Performance Improvement of Open-Graded Asphalt Mixes

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16. Abstract

This report describes a research study on the permeability and strength properties of open-graded asphalt materials. Such asphalt mixes have high porosity, which offers significantly better drainage properties than normal mix designs. However, these materials also exhibit poor durability and strength limiting their use in pavement application. To remedy this, fiber and/or polymer binder modifiers have been proposed. The effects of these modifiers are investigated using standard sample mixes from previous Arizona and Georgia studies, stone matrix asphalt and an in-house mix design. Samples were prepared with and without the modifiers using Marshall mix procedures and were experimentally tested using various standardized testing procedures including percent air void for porosity, falling-head test for permeability and indirect tensile test for strength.

In general, the results indicate that the introduction of fiber modifiers led to minor improvement on strength characteristics of the samples while contributing to significant reduction in permeability. On the other hand, the introduction of polymer modifiers nearly doubled both the strength and permeability and also increased the air voids. However, when both polymer and fiber were used, additional strength improvement was observed but the permeability increase was not as large as that with polymer modifier alone. Consequently, our results indicate that the best strength/permeability characteristics can be achieved by introducing only polymer modifier in the mix. Also, the effects of elevated temperature were investigated and it was found to have significant influence on the strength and permeability characteristics of the mixture.

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ABSTRACT

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In general, the results indicate that the introduction of cellulose fiber modifiers led to minor improvement on strength characteristics of the samples while contributing to significant reduction in permeability. On the other hand, the introduction of SBS polymer modifiers nearly doubled both the strength and permeability and also increased the air voids. However, when both polymer and fiber were used, additional strength improvement was observed but the permeability increase was not as large as that with polymer modifier alone. Consequently, our results indicate that the best strength/permeability characteristics can be achieved by introducing only polymer modifier in the mix. Also, the effects of elevated temperature were investigated and it was found to have significant influence on the strength and permeability characteristics of the mixture.

1. INTRODUCTION

Special asphalt pavement mixes with high degrees of porosity (open-graded mixes) offer significantly better drainage behavior than normal pavement materials. While standard pavements normally allow runoff only along the road surface, high porous asphalt mixes allow for both horizontal and vertical (through pavement) drainage. Such drainage characteristics are very appealing and would greatly increase driver's safety by removing water more rapidly from the driving surface thereby creating a dry driving surface even in moderate rainstorms.

Early applications of porous pavement were investigated by Thelen and Howe (1) and Diniz (2), but these studies were generally limited to parking lots and driveways. Gemayel and Mamlouk (3) presented a study (sponsored by the Arizona DOT), which investigated several engineering properties of open-graded friction course (OGFC). They found that the tensile strength and resilient modulus of open-graded mixes were about half of the value of normal dense-graded asphalt. Furthermore, the open-graded material was extremely sensitive to temperature. At high temperatures, these materials exhibited significant decreases in resilient modulus and stability. This behavior is micromechanical in nature and is related to aggregate contact behavior and to the viscosity increase of the binder material. Additional strength studies of open-graded mixes were limited to emulsion mixtures by Hicks, et al. (4) and asphalt stabilized aggregate bases by Majidzadeh and Elmitiny (5). Qi et al. (6) presented some new research on the development of more durable asphalt binder through the use of polymer modifiers. Preliminary research into drainage and flow in porous pavements was also made by Isenring et al. (7) and Heystraeten et al. (8). A recent survey made by Kandhal and Mallick (9) shows that the design and construction play a key role on determining the performance of open-graded asphalt pavements. Mallick et al. (10,11) reported their results on the evaluation of the performance of OGFC with different aggregate gradation and types of additives. Bolzan et al. (12) summarized previous British studies on the performance of OGFC material. Kanitpong et al. (13) investigated permeability of asphalt material with different aggregate gradations. Maupin (14) studied the effects of sawing specimens for use in permeability testing, and demonstrated that this method introduces surface effects that can modify the fluid transport.

The main challenge in designing an OGFC is determining a reasonable compromise between permeability and strength. Currently, the literature indicates a lack of fundamental understanding in the correlation between permeability and the strength characteristics of open-graded asphalt mixes. This project is directed at providing additional information on this correlation with emphasis on binder modification and its effects on performance improvement in terms of strength and permeability. Furthermore, elevated temperature experiments will be performed on both permeability and strength to determine the effects of temperature on these characteristics.

2. SCOPE

Asphalt is basically a heterogeneous cemented granular material system as shown in Fig. 1. High porosity in OGFC material is produced through appropriate volume fraction mixes of graded particles and cement binder. Such a microstructure is not ideally suited for high stress conditions required for roadway transportation systems. For this reason, most roadway uses of open-graded mixes have been limited to a thin top layer with a typical thickness on the order of the largest aggregate size, as depicted in Fig. 2a. While such a thin layer provides much better friction between the tires and the road, it can only dissipate water along its coarse surface, which may prove to be inadequate under heavy rain conditions. A thicker coarse on the other hand would allow for greater drainage from the road surface through both vertical and horizontal flow

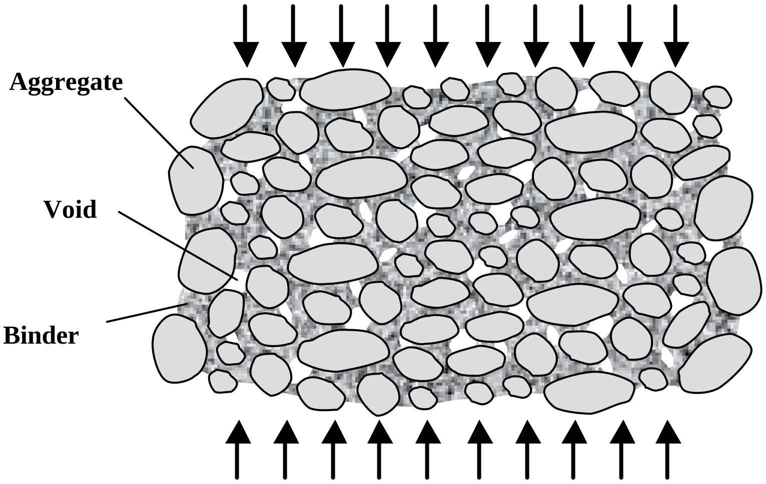


FIGURE 1 High porosity asphalt system.

as shown in Fig. 2b. The obvious disadvantage of using OGFC in a thick layer application is due to its poor strength and durability.

The main objectives of this project are to study the effects of different mixes and types of additives on the performance of several OGFC mixes and to determine the best strength/permeability characteristics. The effects of elevated temperature on the strength and permeability of these mixes are also investigated.

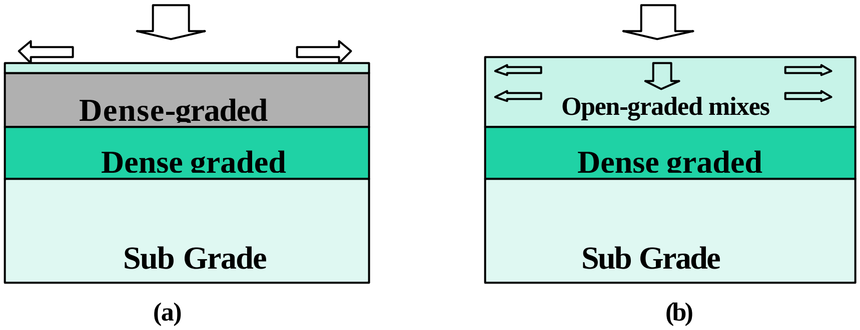


FIGURE 2 Schematic of typical of OGFC layout; (a) Thin Layer Application, (b) Thick Layer Application.

