NCAT Report 93-05

EVALUATION OF LABORATORY PROPERTIES OF SMA MIXTURES

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E.R. Brown
Hemant Manglorkar

October 1993

Work sponsored by NAPA and the NAPA Education Foundation

National Center for Asphalt Technology
NCAT
AUBURN UNIVERSITY
277 Technology Parkway • Auburn, AL 36830

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E.R. Brown
Director
National Center for Asphalt Technology
Auburn University, Alabama

Hemant Manglorkar
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DISCLAIMER

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ABSTRACT

Stone Matrix Asphalt (SMA) has been proven to resist permanent deformation in Europe and has shown promise in the United States as a stable and durable surface mixture. SMA mixtures were developed in Europe and have been used successfully for the past twenty years to provide resistance to rutting under heavy loads and wear from studded tires. The SMA also shows potential for improved long term performance and durability. The success in Europe has encouraged the U.S. to adopt the use of SMA mixtures particularly on high volume roads such as interstates and urban intersections. However, this new methodology has to be evaluated using U.S. materials and construction methods to insure satisfactory performance in the U.S. This NCAT report is an effort to compare, through laboratory tests developed for dense graded mixtures, the properties of SMA mixtures to that of dense graded mixtures. It evaluates the laboratory test properties of SMA mixtures, which will assist in characterizing and understanding performance. Primary emphasis in the laboratory was to evaluate SMA properties for various aggregate types, aggregate gradations, fiber types and contents, and asphalt contents. This report also discusses SMA projects constructed in 1991 and 1992 and provides information on materials used as well as mixture properties.

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INTRODUCTION

Background

A twenty-one member group representing AASHTO, NAPA, FHWA, TRIS, Asphalt Institute, and SHIW participated in a two-week tour of six European nations, in mid September 1990 (*1*). The nations visited were Sweden, Germany, France, Italy, Denmark and United Kingdom.

The study tour members evaluated and reviewed state-of-the-art pavement construction methods and asphalt mixture types that were prevalent in these countries. In the opinion of the European Asphalt Study Tour (EAST) members, the special purpose mixture with the greatest promise for improving performance of mixtures in the U.S., was Stone Matrix Asphalt (SMA) (*1*). A smaller group representing FHWA, AASHTO, and NCAT visited Sweden and Germany in Spring 1991 to look specifically at SMA materials, construction, and performance.

In Europe, SMA mixtures have been used in the upper layer for the past twenty years to reduce the amount of rutting under heavy traffic (*1*, *2*, *3*). The gradation of the aggregate and optimum asphalt content (AC) are considerably different from that used for dense graded mixtures (*2*). Coarse stone-to-stone contact is prevalent in SMA mixtures but does not occur in HMA (*4*). Dense graded mixtures also have aggregate to aggregate contact but most of this takes place within the fine aggregate particles which do not offer the same shear resistance as the coarse aggregate. Inspection of a core removed from an existing dense graded mixture shows that the coarse aggregate is floating in the fine aggregate matrix. The traffic loads for SMA are carried by the coarser aggregate particles instead of the fine aggregate asphalt mortar (*5*, *6*). The European experience (*7*) and established performance records show SMA to be more cost effective than dense graded HMA for high volume roads. However, there exists a number of factors that would influence the SMA performance in the U.S. (*8*). Factors such as changes in asphalt cement source and grade, types of aggregate, environmental conditions, production and construction methods need to be evaluated in the U.S. Evaluation of these factors would help to determine the long term performance of SMA and provide information to make changes as needed to suit U.S. conditions.

There is an SMA Technical Working Group that is attempting to solve many of the problems that may be encountered with the materials, design, construction, or performance of SMA. Information may be obtained from this group by contacting the FHWA, Office of Technology, Washington, D.C.

Objective

One objective of this study was to review the SMA projects constructed during 1991 and 1992 in the U.S. The other objective was to evaluate the potential of existing laboratory tests to predict the performance of SMA mixes. This study used two different types of aggregates and three types of fibers. Their effect was determined by varying the following parameters:

1. Fiber content.
2. Fine aggregate content.
3. Filler content.
4. Asphalt content.

Scope

The laboratory study was conducted using granite and local si.licious gravel aggregates. Three different types of stabilizers (two cellulose and one mineral fiber) were used, with varying filler content and fine aggregate content. One of the cellulose materials was produced in the U.S. and the other was produced in Europe. The mineral fiber was also produced in Europe. Gradation changes were made to determine the effect of gradation on mixture properties. Also, the asphalt content was varied from the job mix formula to determine the sensitivity of each of the SMA mixtures to asphalt content.

For evaluation of test properties of the SMA mixtures the following tests were performed on the laboratory samples:

1. Marshall stability and flow (140°F).
2. Gyratory properties, including Gyratory Elasto Plastic Index (GEPI), Gyratory Shear Index (GSI) and shear stress required to produce a one degree gyration angle.
3. Resilient modulus at temperatures of 40°, 77° and 104°F. The stress level applied was 15 percent of the indirect tensile strength. One load cycle consisted of 0.1 second of applied load and 0.9 second with no load.
4. Indirect tensile strength at 77°F.
5. Creep:
    (a) Static confined (140°F) test at 20 psi confining pressure and 120 psi vertical pressure. The loading time was one hour, and recovery time was 15 minutes.
    (b) Dynamic confined (140°F) test at 20 psi confining pressure and 120 psi vertical pressure. These numbers were selected to represent typical values expected in the in-place pavement. Each load cycle consisted of 0.1 second of applied load and 0.9 second with no load as in the resilient modulus test.

SMA REVIEW

Review

Stone Matrix Asphalt (SMA) is a hot mix asphalt, developed in Germany during the mid-1960s (*1*, *3*). In Europe, it is primarily known as “Splittmastixasphalt,” revealing its German origin (splitt - crushed stone chips, and mastic - the thick asphalt cement and filler). SMA has been referred to over the years as Split Mastic, Grit Mastic, or Stone Filled Asphalt (*1*, *3*). SMA is now in regular use for surface courses in Germany, Austria, Belgium, Holland and the Scandinavian countries (*7*). Japan has also started to use SMA paving mixtures, as well, with good success (*9*). A general definition of SMA developed by the SMA Technical Working Group is “A gap graded aggregate-asphalt hot mix that maximizes the asphalt cement content and coarse aggregate fraction. This provides a stable stone-on-stone skeleton that is held together by a rich mixture of asphalt cement, filler, and stabilizing additive.”

The original purpose of SMA was to provide a mixture that offered maximum resistance to studded tire wear (*1*, *3*). SMA has also been shown to provide high resistance to plastic deformation under heavy traffic loads with high tire pressures as well as good low temperature properties (*3*). A study conducted by the Ministry of Transportation (MTO), Ontario, Canada, on SMA pavement “slabs” trafficked with a wheel tracking machine gave less rut depths in comparison to that occurring in a dense friction course (*7*). The Georgia DOT has also performed a significant amount of wheel tracking tests on SMA mixtures with positive results. Also, the SMA has a rough surface texture as illustrated in Figure 1 (*3*) which provides good friction properties after the surface film of asphalt cement is removed by traffic. Other essential features that enhance the feasibility of SMA in contrast to conventional HMA are increased durability, improved aging properties and reduced traffic noise (*7*).

SMA is a hot mix with a relatively large proportion of stones and substantial quantity of mastic, i.e., asphalt cement and filler (*7*). The main concept, of having a gap gradation of 100 percent crushed aggregates, is to increase the pavement's stability through interlocking and stone-to-stone contact (*7*). The stone-to-stone contact is demonstrated in Figure 2 showing close stone-on-stone contact for an SMA gradation and less contact for a dense graded paving mixture. Notice how the coarse aggregate floats in the fine aggregate matrix for the dense graded mixture.

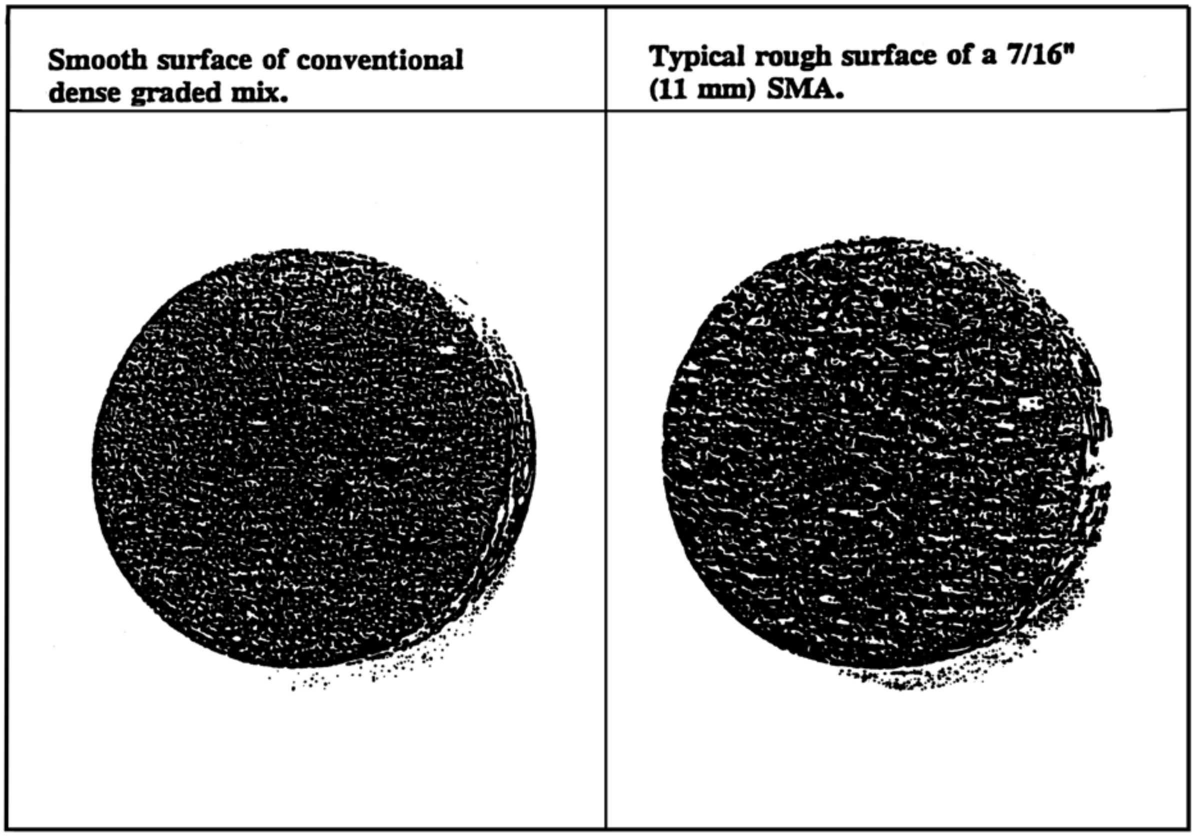


Figure 1. Comparison of SMA and Conventional Dense Graded Mix Surfaces (*3*)

SMA Mixtures in Europe

Aggregates

In Europe, the aggregates are divided into more size fractions during the construction process than in the United States (*11*). This same procedure of increased numbers of stockpiles is used for dense graded mixtures as well as for SMA mixtures. For example, the sizes of coarse aggregate typically available are: 2 to 5 mm, 5 to 8 mm, 8 to 11 mm, 11 to 16 mm, 16 to 22 mm, and 22 to 32 mm. The fine aggregate generally passes the 2 mm sieve. Having more stockpiles available allows for closer control of the aggregate gradation than in the U.S. but all sizes are not used for most work.

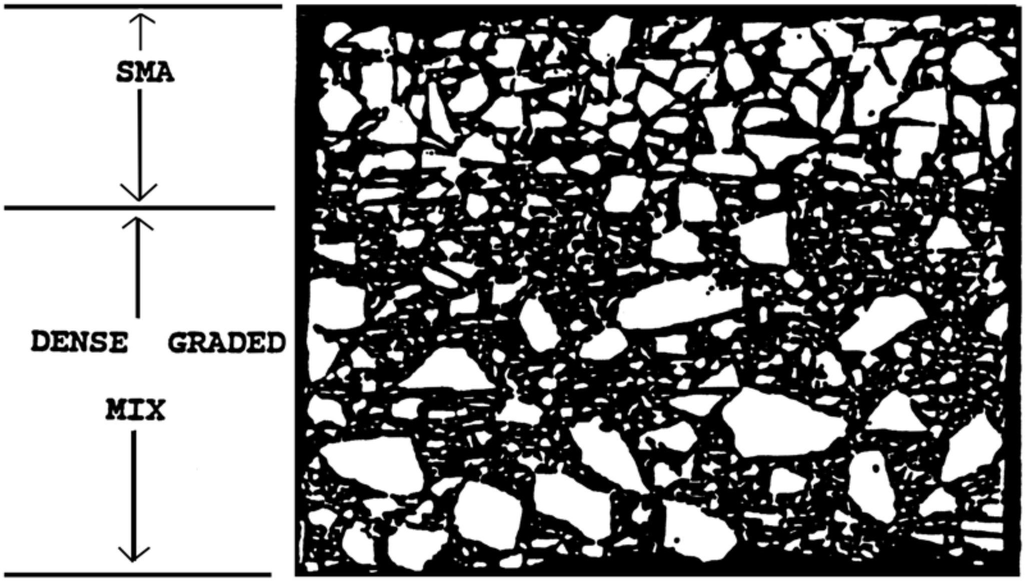


Figure 2. Pavement Section with a Stone Matrix Asphalt (SMA) Surface Course over a Conventional Paving Mix (*7*)

The maximum aggregate size for the European SMA mixes can vary from 1/4 inch to as large as 1 inch, but most SMA mixes tend to use relatively small coarse aggregate particles. In Europe, the size of the largest particles are typically 3/16", 5/16"or 7/16"as illustrated in Figure 3 (*3*). The percent passing each sieve size is illustrated in Figure 3, and the sieve sizes raised to the 0.45 power are given in Figure 4.

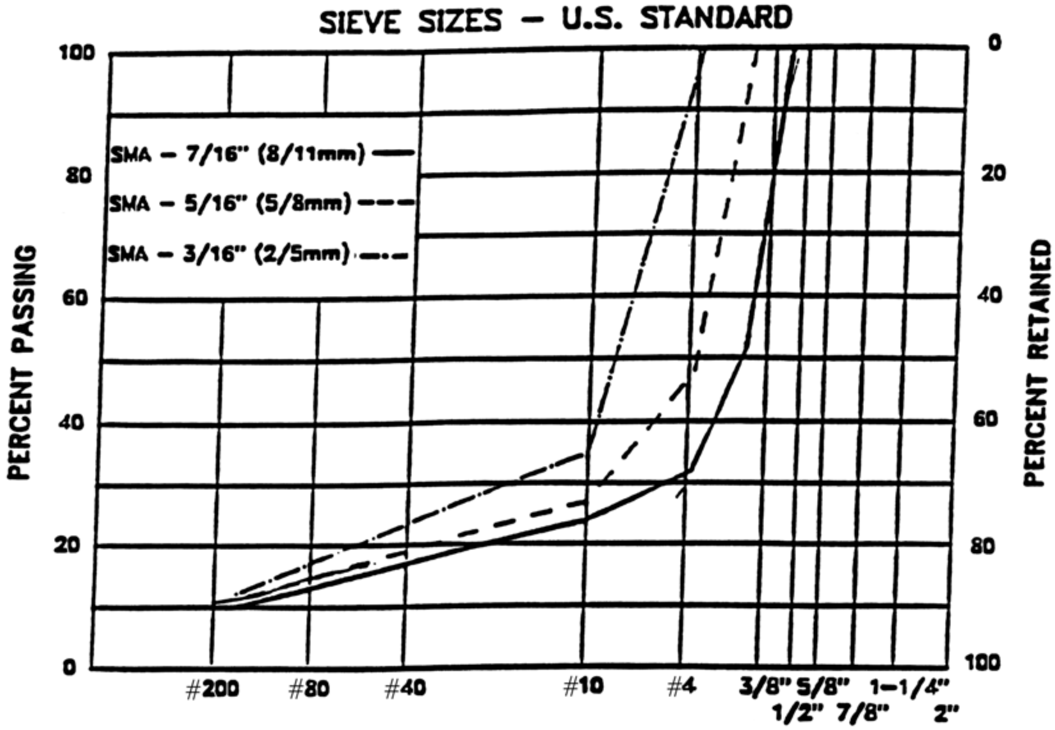


Figure 3. Typical Gradation for SMA Mixes in Europe (*3*)

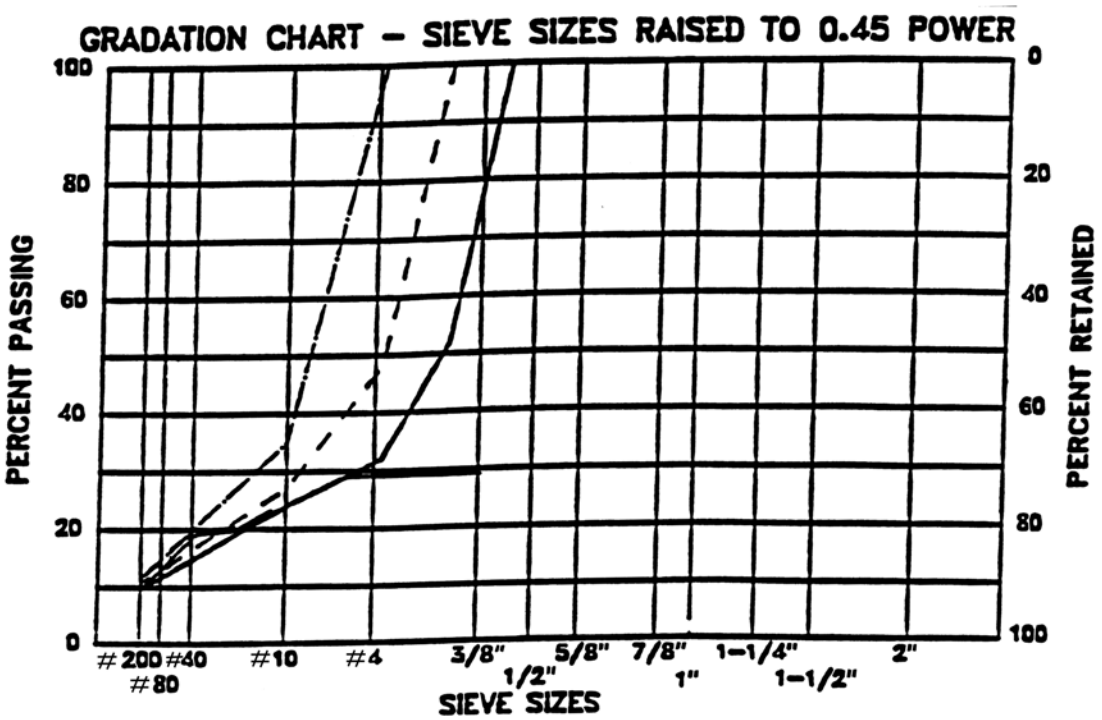


Figure 4. Gradation Chart-Sieve Sizes Raised to 0.45 Power (3)

Mineral Filler

In general, 8-12 percent of the total amount of aggregate in the mix passes the No. 200 sieve (7). This large amount of filler plays an important role in the properties of SMA mix particularly in terms of air voids, voids in the mineral aggregate and optimum asphalt content (3, 7). Since the amount of material passing the No. 200 sieve is relatively large, the SMA handles and performs very differently from other HMA mixtures (7). A primary difference between SMA and open graded mixtures is the low air voids (approximately 3 percent) in the SMA mixtures, whereas open graded friction courses may have more than 20 percent air voids.

Asphalt Content

In Europe, the optimum AC content for SMA mixtures is above 6.0 percent and in some specifications is required to be above 6.5 percent. The voids are filled with mastic, which contains fines, asphalt cement and special stabilizers or fibers. For SMA mixtures which contain organic or mineral fibers the range of optimum AC contents is normally slightly higher than that required when polymers are used as the stabilizer. Typically, the mixtures with organic fibers have slightly higher optimum AC contents than those with mineral fibers. The high AC contents and mastic provide a mixture that has excellent durability.

Mix Design

In Europe, the Marshall method of mix design is used to verify satisfactory voids in SMA mixtures (1, 2). Laboratory specimens are prepared by using fifty blows of the Marshall hammer per side (2). The optimum AC content for SMA mixes is selected to produce approximately 3 percent voids (1, 2). In Europe, Marshall stability and flow values are generally measured for information but not used for acceptance (11).

Fiber Stabilizer

Fibers, as a stabilizing agent, are usually added to reduce the draindown of the binder material during mixing, hauling and placing operations (*1*, *2*). Loose organic fibers, such as cellulose, are typically added at the rate of 0.3 percent by weight of mixture. Mineral fibers are often added at a rate of 0.4 percent by weight of mixture.

In the laboratory, special care is taken to assure that the fibers, either organic or mineral, are uniformly combined with the dry aggregates before the asphalt cement is added (*1*). Mixing continues until all the coarse and fine aggregate, mineral filler and fibers are coated with asphalt cement.

Polymer Stabilizer

Polymer stabilizers have also been used in a more limited basis in SMA mixtures (2). In some cases, the polymers are preblended with the asphalt cement and added to the mix during the mixing process. In other cases, the polymers are added to the aggregate in the plant before the asphalt cement is injected (2). One purpose of the polymer stabilizer is to minimize the asphalt cement draindown during the hauling, mixing, and placing operation (2). The other purpose is to increase the stiffness of the AC at high, in service temperature and/or to improve the low temperature properties of the binder material (2). Polymers are typically added to the mix at a rate of 3.0 to 8.0 percent, by weight of asphalt cement.

Production and Laydown of SMA Mixes in Europe

The total production of HMA in European countries is lower than that in the United States. For example, in West Germany, an average of 40 million tons of HMA is produced annually (*11*), compared to about 500 million tons of mix (13) in the United States. Resurfacing work, for a one lane, three mile section of Autobahn, requiring 15,000 tons of mix is a job of considerable size in Europe (*11*). Most of the German plants (batch plants) use up to six different aggregate sizes in SMA production (*11*). In Europe, aggregates that pass through the screen deck are stored in up to six hot bins, whereas in the U.S. most plants have four hot bins. Hence, the European plants have better aggregate control and flexibility in meeting aggregate gradation requirements.

For batch plants in Europe, fibers are added to the dry mixing cycle in the pugrnill. Mixing time is slightly increased, to ensure thorough distribution of the fibers. An additional 5-10 seconds mix time after introduction of the fibers is usually sufficient (3) in batch plants. The temperature of the SMA mix is generally between 300 to 330°F upon discharge from the mixing plant and should be at least, but usually more than, 275°F upon delivery to the laydown equipment.

In Europe, typically, steel wheel rollers, each having a minimum weight of 10 tons are utilized immediately behind the paver. The compaction should take place between 265°F and 300°F.

SMA Projects in the United States

By 1993 SMA projects had been constructed in at least 12 states in the U.S. At least 5-6 additional states had planned to build SMA sections in 1993. A list of those states, placing SMA in 1992 is shown in Table 1. States planning to construct projects in 1993 are shown in Table 2. (Information in Tables 1 and 2 furnished by John Bukowski, FHWA) This is not a complete list of SMA pavements constructed but is a list of those that are on file at FHWA.

Table 1. Stone Matrix Asphalt 1992 Completed Projects

	Alaska (Seward Hwy)	Maryland (US-15)	Maryland (I-70)	Ohio (US-33)	Wisconsin (I-43)	Texas (I-36/ SH 171)	California (I-40)	Michigan (I-94)	Missouri (I-70)	Georgia (I-75		Virginia (US-29)
Location	Surface 1.5" thick 3-1000 ft sections	Surface & Leveling 2.5" thick 2 miles	Surface 1.75" thick 7 miles	Surface 1.5" thick 4 miles	Surface 1.5" thick 6-400 ft sections	Surface 1.25" thick 6 miles	Surface 1.5" thick 2-1000 ft sections	Surface 1.5" thick 7 miles	Surface 1.75" thick 3 miles	Surface & Binder 1 mile		Surface 1.5" thick 4 lanes
Gradation	(JMF)	(JMF)	(JMF)	(JMF)	(JMF)	(JMF)	(JMF)	(JMF)	(JMF)	Surface	Binder	(JMF)
3/4"	100%	100%	100%	100%	100%	100%	99%	100%	100%	100%	100%	100%
1/2"	86	84	81	97	100	91	86	100	98	100	72	89
3/8"	71	68	61	77	98	69	75	70	70	79	48	65
#4	34	28	28	36	36	28	29	28	34	39	27	26
#8	22	15	15	18	21	(#10) 15	24	20	18	24	20	18
#16		13	12	14	17		19	17	15			16
#30	14	12	11	12	14	(#40) 13	15	15	14			15
#50		12	11	10	13		13	13	13	15	14	13
#100	12	11	10	8	12	(#80) 13	11	11	13			11
#200	9	9	9	6	11	10	9	10	10	8	8	9
AC by wt of mix (actual	6.5%	6.5/6.3 /6.0	6.3/5.9 %	6.6%	7.0% 6.2%	6.4%	5.6/ 5.4%	6.4/6.7%	6.6%	5.9	5.8	6.3/5.8%
Additive	Cellulose Fibers /Polyolefin	Cellulose Pellets / Elastometer / Polyolefin	Domestic Produced Cellulose /Polyolefin	Cellulose Pellets	Elastomer /Polyolefin /Domestic Produced Cellulose /Mineral Fibers	Cellulose Pellets	Polyolefin	Domestic Produced Cellulose /Polyolefin	Cellulose Fibers /Mineral Fibers	Domestic Produced Cellulose /Elastomer		Cellulose Pellets /Polyolefin
Air Voids	3%	2-4%	2-4%	3-5%	3%	4%	3%	3%	3.8%	3.8%	3.4%	3.5%
VMA	17	18	18	16.5	16-18	18		17	18	17	16	18
Plant	Batch	Drum	Drum	Drum	Drum	Drum	Drum	Drum	Batch	Drum		Batch
Quality	4,000 tons	10,000 tons	25,000 tons	16,000 tons	2,000 tons	8,000 tons	1,000 tons	12,000 tons	4,000 tons	1,000 tons		2,000 tons

Table 2. Stone Matrix Asphalt 1993 Planned Projects

State	Location	Size	Description	Stabilizer	Dot Contact
Alaska	Anchorage	20,000 Tons	1.5" Surface Batch Plant	Cellulose/ Polyolefin	Tom Moses
Arizona	I-40	10,000 Tons	1.5" Surface Drum Plant	Cellulose/ Polymer	George Way
California	Rt 152 Santa Clara	1,000 Tons	2" Surface	Cellulose	Jack VanKirk
Georgia	I-95 Savannah	62,000 Tons	1.5" Surface 2.5" Binder Overlay on PCC	Cellulose & Modified Asphalt	Don Watson
Illinois	I-80	12,000 Tons	1.5" Surface	Cellulose	Eric Harm
	I-57	5,000 Tons		Polymer	
	I-55	4,000 Tons		Mineral Fiber	
	US 24	8,000 Tons		Mineral Fiber	
	US 36	16,000 Tons		Cellulose	
	Rt 121	3,000 Tons		Polymer	
	Rt 1	5,000 Tons		Polymer	
	Lamont Rd	11,000 Tons		Cellulose	
Kansas	US 54	1,000 Tons	1.5" Surface	Fiber	Rodney Maag
Maryland	I-95 (Toll Road)	55,000 Tons	1.5" Surface Drum Plant	Cellulose/ Polymer	Larry Michael
	I-83	14,000 Tons			
	I-195	1,000 Tons			
	I-695	34,000 Tons			
	I-70	17,000 Tons			
Michigan	I-96/I-94 US 131	40,000 Tons	1.5" Surface Drum Plant	Cellulose/ Polyolefin	Dan Vreibel
Missouri	I-70	30,000 Tons	1.75" Surface	Cellulose	G. Manchester
Nebraska	Hwy 75	27,000 Tons	1.5" Surface	Polymer	Laird Weishahn
North Carolina	US 264	2,000 Tons	1.5" Surface	Cell./Polymer	Jim Trogden
Ohio	US-23 (Sandusky)	60,000 Tons	1.5" Surface	Cellulose	Roger Green
	I-75 (Findlay)	20,000 Tons			
Texas	US-79	5,000 Tons	1.5" Surface	Cell. Pellets	Paul Krugler
	US-323	7,000 Tons			
	US-60/83	1,000 Tons			
Virginia	I-66	10,000 Tons	1.5" Surface	Cell. Pellets	Bob Horan
Wisconsin	US-51	5,000 Tons	1.5" Surface	Polymers/ Mineral & Cellulose Fibers	Steve Shoeber
	US-63	5,000 Tons			
	US-45	5,000 Tons			
	I-43	15,000 Tons			

All the mix designs for SMA construction have been performed using the 50 blow Marshall hammer. Even though these mixtures are used on heavy duty roads, 75 blow compaction should not be used since it will tend to break down the aggregate more and will not result in a significant increase in density over that provided with 50 blows. SMA mixes have been more easily compacted on the roadway to the desired density than the effort required for conventional HMA mixes (*10*). The air void content has been typically around 3.0 percent in laboratory compacted samples for the SMA mixes and approximately 5-6 percent initially in-place.

Batch and drum plants have been successfully used in SMA production with no major problems existing with either type plant. Addition of the fiber initially had been in the form of pellets through the RAP feeder, halfway down the drum in a drum mix plant. Recently a more common method of addition of loose fibers has been to blow them directly into the drum mix plant. Loose fibers have been added directly to the pugmill in a batch plant (*10*).

Thickness of most of the SMA mixtures produced in the U.S. has been 1 1/2 inches. Compaction has been by static steel wheel rollers however, vibratory rollers have been successfully used, and rubber tire rollers have been tried without success. Vibratory rollers worked well on some projects, but these rollers in some cases may have a tendency to produce bleeding and to breakdown aggregate (*10*). If a vibratory roller is used it must be watched closely to insure that these problems do not occur. Rubber tire rollers have proven to be inappropriate for use on SMA mixtures due to a problem with AC sticking to the rubber tires.

It is too early to draw conclusions on the performance of SMA mixtures in the U.S. but so far initial results have been good. No significant distresses had occurred on the SMA projects constructed in 1991 and 1992 at the time this report was prepared. These initial SMA projects should provide data needed to evaluate performance of SMA mixtures under U.S. conditions, but a centralized effort to collect this performance data needs to be implemented. The SMA Technical Working Group is serving as this centralized effort.

TEST PLAN

Many SMA projects have been constructed and many more will be constructed within the next few years. It is essential that data be developed to provide guidance in mix design and construction to the users of SMA. The test plan for this study was developed to provide guidance to those individuals involved in mix design and quality control of SMA mixtures.

This section describes the materials used, mix design procedures, the various changes in material content and testing methodology for this SMA study. Two aggregate types, one asphalt cement and three types of fibers were used in this study.

Aggregates

The two types of aggregate selected for use were granite and silicious gravel. The granite from Buford, Georgia had an LA abrasion of 35 percent (based on present FHWA guidelines this is a marginal SMA aggregate) and soundness loss of 0.4 percent. Tests (ASTM C127) conducted in the laboratory gave the following results for the coarse granite aggregate:

Apparent specific gravity = 2.674
Bulk specific gravity = 2.632
Absorption (%) = 0.61

Tests (ASTM C128) conducted on the fine granite aggregate gave the following results:

Apparent specific gravity = 2.664

Bulk specific gravity = 2.621
Absorption (%) = 0.60

The gravel from Montgomery, AL had an LA Abrasion of 46.5 percent (based on present FHWA guidelines this aggregate should no be used for SMA. The guidelines at the time this report was written were LA Abrasion less than 30 and only crushed stone aggregates) and sulfate soundness loss of 0.4 percent. The results for the aggregate specific gravity and absorption properties tested in the laboratory are summarized below. The tests were conducted in accordance with ASTM C127 for coarse aggregate and ASTM C128 for the fine aggregate. The coarse aggregate results were:

Apparent specific gravity = 2.643
Bulk specific gravity = 2.599
Absorption (%) = 0.65

The following results were obtained for the fine aggregate:

Apparent specific gravity = 2.655
Bulk specific gravity = 2.611
Absorption (%) = 0.64

These two aggregates were selected for this study since they were locally available, they are common aggregates available in many states, and in some states it will be necessary to use aggregates with LA Abrasion over 30. Even though these aggregates were used for this study, it is recommended at this time that SMAs be built with crushed stone aggregate having LA Abrasion of 30 or below.

Asphalt Cement

The material source for the asphalt cement (AC-20) was Chevron U.S.A., Inc., Mobile, Alabama. Table 3 gives the various test properties for the asphalt cement as supplied by the supplier. The AC meets all the requirements for an AC-20.

