is comparable or better than other traditional stabilized pavement materials.

- The 2-million cycle fatigue endurance limit for this composite is approximately 50% of the static flexural strength.

- The resilient modulus in flexure approximately ranges between 0.7 GPa (100,000 psi) and 1.1 GPa (160, 000 psi).

- The damage accumulation in the material due to repeated load cycles closely follows the Miner’s Rule of cumulative damage.

5.2 TECHNOLOGY TRANSFER INITIATIVE

The Materials Bureau of the New Mexico State Highway and Transportation Department (NMSHTD) is aware of this project and expressed written interests in the final outcome of the experimental program when the project was initiated. A copy of the final report will be forwarded to the pavement design/ pavement materials division in Santa Fe, NM for their review. The possibility of incorporating the new recycled composite in test pavement section will be explored.

CHAPTER 6: REFERENCEs

1. Kandhal, P. S., and Stroup-Gardiner, M. (1998). “An Overview: Flexible Pavement Rehabilitation and Maintenance,” ASTM Special Technical Publication No. 1348, pp. 1-3.

2. Ahmed, I., and Lovell, C. W. (1992). “Use of Waste Materials in Highway Construction: State of the Practice and Evaluation of the Selected Waste Products,” Transportation Research Record 1345, TRB, National research Council, Washington , D. C., pp. 1-9.

3. Environmental Protection Agency. (1992). “Characterization of Municipal Solid Wastes in the United States: 1992 Update,” Report No. EPA 530-R-97-019, EPA, Washington, D. C., pp. 2-12.

4. Carpenter, S. H., Crovetti, M. R., Smith, K. L., Rmeili, E., and Wilson, T. (1992). "Soil and Base Stabilization and Associated Drainage Considerations: Volume I, Pavement Design and Construction Considerations," Report No. FHWA-SA-93-004, Federal Highway Administration, Washington, D. C.

5. Larsen, T. J., and Nussbaum, P. J. (1967). "Fatigue of Soil-Cement." Journal of the Portland Cement Association, Vol. 9, No. 2, pp. 37-59, Skokie, Illinois.

6. Mitchell, J. K., and Shen, C-K. (1967). "Soil-Cement Properties Determined by Repeated Loading in Relation to Bases for Flexible Pavements," Second International Conference on the Structural Design of Asphalt Pavements, University of Michigan, August 7-11, pp. 348-373.

7. Thompson, M. R. (1994). "High-Strength Stabilized Base Thickness Design Procedure," Transportation Research Record No. 1440, Transportation Research Board, Washington, D. C., pp. 1-7.

8. Hoover, J. M., Moeller, D. T., Pitt, J. M., Smith, S. G., and Wainaina, N. W. (1982). "Performance of Randomly Oriented, Fiber-reinforced Roadway Soils." Iowa DOT Project HR-211, College of Engineering, Iowa State University.

9. Craig, R., Schuring, J., Costello, W., and Soong, L. (1987). "Fiber Reinforced Soil Cement." American Concrete Institute, Detroit, Michigan, SP-105, ed. S. P. Shah, and G. B. Batson, pp. 119-139.

10. Crockford, W. W., Grogan, W. P., and Chill, D. S. (1993a) "Strength and Life of Stabilized Layers Containing Fibrillated Polypropylene." Paper No. 930888, 72nd Annual Meeting, Transportation Research Board, Washington, D. C.

11. Maher, M. H., and Ho, Y. C. (1993). "Behavior of Fiber-Reinforced Cemented Sand Under Static and Cyclic Loads." Geotechnical Testing Journal, American Society for Testing and Materials, Philadelphia, PA, Vol. 16, No. 3, pp. 330-338.

12. American Concrete Pavement Association. (1993). "Recycling Concrete Pavement," Publication TB-014P, Concrete Paving Technology, Skokie, Illinois.

13. Yrjanson, W. A. (1989). "Recycling of Portland Cement Concrete Pavements," Synthesis of Highway Practice 154, National Cooperative Highway Research Program, Transportation Research Board, Washington, D. C.