3. MIX CHARACTERISTCS

An open-graded friction course is hot mix asphalt with high void content, which allows water to flow through the mix. Using a larger amount of coarse aggregate creates a higher percentage of air voids in the mix, which in turn creates high permeability. The Federal Highway Administration (15) recommended gradation for OGFC shown in Table 1.

TABLE 1 The FHWA recommended gradation for OGFC

Sieve Size	Percent Passing
½ inch (12.5 mm)	100
3/8 inch (9.5 mm)	95-100
No. 4 (4.75 mm)	30-50
No. 8 (2.36 mm)	5-15
No. 200 (0.075 mm)	2-5

3.1 Mix Design

a) Method

There are three principal asphalt mix design methods in general use. These methods are Marshall Method, Hveem Method and Superpave. Their purposes are to design the most cost effective asphalt mix for specific environmental needs, including such issues as climate and strength conditions.

Marshall mix design is a widely used method throughout North America and Europe. Marshall apparatus often known as the Marshall compactor or hammer is what characterizes this method. The method subjects an asphalt-aggregate blend to a number of blows supplied by a dropping mass, as specified in the ASTM standard ASTM D1559.

The Hveem Mix Design has some similarities to the Marshall mix design, except a kneading compactor is used rather than the Marshall compactor. The calculations of the mix properties such as the voids in the total mixture (VTM), theoretical maximum density (TMD) and bulk specific gravity (BSG) are the same for both methods but different testing equipment are used.

Hveem and Marshall mix designs have been used for many decades. Both methods have performed reasonably well in the past, but current roadway conditions and requirements created the need for a different mix design method. A study to develop such a method to rationally design asphalt mixtures for various environmental and loading conditions was initiated in 1988 by the Strategic Highway Research Program. This work led to new paving criteria called Superpave, which stands for "SUperior PERforming Asphalt PAVEment". The Superpave design took into account asphalt binder evaluations, mix design, and mixture analysis and aggregate size was to be chosen as part of a particular design need depending on traffic load and environmental condition.

Because of the availability of the mix design equipment and consultation with several faculty members at URI, samples were prepared using the Marshall mix design method. Other mix design methods such as Superpave and their effects on permeability of OGFC are reported in the literature, i.e. "Evaluation of Permeability of Superpave Mixes", Final Report, Project NETC 00-2, New England Transportation Consortium, University of Connecticut, 2002.

b) Gradation

In the first phase of the research, four sample mixes were prepared with gradations similar to those used by Mallick (10).

Sample mix A is a gradation similar to the one used by the FHWA and the other three mix samples contain slight variations from this standard blend. The FHWA gradation has 40 percent of material passing the 4.75 mm sieve, and the coarsest of the other three gradations has only 20 percent passing through this sieve. The coarsest gradation is very similar to the gradation that is being used by many states reporting good experiences with OGFC mix designs, such as Georgia. The gradations of these samples tested in this aspect of the research can be seen in Table 2 and Fig. 3. The results for the permeability of these samples were not presented in this report. These experiments were used to benchmark the second phase of the project.

TABLE 2 Gradation chart for the in-house mix design

Sieve Size		Percent passing			
SI (mm)	US(inches)	***A***	***B***	***C***	***D***
19.0	¾	100	100	100	100
12.5	½	95	95	95	90
4.75	0.187	40	30	25	20
2.36	0.0929	12	7	7	8
0.075	0.0029	4	3	3	3

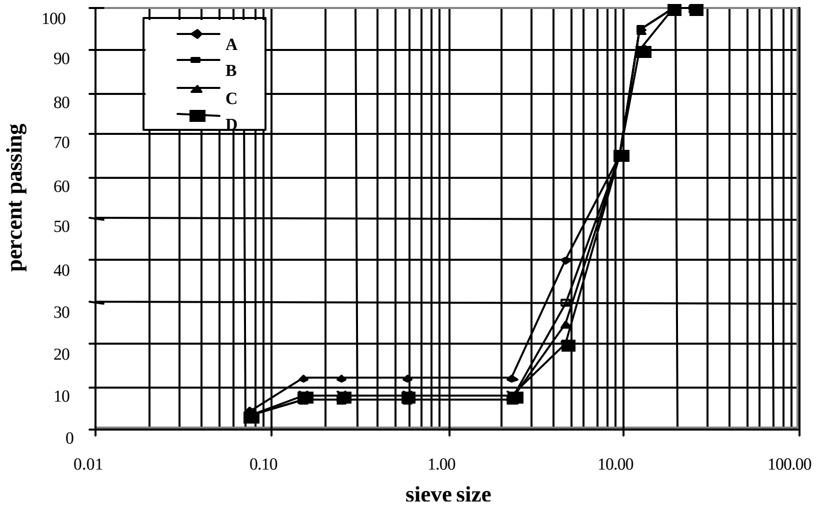


FIGURE 3 The gradation curves for the in-house mix design.

In the second phase of this study, Arizona, Georgia and SMA (Stone Matrix Asphalt) asphalt mixes were used. The samples were all made following the gradation requirement outlined in the chapter 7 of the book by Roberts et al. (16). All three designs and their corresponding gradations are shown in Table 3 and summarized in Fig. 4.

TABLE 3 Gradation chart for Arizona, SMA and Georgia

Sieve Size		**Percent passing**		
SI (mm)	US(inches)	***Arizona***	***SMA***	***Georgia***
19.0	¾	100	100	100
12.5	½	93	90	93
9.5	3/8	85	75	65
4.75	# 4	34	24	18
2.36	# 8	16	20	8
1.18	#16	7	20	8
0.59	# 30	5	14	8
0.25	# 50	3	14	8
0.15	# 100	2	14	8
0.075	# 200	2	9	3

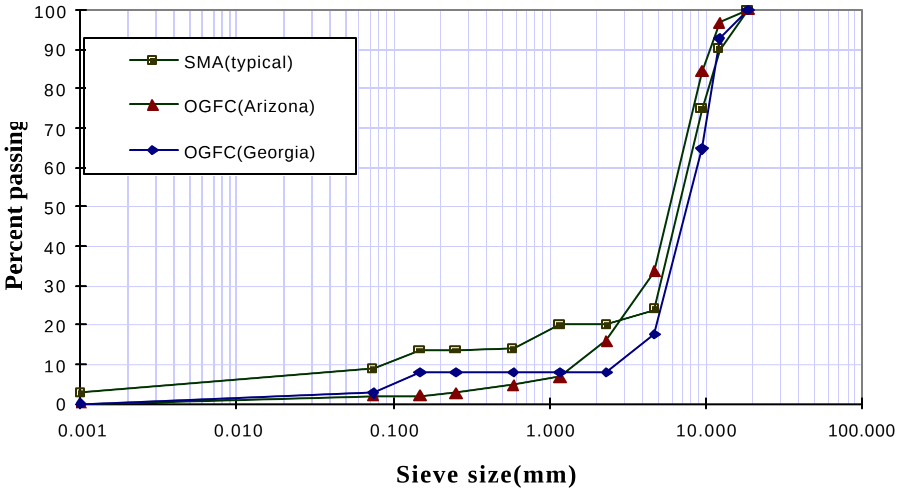


FIGURE 4 Gradation curves for Arizona, SMA and Georgia.

Arizona and Georgia designs are both classified as open-graded friction course mixes. The Arizona gradation was first used in 1970's by Arizona DOT. It was reported to show poor performance in both durability and permeability. The Georgia open-graded mix was emerged in 1970's in Georgia DOT and the mix design procedure is similar to the FHWA procedure.