Table 3. Test Properties for Asphalt Cement

Test Conducted	Results	Specifications
1. Viscosity @ 140°F, Poise	2083	2000±400
2. Viscosity @ 275°F, cst	423	210 min
3. COC Flash, °F	600	450 min
4. Penetration @ 77°F	83	40 min
5. Thin Film Oven Test		
i. Weight Loss, %	0.01	
ii. Viscosity @ 140°F, P	6258	10,000 max
iii. Ductility @ 77°F, cm	150+	20 min
iv. Viscosity ratio	3.00	
6. Specific gravity @ 77°F	1.0208	
7. Lbs/Gallon @ 77°F	8.5018	

Fibers

Three different types of fibers were used in this study. Two were cellulose fibers from different producers, and one was mineral fiber. The additives were:

1. Additive 1 (U.S. Cellulose)
2. Additive 2 (European Cellulose)
3. Additive 3 (European Mineral fiber)

Selecting the Optimum Asphalt Content and Sample Preparation

The optimum AC content for the SMA mixtures was selected to produce 3.5 percent air voids. A total of 18 samples per mix type evaluated in this study were prepared at optimum asphalt content using the Corps of Engineers Gyratory Machine set at 75 revolutions. This compaction effort was selected because it gave the same density as that obtained with 50-blows with the Marshall hammer. The dense graded mix samples were compacted at 300 revolutions of the GTM which is typical of that used for these mixtures. The machine set-up was as follows for both mix types:

1. Vertical pressure = 120 psi
2. Angle of gyration = 1 degree.

The Gyratory Machine was used for compaction so that engineering properties of the mixture could be determined. It is recommended (at this time) that all mix designs for projects be performed with 50 blows of the Marshall hammer. To minimize any differences between the two methods the Gyratory was set to provide the same density as that provided with 50 blows with the hammer. Also previous studies have shown that the Gyratory Machine orients the particles very similar to that obtained in the field.

Eighteen samples for each mixture type studied were prepared for testing. The 3 samples, of the 18 samples prepared, which had VTM farthest from the target value of 3.5 percent were discarded. Also the average VTM of all samples for a particular mixture had to be between 2.5 and 4.5 or the samples were discarded and additional samples made. At the beginning of this study it was noted that there was a significant variability in voids between samples for the SMA mixtures (more than expected for dense graded HMA) and this is the reason that the outliers were discarded. For every change in the fiber content, filler content, percent passing the No. 4 sieve or percent passing the No. 200 sieve it was essential to develop a new optimum AC content to give VTM equal to 3.5 percent. The study was not set up to look at the sensitivity of the mix to changes in proportions but was set up to help establish the optimum proportions. Samples prepared using the optimum asphalt content selected during mix design did not always provide air voids equal to 3.5 percent. That explains why the air voids in the samples prepared for testing were not exactly 3.5 percent.

Summary of Mixtures Evaluated

The samples evaluated in this study were produced using granite and gravel aggregates. Two cellulose fibers and one mineral fiber were used with each type of aggregate as illustrated in Figure 5.

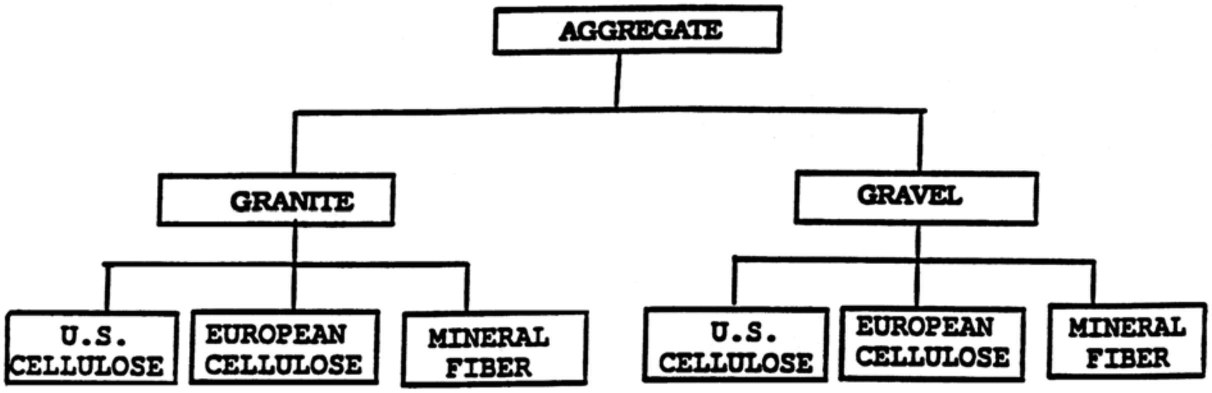


Figure 5. Different Fiber-Aggregate Combinations

For each additive-aggregate combination, the mixture modifications made are presented in Figure 6. The fiber content used for all mixtures was 0.3 percent by weight of mixture. The amount recommended for mineral fiber is 0.4 percent but 0.3 percent was used in this study to provide a direct comparison with cellulose, Variations in fiber content were from 0.0 to 0.5 percent as indicated in Figure 6. The aggregate gradation selected as the JMF for all mixtures is stated in Table 4 and was the same for both aggregate types. The gradation was varied by adjusting the percent passing the No. 200 sieve and the No. 4 sieve, as outlined in Figure 6. Tables 4 and 5 indicate the various gradation changes made.

The following paragraphs describe in more detail the various modifications made in the SMA mixes.

Changes in Amount Passing the No. 200 Sieve

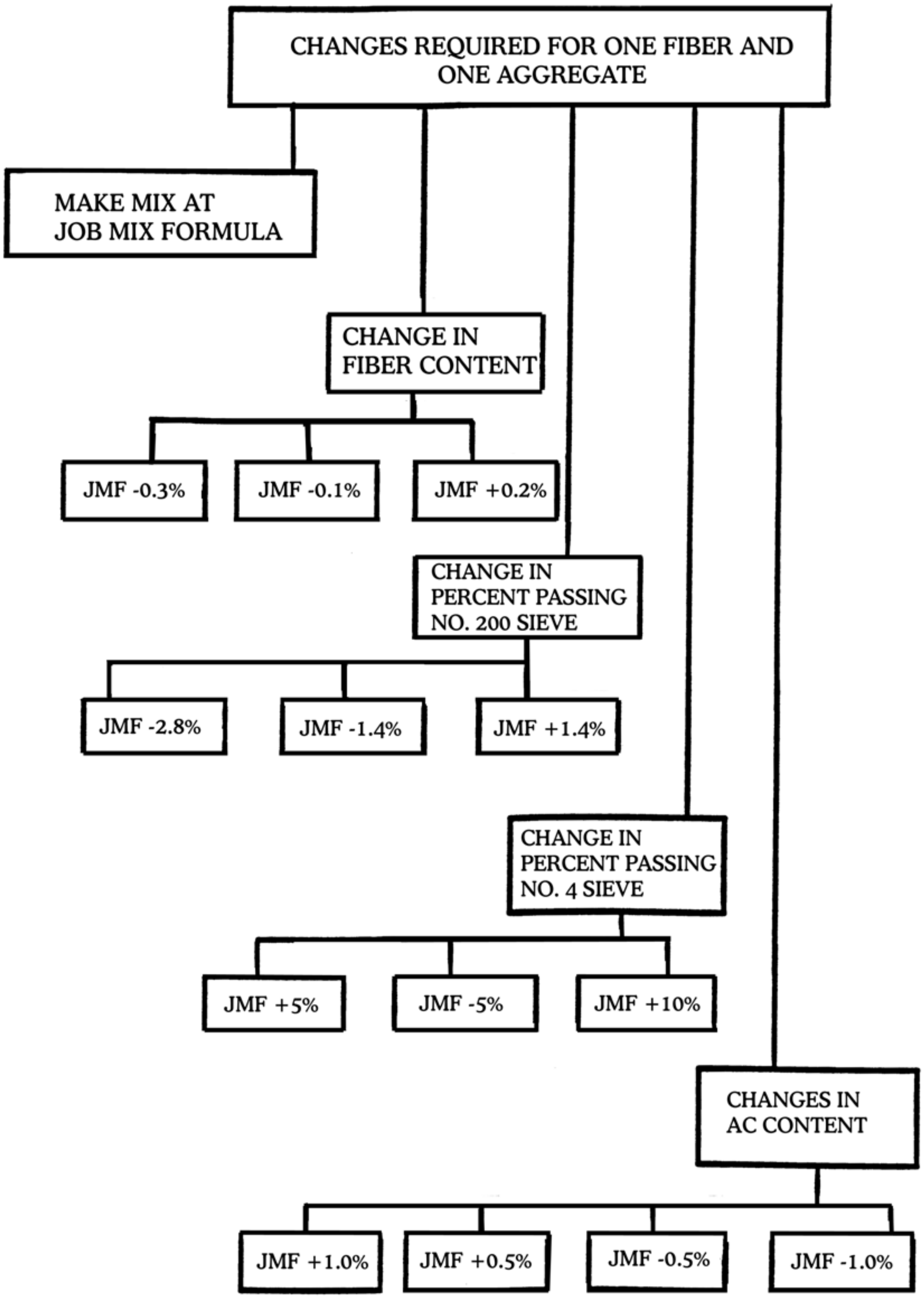
In order to determine the effect of aggregate gradation, changes in the amount passing the No. 200 sieve were made. The material passing the No. 200 sieve was obtained by screening a local agriculture lime. The amount passing the No. 200 sieve was varied from 7.4 to 11.6 percent for the granite and gravel aggregates. Table 4 shows the effect of changing the amount of material passing the No. 200 sieve on the total aggregate gradation.

Changes in Amount Passing the No. 4 Sieve

The percent passing the No. 4 sieve was varied from 24-39 percent for the granite and gravel aggregates. This is the range of most SMA mixtures that had been constructed in the U.S. prior to preparation of this report. However most recent projects have had less than 30 percent passing the No. 4 Sieve. Table 5 gives the gradation changes as a result of changing the amount of material passing the No. 4 sieve.

Changes in the Fiber Content

Samples were produced at the cellulose manufacturer’s suggested fiber content of 0.3 percent by weight of total mixture. The fiber content was varied from 0.0 percent to 0.5 percent. For every change in the mix, the optimum AC content was determined, as stated before, to satisfy the air void content criteria. This approach was used so that information needed to determine the optimum fiber content could be developed.



NOTE: ONE DENSE GRADED MIX WAS MADE FOR EACH AGGREGATE FOR COMPARISON WITH SMA MIXTURES.

Figure 6. Flowchart for the Various Material Combinations

Table 4. Changes in Percent Passing the No. 200 Sieve for Granite and Gravel

Sieve Size	JMF -2.8%	JMF -1.4%	JMF	JMF +1.4%
1/2 inch	100.0	100.0	100.0	100.0
3/8 inch	80.0	80.0	80.0	80.0
No. 4	29.0	29.0	29.0	29.0
No. 8	24.7	24.8	24.9	25.0
No. 16	18.4	18.6	18.8	19.0
No. 30	15.8	16.3	16.8	17.3
No. 50	13.8	14.6	15.4	16.2
No. 1 0	11.5	12.6	13.7	4.8
No. 200	7.4	8.8	10.2	11.6

Table 5. Changes in Percent Passing the No. 4 Sieve for Granite and Gravel

Sieve Size	JMF -5%	JMF	JMF +5%	JMF +10%
1/2 inch	100.0	100.0	100.0	100.0
3/8 inch	79.0	80.0	81.0	82.0
No. 4	24.0	29.0	34.0	39.0
No. 8	22.9	24.9	26.9	28.9
No. 16	17.8	18.8	19.8	20.8
No. 30	16.0	16.8	17.6	18.4
No. 50	14.8	15.4	16.0	16.6
No. 100	13.4	13.7	14.0	14.3
No. 200	10.2	10.2	10.2	10.2

Changes in the AC Content

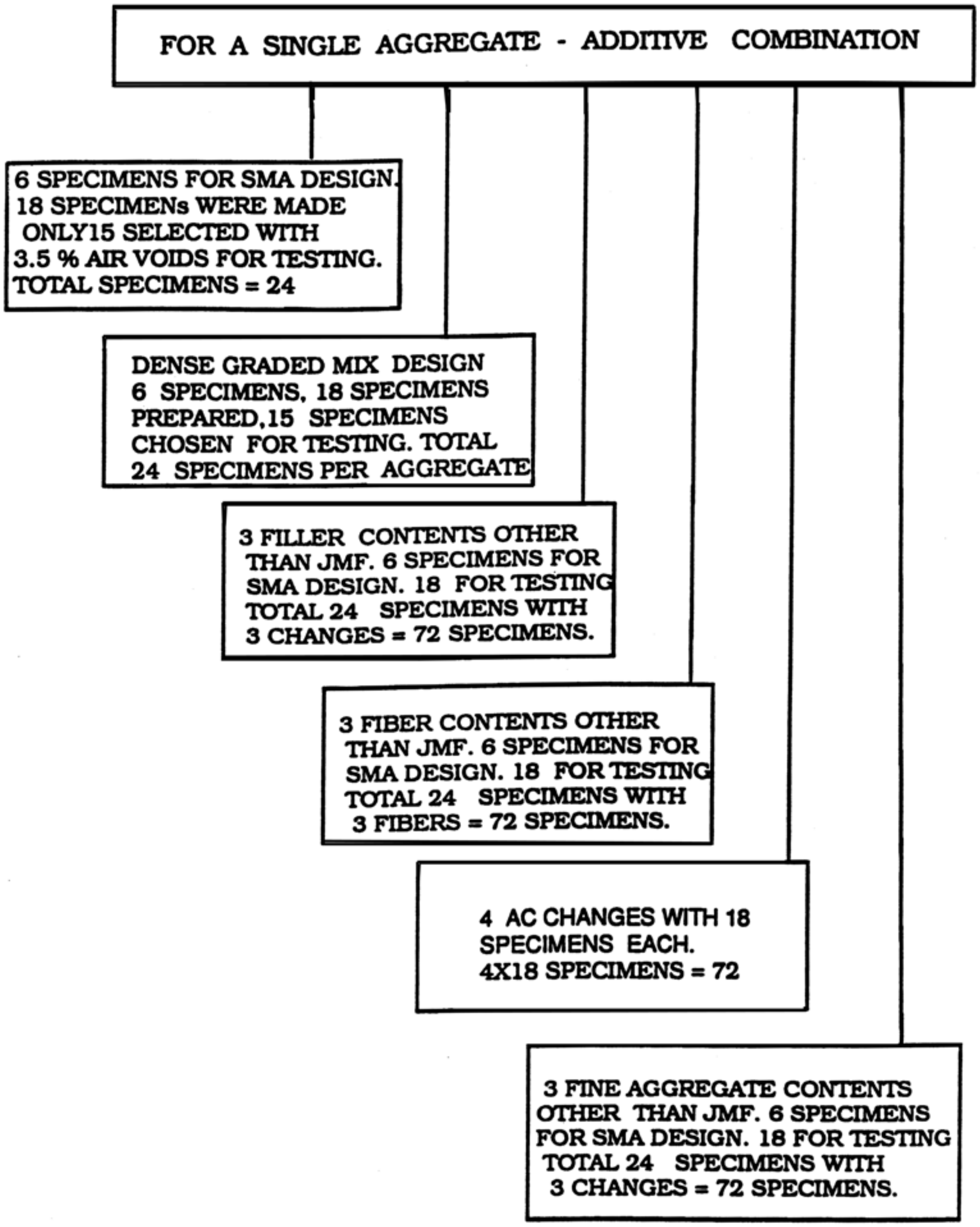
The sensitivity of the mix to asphalt content was evaluated by varying the asphalt content for each JMF. The asphalt content was varied in 1/2 percent increments to 1 percent below and 1 percent above optimum.

The total number of mixtures that were evaluated for each aggregate-fiber type is shown below:

1. Job mix formula (0.3 percent fiber, 29 percent passing the No. 4 sieve, 10.2 percent passing the No. 200 sieve and optimum asphalt content)	= 1
2. Changes in fiber content	= 3
3. Changes in percent passing the No. 4 sieve	= 3
4. Changes in AC content	= 4
5. Changes in percent passing the No. 200 sieve	= 3
TOTAL	14

Therefore, the total number of SMA mixtures that were evaluated in the study for each fiber type and each aggregate type was 14. Since three fiber types and two aggregates were used, a total of 14x6= 84 SMA mixture types were tested. One dense graded mix was made for comparison purposes for each aggregate type, resulting in a total of 86 mixture types being evaluated.

For each mixture, 15 specimens were required for testing. However, 18 specimens per mix were prepared, and 15 selected for testing since some specimens were discarded due to unsatisfactory air voids. Figure 7 illustrates the estimated number of samples prepared for testing in this study. The gradation for the granite and gravel dense graded mixtures are given in Table 6. The gradations were selected based on actual gradations of the materials submitted to the laboratory, therefore the two mixtures do not have the same grading. Both of these mixtures are typical dense graded mixtures and therefore, are acceptable for comparing to the SMA mixtures. The comparison of SMA and dense graded mixtures was not to evaluate which is better than the other but was made to help determine which tests may be applicable to SMA mixtures.



FOR A SINGLE AGGREGATE - ADDITIVE COMBINATION

6 SPECIMENS FOR SMA DESIGN. 18 SPECIMENs WERE MADE ONLY15 SELECTED WITH 3.5 % AIR VOIDS FOR TESTING. TOTAL SPECIMENS = 24

DENSE GRADED MIX DESIGN 6 SPECIMENS, 18 SPECIMENS PREPARED,15 SPECIMENS CHOSEN FOR TESTING. TOTAL 24 SPECIMENS PER AGGREGATE

3 FILLER CONTENTS OTHER THAN JMF. 6 SPECIMENS FOR SMA DESIGN. 18 FOR TESTING TOTAL 24 SPECIMENS WITH 3 CHANGES = 72 SPECIMENS.

3 FIBER CONTENTS OTHER THAN JMF. 6 SPECIMENS FOR SMA DESIGN. 18 FOR TESTING TOTAL 24 SPECIMENS WITH 3 FIBERS = 72 SPECIMENS.

4 AC CHANGES WITH 18 SPECIMENS EACH. 4X18 SPECIMENS = 72

3 FINE AGGREGATE CONTENTS OTHER THAN JMF. 6 SPECIMENS FOR SMA DESIGN. 18 FOR TESTING TOTAL 24 SPECIMENS WITH 3 CHANGES = 72 SPECIMENS.

Total No. of samples for all combinations $= (24)(3)(2) + (24)(2) + 4\,[(72)(3)(2)]$
$= 1920$ specimens

Figure 7. Estimate for the Number of Samples Made

Table 6. Gradations and Mix Properties for Gravel and Granite Dense Graded Mixes

	Granite Dense Mix	Gravel Dense Mix
Sieve No.	**% Passing**	**% Passing**
1/2 inch	100.0	100.0
3/8 inch	85.0	96.0
No. 4	67.0	82.3
No. 8	50.0	55.4
No. 16	30.3	35.7
No. 30	21.3	27.6
No. 50	15.0	17.8
No. 100	11.1	9.3
No. 200	6.7	5.6
T.M.D.	2.476	2.506
AC%	4.5	3.9
Bulk Sp. Gr.	2.372	2.413
Air Voids %	4.2	3.7

Tests Conducted

The following tests were conducted on samples of each mixture type:

1. Gyratory Properties (15 samples per mix. These tests were conducted during compaction and the samples were then used for other tests.):
   a. Gyratory Shear Index (GSI).
   b. Gyratory Elasto Plastic Index (GEPI).
   c. Shear stress to produce 1 degree angle.
2. Stability and flow (3 samples).
3. Indirect Tensile strength at 77°F (3 samples).
4. Resilient Modulus at 40°, 77°, & 104°F(3 samples).
5. Creep:
   a. Static confined at 140°F (3 samples).
   b. Dynamic confined at 140°F (3 samples).

The 15 samples for each mixture evaluated were tested as illustrated in Figure 8. The test data obtained was analyzed to determine the effect of various mixture proportions on the laboratory properties.

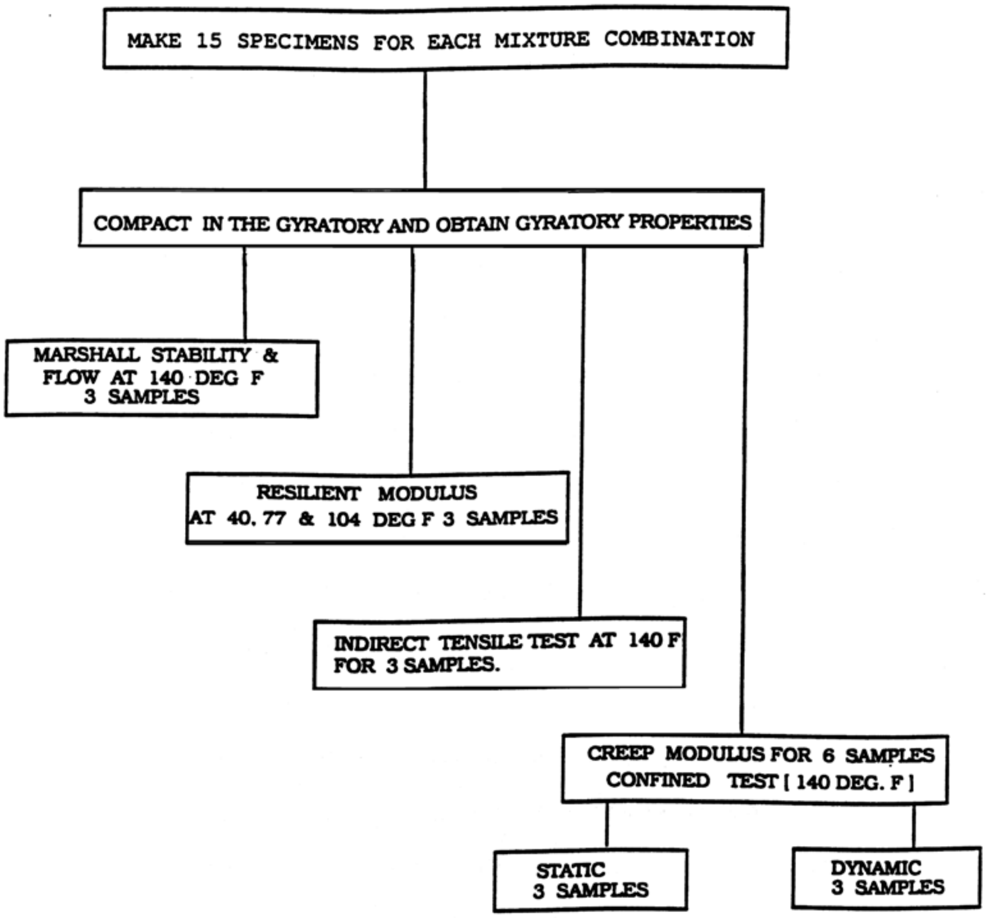


Figure 8. Flowchart for Testing of Mixture for Each Aggregate and Material Variation

TEST RESULTS AND ANALYSIS

All tests were conducted as outlined in the previous section. A discussion of test results is provided in the following paragraphs.

Voids in Total Mix

The target air void content was 3.5 percent for all SMA mixes, except those in which the asphalt content was varied. Due to variability in the air voids for the SMA specimens, the acceptable range was set between 2.5 and 4.5 percent. Since there are too many factors which influence the variability in air void content it was not reasonable to control them closer than plus or minus one percent. Tables 7 through 12 list the void results along with the other test results for the various aggregate-fiber combinations. Figure 9a shows the trend for the granite aggregate mixtures for increasing AC contents. The SMA mixtures with mineral fiber (optimum AC = 5.5 percent) have lower optimum AC contents than those mixtures with cellulose fiber (optimum AC = 5.8 percent for both cellulose fibers). This optimum asphalt content is slightly below the recommended minimum of 6.0 percent. When this study was initiated it was felt that 3.5 percent air voids should be used and this may be true but most agencies are now using 3 percent air voids and this would have resulted in a higher optimum AC content. Use of mineral fiber results in mixtures having an optimum asphalt content approximately 0.3 percent lower than that for either of the

Table 7. Summary Sheet for Granite and American Cellulose

Project	Stone Matrix Asphalt							SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE											
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.7	3.3	15.3	78.5	1472	16	2350	150.2	2394	495	*	0.0046	26087	0.0370	3243	1.00	1.00	39.22
0.2	5.7	146.0	3.6	16.4	77.9	1403	16	1392	135.4	2335	897	*	0.0057	21053	0.0306	3922	1.00	1.10	36.00
0.3	5.8	145.7	3.5	16.7	78.7	1437	15	1635	103.7	1506	374	*	0.0038	31579	0.0332	3614	1.00	1.10	33.85
0.5	5.9	145.1	3.9	17.1	77.2	1434	15	1592	99.8	2215	457	*	0.0063	19048	0.0694	1729	1.00	1.09	35.32
AC, %																			
JMF-1%AC	4.8	144.6	5.8	16.4	64.5	1378	14	1670	105.0	1454	230	127	0.0069	17391	0.0295	4068	1.00	1.10	43.45
JMF-.5%AC	5.3	144.8	5.1	16.7	69.9	1322	16	1873	117.8	2237	378	85	0.0052	23077	0.0380	3158	0.98	0.98	36.46
JMF	5.8	145.7	3.5	16.7	79.7	1437	15	1635	103.7	1506	374	*	0.0039	30769	0.0332	3614	1.00	1.00	33.85
JMF+.5%AC	6.3	146.7	2.3	16.5	86.1	1759	16	1883	120.0	2005	549	99	0.0098	12245	0.0941	1477	1.06	1.06	36.60
JMF+1.0%AC	6.8	146.6	1.6	16.9	90.3	1409	16	1708	108.8	2092	432	82	0.0064	18750	0.1306	919	1.00	1.00	35.80
% Passing No. 200																			
7.4	5.6	144.8	4.5	17.5	74.6	1239	13	1937	120.7	2002	312	78	0.0095	12632	0.0381	3150	1.03	1.03	40.40
8.8	5.6	144.5	3.8	16.9	77.4	1206	16	1818	112.7	1396	346	71	0.0115	10435	0.0629	1908	1.07	1.07	38.63
10.2	5.8	145.7	3.5	16.7	78.7	1437	15	1635	103.7	1506	374	*	0.0039	30769	0.0332	3614	1.00	1.00	33.95
11.6	5.6	146.9	3.0	15.8	81.2	1468	12	1812	114.9	2310	338	100	0.0114	10526	0.0401	2993	1.01	1.01	33.61
% Passing No. 4																			
24	5.7	146.3	3.5	16.5	79.1	1260	17	1856	117.9	2463	342	81	0.0083	14458	0.0555	2162	1.00	1.00	39.30
29	5.8	145.7	3.5	16.7	78.7	1437	15	1635	103.7	1506	374	*	0.0039	30769	0.0332	3614	1.00	1.00	33.95
34	5.6	146.8	3.3	16.2	79.7	1617	16	2233	143.3	2409	610	101	0.0085	14118	0.0580	2069	1.13	1.13	36.77
39	5.4	147.4	3.0	15.3	80.3	1405	15	2147	137.9	2392	485	90	0.0104	11538	0.0708	1695	1.00	1.00	35.91
Dense Mix																			
300 Rev.	4.5	147.9	4.2	14.6	70.9	2500	12	2383	157.3	2301	413	117	0.0070	17143	0.0160	7477	1.00	1.10	40.70

* Outliers

Table 8. Summary Sheet for Granite and European Cellulose

Project	Stone Matrix Asphalt							SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE											
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.7	3.3	15.3	78.5	1472	16	2350	150.2	2394	495	*	0.0046	26087	0.0370	3243	1.00	1.00	39.22
0.2	5.6	146.8	3.2	16.0	80.1	1400	12	1908	121.0	2281	308	86	*	*	0.0258	4651	1.00	1.10	35.72
0.3	5.8	145.8	3.0	16.2	91.8	1153	14	1537	96.0	2131	305	73	*	*	0.0328	3659	1.00	1.10	39.33
0.5	6.5	145.8	2.9	17.6	83.6	1456	14	1870	116.0	2005	257	91	*	*	0.0526	2281	1.00	1.20	36.67
AC, %																			
JMF-1%AC	4.8	144.6	5.8	15.9	67.8	1335	15	1717	107.0	1836	353	84	*	*	0.0395	3038	1.00	1.10	36.50
JMF-.5%AC	5.3	144.9	5.1	16.2	74.0	1127	16	1867	117.0	2278	250	93	*	*	0.0541	2218	1.00	1.10	35.70
JMF	5.8	145.8	3.0	16.2	81.8	1472	14	1537	96.0	2131	305	73	*	*	0.0329	3659	1.00	1.10	38.33
JMF+.5%AC	6.3	146.2	2.3	16.3	87.7	1238	15	1738	109.0	2544	362	111	*	*	0.0679	1767	1.00	1.10	33.90
JMF+1.0%AC	6.9	147.3	0.8	16.2	96.3	1779	16	1795	115.0	2439	443	86	*	*	0.1558	770	1.00	1.10	34.40
% Passing No. 200																			
7.4	6.3	145.0	3.9	17.9	81.2	1371	14	1342	83.6	2310	263	78	*	*	0.097	1237	1.00	1.10	37.50
8.8	6.0	145.8	3.2	16.9	81.1	1439	16	1600	100.9	3363	285	89	*	*	0.0562	2135	1.00	1.10	35.70
10.2	5.8	145.8	3.0	16.2	81.8	1153	14	1537	96.0	2131	305	73	*	*	0.0329	3659	1.00	1.10	38.33
11.6	5.8	147.2	28	16.1	82.7	1439	13	1817	116.0	2273	399	76	*	*	0.0629	1908	1.00	1.10	34.30
% Passing No. 4																			
24	5.5	145.8	4.3	16.6	74.6	1259	14	1563	99.0	1803	405	86	*	*	0.037	3243	1.00	1.10	32.20
29	5.8	145.8	3.0	16.2	81.9	1153	14	1537	96.0	2131	305	73	*	*	0.0329	3659	1.00	1.10	38.33
34	6.0	146.5	3.3	17.0	80.5	1329	13	1633	103.0	2457	438	83	*	*	0.0671	1788	1.00	1.10	37.70
39	5.8	146.3	3.3	16.5	79.9	1309	14	1709	107.0	2436	315	71	*	*	0.0325	3692	1.00	1.10	35.20
Dense Mix																			
300 Rev.	4.5	147.9	4.2	14.6	70.9	2500	12	2383	157.3	2301	413	117	0.0070	17143	0.0160	7477	1.00	1.10	40.70

* Outliers

Table 9. Summary Sheet for Granite and Mineral Fiber

Project	Stone Matrix Asphalt							SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE											
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.7	3.3	15.3	78.5	1472	16	2350	150.0	2394	495	*	0.0046	26087	0.0370	3243	1.00	1.00	39.22
0.2	5.5	148.1	3.2	15.9	79.7	1419	12	1508	97.0	2741	656	97	0.0049	24490	00264	4545	1.00	1.10	34.90
0.3	5.5	148.1	2.6	15.2	83.3	1579	14	1608	104.0	2058	316	105	0.0066	18192	0.0275	4364	1.00	1.10	37.90
0.5	5.5	147.3	3.7	16.3	77.4	1753	14	1742	111.0	3007	758	109	0.0078	15395	0.0271	4428	1.00	1.10	35.80
AC, %																			
JMF-l%AC	4.5	146.5	5.1	15.3	67.0	1540	14	1683	107.0	2155	414	74	0.0049	24490	0.0261	4598	1.00	1.10	37.90
JMF-.5%AC	5.0	148.5	3.8	15.2	75.1	1453	12	1598	100.0	2945	534	97	0.0059	20339	0.0127	9449	1.00	1.10	39.40
JMF	5.5	147.7	2.5	15.2	78.5	1472	14	2350	104.0	2394	495	105	0.0066	19192	0.0275	4364	1.00	1.00	39.22
JMF+.S%AC	6.0	148.5	1.9	15.7	88.0	1457	13	1600	103.0	2093	451	83	0.0071	16901	0.0351	3419	1.00	1.10	35.50
JMF+1.0%AC	6.5	148.5	1.4	16.3	91.6	1439	16	1695	108.0	2512	561	00	0.0091	13197	0.1330	902	1.00	1.10	34.30
% Passing No. 200																			
7.4	6.2	145.8	4.0	17.8	77.6	1341	12	1537	95.0	1382	247	48	0.0054	2222	0.0262	4580	1.00	1.10	39.90
8.8	5.5	147.2	3.8	16.3	76.7	1417	12	1700	109.0	1264	268	59	0.0095	12632	0.0232	5172	1.00	1.10	39.90
10.2	5.5	149.1	3.3	15.2	78.5	1472	14	1608	104.0	2394	495	105	0.0046	26097	0.0370	3243	1.00	1.00	37.90
11.6	5.3-	148.5	3.0	15.2	90.5	1860	13	1935	119.0	1243	279	80	0.0091	14915	0.0363	3306	1.00	1.10	37.70
% Passing No. 4																			
24	5.8	147.8	2.6	16.0	93.7	1400	17	1730	110.0	1258	354	115	0.0119	10094	0.0249	4819	1.00	1.10	37.30
29	5.5	148.1	3.3	15.2	78.5	1472	14	1608	104.0	2394	495	105	0.0066	19192	0.0275	4364	1.00	1.00	39.22
34	5.3	147.8	3.1	15.2	79.9	1538	13	2200	142.0	1179	381	56	0.0093	14458	0.0227	5286	1.00	1.10	39.60
39	5.3	148.0	3.3	15.5	78.6	1400	13	1833	118.0	2993	350	116	0.0119	10169	0.0244	4918	1.00	1.10	34.80
Dense Mix																			
300 Rev.	4.5	147.9	4.2	14.6	70.9	2500	12	2393	157.3	2301	413	117	0.0070	17143	0.0160	7477	1.00	1.10	40.70