14. Sobhan, K., and Krizek, R.J. (1999). "Fatigue Behavior of Fiber-Reinforced Recycled Aggregate Base Course," Journal of Materials in Civil Engineering, American Society of Civil Engineers, Vol. 11, No. 2, pp. 124-130.

15. Sobhan, K., and Krizek, R. J. (1998). "Resilient Properties and Fatigue Damage in a Stabilized Recycled Aggregate Base Course Material," Transportation Research Record 1611, Transportation Research Board, Washington, D.C., pp. 28-37.

16. NCHRP 1-37A, (in progress), Development of the 2002 Guide for the Design of New & Rehabilitated Pavement, National Cooperative Highway Research Program, Transportation Research Board, National Research Council.

17. Cavey, J. K., Krizek, R. J., Sobhan, K., and Baker, W. H. (1995). "Waste Fibers in Cement-Stabilized Recycled Aggregate Base Course Material," Transportation Research Record 1486, Transportation Research Board, Washington, D.C., pp. 97-106.

18. Benson, C. H., and Khire, M. V. (1994). "Reinforcing Sands with Strips of Reclaimed High-Density Poly Ethylene," Journal of Geotechnical Engineering, American Society of Civil Engineers, Vol. 120, No. 8, pp. 1381-1393.

19. ASTM D 15557-91, (1999) "Modified Proctor Test", American Society for Testing and Materials, Annual book of ASTM standards, Vol. 4.08, pp127-134.

20. ASTM C-39, (1999), "Compressive Strengths of Cylindrical Concrete Specimens", American Society for Testing and Materials, Annual book of ASTM standards, Vol. 4.02, pp18-22.

21. ASTM C-496, (1999) "Splitting tensile Strength of Cylindrical Concrete Specimens", American Society for Testing and Materials, Annual book of ASTM standards, Vol. 4.02, pp127-134.

22. ASTM C 1018-97, (1999) "Flexural Toughness and First Crack Strength of Fiber Reinforced Concrete (Using Beam with Third Point Loading)", American Society for Testing and Materials, Annual book of ASTM standards, Vol. 4.02, pp510-517.

23. American Concrete Institute Committee 544. (1990). " Considerations for Design of Concrete Structures Subjected to Fatigue Loading," ACI Manual of Concrete Practice, Part I, pp 215-1 to 215-25.

24. ASTM C116-90, (1999) "Compressive Strength of Concrete using Portions of Beams Broken in Flexure", American Society for Testing and Materials, Annual book of ASTM standards, Vol. 4.02, p53.

25. Sobhan, K., Jesick, M. R., Deodominics, E., and McFadden, J. P. (1999). " A Soil-Cement-Fly Ash Pavement Base Course Reinforced with Recycled Plastic Fibers." Paper No. 990886. Presented at the 78th Annual Meeting of the Transportation Research Board, Washington D.C., January 10-14.

26. Ramakrishnan, V., Wu, G. Y., and Hosalli, G. (1989). "Flexural Fatigue Strength, Endurance limit, and Impact Strengths of Fiber Reinforced Concretes," Transportation Research Record No. 1226, Transportation Research board, Washington, D. C., pp. 17-24.

27. Miner, M. A. (1945). " Cumulative Damage in Fatigue," Transactions of the American Society of Mechanical Engineers, Vol. 67, pp. A159-A164.

28. AASHTO T 274-82. (1982). "Standard Method of Test for Resilient Modulus of Subgrade Soils," American Association of State Highway and Transportation Officials, Washington, D.C.

29. ASTM D 4123-82. (1987). "Standard Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures," American Society for Testing and Materials, West Conshohocken, Pennsylvania.

30. Vinson, T. S. (1990). "Fundamentals of Resilient Modulus Testing," Report FHWA-TS-90-031, Federal Highway Administration, U.S. Department of Transportation.