SMA is not an open-graded mix, but was developed to provide a pavement with maximum strength to prevent rutting. Although not an OGFC, SMA contains a higher portion of coarse aggregate. For this reason, SMA samples were included in our study to provide strength and permeability comparisons with the open-grade mixes.

c) Asphalt Content

In the early phase of the project, asphalt content was a design parameter that was manipulated. Samples were tested at 5% and 6% to observe the effects of asphalt content on the permeability of the specimens.

In the second part of the project, the procedure used for obtaining the percentage of asphalt was the process described under the Marshall method. The asphalt content is estimated from the surface capacity K_c. The procedure is conducted in accordance with that mentioned in the report, FHWA-RD-74-2, which uses the relationship between the percent oil retained by the aggregate and the surface capacity K_c, as shown in Fig. 5.

Using the surface capacity K_c, so obtained, the asphalt content was computed from an

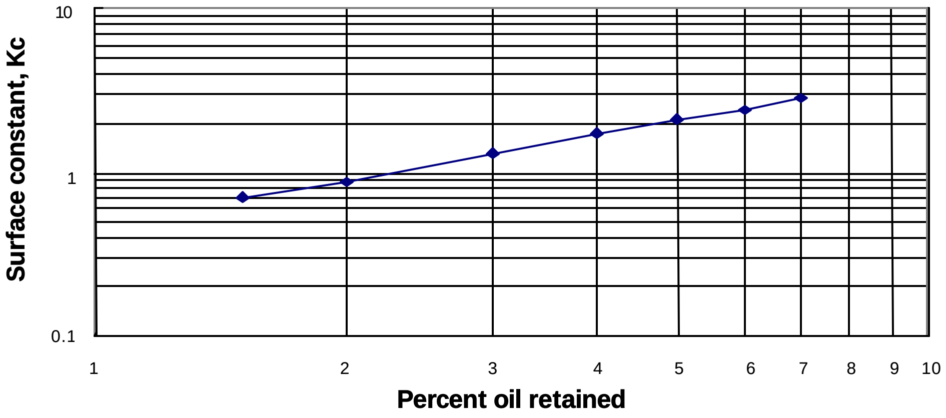


FIGURE 5 Chart for Determining Surface Capacity (K_c) of Coarse Aggregate.

established simple linear relationship acquired from field experience on similarly graded mixtures as,

$$Percent\ Asphalt = 2.0 * (Kc) + 4.0 \tag{1}$$

Note that the asphalt content in this procedure is determined based upon the weight of the aggregate. The asphalt content computed from equation (1) would be the same regardless of the asphalt grade. The test results from the asphalt content procedure for Arizona, Georgia and SMA mixtures is summarized in Table 4.

TABLE 4 Percentage of Asphalt Content

Gradation	Immersed Aggregate (g)	Percent Oil Retained (%)	Surface constant (K_c)	Percent Asphalt (%)
Arizona	101.5	1.5	0.75	5.50
Georgia	102.0	2.0	0.92	5.84
SMA	101.9	1.9	0.90	5.80

d) Additives

Additives are generally used to increase strength and durability of asphalt mixes. Recently, a survey was conducted on open-grade asphalt materials by the National Center for Asphalt Technology (10,13). They recommended a higher percentage of both asphalt content and coarser gradation to improve permeability. The additives used in this study were fibers and polymers.

(i) Fibers

The two types of fibers that are used in Hot Mix Asphalt (HMA) mixtures are cellulose and mineral fibers. These fiber additives are generally used to prevent drain down of the asphalt cement so as to maintain uniform distribution of the cement content. It also contributes to significant reduction in permeability as will be seen from our experimental results.

(ii) Polymers

Polymers are usually used to increase the viscosity and decrease the drain down of asphalt cement, resulting in a more consistent thickness of asphalt film. The two types of polymers used in asphalt enhancement are elastomers and plastomers. The difference between the two types is whether they exhibit elastic or plastic behavior during deformation. Plastomers have a three-dimensional structure and a stiff characteristic. They add to the mix's resistance to deformation, but under high strains may fracture. The most commonly used elastomeric polymers are SBR (styrene-butadiene rubber) and SBS (styrene-butadiene-styrene). These polymers tend to also resist deformation but return to their original shape after loading and can increase tensile strength.

CITGO brand CITGOFLEX SP asphalt PG-64 22 was the asphalt cement used in this study. It was mixed with TECHNOCEL 1004 fiber additive, a cellulose based fiber, provided from the Cellulose fiber factory. The polymer additive used was the CITGO brand SBS polymer additive supplied premixed at 3 percent in the asphalt binder. The mixing and compaction temperatures for the unmodified and modified asphalt mixes were approximately at 290 °F.

3.2 Volumetric Properties

a) Bulk Specific Gravity (BSG)

The bulk specific gravity of parafilm-coated specimens was determined in accordance with ASTM standard test procedure D1188-96. A brief description follows.

First, the mass of the dried specimen was obtained and was designated as mass "A". The specimen was then coated with parafilm, by pressing and folding it over the specimen's surface filling all voids. The mass “D”of the dry coated specimen was determined in air, and this procedure was repeated in a 25°C water bath to determine the mass designated as “E”.

Using similar weighing procedures, the apparent specific gravity of the parafilm was calculated by first determining the specific gravity of the calibration cylinder

$$G_{Al} = \frac{A_{Al}}{(A_{Al}-B_{Al})} \qquad (2)$$

where A_{Al} is the dry mass in air and B_{Al} is the mass underwater. The specific gravity of parafilm was then determined using the following relation

$$F = \frac{D_{Al}-A_{Al}}{D_{Al}-E_{Al}-(A_{Al}/G_{Al})} \qquad (3)$$

where D_{Al} is the dry mass of the wrapped specimen and E_{Al} is mass of the wrapped specimen under water.

Finally, from equations (2) and (3) the bulk specific gravity, (G_{mb}), of the film-coated specimen can be obtained as

$$G_{mb} = \frac{A}{D-E-(D-A)/F} \qquad (4)$$

b) Theoretical Maximum Density (TMD)

TMD is a hypothetical value representing a compacted specimen containing no air voids. The theoretical maximum density of the specimen was obtained in accordance with ASTM standard test method D2041-95, and the following equation was used

$$Gmm = \frac{P_{mm}}{(P_s/G_{se})+(P_b/G_b)} \qquad (5)$$

where G_{mm} is the Theoretical Maximum Density, P_{mm} is the total weight of the mix, P_s is the percent weight of the aggregate in the total mix, G_{se} is the effective specific gravity of the aggregate coated with asphalt, P_b is the percent weight of asphalt in the total mix and G_b is the specific gravity of asphalt

c) Voids in Total Mixture (VTM)

VTM is the total volume air voids between the coated aggregate particles throughout a compacted mixture. It is expressed as the percentage of the bulk volume of the specimen. The voids in a compacted mixture were obtained in accordance with ASTM standard test method D3202-94. Research has shown that the amount of air voids in a mixture affects the stability, durability and permeability. The following equation represents the percentage of air voids in the specimen.

$$\text{VTM}(\%) = 100(1 - G_{mb}/G_{mm}) \tag{6}$$

where G_{mb} is bulk specific gravity of the compacted mixture and G_{mm} is maximum theoretical specific gravity of the mixture

3.3 Results of Volumetric Properties

Table 5 presents the average volumetric properties determined for each mix design using equations (4)-(6). The complete volumetric property data is given in Appendix A.