* Outliers

Table 10. Summary Sheet for Gravel and American Cellulose

Project	Stone Matrix Asphalt							SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE											
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.1	3.4	14.9	77.0	1435	13	1693	107.1	1574	252	66	9.002	13043	0.0209	5742	1.00	1.15	43.89
0.2	4.8	146.6	3.4	14.4	76.4	1201	13	1683	107.3	1233	236	82	0.0061	19672	0.0261	4599	1.00	1.15	41.72
0.3	4.7	146.6	3.6	14.4	74.9	1544	11	1633	103.9	1197	196	63	0.0045	26667	0.0292	4110	1.00	1.15	44.83
0.5	5.2	146.1	3.3	15.1	78.2	1513	12	1745	110.6	1337	267	67	0.0067	17910	0.0367	3270	1.00	1.19	46.19
AC, %																			
JMF-l%AC	3.7	144.6	6.6	14.9	55.9	1526	13	1424	88.7	1297	238	65	0.0051	23529	0.0141	8511	1.00	1.20	48.06
JMF-5%AC	4.2	145.0	5.5	15.0	63.3	1824	14	1350	95.0	1290	255	64	0.0060	20000	0.0266	4511	1.00	1.20	46.98
JMF	4.7	146.6	3.6	14.4	74.9	1544	11	1633	103.9	1197	196	63	0.0045	26667	0.0292	4110	1.00	1.15	44.93
JMF+.5%AC	5.2	146.5	3.2	15.1	78.8	1335	12	1630	103.0	1312	249	43	0.0112	10714	0.0270	4444	1.00	1.14	44.14
JW+1.0%AC	5.7	147.0	2.2	15.2	85.6	1410	11	1612	1025	1122	204	70.	00082	14634	0 0320	3750	1.00	1.20	42.44
% Passing No. 200																			
7.4	5.8	145.0	3.4	16.7	79.2	1245	13	1327	94.5	1347	380	52	0.0061	19672	0.0246	4879	1.00	1.20	39.99
8.8	5.2	147.0	3.1	14.9	79.9	1335	14	1158	73.8	1292	221	47	0.0093	14459	0.0199	6349	1.00	1.22	45.09
10.2	4.7	146.6	3.6	14.4	74.9	1544	11	1633	103.9	1197	196	63	0.0045	26667	0.0292	4110	1.00	1.15	44.83
11.6	4.2	147.9	2.9	13.9	79.1	1726	15	1453	93.5	1295	202	80	0.0034	35294	0.0204	5992	1.00	1.20	45.20
% Passing No. 4																			
24	5.0	146.2	3.7	15.1	75.5	1351	14	1775	112.0	1557	230	51	0.0087	13793	0.0207	5797	1.00	1.20	41.99
29	4.7	146.6	3.6	14.4	74.9	1544	12	1633	103.9	1197	196	63	0.0045	26667	0.0292	4110	1.00	1.15	44.93
34	4.7	147.6	3.2	14.0	77.3	1999	15	1947	125.0	1947	328	68	0.0088	13636	0.0216	5556	1.00	1.20	41.98
39	4.8	149.1	2.5	13.6	81.9	1739	11	1572	103.0	1705	262	87	0.0100	12000	0.0560	2143	1.00	1.25	44.35
Dense Mix																			
300 Rev.	3.9	150.6	3.7	12.8	71.4	3725	10	2192	142.4	2254	298	77	0.0059	20236	0.0193	6219	1.00	1.01	40.53

* Outliers

Table 11. Summary Sheet for Gravel and European Cellulose

Project	Stone Matrix Asphalt								SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE									
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.1	3.4	14.9	77.0	1435	13	1693	107.1	1574	252	66	0.0092	13043	0.0209	5742	1.00	1.15	43.99
0.2	5.3	147.5	2.7	14.8	81.9	1275	13	1678	106.5	1299	211	52	0.0100	11964	0.0234	5128	1.00	1.20	42.50
0.3	5.3	147.3	2.7	14.8	81.9	1346	12	1445	92.7	1914	235	56	0.0113	10619	0.0295	4211	1.00	1.23	43.43
0.5	5.4	146.0	3.2	15.5	79.2	1423	14	1448	92-0	1853	228	46	0.0141	8511	0.0299	4013	1.00	1.23	45.07
AC, %																			
JMF-1%AC	4.3	145.9	4.9	14.7	66.5	1465	14	1650	104.0	1479	236	60	0.0089	13493	0.0176	6818	1.00	1.20	46.44
JMF-5%AC	4.8	145.3	4.7	15.5	70.1	1483	11	1791	111.0	1390	241	48	0.0067	17910	0.0194	6196	1.00	1.20	41.29
JMF	5.3	147.3	2.7	14.8	81.9	1346	12	1445	93.0	1914	235	56	0.0113	10619	0.0295	4211	1.00	1.20	43.43
JMF+.5%AC	5.8	147.2	2.3	15.3	86.6	1380	12	1687	108.0	2296	205	51	0.0102	11765	0.0371	3235	1.00	1.20	39.95
JMF+1.0%AC	6.3	147.3	1.9	15.7	92.0	1462	is	1588	1020	1633	169	44	0.0113	10619	0.0434	2765	1.00	1.40	38.74
% Passing No. 200																			
7.4	6.4	144.4	3.2	17.6	81.8	1167	16	1367	85.0	1378	151	35	0.0127	9449	0.0259	4633	1.00	1.20	39.99
8.8	5.7	146.1	2.9	16.0	82.3	1178	13	1597	100.0	1538	236	47	0.0149	8054	0.0199	6061	1.00	1.20	40.42
10.2	5.3	147.3	2.7	14.8	81.9	1346	12	1445	93.0	1914	235	56.	0.0113	10619	0.0295	4211	1.00	1.20	43.43
11.6	4.9	147.2	3.3	14.5	77.4	1481	12	1699	107.4	1920	223	53	0.0162	7407	0.0273	4396	1.00	1.20	47.70
% Passing No. 4																			
24	5.9	144.9	3.4	16.9	79.7	1075	14	1492	94.0	1404	201	46	0.0130	9231	0.0250	4800	1.00	1.20	40.70
29	5.3	147.3	2.7	14.8	81.9	1346	12	1445	93.0	1914	235	56	0.0113	10619	0.0295	4211	1.00	1.20	44.83
34	5.0	147.4	3.0	14.5	79.0	1529	11	1583	102.0	1209	197	50	0.0119	10084	0.0310	3971	1.00	1.20	41.88
39	4.8	148.1	2.9	13.9	79.5	1812	13	1700	111.0	1800	244	65	0.0130	9231	0.0293	4096	1.00	1.20	44.35
Dense Mix																			
300 Rev.	3.9	150.6	3.7	128	71.4	3725	10	2192	142.4	2254	298	77	0.0059	20236	0.0193	6218	1.00	1.01	40.53

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* Outliers

Table 12. Summary Sheet for Gravel and Mineral Fiber

Project	Stone Matrix Asphalt							SUMMARY SHEET FOR GRANITE-AMERICAN CELLULOSE											
Mix Type (75 Rev.)	Asphalt Content (%)	Unit Weight (pcf)	Voids			Marshall Stability		Indirect Tensile Strength		Resilient Modulus			Static Creep		Dynamic Creep		Gyratory Properties		
Changes			Total (%)	VMA (%)	Filled (%)	Stability	Flow	Pult @ 77F (lb)	Strength @ 77F (psi)	Modulus @ 40F (ksi)	Modulus @ 77F (ksi)	Modulus @ 104F (ksi)	Perm. Strain (in/in)	Creep Modulus (psi)	Perm. Strain (in/in)	Creep Modulus (psi)	GSI	GEPI	Shear Stress (psi)
Fiber, %																			
0	5.5	147.1	3.4	14.9	77.0	1435	13	1683	107.1	1574	252	66	0.0092	13043	0.0209	5742	1.00	1.15	43.89
0.2	4.2	147.4	4.2	13.9	69.6	1654	13	1518	96.7	2025	198	75	0.0078	15385	0.0259	4633	1.01	1.20	38.30
0.3	4.6	147.9	3.3	13.7	76.5	1472	14	1725	110.1	1902	245	62	0.0092	13043	0.0180	6678	1.00	1.27	4103
0.5	5.0	147.0	3.6	15.1	76.0	1396	12	1559	99.1	1427	187	52	0.0137	8759	0.0210	5722	1.00	1.24	40.49
AC, %																			
JMF-1%AC	3.6	144.9	6.5	14.9	55.7	1544	12	1317	82.6	1403	129	48	0.0093	12903	0.0124	9677	1.00	1.13	42.36
JMF-.5%AC	4.1	146.7	4.7	14.1	66.7	1535	11	1558	99.7	1800	249	75	0.0044	27273	0.0111	10911	1.00	1.20	40.40
JMF	4.6	147.9	3.3	13.9	76.5	1472	14	1125	110.1	1902	245	62	0.0092	13043	0.0180	6679	1.00	1.27	42.03
JMF+.5%AC	5.1	148.2	13	14.1	83.7	1481	12	1659	105.8	1803	176	54	0.0069	17391	0.0129	9375	1.00	1.20	38.77
JMF+1.0%AC	5.6	147.8	1.9	14.9	97.3	1369	14	1337	87.0	2253	268	49	0.0089	13493	0.0353	3399	1.00	1.17	39.20
% Passing No. 200																			
7.4	5.6	145.2	3.9	16.3	75.8	1496	18	1425	89.1	2081	151	43	0.0080	15000	0.0180	6678	1.00	1.20	42.32
8.8	4.8	146.3	4.2	15.0	72.3	1469	15	1795	113.0	1459	215	48	0.0047	25532	0.0214	5607	1.00	1.15	47.11
10.2	4.6	147.9	3.3	13.7	76.5	1472	14	1725	110.1	1902	245	62	0.0092	13043	0.0180	6678	1.00	1.27	47.03
11.6	4.3	147.8	3.7	13.5	73.0	1544	12	1749	112.2	1509	251	72	0.0075	16000	0.0154	7777	1.00	1.20	43.76
% Passing No. 4																			
24	5.0	146.6	3.7	15.1	75.4	1435	14	1725	109.0	1900	253	60	0.0185	6486	0.0107	11215	1.00	1.20	46.92
29	4.6	147.9	3.3	13.7	76.5	1472	14	172S	110.1	1902	245	62	0.0092	13043	0.0180	6678	1.00	1.27	42.03
34	4.3	147.6	3.9	13.8	71.6	1700	13	1774	113.0	2194	292	66	0.0056	21429	0.0134	9955	1.00	1.12	41.63
39	4.4	148.1	3.5	13.6	74.5	1912	13	1782	115.8	2195	293	66	0.0167	7186	0.0200	6009	1.00	1.10	45.01
Dense Mix																			
300 Rev.	3.9	150.6	3.7	12.8	71.4	3725	10	2192	142.4	2254	298	77	0.0059	20236	0.0193	6218	1.00	1.01	40.53

cellulose fibers. Both cellulose fibers show similar trends. The reason for the higher AC content for the samples with cellulose fibers seems to be the bulking effect created by these fibers and/or some breakdown of the mineral fiber during mixing resulting in production of a filler size material causing a lower optimum asphalt content. The dense graded mixture for granite had an optimum AC content of 4.5 percent well below that for the SMA. This is one of the advantages of SMA, more AC can be added without the mixture becoming unstable.

The VTM versus AC content graph for the gravel mixtures shows a typical trend (Figure 9b). The VTM reduces as the AC content increases. The mixture containing gravel and mineral fiber had an optimum asphalt content of 4.6 percent compared to 4.7 percent for American Cellulose and 5.3 percent for European Cellulose. The dense graded mixture had an optimum AC content of 3.9 percent. This mixture tends to pack easily and the gradation would need to be changed or aggregates changed to get this optimum AC up to the minimum 6.0 percent recommended for SMA. As stated earlier the LA Abrasion of this aggregate is 46.5 percent which significantly exceeds the recommended maximum value of 30. This high LA Abrasion may have resulted in a closer packing of the aggregate and lower optimum asphalt content.

Unit Weight

Figures 10a and 10b indicate the trends for density for all the fibers. The unit weight is typically 2-3 pounds per cubic foot higher for the mixtures containing mineral fiber than for the two mixtures with cellulose. The two cellulose fibers show almost the same results. One possible reason for higher density for mineral fiber samples is the mineral fiber tends to breakdown during mixing generating filler material leading to higher density on compaction. Figures 11a and 11b show that the unit weight for European cellulose and American cellulose samples generally decreases as the fiber content increases above zero. For the mineral fiber the unit weight increases to a peak at approximately 0.3 percent and then drops at higher fiber contents. This indicates that higher fiber contents tend to lower the density and thus increase the VMA. Higher fiber contents tend to lower the density by pushing apart the aggregate resulting in lower stability if the fiber content is too high. Hence, the fiber content should be kept low enough so that the mixture is stable and high enough so that draindown of the AC does not occur.

Increasing the percent passing the No. 4 sieve results (Figures 12a and 12b) in an increase in unit weight for all three fibers, but as expected the density is higher for the mineral fiber. The granite aggregate shows very little loss in density with a decrease in percent passing the No. 4 sieve which indicates that stone-on-stone contact has probably not developed even when the percent passing the No. 4 sieve is reduced to 24 percent. The gravel mixture however shows a decrease in density with a decrease in percent passing the No. 4 sieve when the percent passing is reduced below 29 percent which indicates that stone-on-stone contact is beginning to develop as the fine fraction is reduced. When stone-on-stone contact develops, decreasing the percent passing the No. 4 sieve will simply increase the voids in the mineral aggregate resulting in a decrease in density since the coarse aggregate can not move closer together. Increasing the amount of material passing the No. 200 sieve also increases the unit weight of the SMA mixtures for both aggregates (Figures 13a and 13b). A decrease in the percent passing the No. 200 sieve results in a decrease in density but probably does not result in stone-on-stone contact as long as the percent passing the No. 4 sieve remains constant. In this case the loss in density is due to loss in voids in the fine aggregate portion and not a closer packing of the coarse aggregate portion which is necessary for stone-on-stone contact.

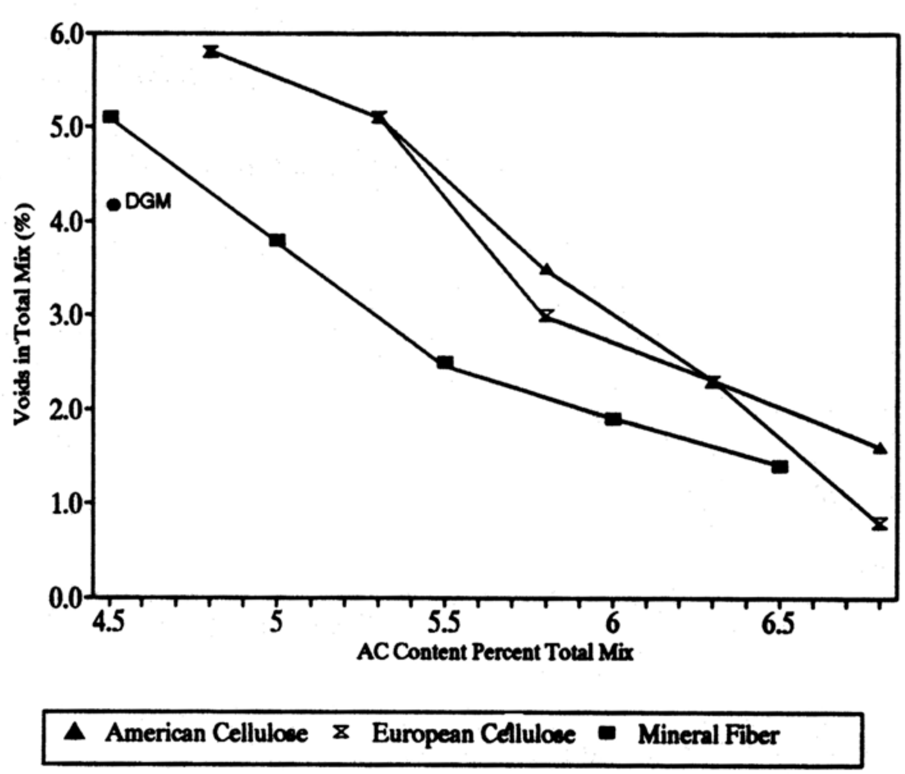

Figure 9a. VTM vs. AC Content for Granite Aggregate

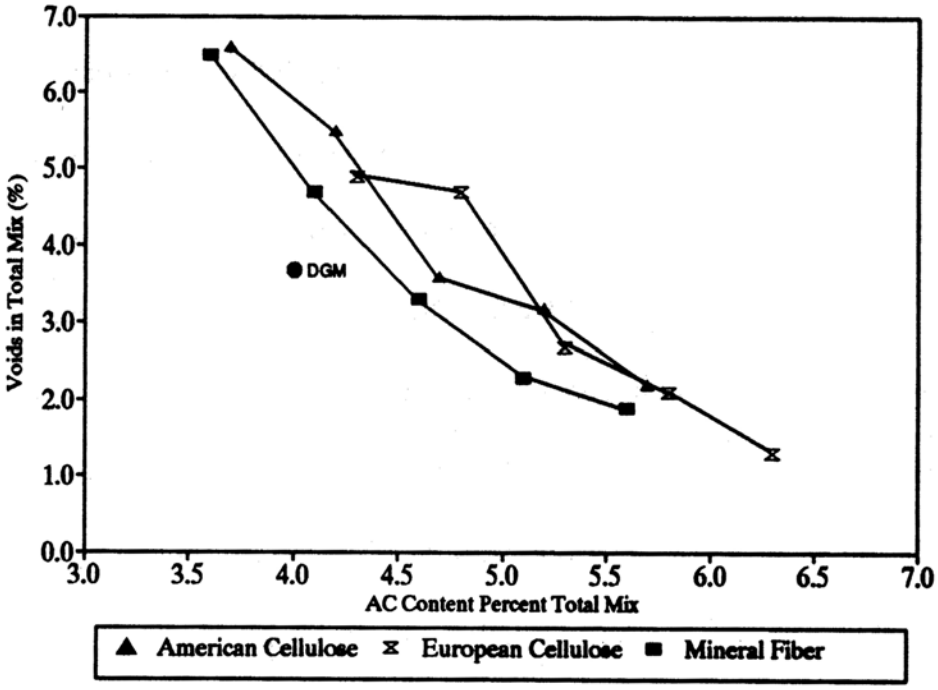

Figure 9b. VTM vs. AC Content for Gravel Aggregate

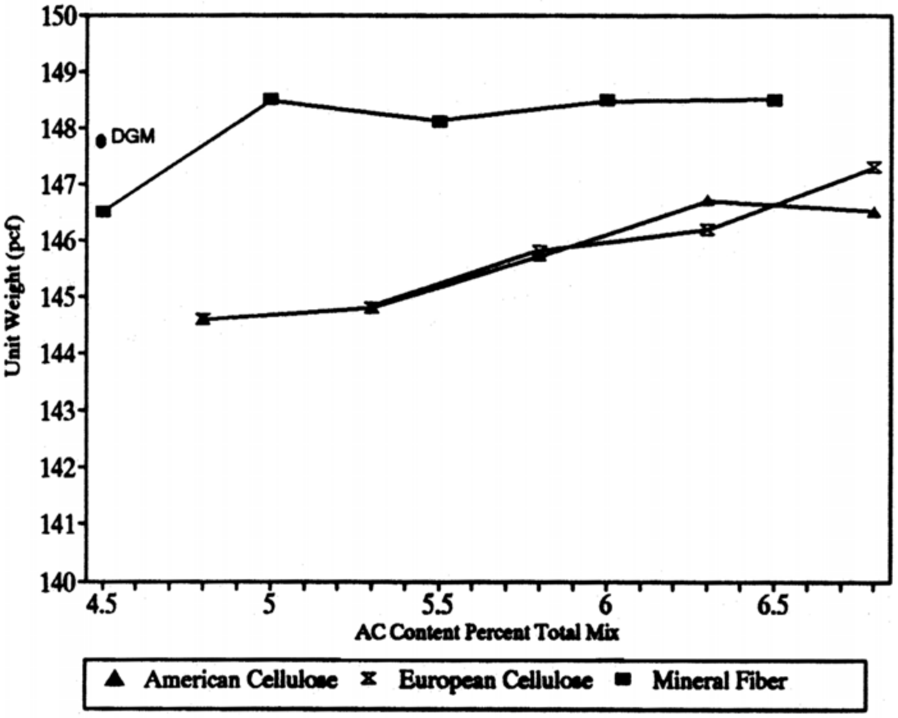

Figure 10a. Unit Weight vs. Percent AC for Granite Aggregate

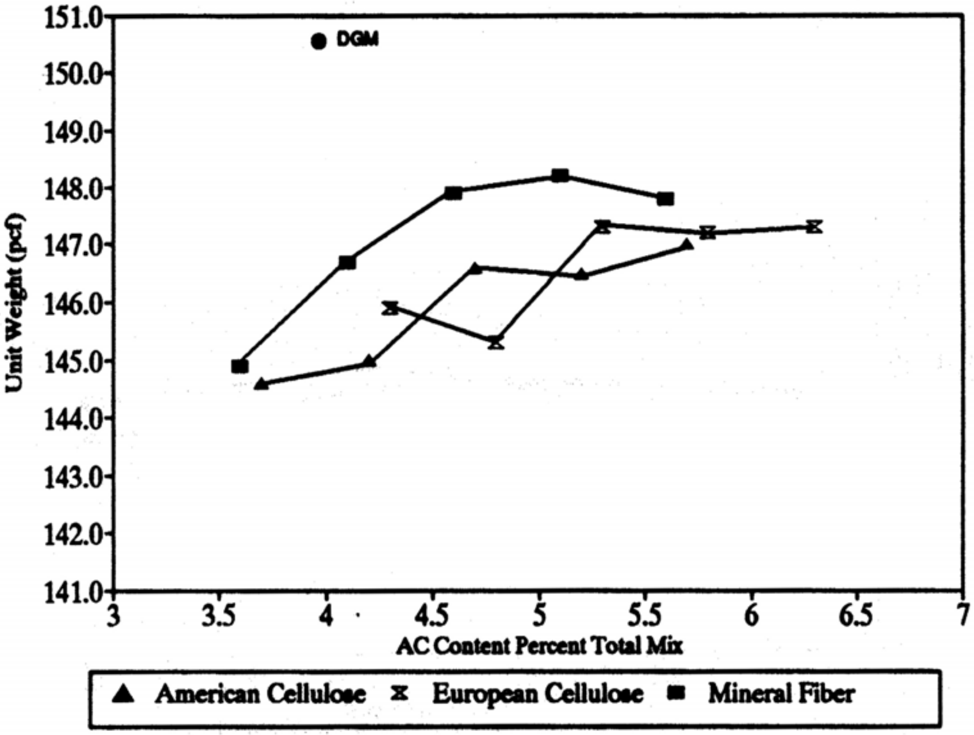

Figure 10b. Unit Weight vs. Percent AC for Gravel Aggregate

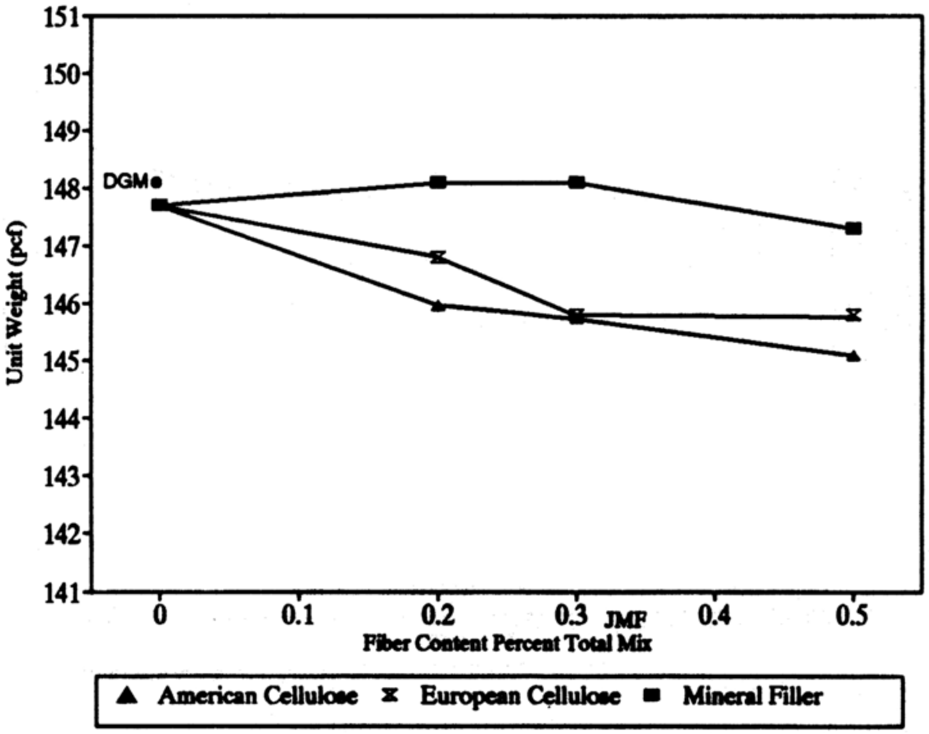

Figure 11a. Unit Weight vs. Fiber Content for Granite Aggregate

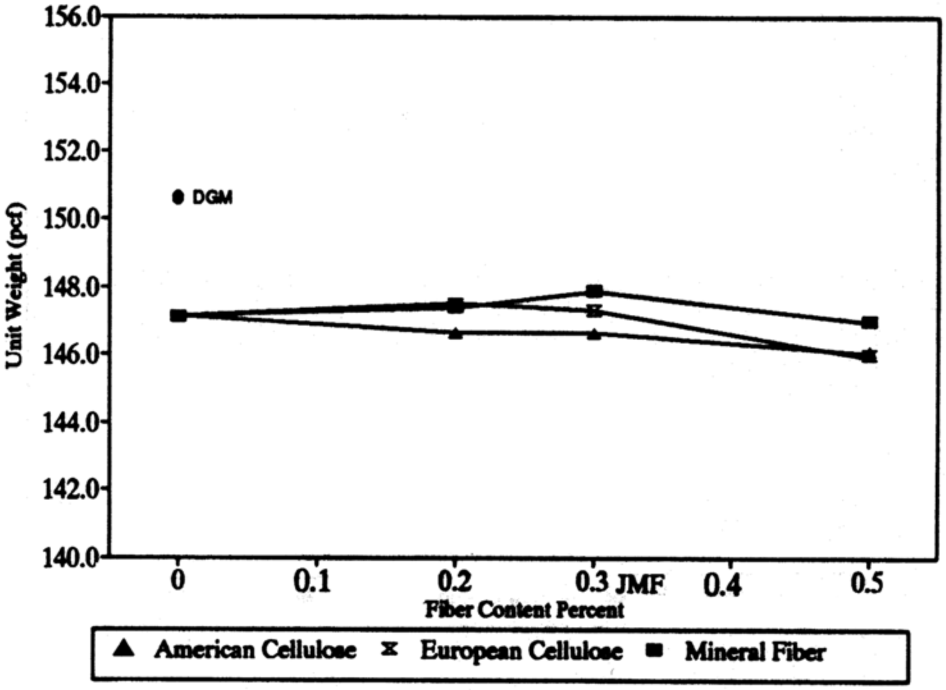

Figure 11b. Unit Weight vs. Fiber Content for Gravel Aggregate

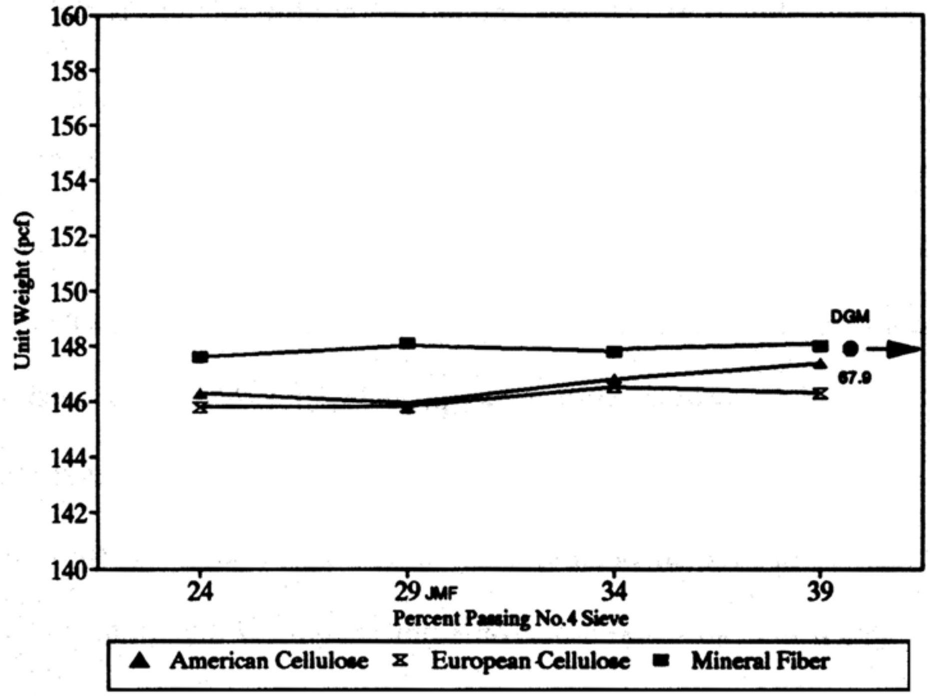

Figure 12a. Unit Weight vs. Percent Passing No. 4 Sieve for Granite Aggregate

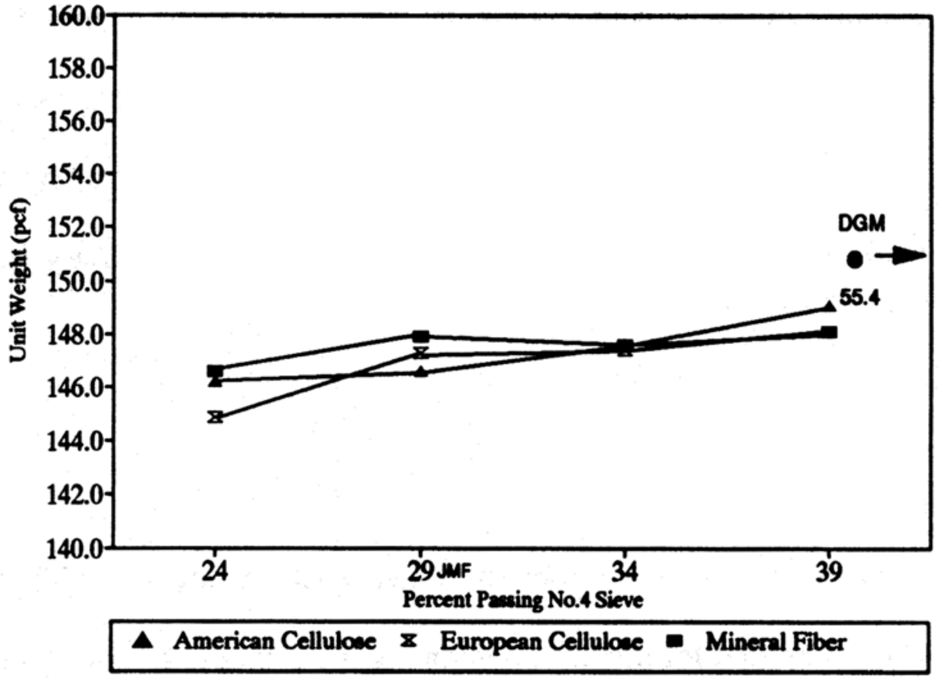

Figure 12b. Unit Weight vs. Percent Passing No. 4 Sieve for Gravel Aggregate

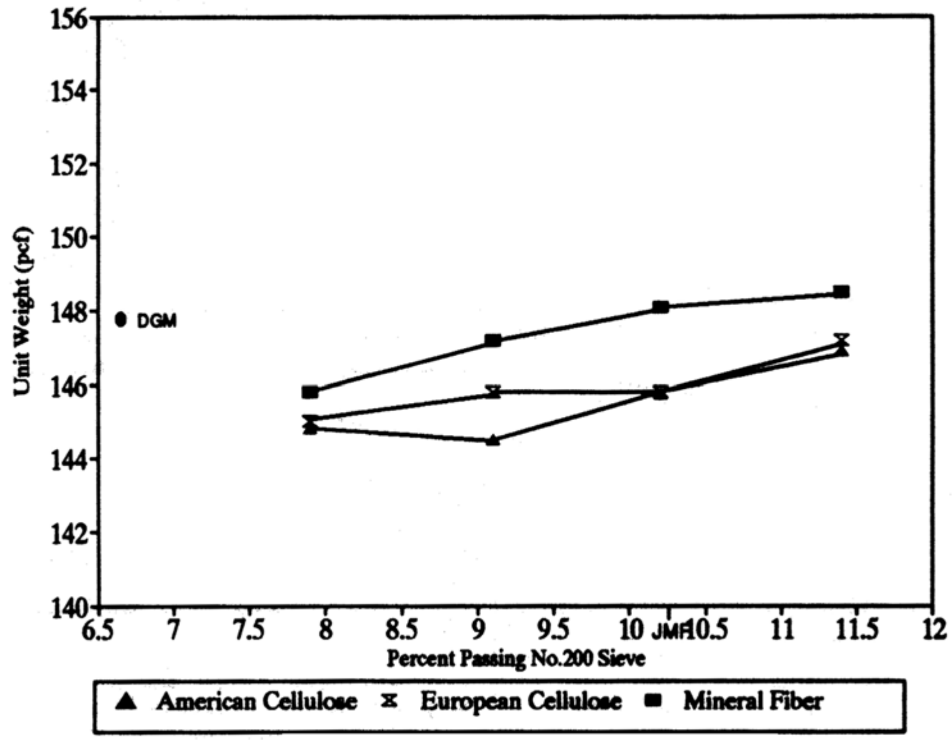

Figure 13a. Unit Weight vs. Percent Passing No. 200 Sieve for Granite Aggregate

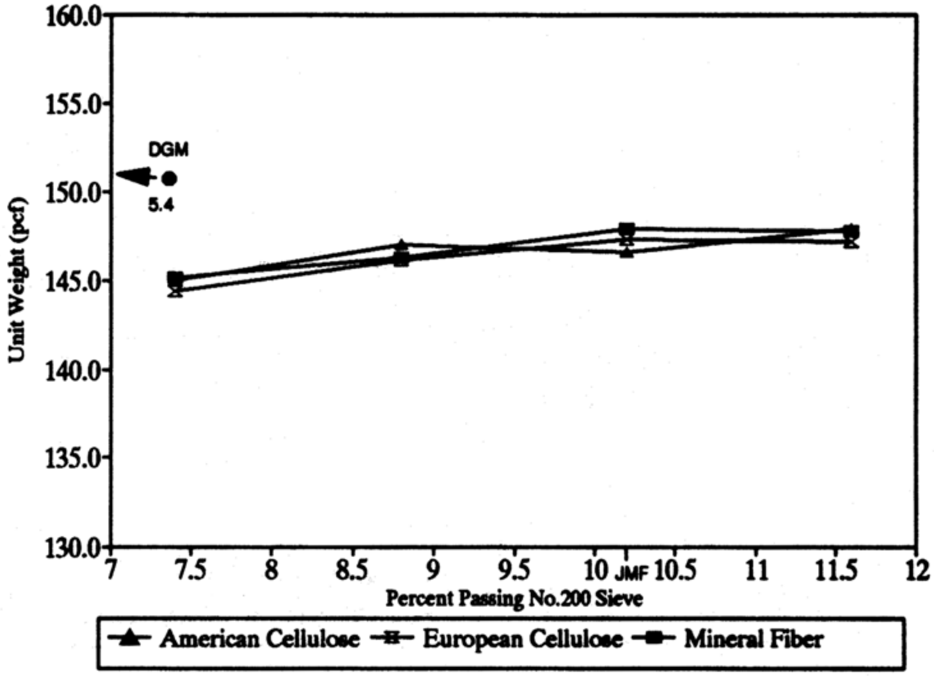

Figure 13b. Unit Weight vs. Percent Passing No. 200 Sieve for Gravel Aggregate

Voids in Mineral Aggregate (VMA)

Figures 14a and 14b illustrate the trend for VMA vs AC content. The VMA for the mineral fiber samples are lower than that for mixtures containing the cellulose fibers. An increase in VMA for an increase in asphalt content is caused by the asphalt cement pushing the aggregate apart. This can result in a loss in stability at higher asphalt contents. The gravel aggregate is being pushed apart (higher VMA) at higher asphalt contents but this is apparently not occurring in the granite aggregate (no change in VMA) for the asphalt contents evaluated. The probable reason for this difference in the two aggregates is the higher VMA in the granite mixture. Figures 15a and 15b show the trend for VMA vs fiber content. The VMA is usually higher at high fiber contents. The fibers tend to push the aggregate apart at higher fiber content. Hence, the amount of fibers must be limited to some reasonable amount to prevent mixture instability. For the mixtures evaluated the aggregate generally begins to be forced apart at a fiber content above 0.3 percent.

An increase in the percent passing the No. 200 sieve (Figures 16a and 16b) results in a decrease in VMA. Mixtures containing mineral fiber produced lower VMA than mixtures prepared with cellulose fibers. So one way to decrease the VMA would be to reduce the amount passing the No. 200 sieve but if reduced too much, the asphalt cement may not be stiffened sufficiently by the filler to prevent draindown during construction.

An increase in percent passing the No. 4 sieve generally resulted in a decrease in VMA for the gravel aggregate but little change for the granite (Figures 17a and 17b). At some point the amount of VMA begins to increase with a reduction in the amount of material passing the No. 4 sieve. This point appears to be around 29 percent for both aggregates investigated in this study (Figures 17a and 17b). The VMA begins to increase with a reduction in the percent passing the No. 4 sieve because stone-on-stone contact begins to occur. For these two aggregates the percent passing the No. 4 sieve would have to be slightly below 24 to get a VMA of 17 which is sometimes specified as the minimum VMA for SMA. Once stone-on-stone contact begins to occur (increasing VMA) a small change in gradation during construction will significantly change the VMA and thus the voids in the mix. Hence, for the SMA mixture it is very important that the gradation be closely controlled.

Gyratory Shear Index (GSI)

The Gyratory Shear Index (GSI) is a measure of the stability of an HMA mixture. The GSI has been shown to be related to permanent deformation in dense graded mixtures and is likely related to permanent deformation for SMA mixtures. Typically, mixtures with values close to 1.0 are more likely to be stable than mixtures with GSI values greater than 1.0 (13). The GSI values for all mixtures evaluated in this study were 1.1 or below so there is no indication of instability problems (Tables 7-12).

Gyratory Elasto-Plastic Index (Gepi)

The GEPI is a measure of permanent deformation potential for dense graded mixtures. However, no criteria has been developed to predict the rutting potential for dense graded nor SMA mixes. Data has shown that higher GEPI values are an indication of lower mixture stability as shown in Tables 7-12. There is no general trend between GEPI and mixture proportions for the mixtures evaluated.

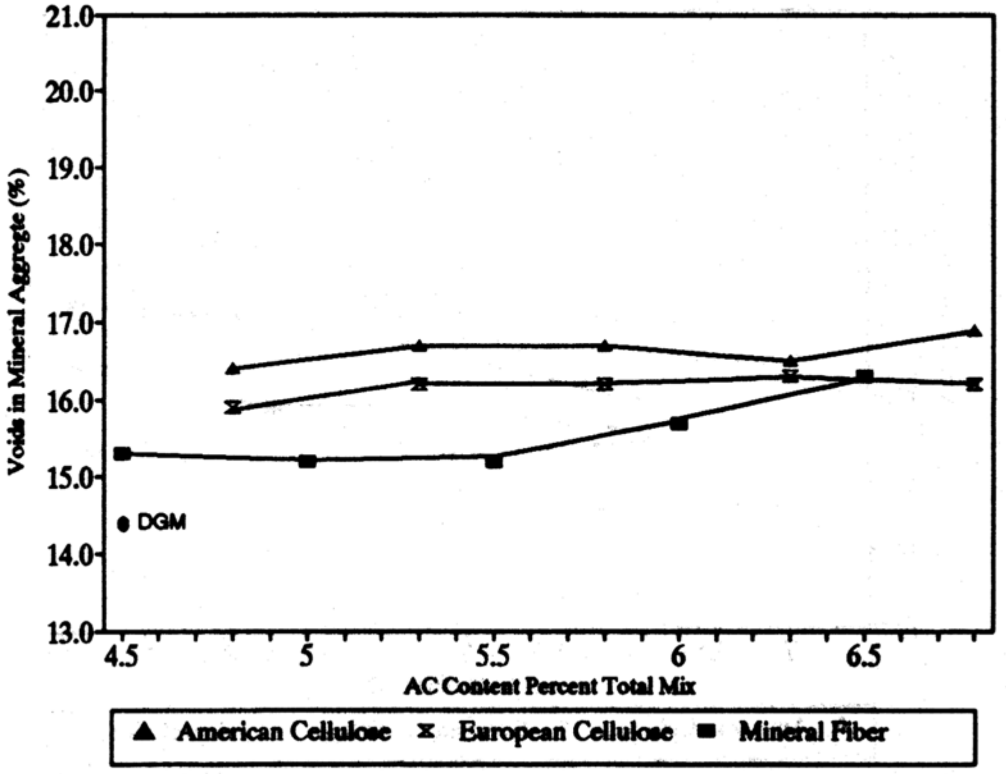

Figure 14a. VMA vs. AC Content for Granite Aggregate

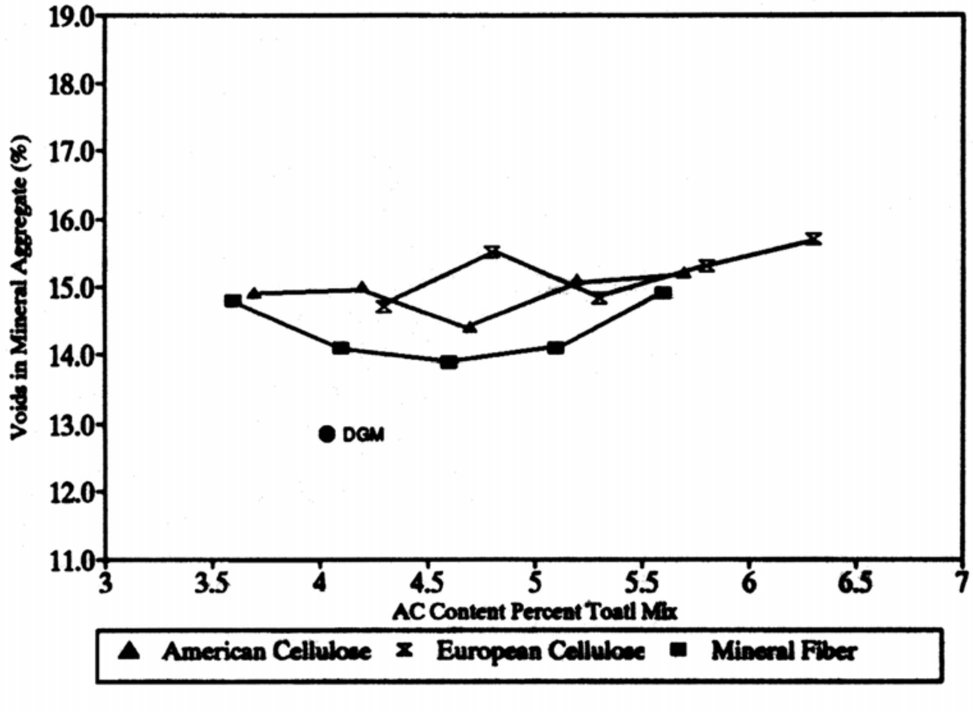

Figure 14b. VMA vs. AC Content for Gravel Aggregate

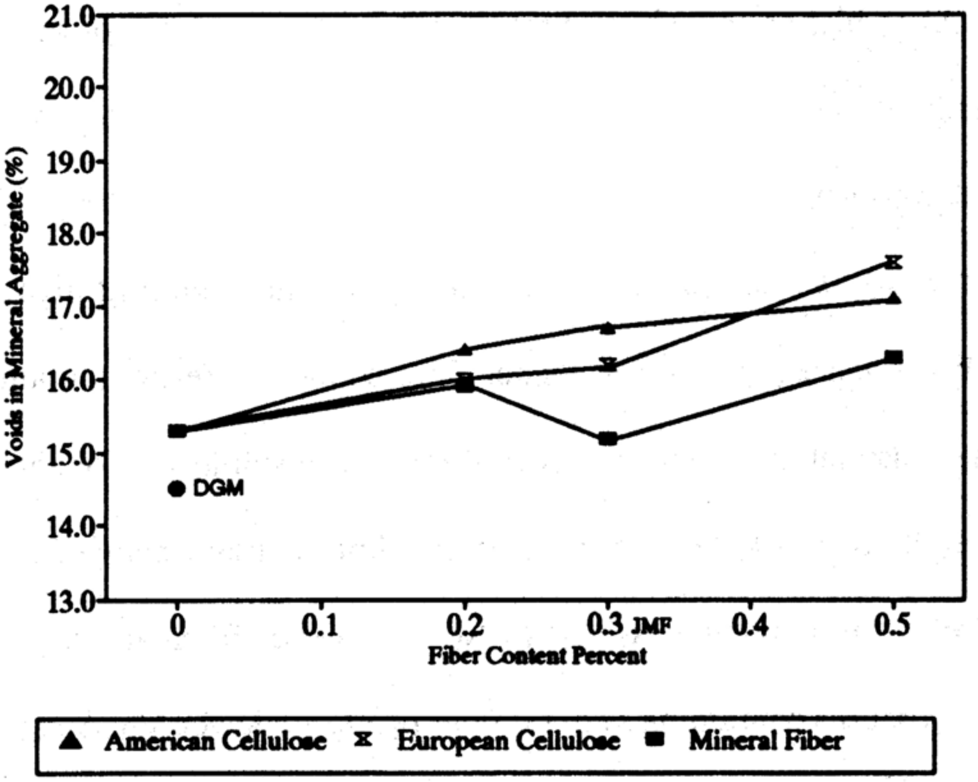

Figure 15a. VMA vs. Fiber Content for Granite Aggregate

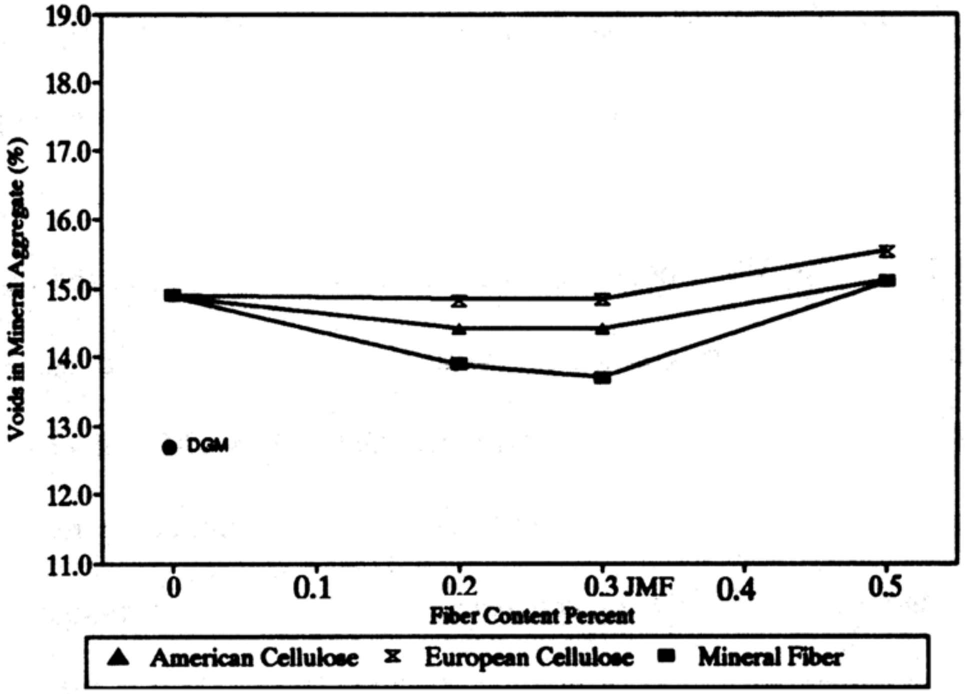

Figure 15b. VMA vs. Fiber Content for Gravel Aggregate

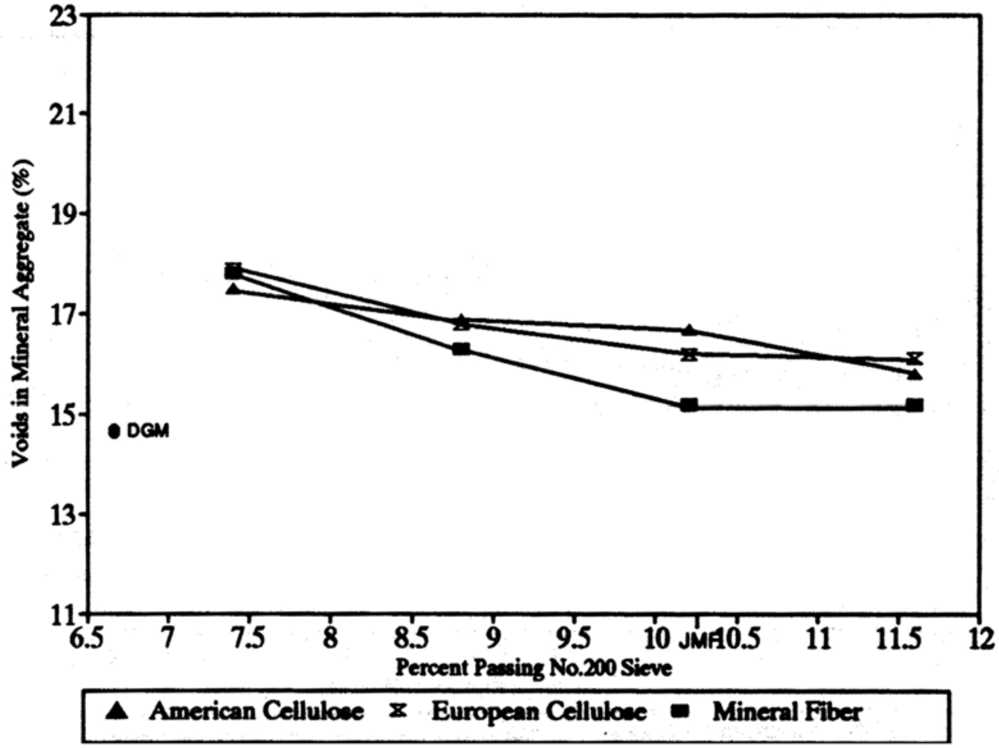

Figure 16a. VMA vs. Percent Passing No. 200 Sieve for Granite Aggregate

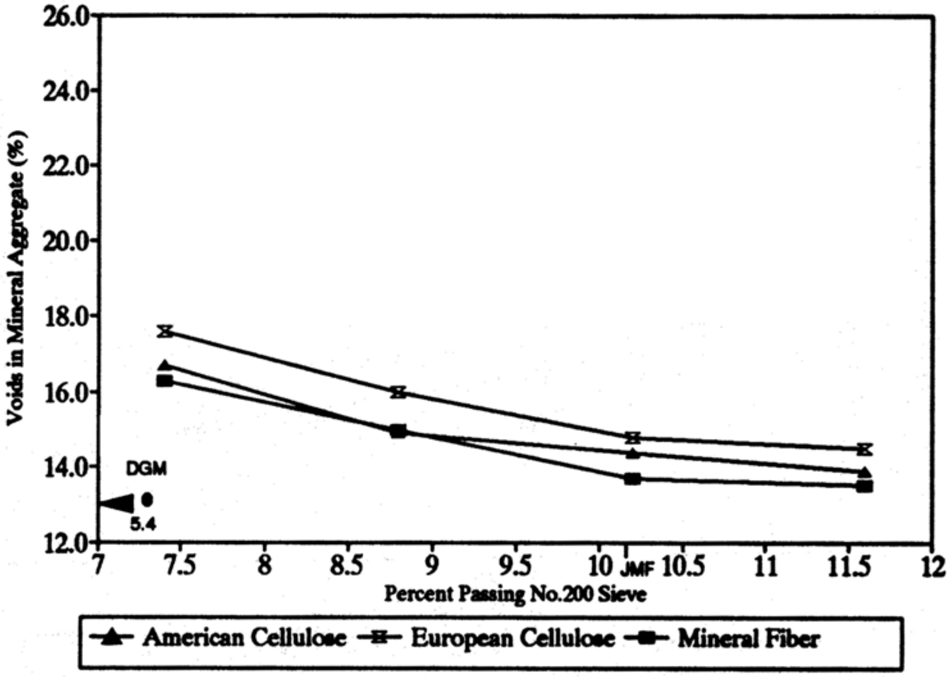

Figure 16b. VMA vs. Percent Passing No. 200 Sieve for Gravel Aggregate

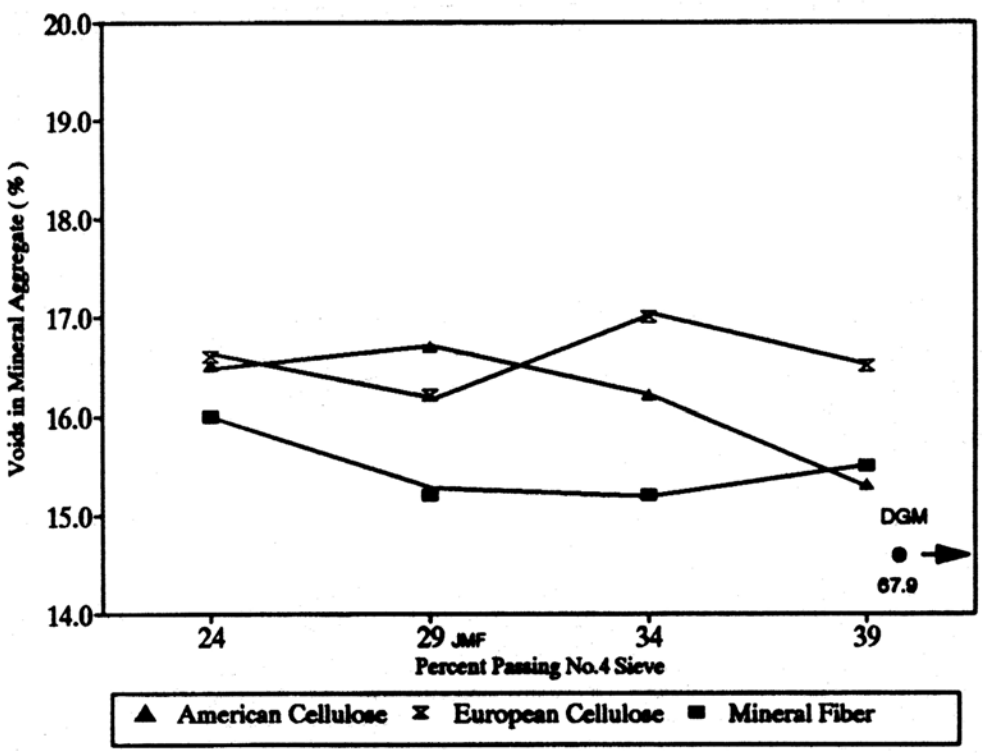

Figure 17a. VMA vs. Percent Passing No. 4 Sieve for Granite Aggregate

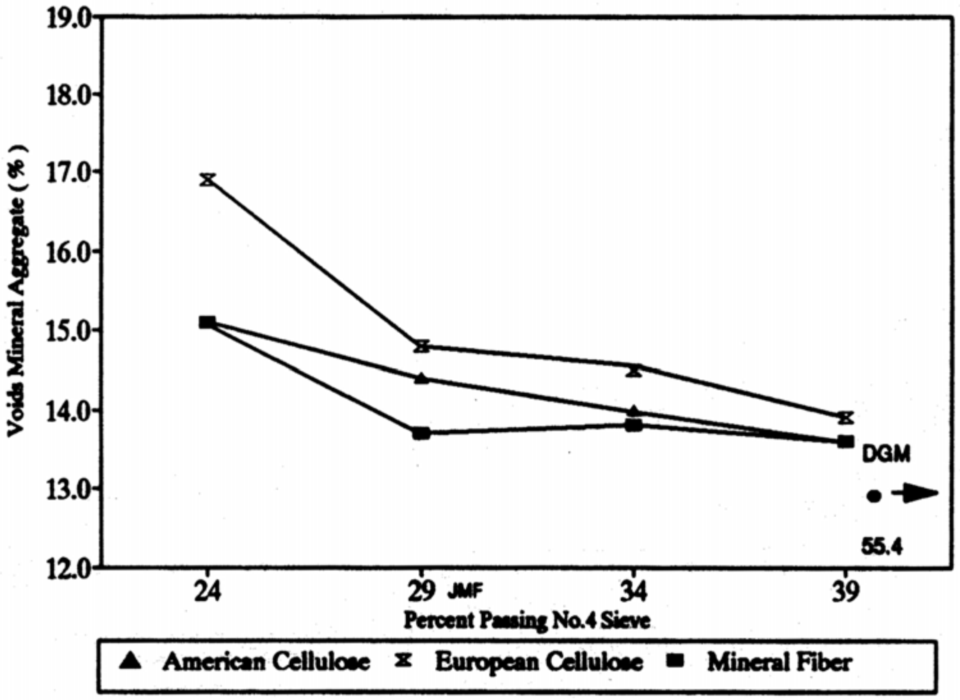

Figure 17b. VMA vs. Percent Passing No. 4 Sieve for Gravel Aggregate

Gyratory Shear Stress

The Gyratory shear stress required to produce one degree angle is one important GTM property for evaluating the permanent deformation resistance. Previous work has indicated a relationship between rutting and shear stress to produce one degree angle for HMA (*8*). Higher shear stresses required to produce a one degree angle indicate a more stable mixture. Figures 18a and 18b show the trend for gyratory shear with changes in AC content. Higher AC contents slightly reduce the shear strength of the mix for both aggregates. This drop is to be expected but the only slight decrease indicates the high tolerance to changes in AC content for SMA mixtures.

Figures 19a and 19b show the results for gyratory shear versus fiber content. An increase in fiber content appears to lower the shear strength for granite mixtures and has very little effect for gravel mixtures. Again the changes in shear stress are not sufficient to be of major concern. Hence the amount of fiber over the range investigated does not significantly affect shear strength of the SMA mixture.

Figures 20a and 20b show the results for gyratory shear versus percent passing the No. 4 sieve. The percent passing the No. 4 sieve appears to have little effect on the shear strength but a previous study (*8*) has shown that the SMA mixture becomes more sensitive to changes in the AC content at higher amounts passing the No. 4 sieve.

Figures 21a and 21b show the effect of percent passing the No. 200 sieve on shear strength. An increase in percent passing the No. 200 sieve for granite mixtures decreases the gyratory shear slightly while for gravel mixtures this increase in percent passing the No. 200 sieve increases the gyratory shear slightly. The reason for this difference in performance for the two aggregates is not clear.

Marshall Stability

The Marshall stability test, though extensively used to measure the stability of HMA, does not have a good correlation with the actual performance of HMA. However, it does help in evaluating the consistency and hence quality of dense graded mixtures (*13*). Figures 22a and 22b indicate that asphalt content has very little effect on the Marshall stability of SMA mixtures. The Marshall stability for SMA mixtures is significantly lower than that for dense graded mixtures. This is not an indication that dense graded mixtures are more stable than SMA mixtures but is an indication that Marshall stability may not be applicable for SMA. The quality of SMA mixtures is better controlled by the volumetric properties than by Marshall stability.

The relationship between fiber content and Marshall stability is shown in Figures 23a and 23b. These figures show that the Marshall stability for SMA mixtures is insensitive to fiber content. Figures 24a and 24b show the effect of percent passing the No. 4 sieve on Marshall stability. The trend indicates that the Marshall stability for the SMA mixtures increases with increasing percent passing the No. 4 sieve.

Figures 25a and 25b show the effect of percent passing the No. 200 sieve on Marshall stability. As expected, an increase in percent passing the No. 200 sieve generally slightly increases the stability of SMA mixtures.

In summary, the Marshall stability is not very sensitive to changes in SMA mixture components. The Marshall stability value was always lower for SMA than for the control dense graded mixtures. The Marshall stability is not a good prediction of performance for SMA just as it is not with dense graded mixtures but very low stabilities may still be an indication of mixture problems as it is with dense graded mixtures.