Fig. 6 summarizes the air void percent vs. mix design. As depicted in the figure, the SMA mix exhibits the lowest overall porosity, Georgia the highest and Arizona somewhere in between. The effects of modifiers on the asphalt characteristics are also shown here. For Arizona and SMA mixes, the percent air voids decreases with the addition of fiber, increases with polymer, and again decreases when both fiber and polymer are added. The Georgia mix exhibited slightly different results.

TABLE 5 Volumetric properties of each mix design

PG64-22	TMD	BSG	VTM(%)
Arizona	2.52	2.18	13.4
SMA	2.54	2.29	10.0
Georgia	2.51	2.07	17.6
PG64-22F	TMD	BSG	VTM(%)
Arizona	2.52	2.19	12.9
SMA	2.54	2.29	9.7
Georgia	2.51	2.06	17.8
PG64-22S	TMD	BSG	VTM(%)
Arizona	2.52	2.15	14.6
SMA	2.54	2.24	11.8
Georgia	2.51	2.10	16.5
PG64-22SF	TMD	BSG	VTM(%)
Arizona	2.52	2.19	13.2
SMA	2.54	2.30	9.5
Georgia	2.51	2.10	17.0

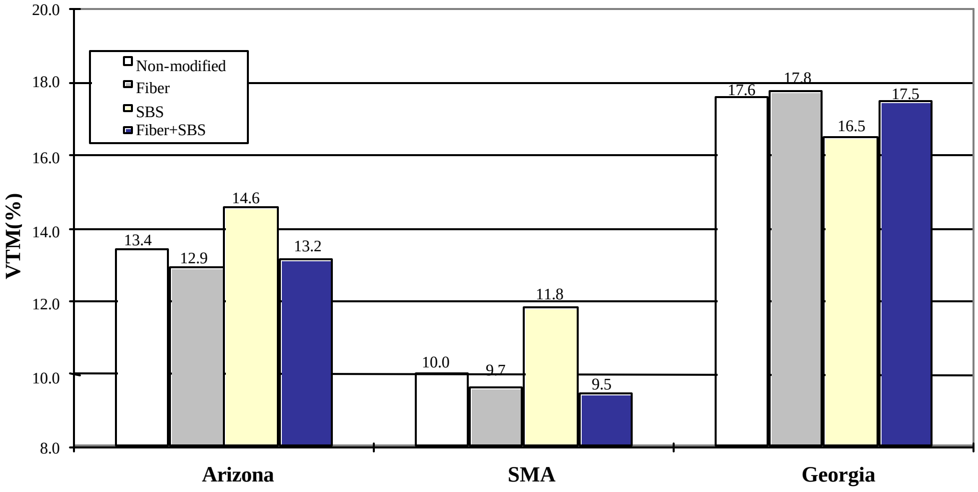


FIGURE 6 Percent air void vs mix design.

4. PERMEABILITY STUDIES

4.1 Theoretical Background

Permeability or hydraulic conductivity is a measure of the material's ability to spatially transfer pore fluid. It is related to the material's porosity, but it is most dependent on the void geometry such as the interconnectivity of the void pathways, Hall and Ng (17). Flow through porous media is normally governed by Darcy's Law, but in some cases a non-Darcy theory is a better predictor of the fluid transport. With regards to asphalt materials, the mix characteristics will determine which theory would be the most appropriate. For laminar flow with Reynolds number ranging from 1 to 10, Darcy's law is generally valid, and is given by the following relation

$$v = ki \tag{7}$$

where k is the coefficient of permeability of the material, i is the hydraulic gradient across the sample or head loss per unit length and v is the specific discharge or an equivalent average velocity through the sample. If the hydraulic gradient and the specific discharge are known, relation (7) can be used to determine the permeability, k.

When the Reynolds number is greater than 10, Darcy's law, equation (7), is invalid and the flow behavior is commonly characterized by a *modified Darcy's law* of the form

$$v = ki^m \tag{8}$$

where m is a non-Darcy parameter that accounts for the non-linearity of the flow.

4.2 Measurement Procedures

The usual laboratory-testing methods that can be performed to determine permeability in asphalt mixes are the constant-head and falling-head tests. The apparatus for both methods have been setup in our laboratory and tested extensively. After comparative testing of each method, it was determined that the falling-head test is more suitable for our purpose both in terms of accuracy and ease of use. The procedures used to conduct both tests are as follows.

a) Falling Head Test

The falling-head test (FHT) essentially consists of measuring the change in head and quantity of flow over time. The schematic setup used to conduct the falling head permeability test is illustrated in Figure 7. The apparatus consists of a metal cylinder with a flexible membrane on the inside of the cylinder to which air pressure can be applied. The asphalt sample is placed inside between plastic plates on the bottom and top, and clamps are used to compress and seal the assembly together. The top plate has a hole that attaches to the graduated cylinder for the introduction of water. The hole on the bottom plate is connected to an outlet pipe, which is fitted with a valve for the water to flow out. The outflow of water is directed to a reservoir that has an overflow slot so that the reference head is kept constant. Pressurized air is then induced into the space between cylinder and membrane using a hand pump. The pressure exerted on the rubber membrane seals the flow paths along the sides of the asphalt sample. The attached

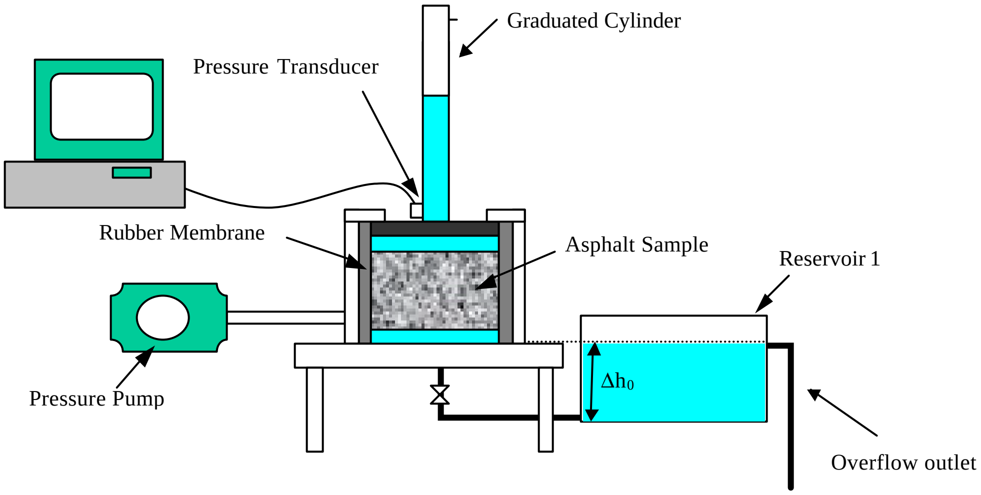


FIGURE 7 Schematic setup for falling head test.

graduated cylinder is then filled with water, and the permeameter is tilted and tapped gently to remove air bubbles.

To initiate the test, water is allowed to flow through the specimen by opening the valve on the bottom of the permeameter. Measurement of the falling-head time history through the sample is made with a high precision pressure transducer at the base of the cylinder. This data is then transmitted directly to a computer equipped with LabTech data analysis software. Regression analysis of the head *vs*. time gives the specific discharge velocity using the relation

$$v = \frac{dh}{dt} \tag{9}$$

The permeability coefficient k, and the non-Darcy parameter m, can be determined by plotting a log-log relation of the modified Darcy law as

$$\log v = \log k + m \log i \tag{10}$$

where m is the slope and k is the v-intercept at i=1. Each sample was tested several times and the results were averaged to minimize experimental errors.

b) Constant Head Test

The schematic setup used to conduct the constant head permeability test (CHT) is illustrated in Fig. 8. As can be seen in the figure, the sample casing is the same as in the falling head test except instead of the graduated cylinder, the inlet opening is connected to a constant head reservoir (constant water level).

To initiate the test, the inlet valve is opened, and when an equilibrium flow condition is established, a shallow dish collector and a computerized flow meter were used to measure and compute the total specific discharge.

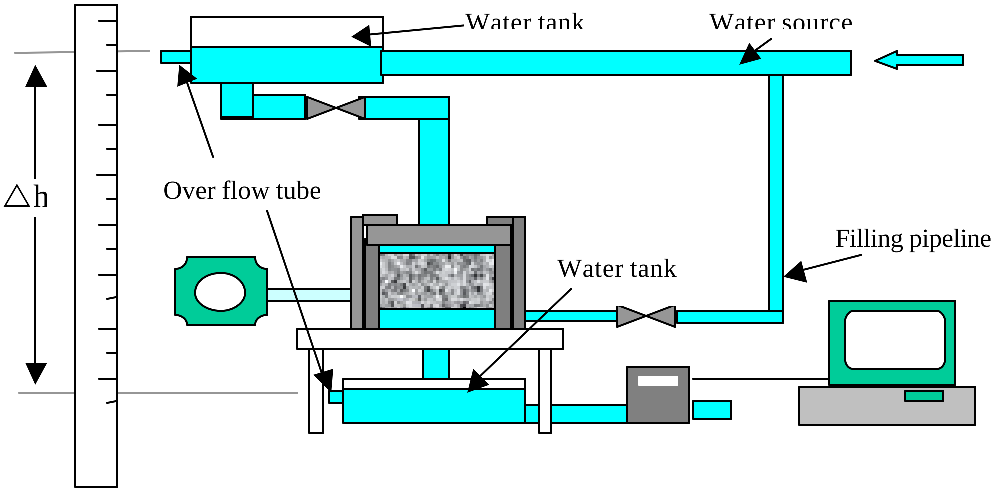


FIGURE 8 Schematic setup for constant head test.

The permeability coefficient *k*, and the non-Darcy parameter *m*, can be determined by using equation (8) for two different positions of the overflow tube, yielding two relations for the unknowns *k* and *m* as

$$\begin{aligned} v_2 &= k i_2^{\,m} \\ v_1 &= k i_1^{\,m} \end{aligned} \tag{11}$$

4.3 Result of Permeability Measurement

At least three different samples were tested for each mix design, and each sample was tested a minimum of three times. The average permeability, non-Darcy parameter and air void percentage for each mix design and their modified counterparts are presented in Table 6. The uncertainty of the permeability and the non-Darcy parameter was also recorded in this table.

The effects of mix design and binder modifiers on permeability are shown in Figure 9. The SMA mix was found to be relatively impermeable and therefore was not shown in this figure. On the other hand, Arizona and Georgia mixes exhibited relatively higher permeability with Georgia being the highest.

TABLE 6 Average permeability and VTM results for each mix design

PG64-22	VTM(%)	k	uncertainty	m	uncertainty
Arizona	13.4	0.080	0.026	0.712	0.124
SMA	10.0	0.000	0.000	0.000	0.000
Georgia	17.6	0.282	0.135	0.572	0.090
PG64-22F	VTM(%)	k	uncertainty	m	uncertainty
Arizona	12.9	0.019	0.013	0.963	0.393
SMA	9.7	0.000	0.000	0.00	0.000
Georgia	17.8	0.187	0.063	0.602	0.136
PG64-22S	VTM(%)	k	uncertainty	m	uncertainty
Arizona	14.6	0.150	0.038	0.511	0.912
SMA	11.8	0.000	0.000	0.000	0.000
Georgia	16.5	0.398	0.102	0.496	0.794
PG64-22SF	VTM(%)	k	uncertainty	m	uncertainty
Arizona	13.2	0.153	0.017	0.566	0.918
SMA	9.5	0.00	0.00	0.00	0.00
Georgia	17.0	0.290	0.198	0.44	0.605

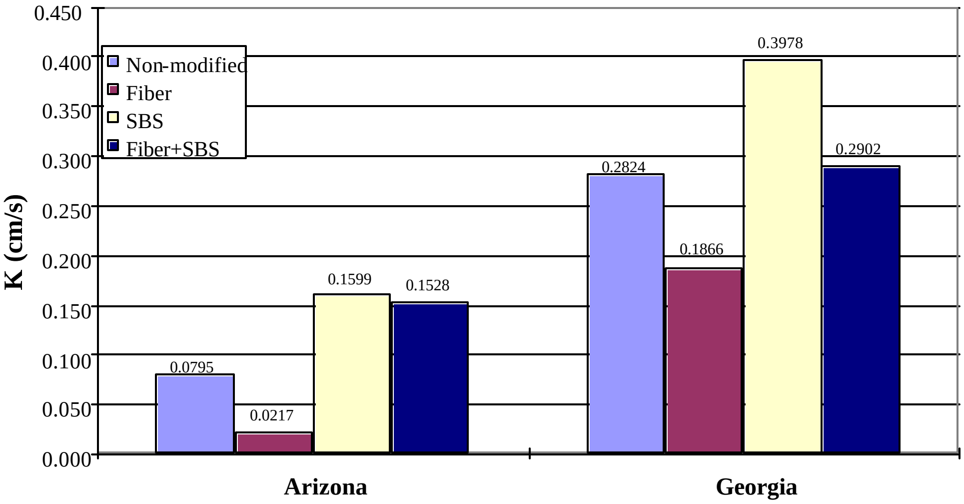


FIGURE 9 Permeability (cm/sec) results for Arizona and Georgia mix designs.

The comparison on the effects of additives generally followed the same trend on permeability for both mixes. As shown in Fig. 9, permeability decreased with fiber additive but increased with polymer (SBS) additive. When both fiber and polymer were used as modifiers, the permeability increase due to the polymer additive was reduced by the fiber content in the Arizona mix, but was nearly unchanged in the Georgia mix. In general, the reduction of the permeability due to fiber additives was nearly a factor of two while the opposite was true for polymer additives.

4.4 Effects of Elevated Temperature on Permeability

The effect of elevated temperatures on permeability was measured using the FHT. The original permeameter design was modified to accommodate the elevated temperature testing as shown in Figure 10 (the modifications depicted by the components shown in dotted lines). This was done by incorporating a controlled temperature bath into the system to both maintain the specimens and the system water at the required elevated temperature. A second reservoir was also added because the controlled temperature bath did not hold enough water to fill the whole

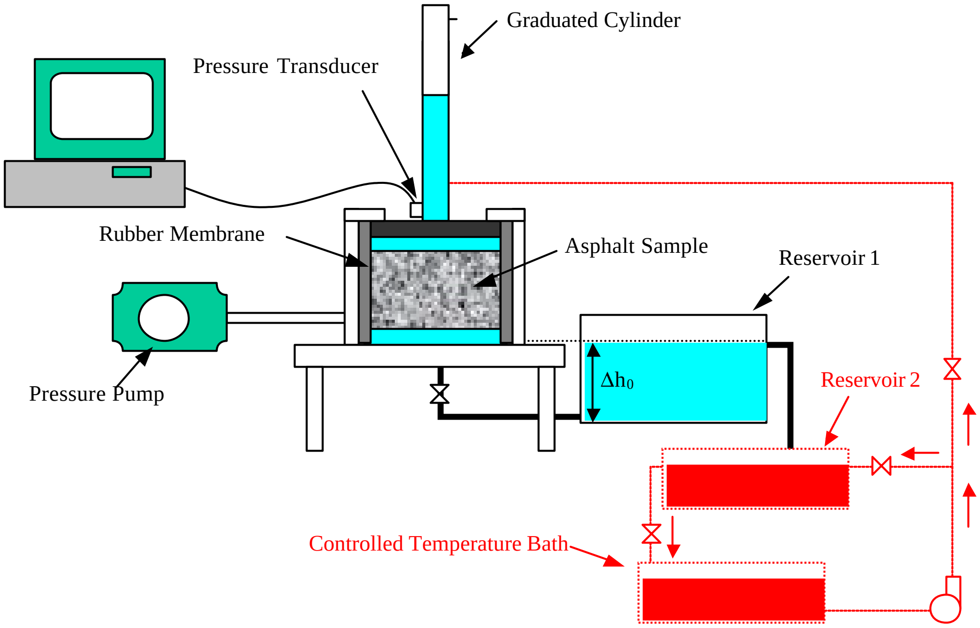


FIGURE 10 Schematic setup for falling head test with elevated temperature test modification in dotted lines.

system while housing the remaining heated samples. To maintain constant temperature between the two reservoirs, heated water was continuously circulated between this reservoir and the control bath.