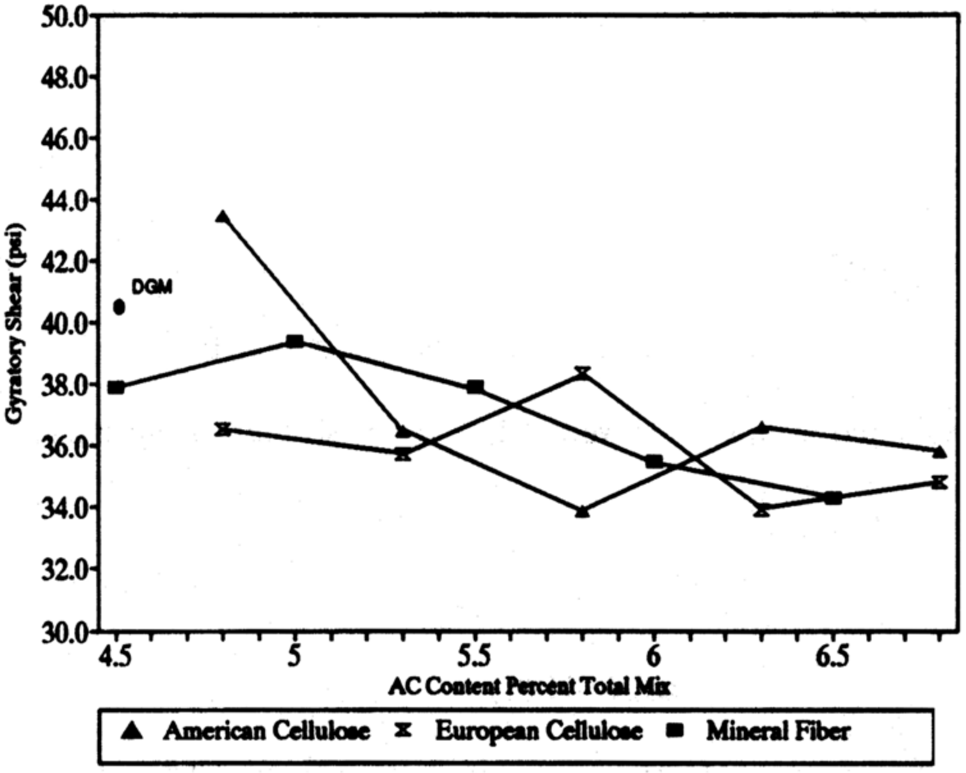

Figure 18a. Gyratory Shear vs. AC Content for Granite Mixtures

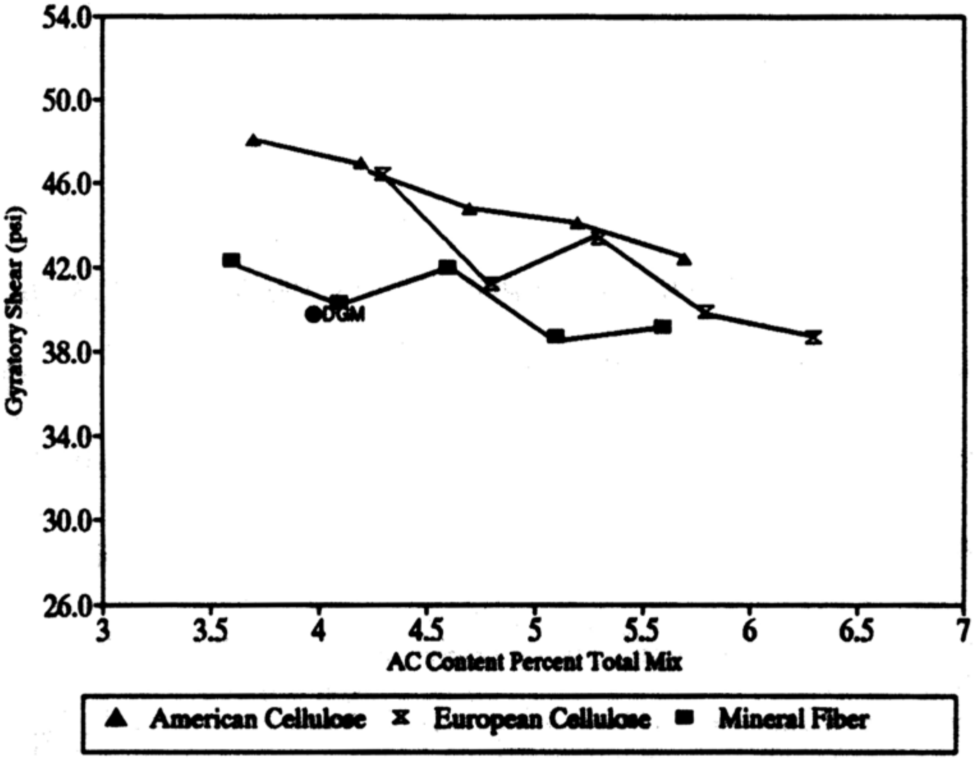

Figure 18b. Gyratory Shear vs. AC Content for Gravel Mixtures

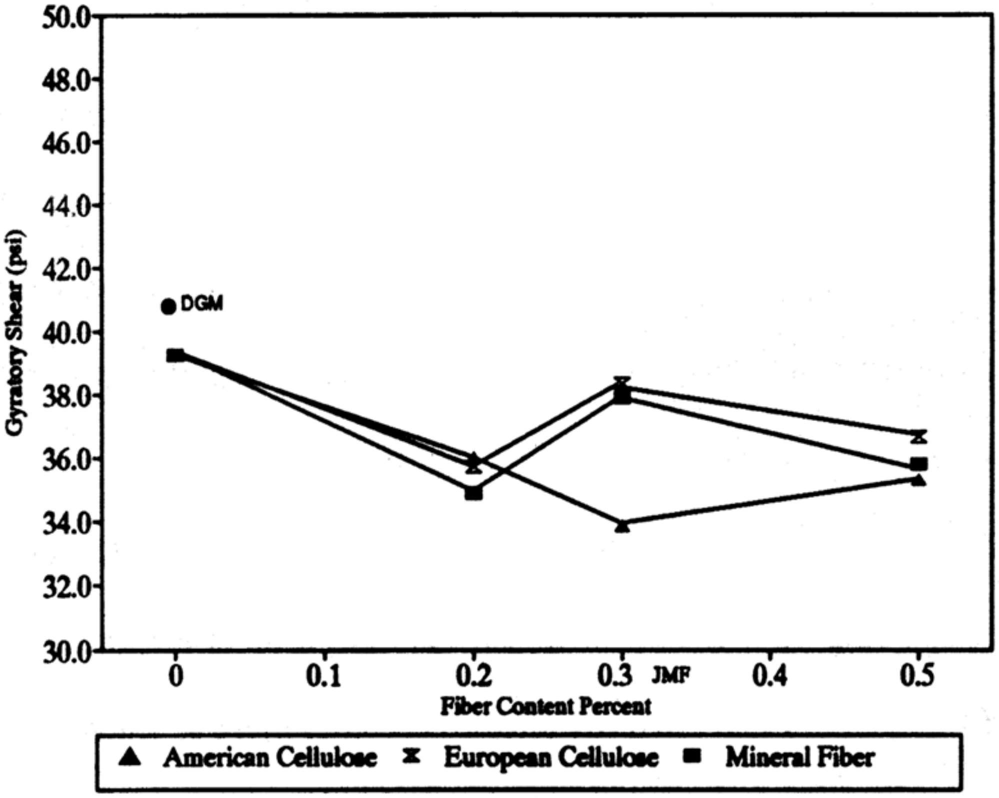

Figure 19a. Gryatory Shear vs. Fiber Content for Granite Mixtures

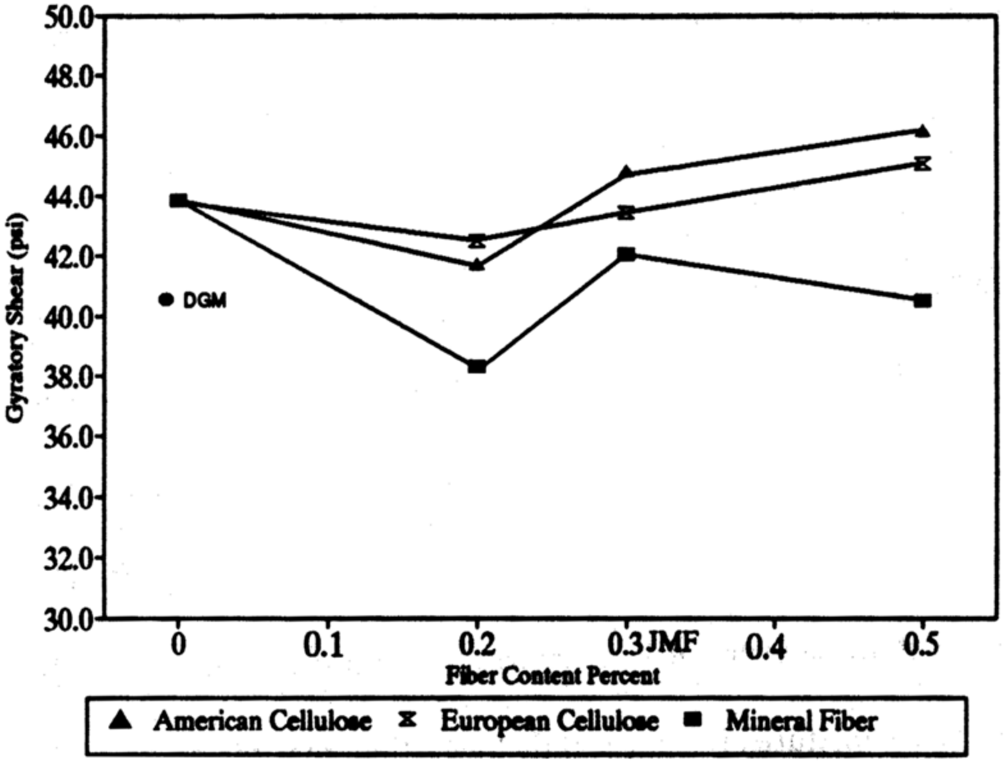

Figure 19b. Gryatory Shear vs. Fiber Content for Gravel Mixtures

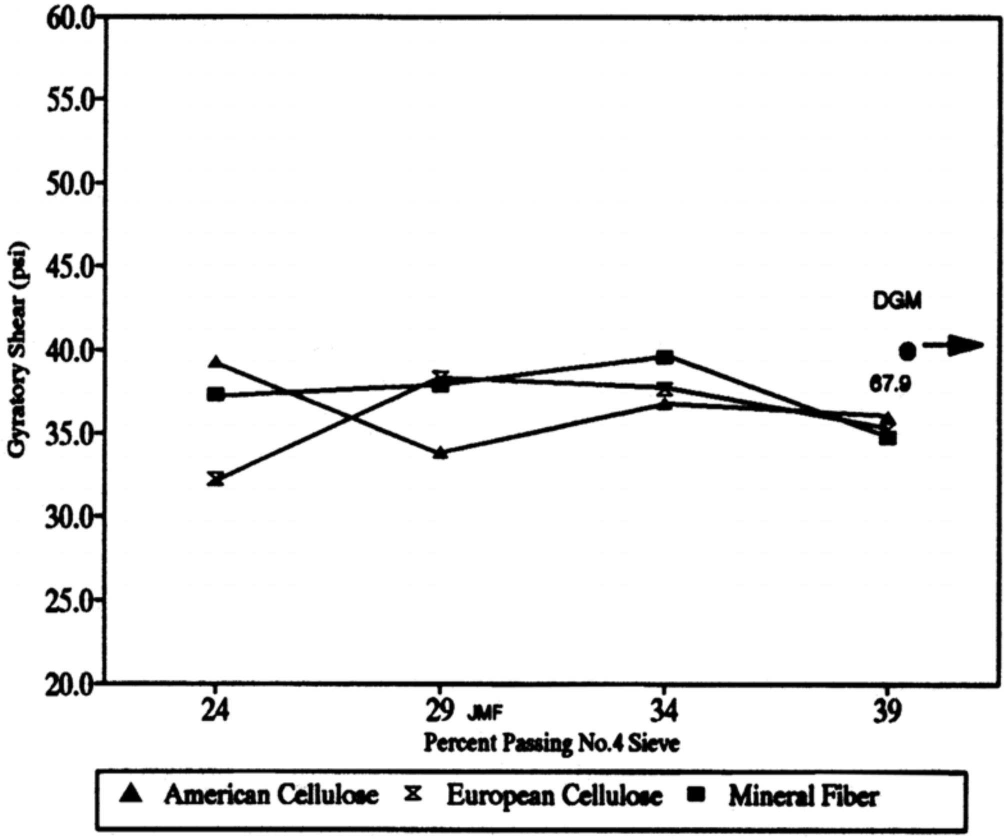

Figure 20a. Shear Stress vs. Percent Passing No. 4 Sieve for Granite Mixtures

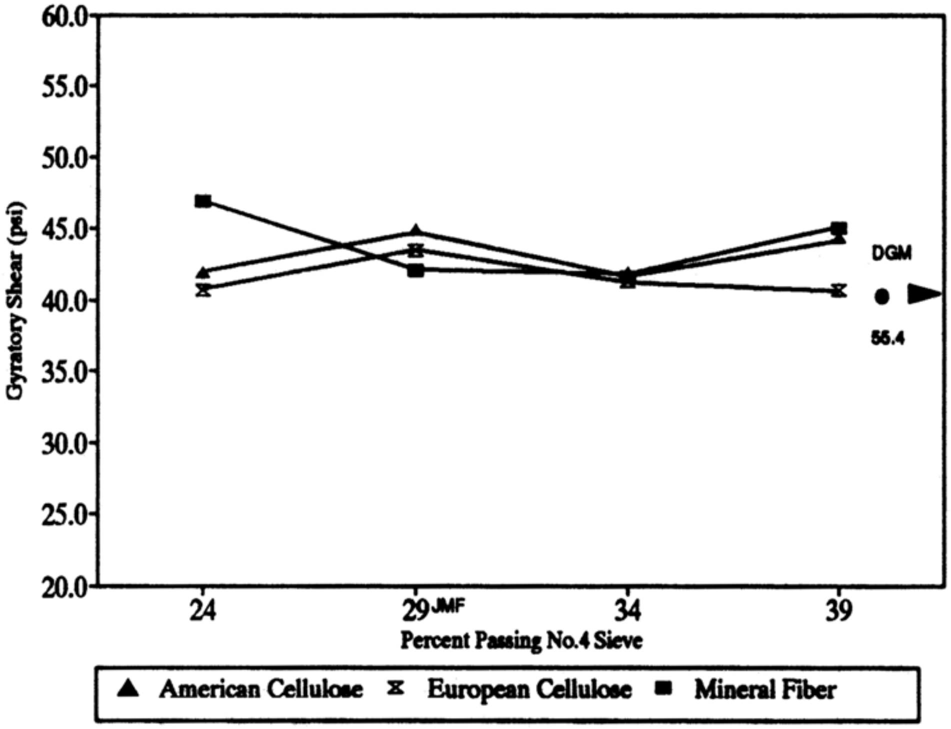

Figure 20b. Shear Stress vs. Percent Passing No. 4 Sieve for Gravel Mixtures

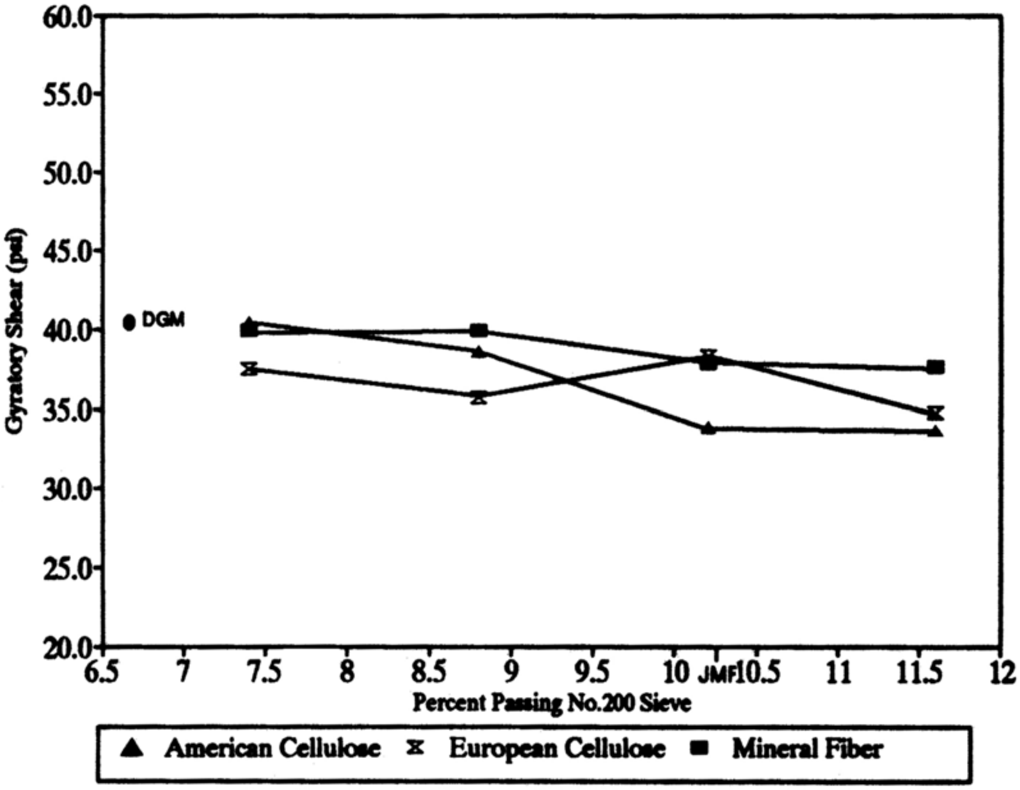

Figure 21a. Shear Stress vs. Percent Passing No. 200 Sieve for Granite Mixtures

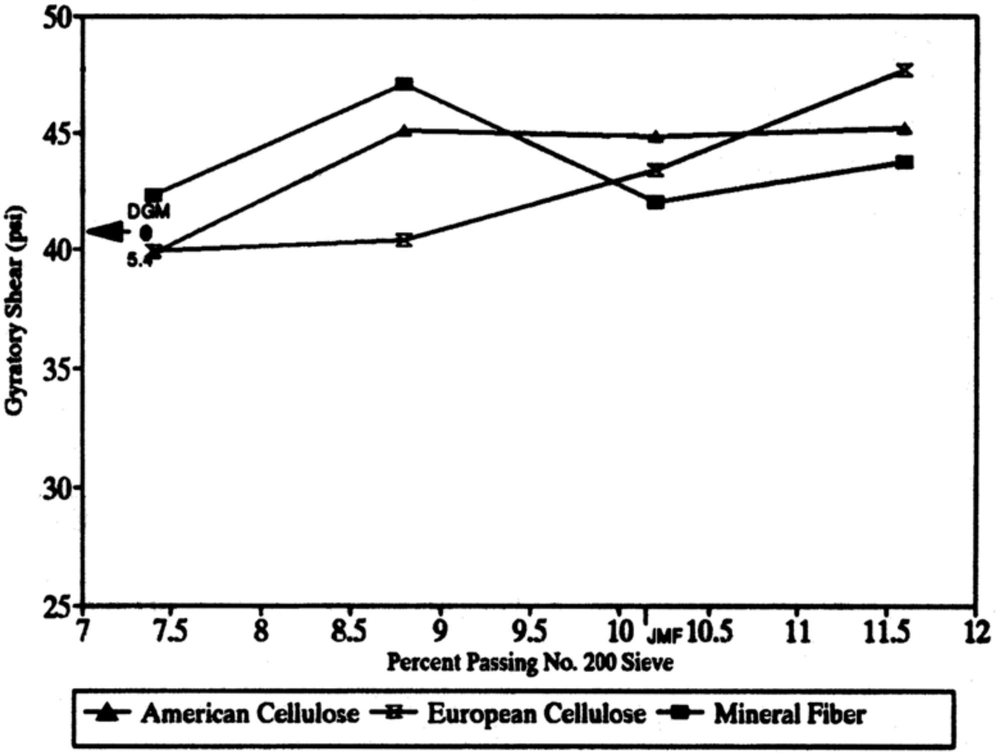

Figure 21b. Shear Stress vs. Percent Passing No. 200 Sieve for Gravel Mixtures

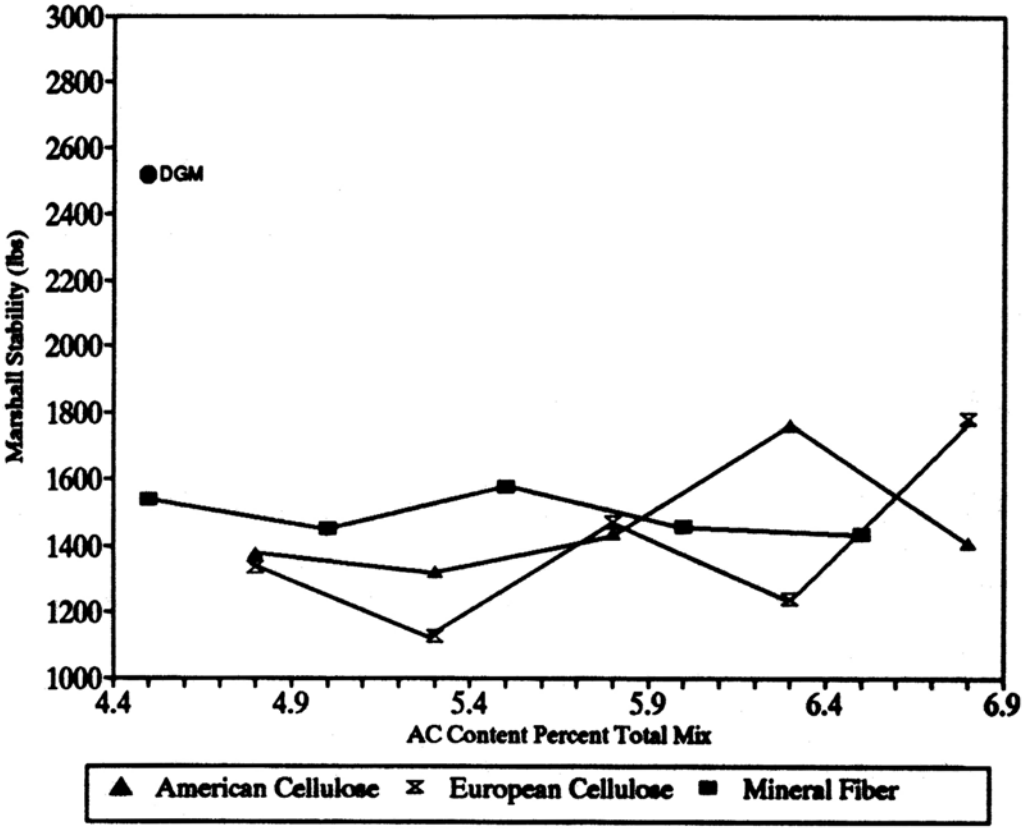

Figure 22a. Stability vs. AC Content for Granite Mixtures

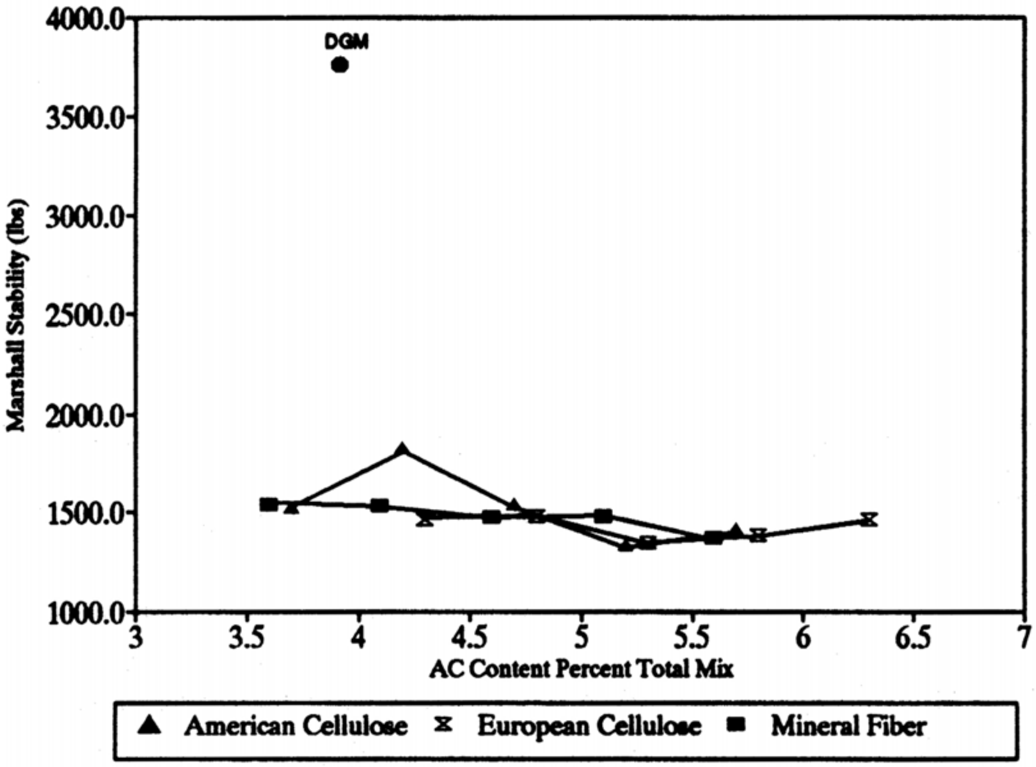

Figure 22b. Stability vs. AC Content for Gravel Mixtures

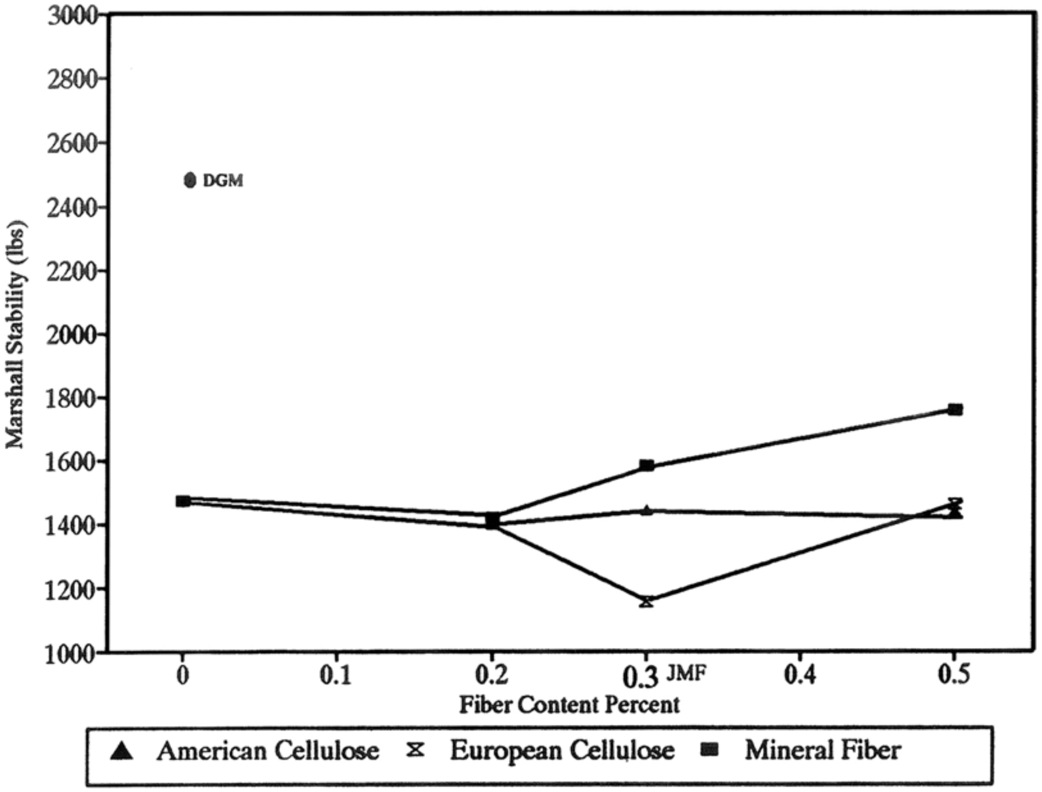

Figure 23a. Stability vs. Fiber Content for Granite Mixtures

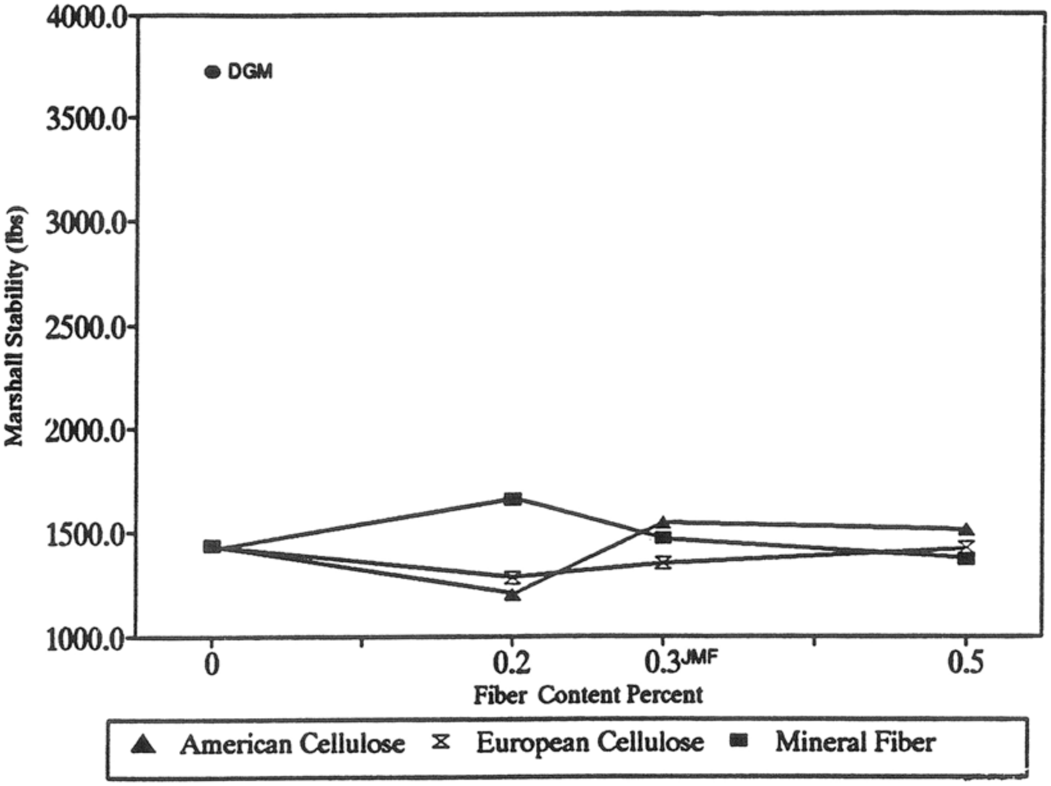

Figure 23b. Stability vs. Fiber Content for Gravel Mixtures

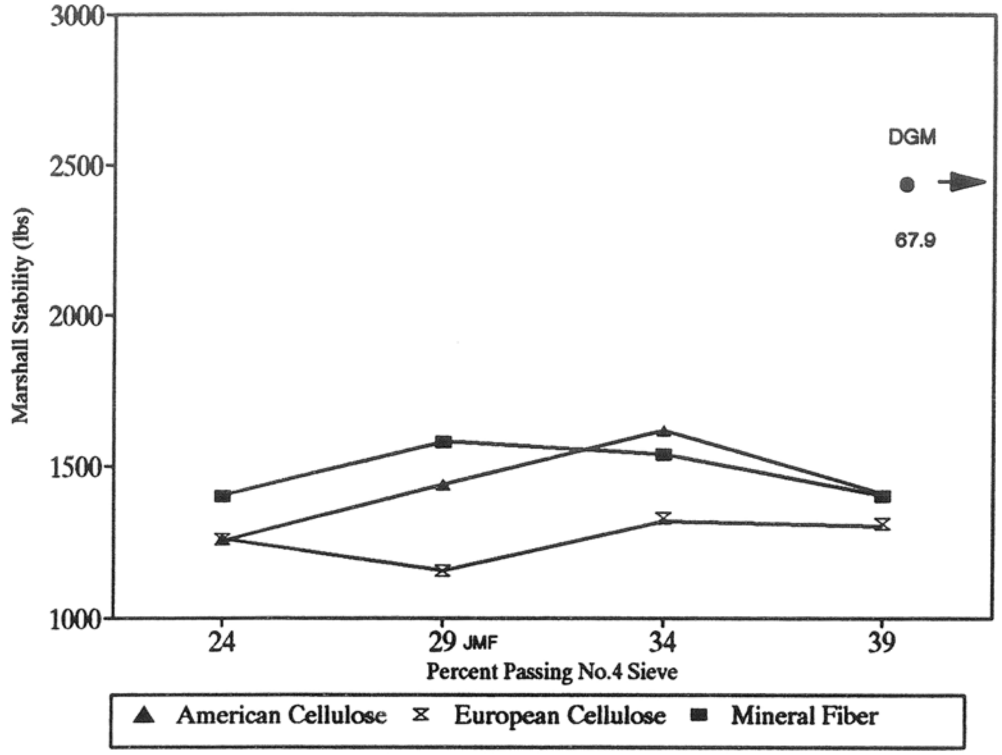

Figure 24a. Stability vs. Percent Passing the No. 4 Sieve for Granite Mixtures

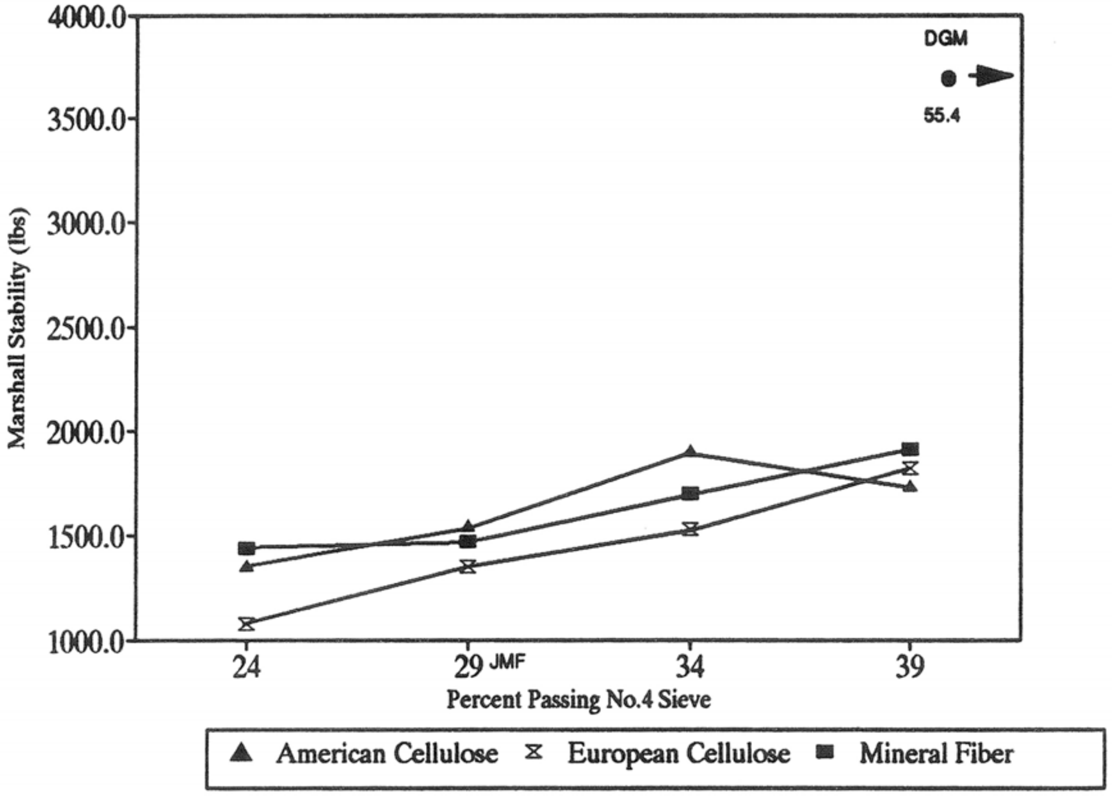

Figure 24b. Stability vs. Percent Passing the No. 4 Sieve for Gravel Mixtures

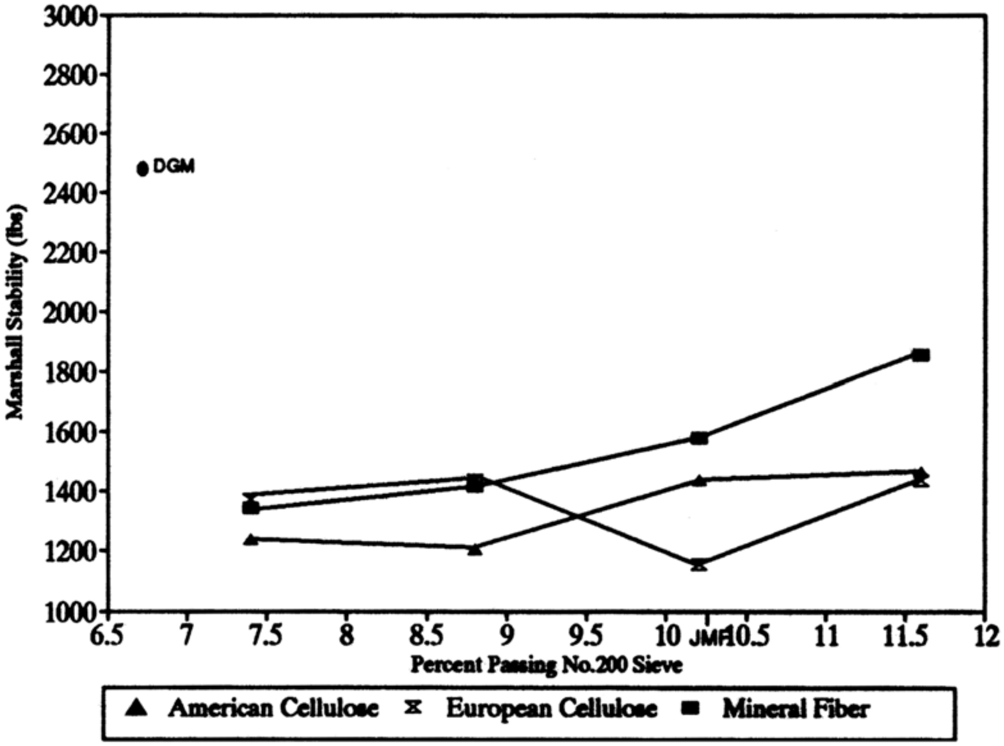

Figure 25a. Stability vs. Percent Passing the No. 200 Sieve for Granite Mixtures

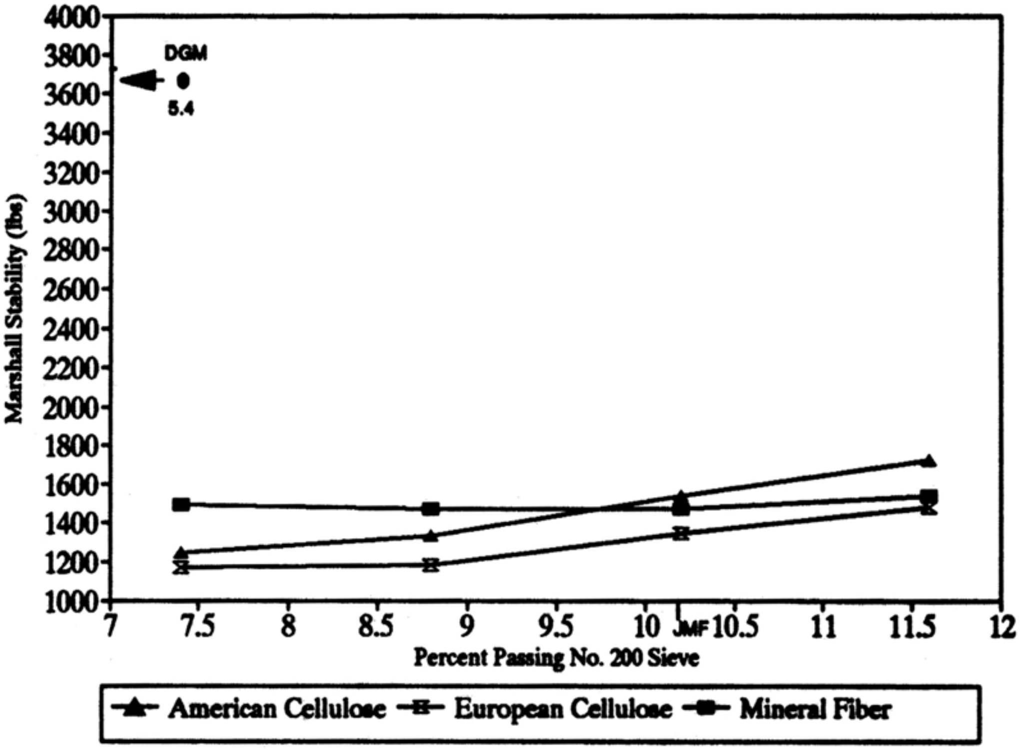

Figure 25b. Stability vs. Percent Passing the No. 200 Sieve for Gravel Mixtures

Flow

The flow value is a general indication of potential for permanent deformation in dense graded mixtures. A high flow value (greater than 16) usually is considered as an indication that the mixture may be unstable under traffic. Figures 26a and 26b show that asphalt content has very little effect on flow for SMA. This again shows that SMA mixture properties are not highly sensitive to changes in asphalt content. The flow of SMA mixtures is always higher than that for dense graded mixtures which may be an indication that the SMA mixtures are more flexible.

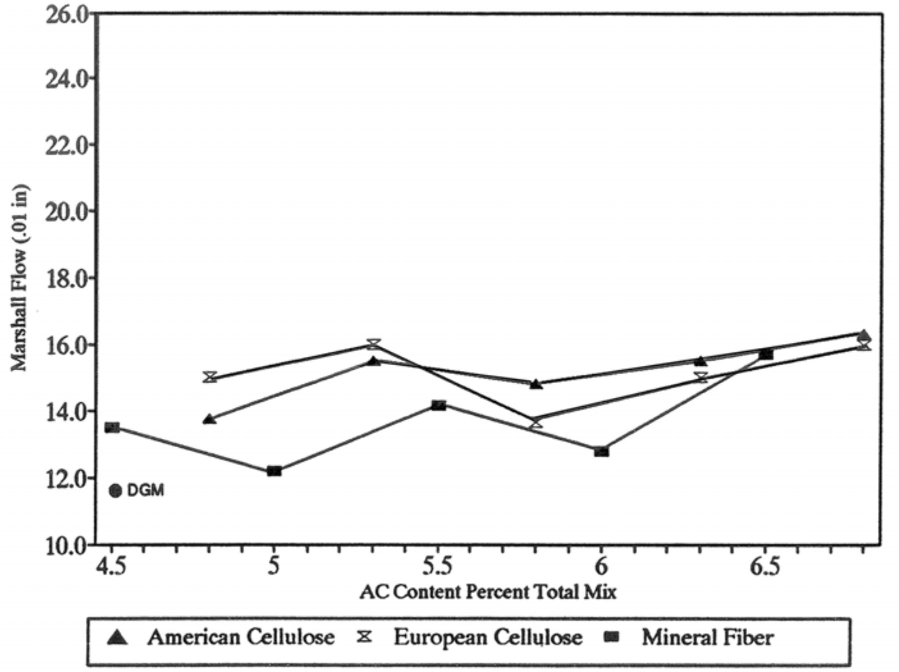

Figure 26a. Flow vs. AC Content for Granite Mixtures

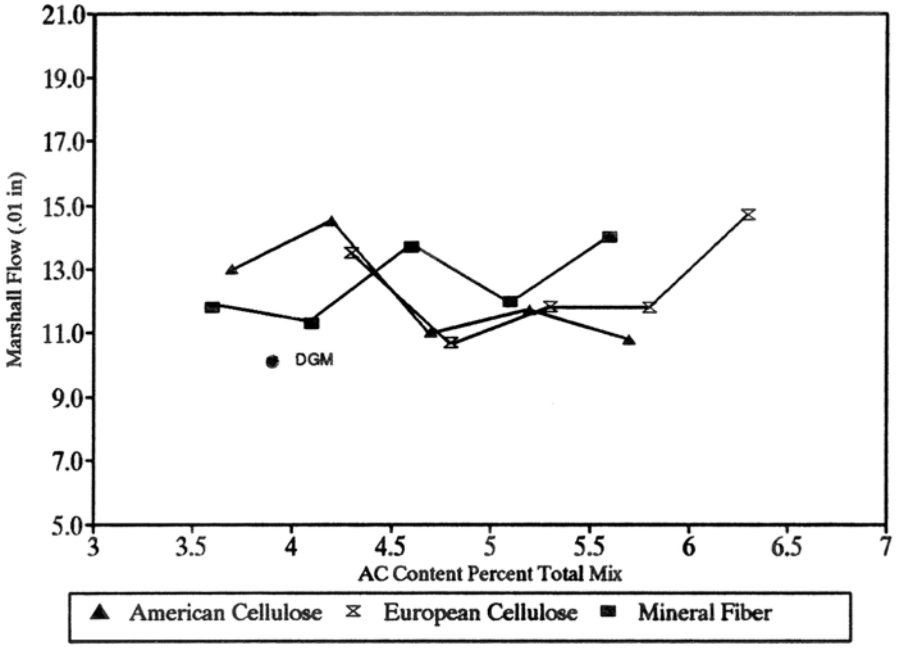

Figure 26b. Flow vs. AC Content for Gravel Mixtures

Figures 27a and 27b show the effect of fiber content on flow. The flow appears to decrease slightly at higher fiber content; however, there is a lot of scatter in the data resulting in no obvious trend being identified.

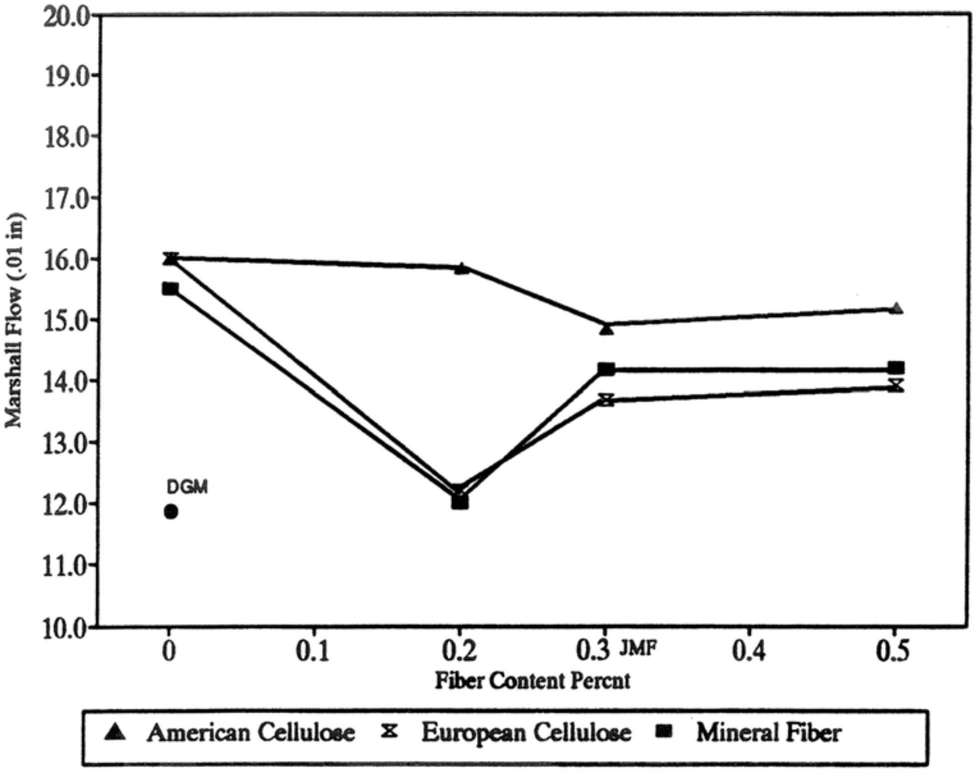

Figure 27a. Flow vs. Fiber Content for Granite Mixtures

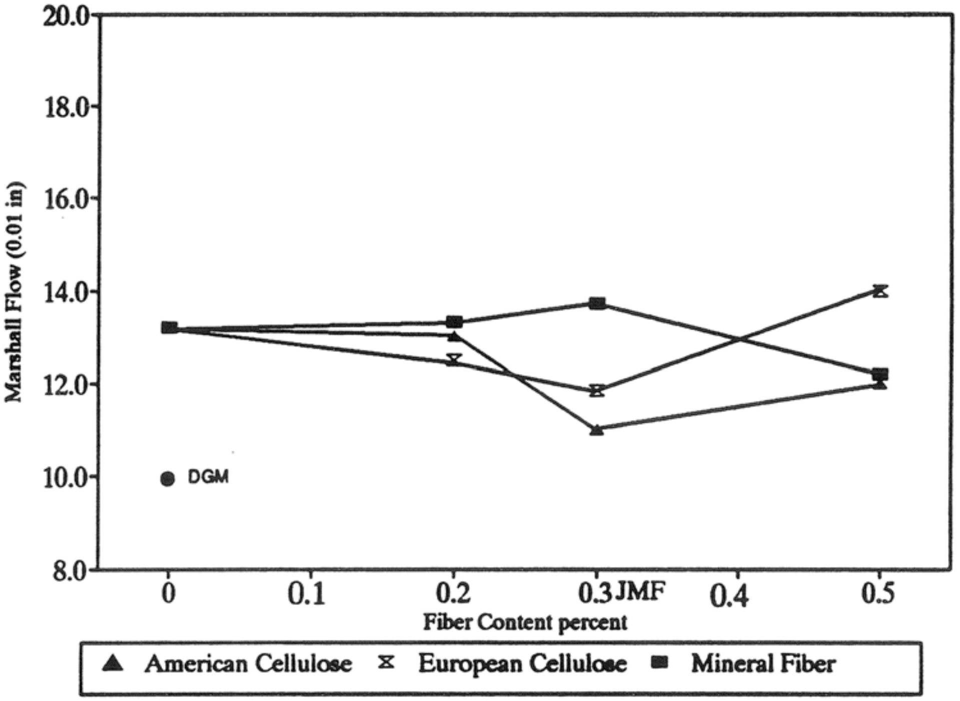

Figure 27b. Flow vs. Fiber Content for Gravel Mixtures