Once the system reached the desired equilibrium temperature, the sample was removed from the controlled bath and placed inside the permeameter. The flow from the hot water bath was then redirected from the reservoir to the insulated graduated cylinder using a series of valves and insulated tubing as shown in Figure 10. Once the graduated cylinder was full, the permeability test was conducted in the same manner as previously described.

Upon completion of the test, the sample was returned to the hot water bath and the procedure was repeated for all samples through the temperature range of 25°C to 55°C. During the test, thermocouple probes were used to check the temperatures and/or temperature differences throughout the system to ensure that the desired temperature was maintained. After the completion of each test, a temperature reading was also taken on the specimen's core, to make certain, a significant change in temperature had not occurred.

4.5 Permeability/Temperature Results

Four Georgia samples were tested for permeability through the elevated temperature range. The results obtained from the testing are given in Figure 11. As shown, it is evident that the sample's permeability is proportional to its temperature. That is, as the temperature was raised, the permeability of the samples also increased.

Repeated testing under elevated temperature also revealed that the permeability of the samples was not only temperature dependant but also cycle dependent. This prompted the investigation of thermal cycling effects. First, sample 2 was retested through the temperature range. However, it was noted that repeated cycling lead to deformation of the sample. The

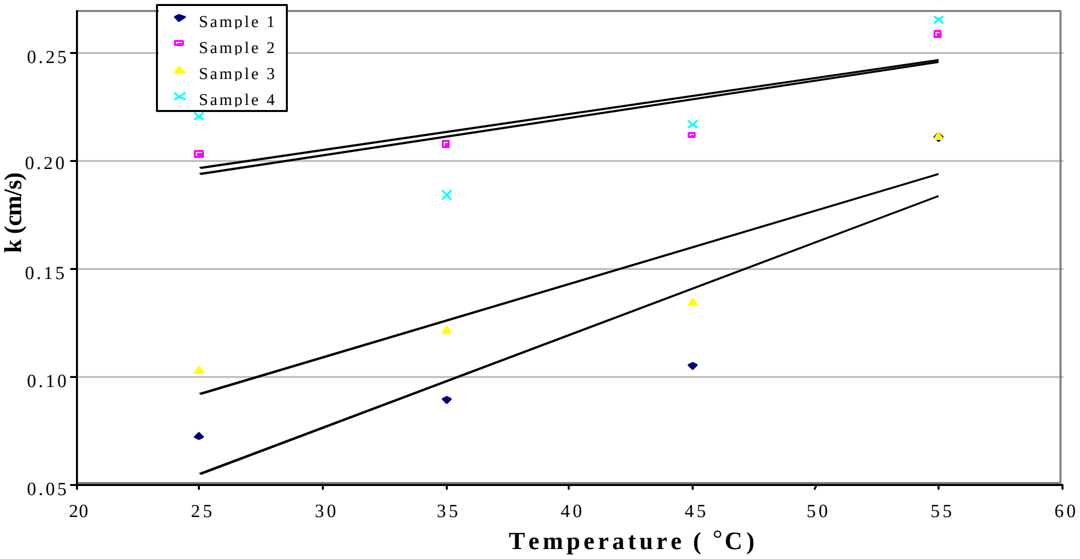
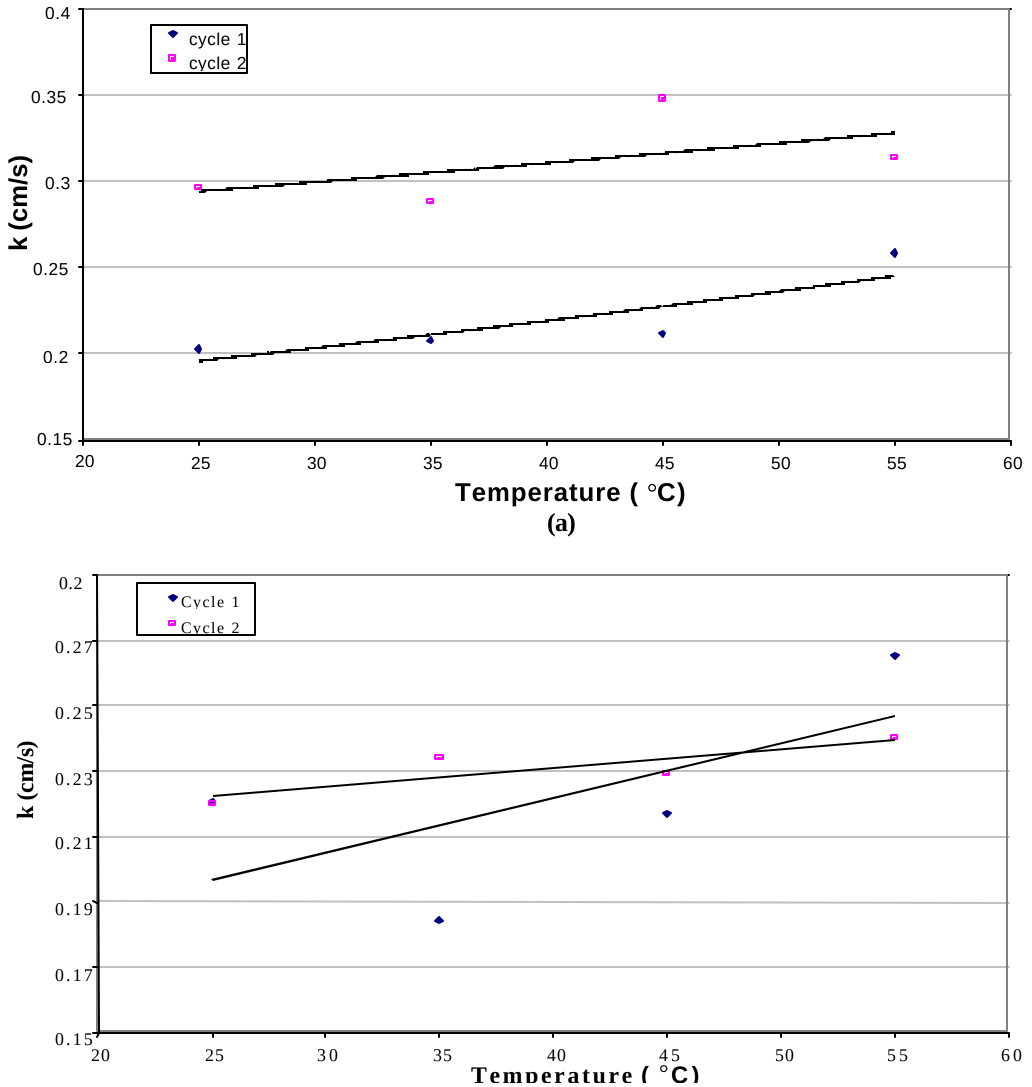


FIGURE 11 Permeability vs. temperature.

deformation made it difficult to fit the sample into the permeameter and required remolding, which was thought to affect the volumetric properties of the sample. Another testing scheme was conducted on sample 4, whereby the sample was placed into a mold while being heated and this eliminated the extensive deformation from the previous test method. The results for both cases are shown in Figs. 12 (a) and (b). As shown in the figures, the permeability plot shifts upwards with each cycle, and produces a gradual decrease in the slope through the temperature range. This behavior is expected to continue until the permeability of the sample reaches a maximum, and the plot would presumably reach a zero-slope condition. This behavior is most evident in Figure 12 (b).