Figures 28a and 28b show the effect of percent passing the No. 4 sieve on flow. The trend indicates a reduction in flow for higher percents passing the No. 4 sieve. In all cases, the flow for the SMA mixtures is higher than that for the dense graded mixtures. The flow approaches that for dense graded mixtures as the percent passing the No. 4 sieve increases.

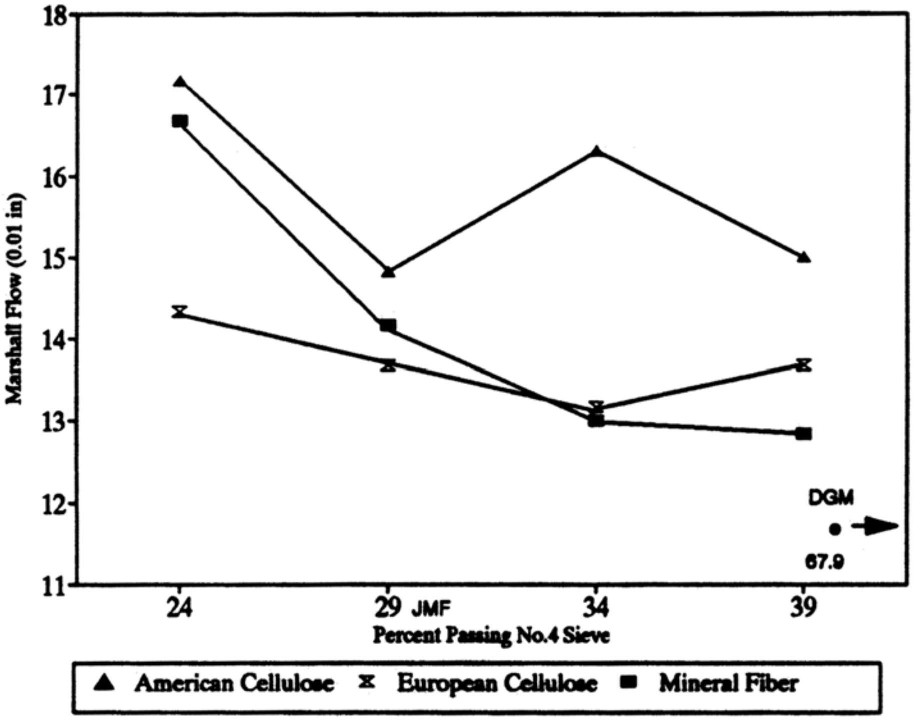

Figure 28a. Flow vs. Percent Passing the No. 4 Sieve for Granite Mixtures

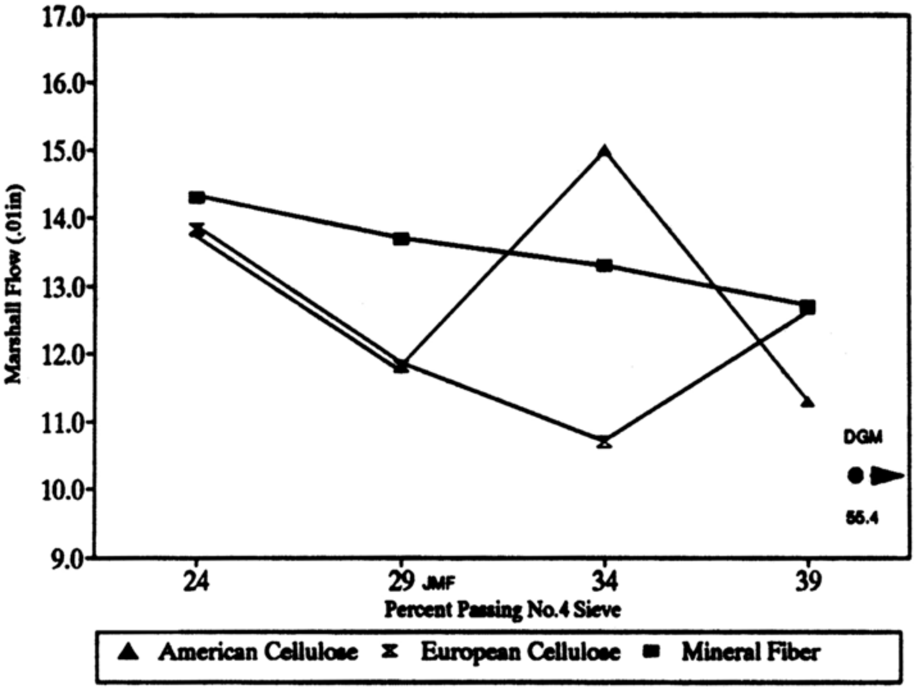

Figure 28b. Flow vs. Percent Passing the No. 4 Sieve for Gravel Mixtures

Figures 29a and 29b show the effect of percent passing the No. 200 sieve on flow. For the granite mixtures, the flow appears to increase to a point and then decrease with increasing amount of percent passing the No. 200 sieve. The trend for the gravel SMA mixtures was downward for increasing amounts of material passing the No. 200 sieve. As expected, an increase in percentage passing the No. 200 sieve tends to stiffen the binder generally resulting in a lower measured flow.

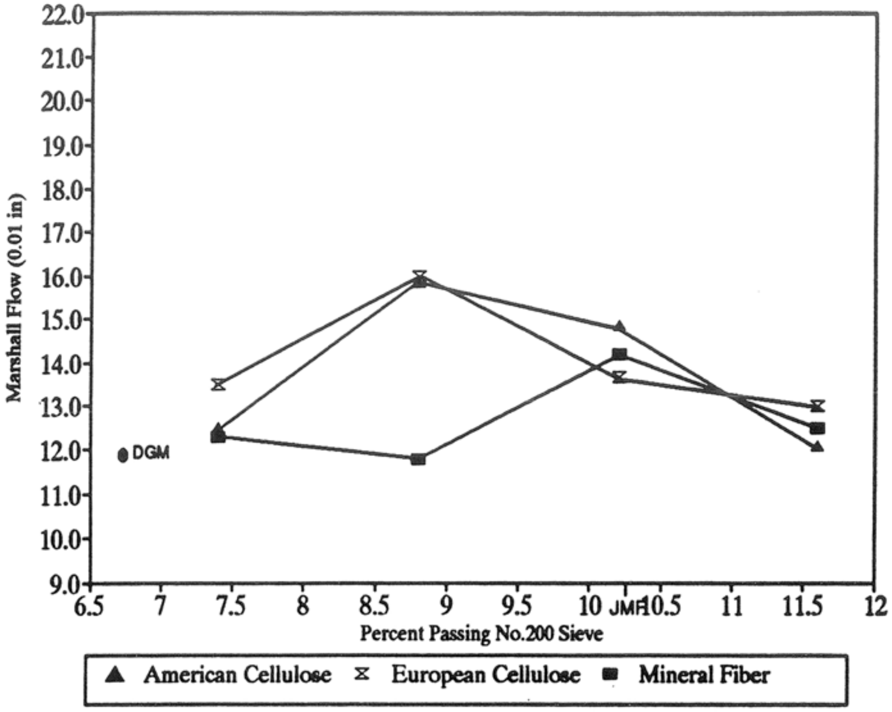

Figure 29a. Flow vs. Percent Passing the No. 200 Sieve for Granite Mixtures

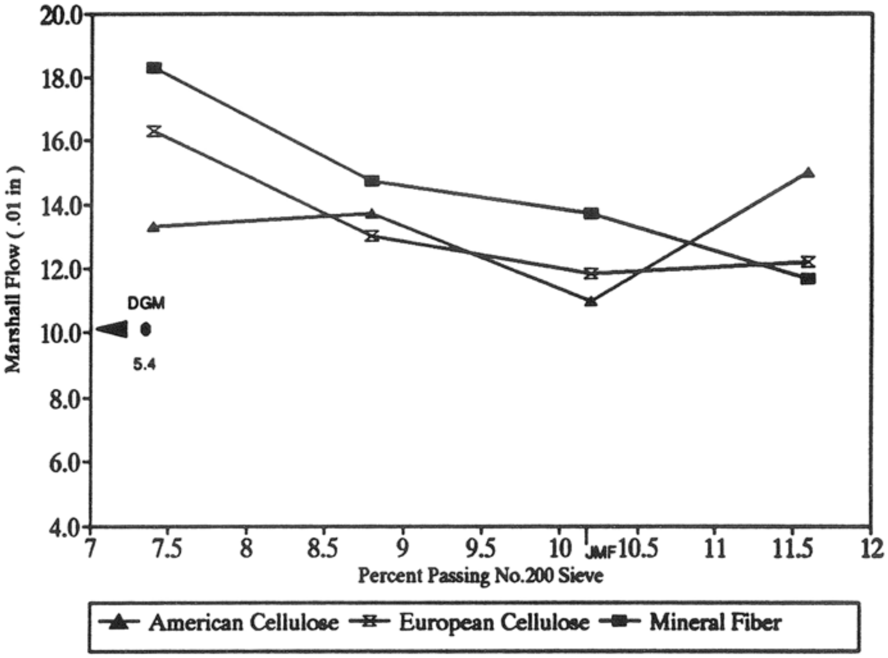

Figure 29b. Flow vs. Percent Passing the No. 200 Sieve for Gravel Mixtures

Indirect Tensile Strength

The indirect tensile test was measured at 77°F at a loading rate of 2 inches per minute. An increase in asphalt content resulted in a gradual increase in tensile strength (Figures 30a and 30b). Tensile strength is mostly a measure of the strength of the asphalt cement and an increase in the amount of asphalt cement may provide more cross sectional area of asphalt cement and therefore a higher measured strength. The tensile strength values of the SMA mixtures are always lower than that for the dense graded mixtures.

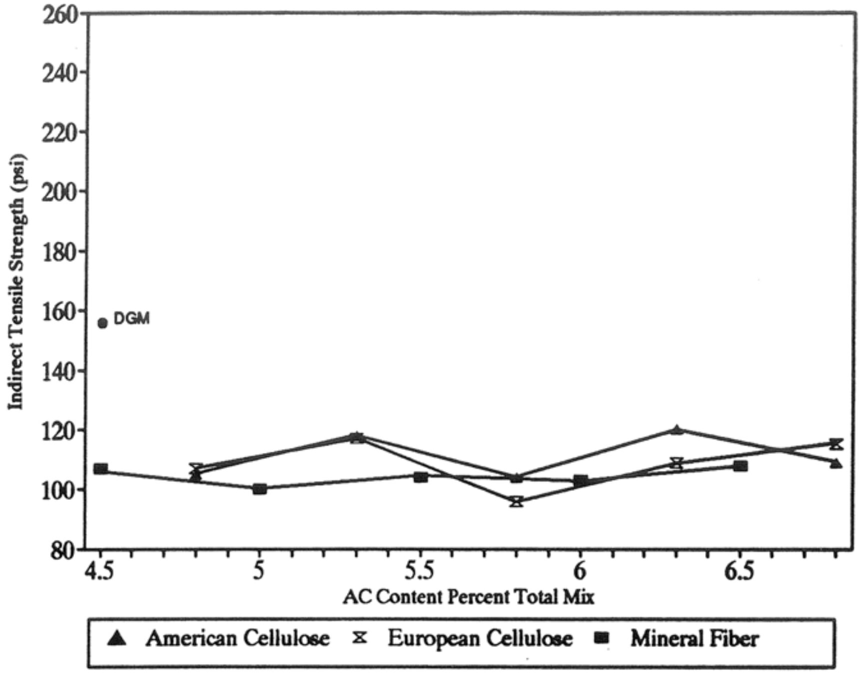

Figure 30a. Indirect Tensile Strength vs. AC Content for Granite Mixtures

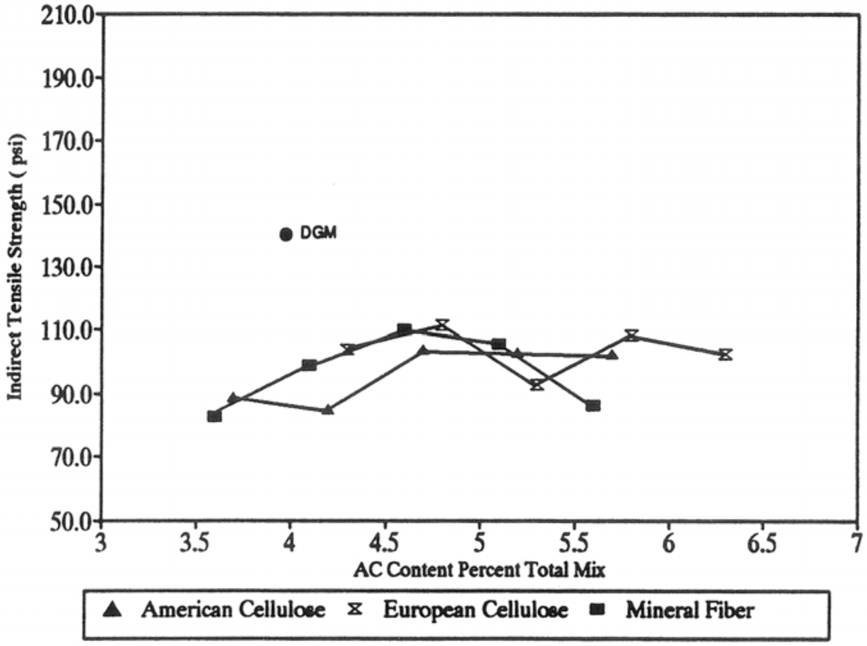

Figure 30b. Indirect Tensile Strength vs. AC Content for Gravel Mixtures

Figures 31a and 31b show the effect of fiber content on indirect tensile strength. The trend in tensile strength is downward for increasing fiber content for the granite mixture, but no trend is apparent for the gravel mixtures. It seems logical that the addition of fiber would increase the tensile strength but loss in density due to the increase in some fibers may have offset any reinforcing benefits of the fibers. There was not a loss in density when the mineral fibers were used however, the abrasion and possible partial breakdown of the fibers may have affected the results.

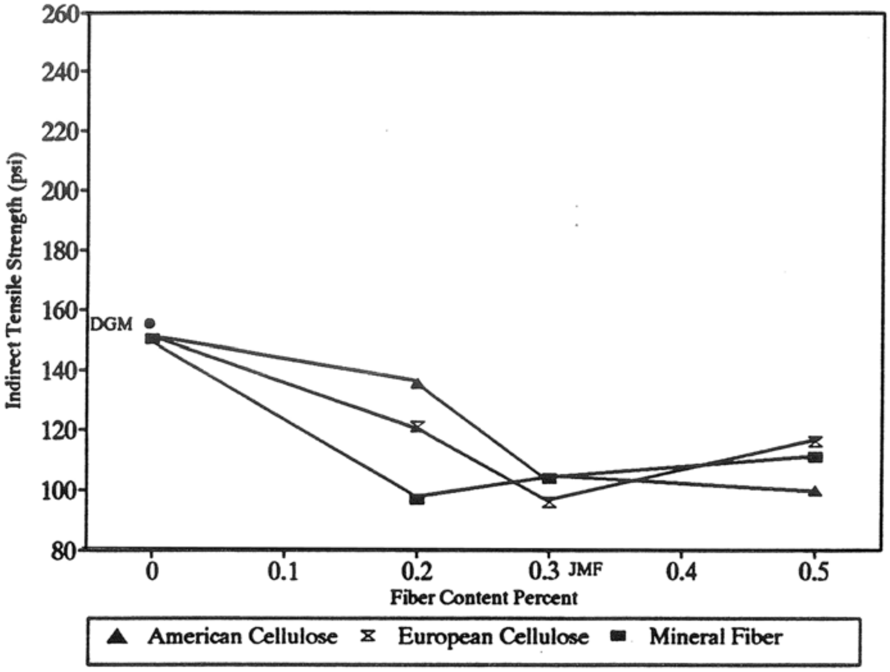

Figure 31a. Indirect Tensile Strength vs. Fiber Content for Granite Mixtures

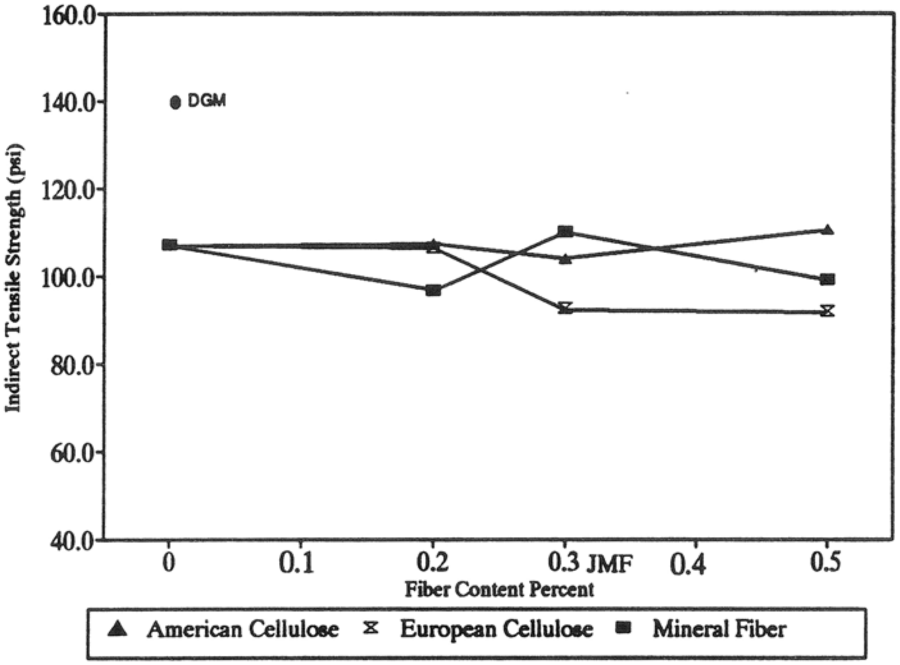

Figure 31b. Indirect Tensile Strength vs. Fiber Content for Gravel Mixtures

Figures 32a and 32b show the effect of percent passing the No. 4 sieve on tensile strength. There is considerable scatter in the data, but the trend indicates an increase in tensile strength with increasing amounts passing the No. 4 sieve. The tensile strength approaches that of the dense graded mixture as the percent passing the No. 4 sieve increases.

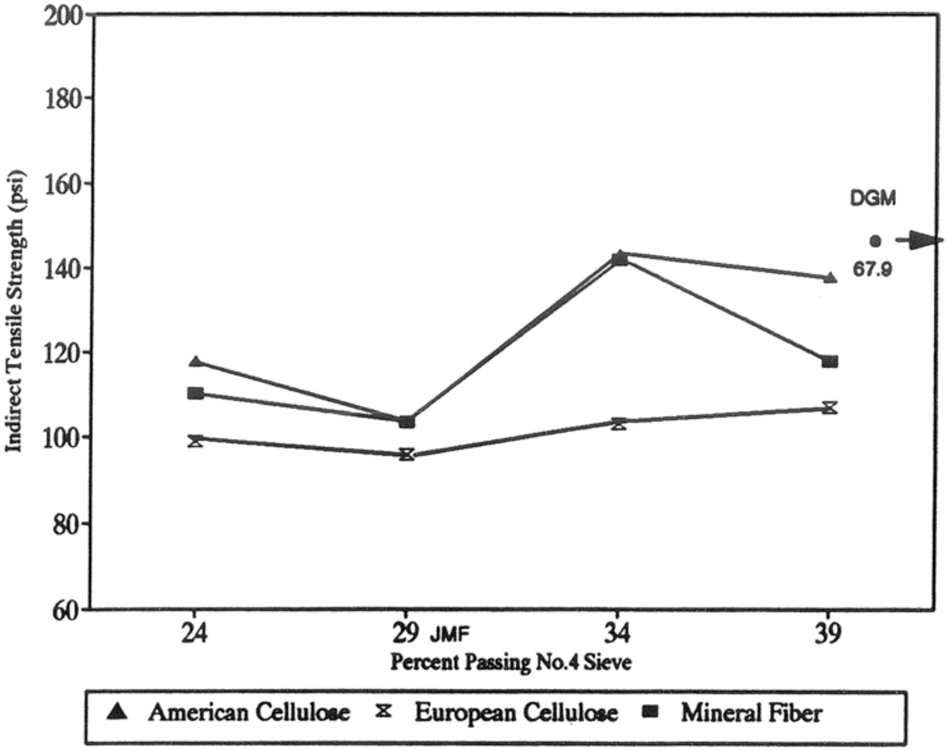

Figure 32a. Indirect Tensile Strength vs. Percent Passing No. 4 Sieve for Granite Mixtures

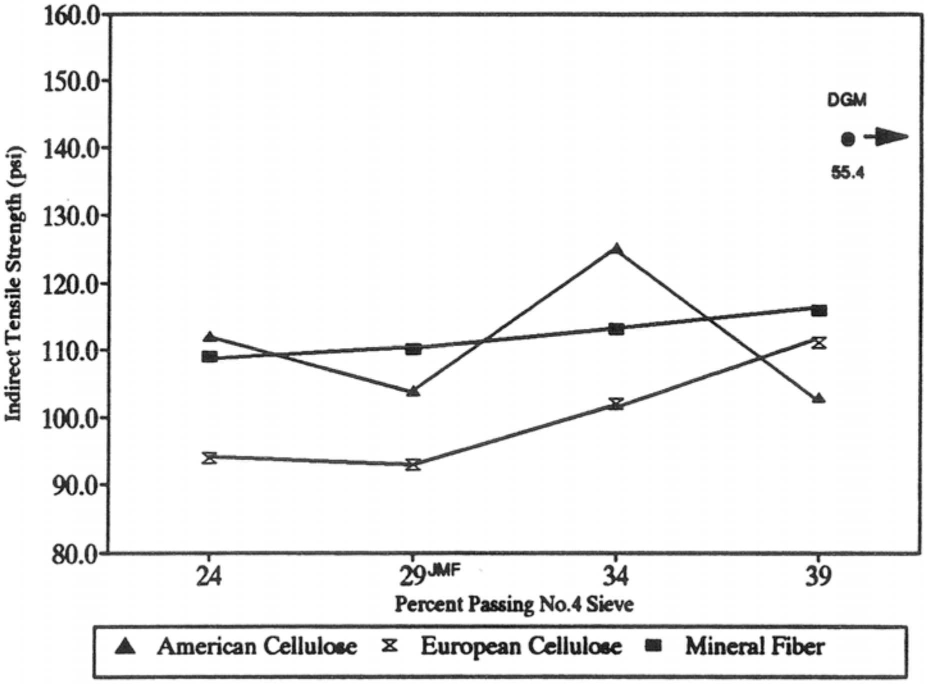

Figure 32b. Indirect Tensile Strength vs. Percent Passing No. 4 Sieve for Gravel Mixtures

Figures 33a and 33b show the effect of percent passing the No. 200 sieve on tensile strength. The results indicate a slight increase in tensile strength for increasing amounts of material passing the No. 200 sieve. The material passing the No. 200 sieve likely stiffens the asphalt cement resulting in a higher measured strength.

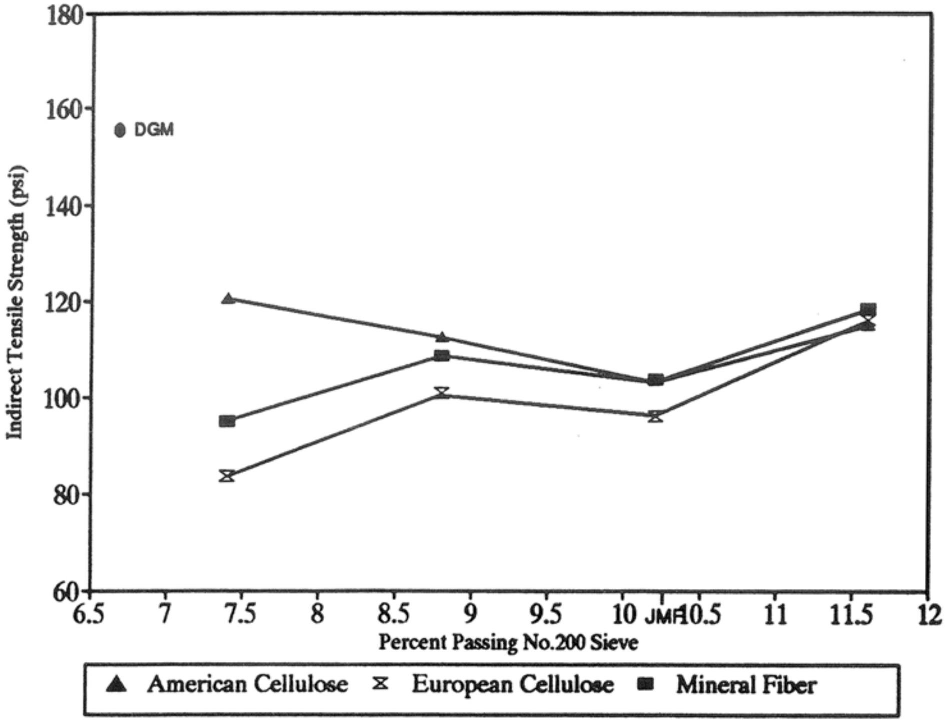

Figure 33a. Indirect Tensile Strength vs. Percent Passing No. 200 Sieve for Granite Mixtures

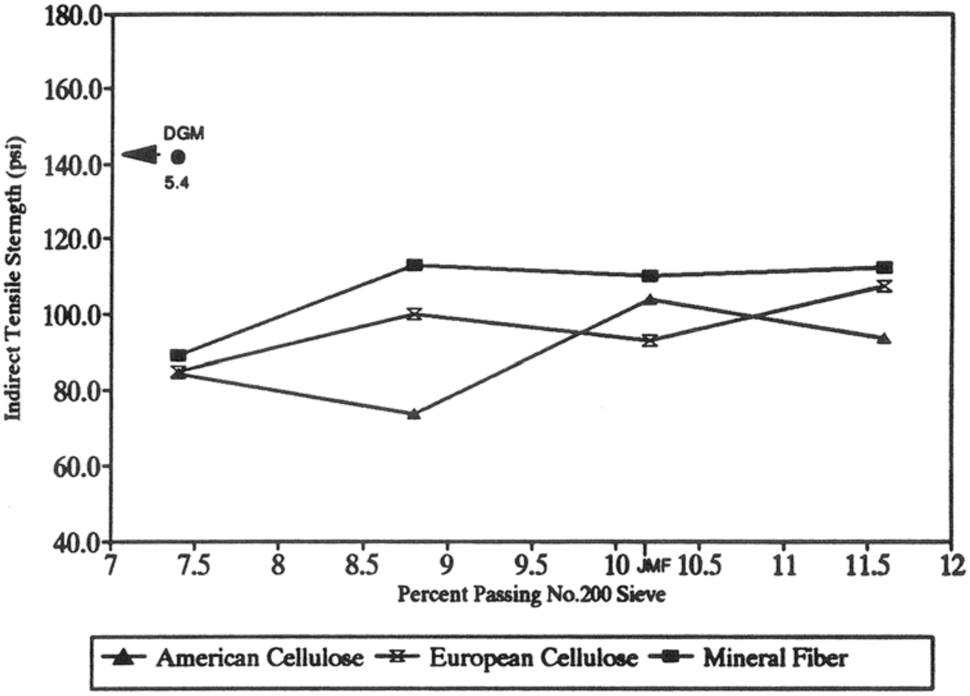

Figure 33b. Indirect Tensile Strength vs. Percent Passing No. 200 Sieve for Gravel Mixtures

Resilient Modulus

There is no good correlation between MR and rutting, but high M_R at low temperatures may result in low temperature cracking (*13*). The results of M_R testing for 40°, 77° and 104°F are provided in Tables 7-12. The data does not show any significant trends, primarily due to the high variability, but the following general trends were observed. The variability of M_R for dense graded mixtures is high but appears to be even higher for SMA mixtures which may be caused by the larger stone content in the mixture. The SMA mixtures with granite aggregate typically had M_R values approximately equal to that of the dense graded mixtures. The SMA mixtures with gravel aggregate typically had M_R values lower than that of the dense graded mixtures.

Static Creep

The static creep test was conducted on all the mixtures evaluated using the standard Marshall size samples. The tests were conducted with an applied stress of 120 psi, a confining pressure of 20 psi, and a temperature of 140°F. The creep stiffness is determined by dividing the normal stress by the creep strain. The total time of loading was one hour with 15 minutes allowed for rebound. The results are shown in Figures 34a-37b.

The static creep data for the granite-mineral fiber mixtures is not included in this report. The data was obviously in error and was discarded.

The creep was approximately equal for the SMA mixtures containing each of the three fibers and for the dense graded mixture. As expected, the creep typically increased slightly for increased asphalt content, however the increase was not great. Typically an increase in fiber content slightly increased the creep. The creep decreased with an increase in the percent passing the No. 4 sieve to a point then began to increase with an additional increase in the percent passing the No. 4 sieve (Figure 36a and 36b). This indicates that there might be an optimum percentage passing the No. 4 sieve.

Permanent Deformation (“Dynamic Creep”)

The permanent deformation test was conducted on all mixtures using the standard Marshall size samples. The test applied 120 psi normal load and 20 psi confining pressure and was conducted at 140°F. This load was applied at one cycle per second at a temperature of 140°F. The load was applied for 0.1 second and removed for 0.9 second for each cycle. The permanent deformation modulus was determined by dividing the normal stress by the permanent strain. The total time of loading was one hour. The results are provided in Figures 38a-41b. The data shows that there is no significant difference in the test results for the three fibers. The measured creep in the SMA mixture is normally approximately equal or slightly higher than that of the dense graded mixture.

The data for the SMA granite mixtures (Figure 38a) shows that increasing asphalt content above 5.8 percent significantly increases the measured creep of the samples. There is a gradual increase in creep for increasing asphalt content for the SMA mixtures containing gravel (Figure 38b). Based on the VMA test results the gravel mixture likely had more stone-on-stone contact than the granite mixture. For this reason the gravel SMA mixture was likely less sensitive to increases in asphalt content. Only one of the gravel mixtures had an asphalt content above 6 percent which may not be high enough to see a significant increase in creep.

An increase in fiber content above 0.3 percent (Figures 39a and 39b) generally resulted in a slight increase in permanent deformation. A increase in the percent passing the No. 4 sieve also resulted in very little change in permanent deformation (Figures 40a and 40b). There is no clear trend in the effect of increasing the percent passing the No. 200 sieve on permanent deformation (Figures 41a and 41b).

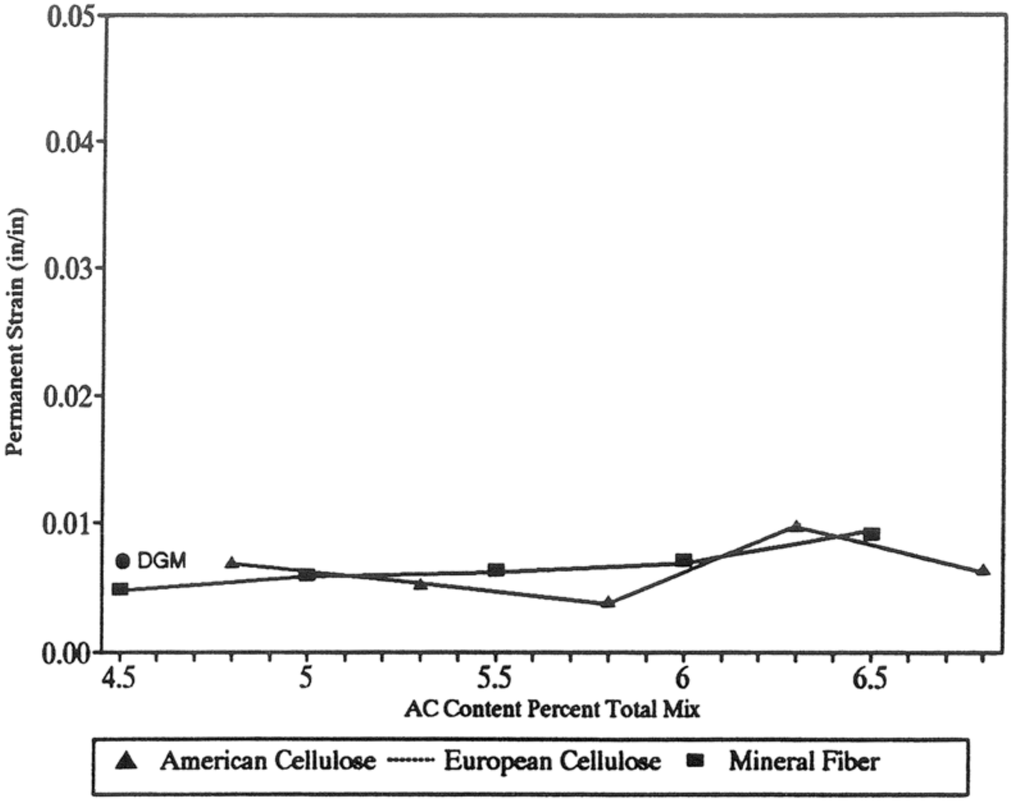

Figure 34a. Permanent Strain vs. AC Content for Granite Mixtures (Static Creep)

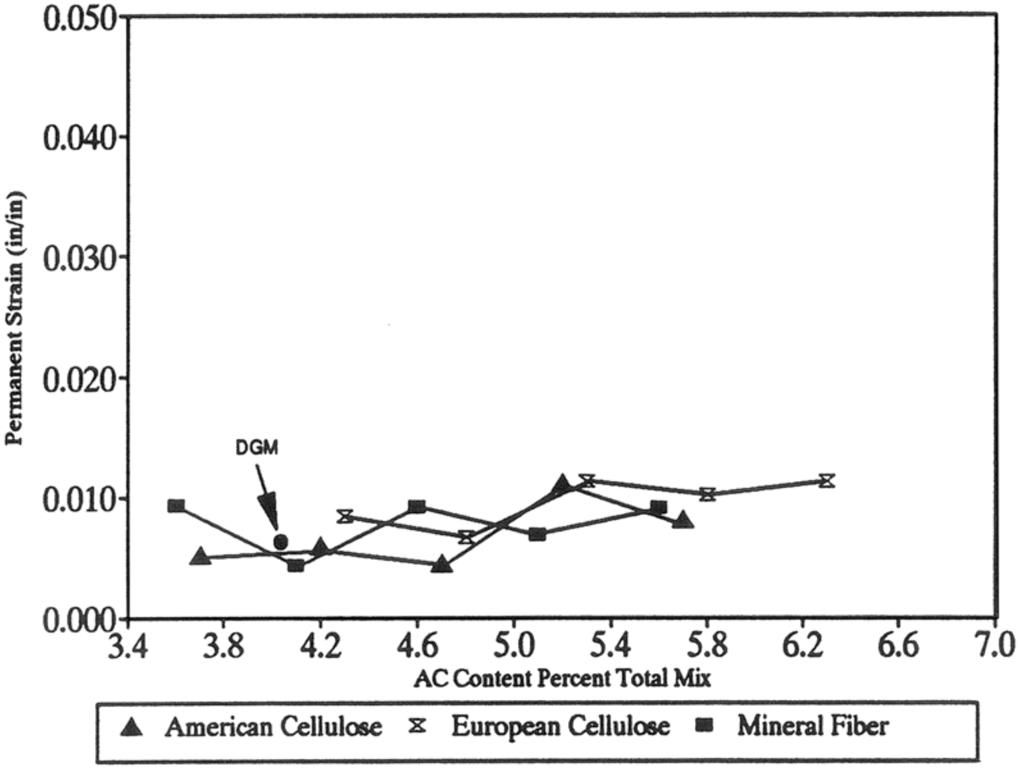

Figure 34b. Permanent Strain vs. AC Content for Gravel Mixtures (Static Creep)

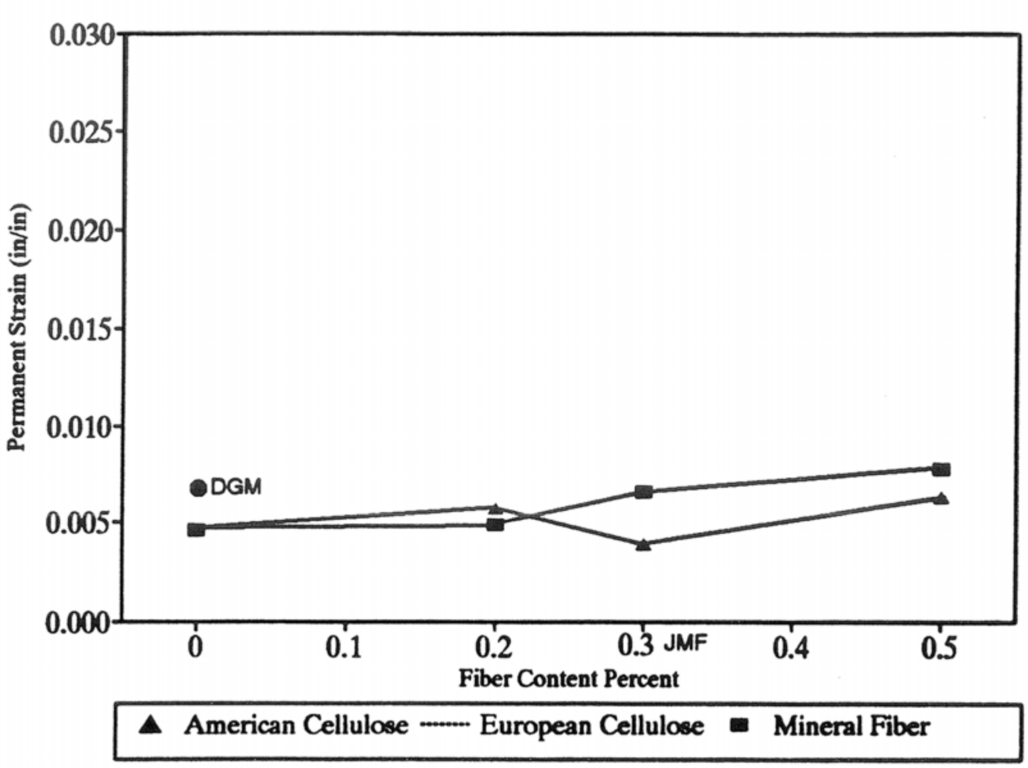

Figure 35a. Permanent Strain vs. Fiber Content for Granite Mixtures (Static Creep)

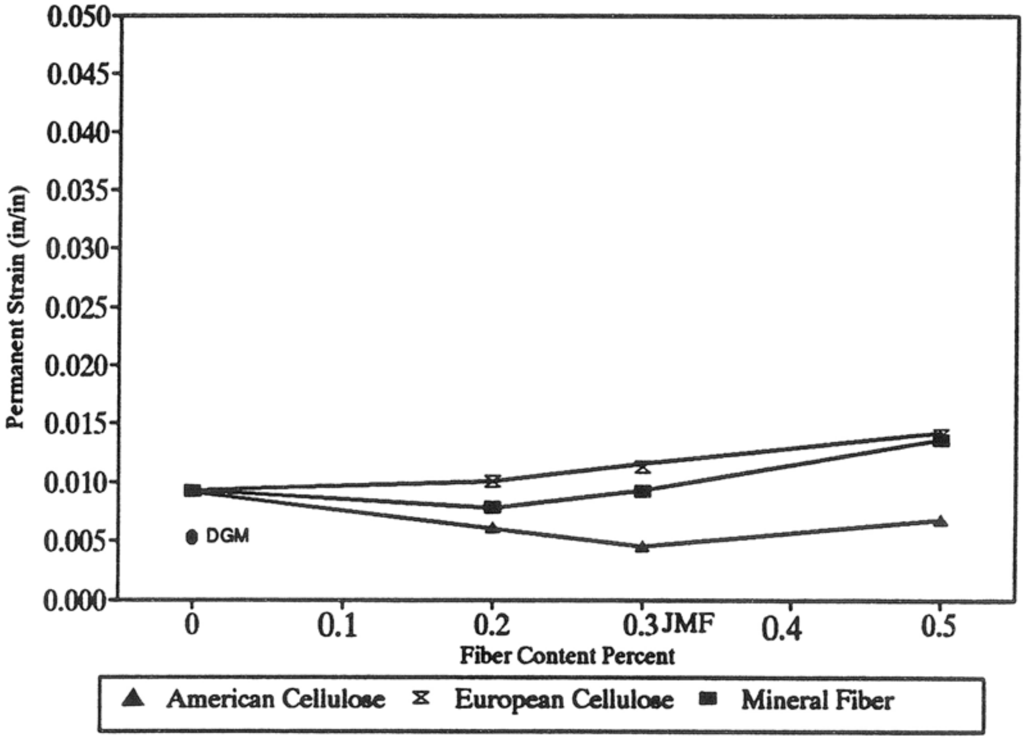

Figure 35b. Permanent Strain vs. Fiber Content for Gravel Mixtures (Static Creep)

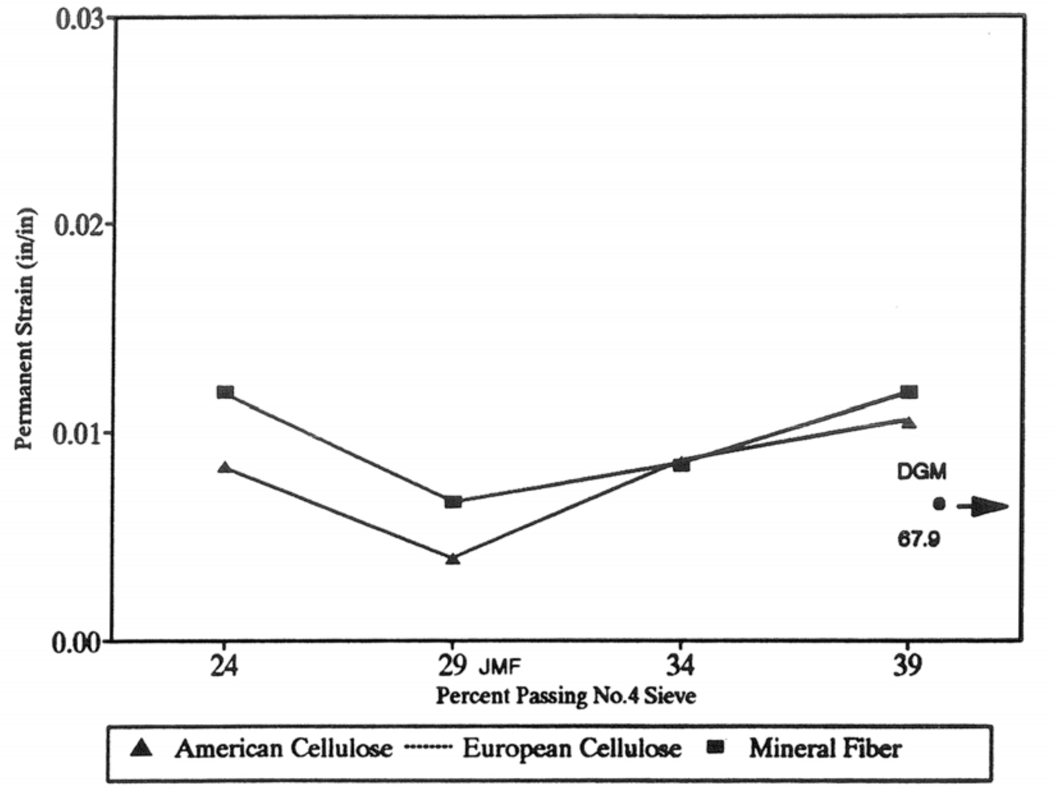

Figure 36a. Permanent Strain vs. Percent Passing No. 4 Sieve for Granite Mixtures (Static Confined Creep)

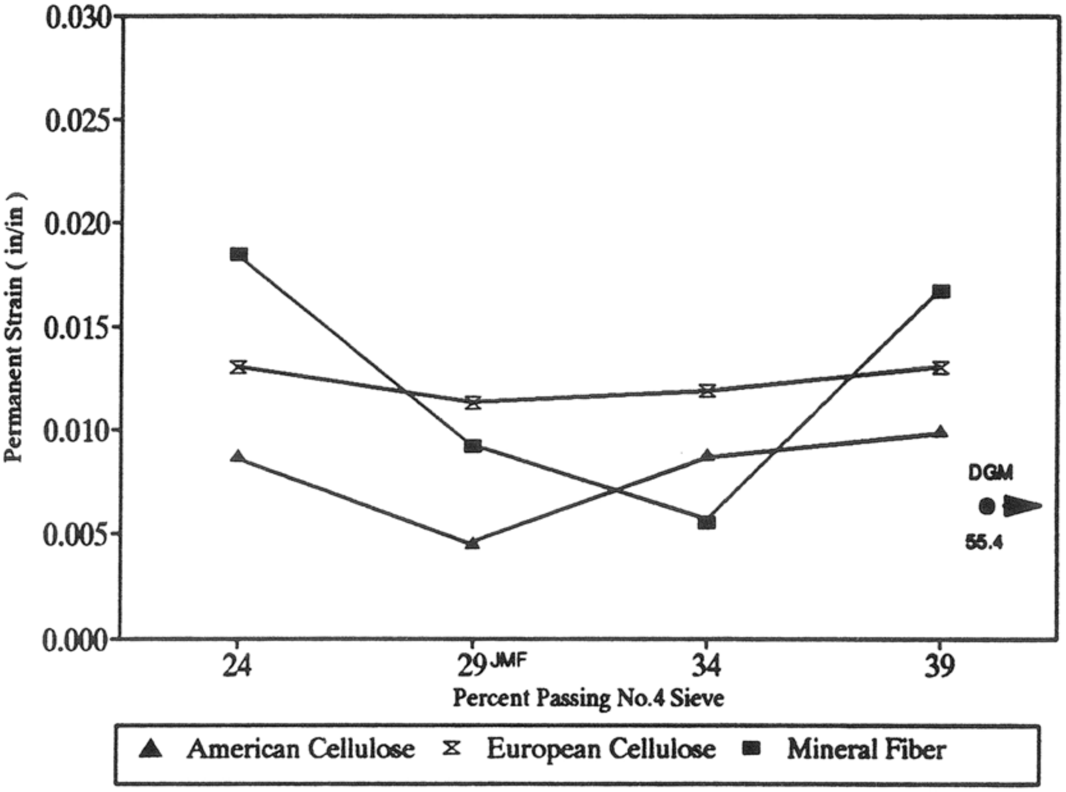

Figure 36b. Permanent Strain vs. Percent Passing No. 4 Sieve for Gravel Mixtures (Static Confined Creep)

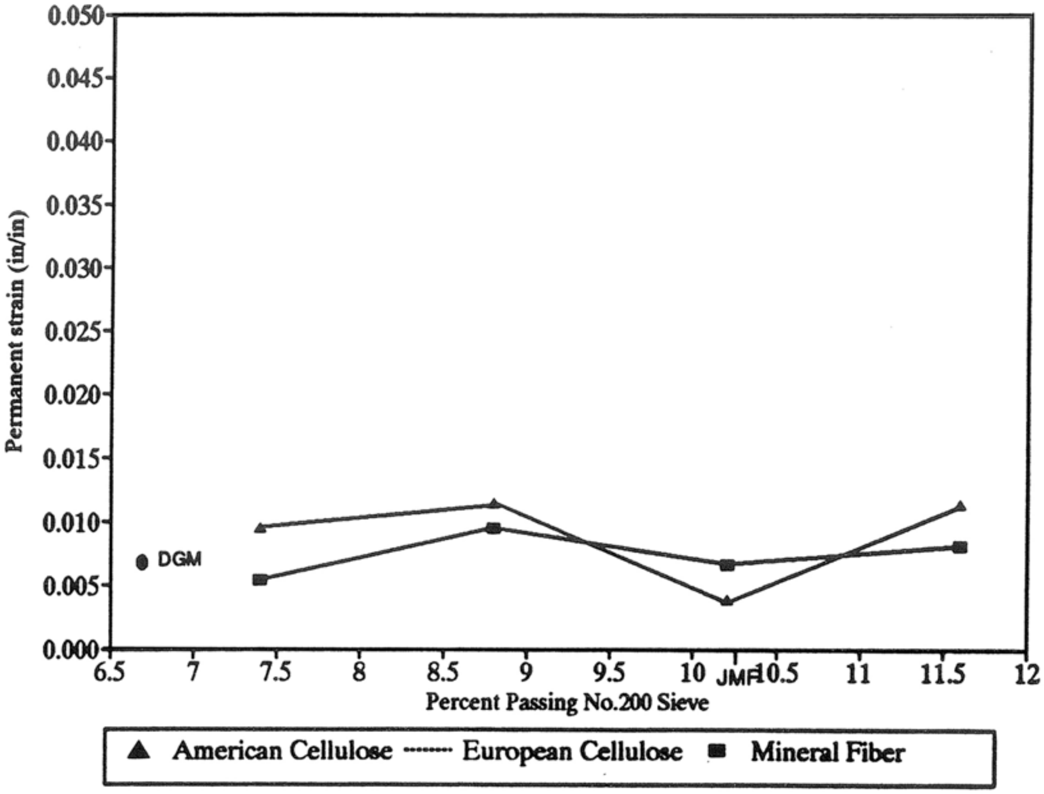

Figure 37a. Permanent Strain vs. Percent Passing No. 200 Sieve for Granite Mixtures (Static Confined Creep)

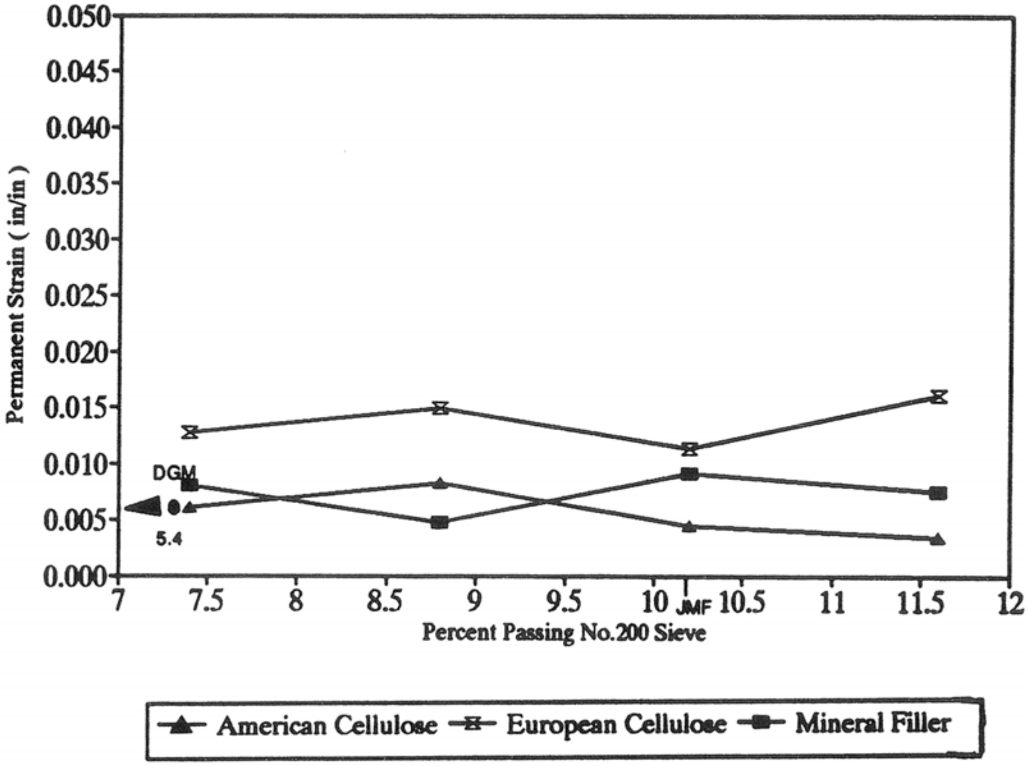

Figure 37b. Permanent Strain vs. Percent Passing No. 200 Sieve for Gravel Mixtures (Static Confined Creep)