(a)

(b)

FIGURE 12 Effects of test cycles on permeability vs. temperature; a) sample 2, b) sample 4.

5. STRENGTH STUDIES

In order to determine particular strength properties of the open graded asphalt material under study, indirect tension tests were conducted on samples previously used for the permeability measurements. This mechanical testing included samples of the Arizona, Georgia and SMA mixes, including material with and without additives. The goal of this testing program was to provide correlation of the mechanical/strength properties with the permeability.

5.1 Theoretical Background

The mechanical/strength behaviors were determined from standard indirect tension tests (IDT). The experimental procedure is widely used to determine the tensile or splitting strength and moduli of bituminous materials. Fig. 13 illustrates the typical IDT test geometry whereby a cylindrical specimen is loaded diametrically in compression creating a somewhat uniform tension zone along the specimen's loaded diameter.

From elasticity theory, the tensile stress normal to the diameter is given by the relation

$$S = \frac{2P}{p\,Dt} \tag{12}$$

where P is the applied load, D is the sample diameter and t is the thickness. Under simplifying assumptions of isotropic elasticity, additional relations have been developed by Dhalaan, (18) for material moduli and failure strain

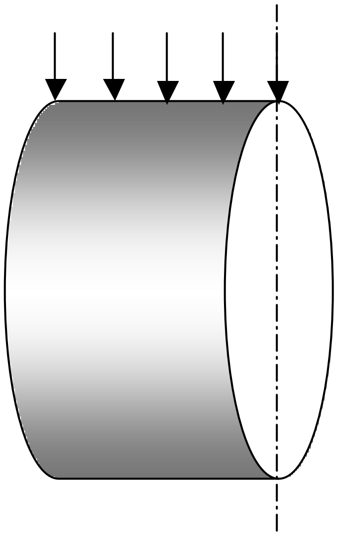


FIGURE 13 IDT Geometry.

$$
\begin{aligned}
\nu &= \frac{S_v A_1 + B_1}{S_v A_2 + B_2} \\
E &= \frac{S_h}{t}(A_3 - \nu A_4) \\
\varepsilon_f &= \Delta X \, \frac{A_5 - \nu A_6}{A_1 - \nu A_2}
\end{aligned}
\tag{13}
$$

where v is Poisson's ratio, E is the modulus of elasticity, ε_f is the sample's center-point tensile strain at failure, S_v is the slope of the line representing vertical to horizontal sample deformation, S_h is the slope of the line relating applied load to horizontal deformation, and A_i and B_i are numerical factors dependent on the sample geometry given by Dhalaan, (18). Several other tests could also be used to characterize additional mechanical properties such as rutting, raveling or abrasion associated with aging of mixes. These tests will be conducted in the second year of the project.

5.2 IDT Measurement Procedures

The IDT testing procedures were performed in accordance with ASTM standard test method D4123-82. Cylindrical samples had a standard four-inch (101mm) diameter and a thickness in the range of 2.5-2.75 inches (63-70mm). Testing was conducted on an Instron testing machine that provided output of the vertical load and deformation. The horizontal specimen deformation was measured using a special displacement fixture shown in Figure 14. As per ASTM standards, 0.5-inch (12mm) loading strips were used on the top and bottom of the specimen. The loading rate (head rate) was kept at 0.2 in/min (5mm/min). Within each mix design, several samples were tested and the results were averaged.

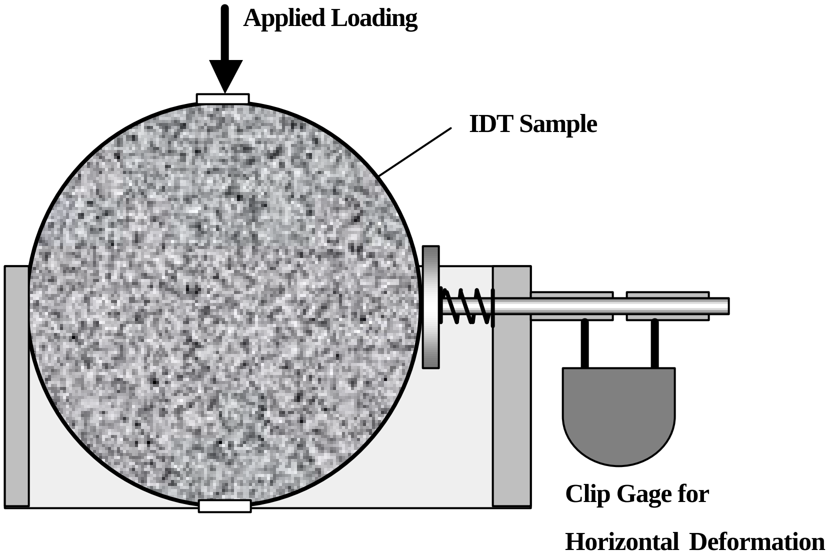


FIGURE 14 Apparatus for Measuring Horizontal Deformation.

5.3 Results of IDT Testing

The results of IDT testing are summarized in Table 7 and the complete data sets can be found in Appendix C. Shown here is the tensile strength *S*, the modulus of elasticity *E*, and Poisson's ratio *v* for each mix design as well as their modified counterparts. Of particular interest is the relationship between the sample's strength and mix design, as illustrated in Figure 15. As shown, the strength of each mix design increases only slightly with the addition of fiber alone. However, the strength nearly doubles with addition of polymer-SBS, and an even higher increase is found when both fiber and polymer are used. For the Arizona mix, very little strength effect was found due to fiber additives. Even when combined with polymer, the effects of fiber still showed little influence on the Arizona mix design.