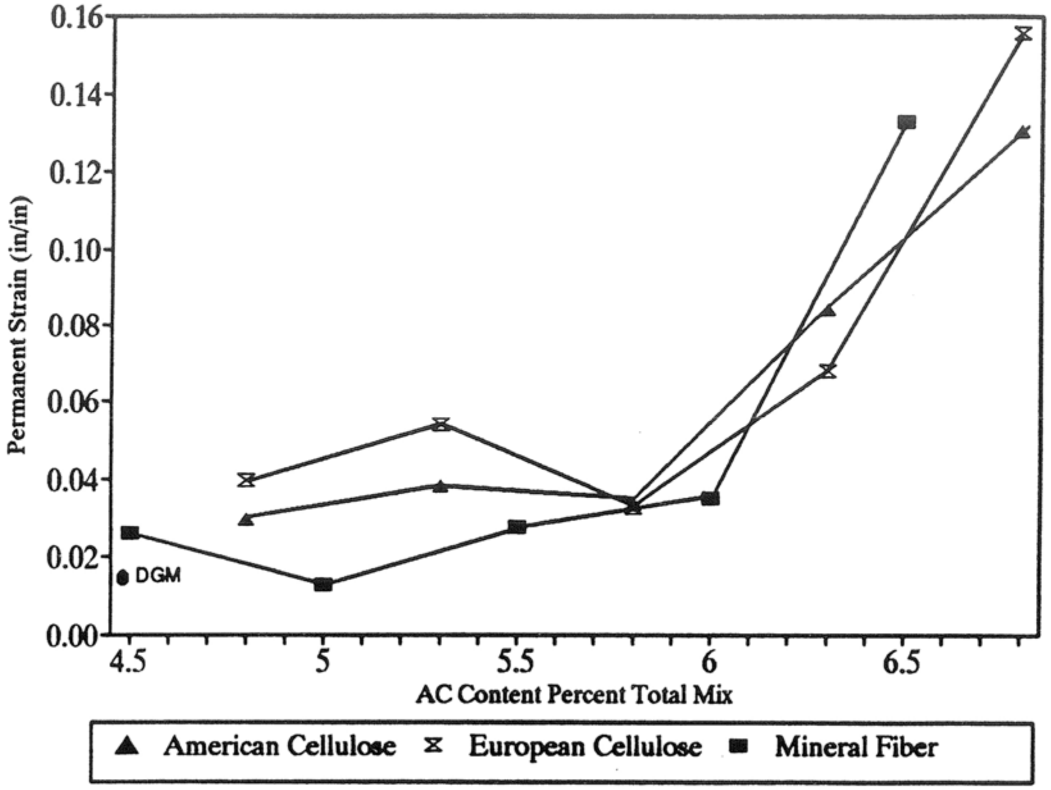

Figure 38a. Permanent Strain vs. AC Content for Granite Mixtures (Dynamic Creep)

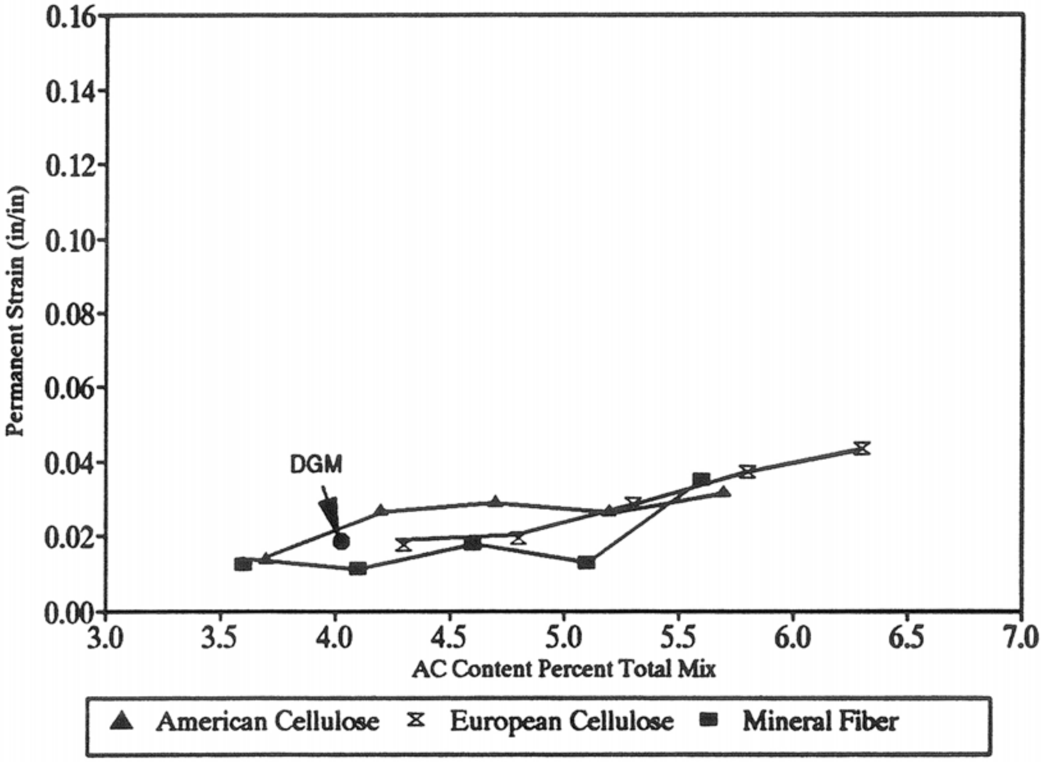

Figure 38b. Permanent Strain vs. AC Content for Gravel Mixtures (Dynamic Creep)

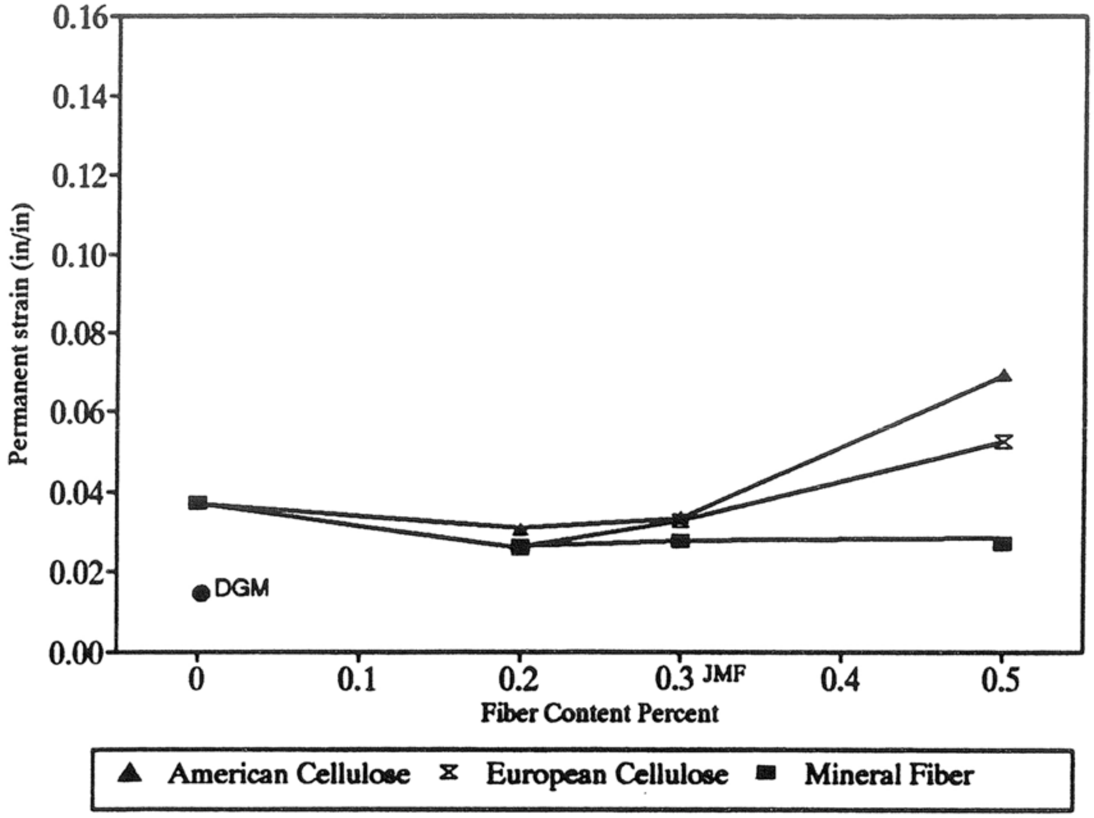

Figure 39a. Permanent Strain vs. Fiber Content for Granite Mixtures (Dynamic Creep)

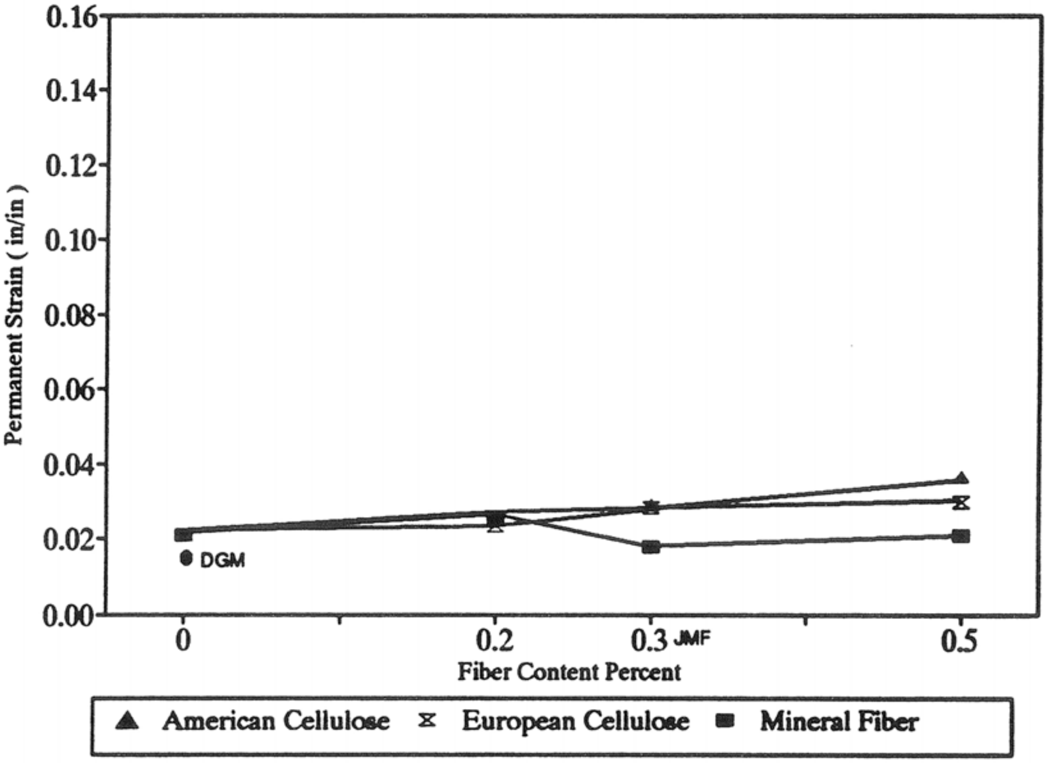

Figure 39b. Permanent Strain vs. Fiber Content for Gravel Mixtures (Dynamic Creep)

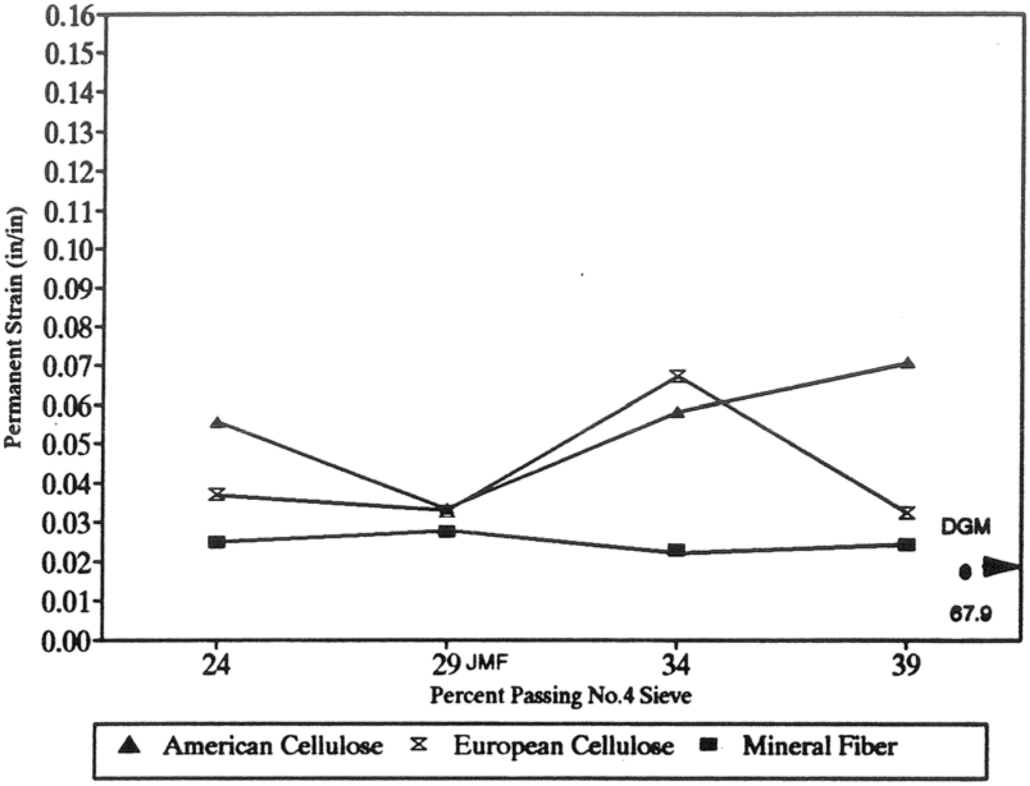

Figure 40a. Permanent Strain vs. Percent Passing No. 4 Sieve for Granite Mixtures (Dynamic Creep)

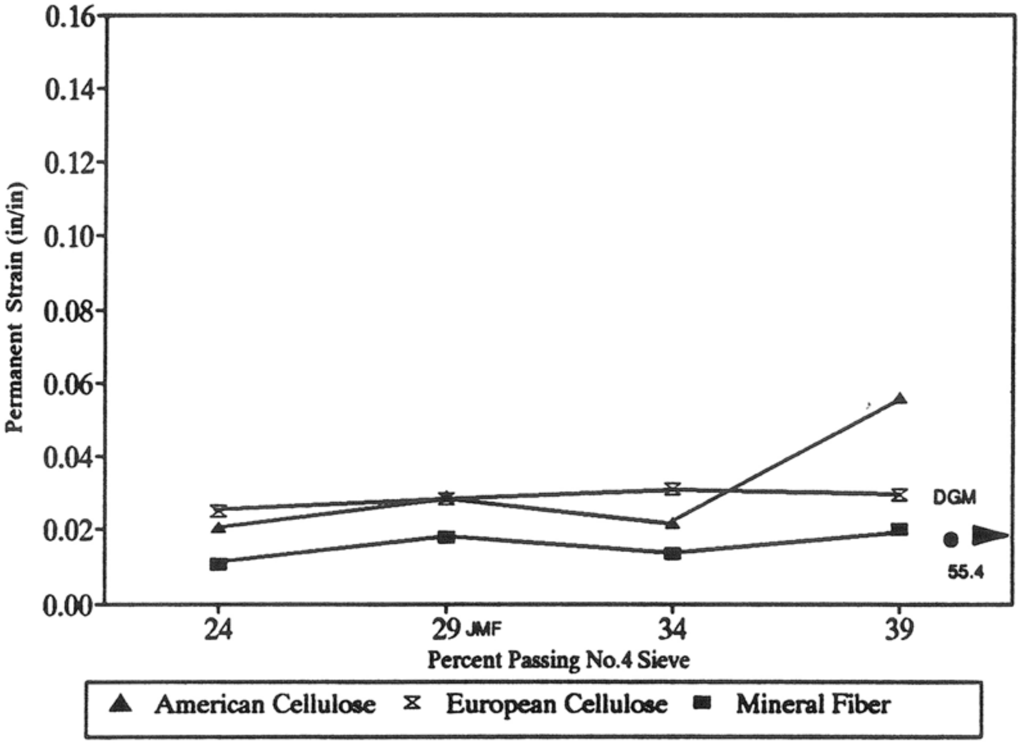

Figure 40b. Permanent Strain vs. Percent Passing No. 4 Sieve for Gravel Mixtures (Dynamic Creep)

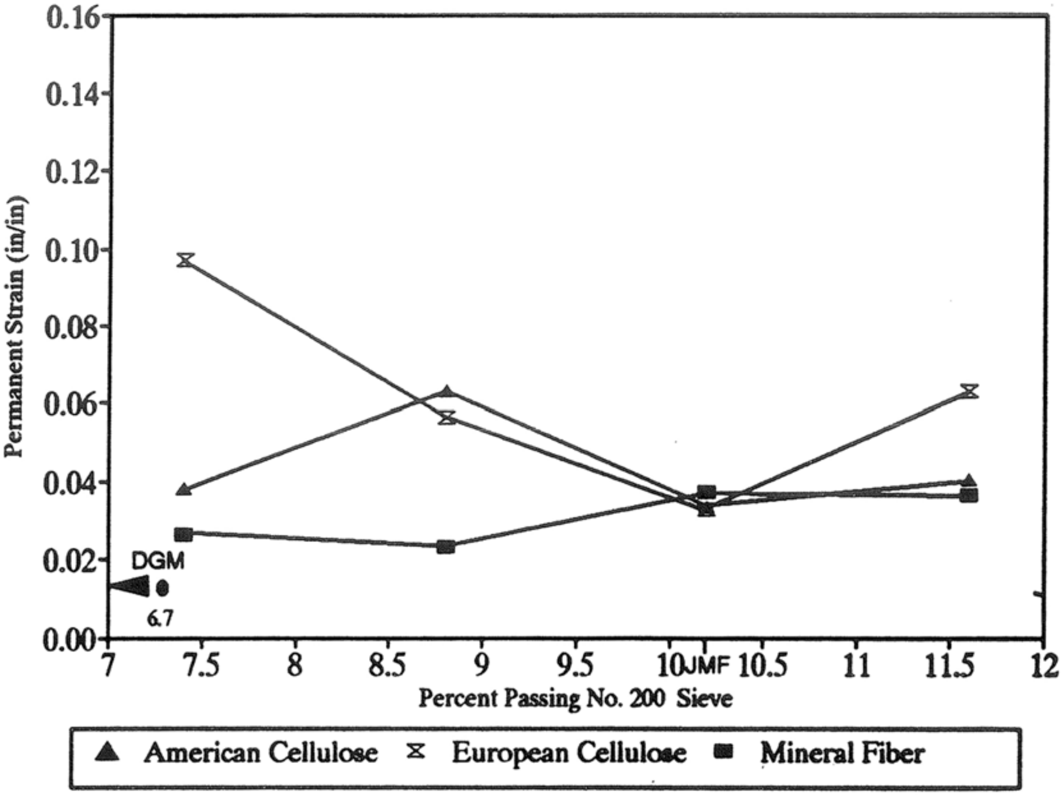

Figure 41a. Permanent Strain vs. Percent Passing No. 200 Sieve for Granite Mixtures (Dynamic Confined Creep)

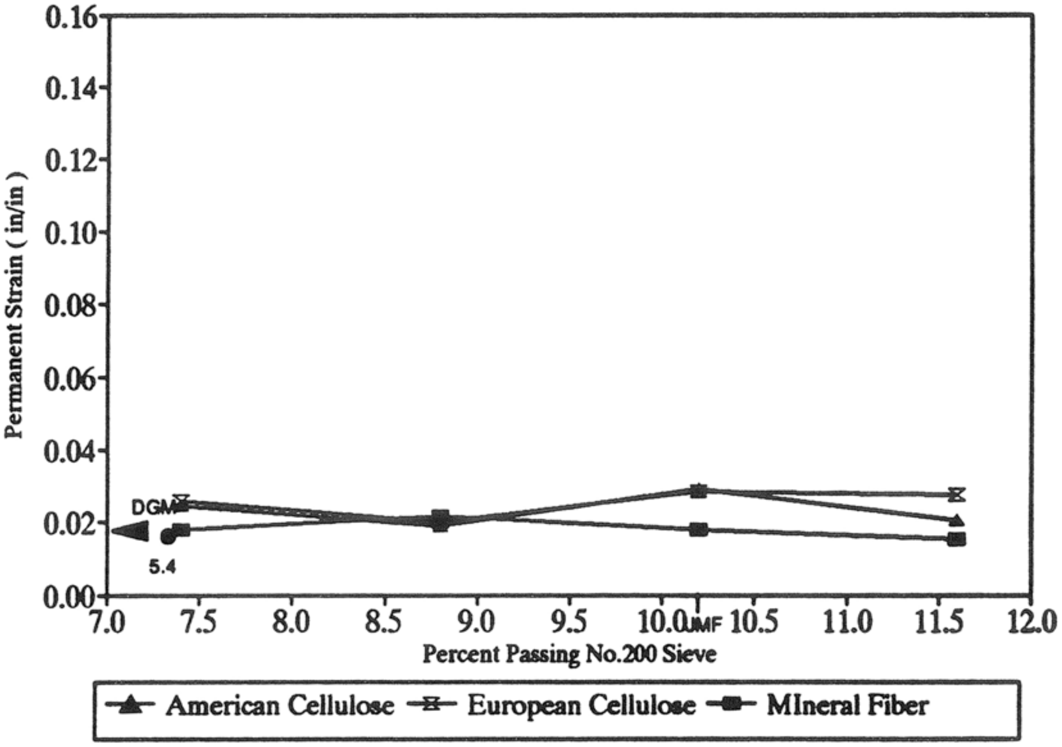

Figure 41b. Permanent Strain vs. Percent Passing No. 200 Sieve for Gravel Mixtures (Dynamic Confined Creep)

Effect of Changes in Aggregate Type

As stated earlier, a silicious gravel and granite were used in the SMA mixtures evaluated. A comparison of the test results for granite and gravel SMA mixtures is shown in Table 13 for mixtures containing 24 percent and 29 percent passing the No. 4 sieve. These two gradations are typical of those being used for SMA.

Table 13. Comparison of SMA mixtures with Silicious Gravel and Granite Aggregates

	American Cellulose		European Cellulose		Mineral Fiber	
	Gravel	Granite	Gravel	Granite	Gravel	Granite
29% passing No. 4 sieve						
Asphalt Content	4.7	5.8	5.3	5.8	4.6	5.5
Air Voids	3.6	3.5	2.7	3.0	3.3	2.5
VMA	14.4	16.7	14.8	16.2	13.7	15.2
Stability	1544	1437	1346	1153	1472	1579
Flow	11	15	12	14	14	14
Tensile Strength	104	104	93	96	110	104
M_R@40	1197	1506	1914	2131	1902	2058
M_R@77	196	374	235	305	245	316
M_R@104	63	151	56	73	62	105
Static Creep Modulus	26667	38386	10619	---	13043	32894
Dynamic Creep Modulus	4110	3818	4211	3828	6678	4409
Shear Strength	44.81	33.85	43.4	38.33	42.0	37.9
24% passing No. 4 sieve						
Asphalt Content	5.0	5.7	5.9	5.5	5.0	5.8
Air Voids	3.7	3.5	3.4	4.3	3.7	2.6
VMA	15.1	16.5	16.9	16.6	15.1	16.0
Stability	1351	1260	1075	1259	1435	1400
Flow	14	17	14	14	14	17
Tensile Strength	112	118	94	99	109	110
M_R@40	1557	2463	1404	1803	1900	1258
M_R@77	230	342	201	405	253	354
M_R@104	51	81	46	86	60	63
Static Creep Modulus	13793	18415	9231	---	6486	10294
Dynamic Creep Modulus	5 97	2693	4790	3129	11215	5233
Shear Strength	41.9	39.3	40.7	32.2	46.9	37.3

The results indicate that the two aggregates have different VMA values. The gradation of the 2 aggregates may have to be different to meet the required VMA specifications if VMA is specified for SMA. For example, if the VM.A requirement is set at 16 then the granite aggregate could have as high as 29 percent passing the No. 4 sieve and meet the requirements, however, the gravel aggregate could have no more than 24 percent or possibly lower passing the No. 4 sieve.

The aggregate type does not appear to affect the Marshall Stability for these mixtures, but it does appear to affect the flow (average flow for gravel equals 13 and for granite equals 15). This higher flow for granite aggregate is likely the result of higher optimum asphalt contents for the granite mixture. The average optimum asphalt content for the gravel SMA mixture is 5.2 percent and for the granite SMA mixture the average is 5.7 percent. So the gradation and aggregate type have a significant effect on the optimum asphalt content and ultimately on the durability. Both of these mixtures fail to meet the desired 6.0 percent minimum asphalt content. This could have been met by decreasing the void requirements to 3.0 percent and/or by decreasing the percent passing the No. 4 sieve.

The aggregate type does not have a significant effect on tensile strength. This is probably affected more by asphalt cement type than aggregate type. The data appears to indicate that the tensile strength is lower for mixtures with European cellulose but there is not sufficient data for a detailed statistical analysis.

The resilient modulus is almost always higher for the granite aggregate than for the gravel. The percent difference appears to be largest at 77°F and 104°F. It is not clear why the resilient modulus for granite aggregate is larger than that for gravel. It was assumed that the resilient modulus and indirect tensile strength would show similar results; however, the aggregate type appears to affect resilient modulus but not tensile strength.

In most cases, the static creep modulus is higher for the granite (10294-38386 psi) than for the gravel mixtures (6486-26667 psi). However, the dynamic creep modulus is higher for the gravel mixtures (4110-11215 psi) than for the granite mixtures (2693-5233 psi). It is not clear why the two types of creep tests provide different results. However, past work has indicated that mixtures with slightly high AC have a tendency to perform better than slightly lean mixes in the static creep test. The granite mixture generally had the higher AC.

The shear strength measured during compaction with the gyratory machine is always higher for the gravel mixture (40.7-46.9 psi) than for the granite mixture (32.2-39.3 psi) which also compares with the results with the dynamic creep modulus.

The results indicate that the mixes with 24 percent passing the No. 4 sieve on the average have higher VMAS, lower stabilities, higher flows, higher tensile strengths, similar resilient moduli, lower static creep moduli, similar dynamic creep moduli, and similar shear strengths when compared with mixtures having 29 percent passing.

CONCLUSIONS

The primary purpose of this report was to develop a database of information on SMA mixtures. Gradation, asphalt content, aggregate type, fiber type, and fiber quantity were varied to help evaluate the effect of these variables on the laboratory properties of SMA. This study was intended to provide information that would validate the recipes now used in Europe for production of SMA and provide data to indicate why these recipes are successful.

Field studies have shown SMA mixtures to provide excellent performance so a laboratory study to verify the performance of SMA is not needed. However, there is a need to determine which laboratory tests are able to predict the quality of SMA. That was the goal of this study.

SMA mixtures did not perform as well as the dense graded mixtures on many of the tests. For example stability was lower, flow was higher, and resilient modulus was lower for SMA. This does not mean that SMA will not perform as well as a dense graded mix but means that the tests are either not applicable to SMA or the limits for the test results should be adjusted. Some of the tests did show SMA to perform equal to or better in some cases than the dense graded mixtures. These tests which include gyratory shear, confined creep, and permanent deformation (dynamic creep) will likely be more accurate in predicting the performance of SMA.

Most of the mixtures evaluated in this study would not meet the present requirements for SMA because of the low optimum asphalt content, When this study began most SMA projects were being constructed with a mixture having more than 30 percent of the aggregate passing the No. 4 sieve. This study showed for the two aggregates investigated that the percent passing should be below 30 percent and maybe below 25 percent. The results are still applicable in evaluating the effect of changes in mixture proportions on properties of SMA mixtures.

The following specific conclusions can be made from these test results.

1. SMA mixtures using mineral fiber will typically have lower optimum asphalt content and lower VMA than SMA mixtures containing cellulose. All the SMA mixtures had higher VMA values than the dense graded mixtures. This is necessary for SMA so that a sufficiently high asphalt content can be added to provide for improved durability.
2. Increasing the fiber content of SMA mixtures results in a slight increase in VMA which allows for a slightly higher optimum asphalt content.
3. Changing the percent passing the No. 200 sieve or No. 4 sieve for the SMA mixtures results in a significant change in VMA. This indicates that close control of gradation is necessary during production to insure a satisfactory product. Increasing the percent passing the No. 200 sieve will fill the voids in the mastic to a point and then begin to push the aggregate apart. Increasing the percent passing the No. 4 sieve will ill the voids in the coarse aggregate matrix to a point and then begin to increase the voids in the coarse aggregate.
4. The shear strength of SMA mixtures only decreases slightly with increasing asphalt content. This indicates some tolerance for SMA to AC changes. The shear strength of the SMA mixtures ranged from slightly lower to slightly higher than that for the dense graded mixtures.
5. The Marshall stability of SMA mixtures was always significantly lower than that for dense graded mixtures. This indicates that the Marshall stability requirements should be lowered for SMA or the test should be deleted from the specifications. The stability of SMA mixtures increased with increasing amounts of materials passing the No. 4 and No. 200 sieve. This lower Marshall stability for SMA does not indicate a lack of stability in SMA mixtures but instead indicates a lack of the Marshall stability test to actually measure the mixture stability.
6. The measured flow was higher for SMA mixtures than for dense graded mixtures. This is an indication that the SMA mixture is more flexible than dense graded mixtures.
7. The indirect tensile strength of SMA mixtures was always lower than that for dense graded mixtures. The tensile strength of the mixture is not as important as the tensile strain at failure. Future work should evaluate the tensile strain at failure to better evaluate the potential of SMA mixtures to provide good performance. The strain at failure was not measured in this study.
8. The resilient modulus of SMA mixtures was typically lower than that for dense graded mixtures. This simply means that SMA is not as stiff in tension as a dense graded mixture. Ideally mixtures should be flexible in tension and stiff in

compression or shear. The variability of the resilient modulus values for SMA was high.

9. The permanent deformation of the SMA determined from the static creep test had values approximately equal to that of the dense graded mixtures.
10. The dynamic permanent deformation tests showed that the SMA mixtures usually had slightly higher permanent strain values than the dense graded mixtures. However, previous studies have shown that SMA mixtures are less sensitive to a small decrease in air voids thus SMA is less affected by variations in mixture proportions.
11. Generally speaking, all three fibers produced SMA mixtures that should provide satisfactory performance. Changes in aggregate gradation, fiber type and fiber content did not greatly affect the mechanical properties when the optimum asphalt content for each mixture was used. Some of these changes would likely affect the draindown of asphalt cement during construction, but draindown was not evaluated in this study.
12. SMA mixtures have proven to provide good performance in Europe and have shown promise in the U.S. The data developed within this report indicates the range of test results to expect with standard U.S. tests for SMA mixtures. These results should be helpful in setting criteria for SMA mixtures or for identifying areas where new tests may be needed. The data in this report can not be used to compare performance of SMA mixtures to that of dense graded mixtures but can be used to help establish tests to be specified and criteria for these tests. The comparison of performance for SMA and dense graded mixtures must be done in the field for a significant amount of time.

RECOMMENDATIONS

This study looked at the effect of fibers, gradation, asphalt content, and aggregate type on the mechanical properties of SMA mixtures. The fibers have very little effect on the mechanical properties however, the primary purpose of the fibers is to prevent draindown of these rich asphalt mixtures during construction. Additional work needs to be performed to evaluate the effect of various types of fibers and polymers on asphalt cement draindown.

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