TABLE 7 Average strength results for each mix design

PG64-22	S [MPa]	E [MPa]	ν
Arizona	0.445	5.4	0.516
SMA	0.509	-	-
Geogia	0.337	6.4	-
PG64-22F			
Arizona	0.443	12.6	0.52
SMA	0.601	-	-
Geogia	0.393	6	-
PG64-22S			
Arizona	0.776	22.3	0.387
SMA	1.038	-	-
Geogia	0.7290	18.4	-
PG64-22SF			
Arizona	0.825	20.2	0.286
SMA	1.260	-	-
Geogia	0.893	21.9	-

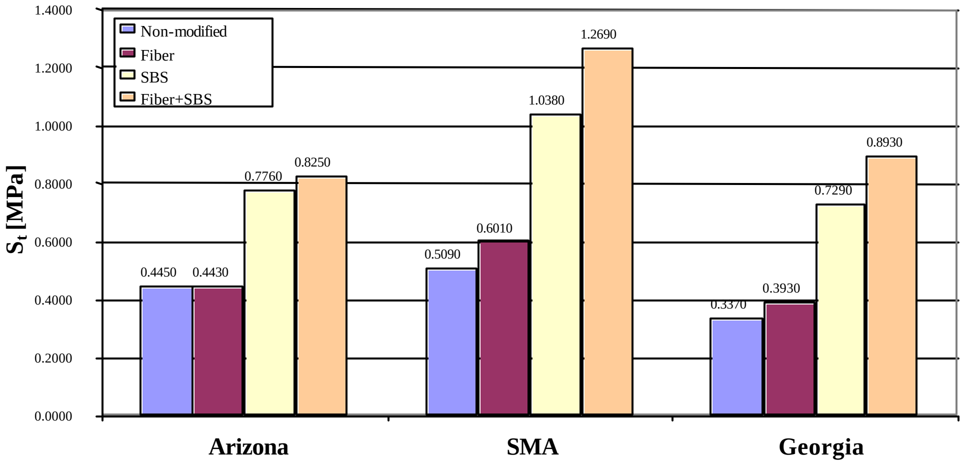


FIGURE 15 Strength results vs mix design

5.4 Effects of Elevated Temperature on Strength

The indirect tensile test was once again used to determine the strength of the specimen at elevated temperatures. The testing was conducted in the same manner as previously discussed in section 5.2 except in this case, the specimen was immersed into a controlled hot water bath set to a specific testing temperature prior to performing the actual strength tests. The specimen was not placed directly into the water, but rather into a plastic bag in order to keep the sample dry. A thermocouple was used to monitor the core sample temperature. The strength test was conducted when the sample reached the equilibrium temperature. These tests were conducted at room temperature (25°C), and at elevated temperatures of 35°C, 45°C and 55°C.

5.5 Strength/Temperature Result

As before, only the Georgia specimens were tested for strength properties at the elevated temperatures. Three specimens from the same mix were tested at each temperature. Applied load, horizontal and vertical deflections were measured and recorded. Tensile strength, modulus of elasticity and Poisson's ratio were the three properties of interest that were calculated. Results of these tests are presented in Table 8. The large values of Poison's ratio at elevated temperature are certainly not accurate and are a likely the result of inelastic deformation of the sample.

TABLE 8 Georgia strength testing at elevated temperatures

25 ºC	**1**	**2**	**3**	**Ave**
S [MPa]	0.361	0.381	0.413	0.385
E [MPa]	5.195	6.517	7.025	6.246
ν	0.485	0.149	0.410	0.348
35 ºC	**1**	**2**	**3**	**Ave**
S [MPa]	0.178	0.172	0.144	0.165
E [MPa]	2.895	3.372	1.998	2.755
ν	0.972	0.945	0.571	0.829
45 ºC	**1**	**2**	**3**	**Ave**
S [MPa]	0.068	0.054	0.067	0.063
E [MPa]	1.194	0.770	1.370	1.111
ν	0.933	0.572	0.676	0.727
55 ºC	**1**	**2**	**3**	**Ave**
S [MPa]	0.036	0.032	0.037	0.035
E [MPa]	0.647	0.578	0.719	0.648
ν	0.844	1.259	0.667	0.923

Figure 16 illustrates the effect of temperature on the average strength S taken from Table 8. As the testing temperature increased, the specimen's strength decreased significantly. It is felt that the pronounced strength decrease was enhanced since the material was an open graded mix.

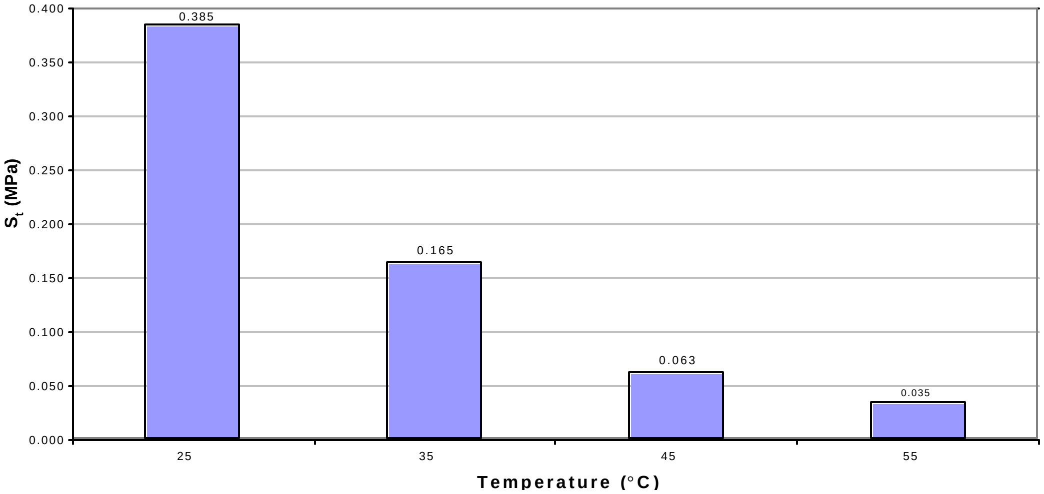


FIGURE 16 Average strength results for Georgia sample at elevated temperatures.

6. CORRELATION OF RESULTS

As mentioned earlier, percent air void of an asphalt mix is normally related to its permeability. Such a relationship for our data is illustrated in Fig. 17. Also shown in this figure, is the trendline of results given by Mallick et al (11) for dense graded mixes with no binder modifications. There is a significant difference between the two trendlines. The data range of Mallick's results is between 2.0% to 10% of air void while our data covers a wider range of air void percentage. In the range of 2.0% to 10%, the two trendlines are reasonably close. As for the effects of binder additives, the mixes with fiber additives shows lower permeability than its non-modified counterparts and the opposite is true for the mix samples with polymer modifiers. Note

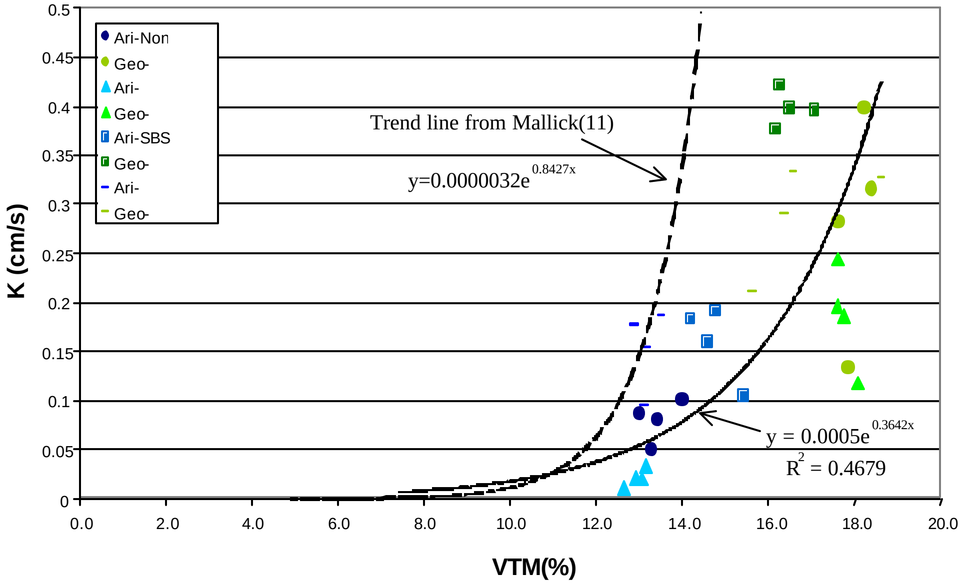


FIGURE 17 Permeability vs. VTM(%).

that the data including both modifiers lies in the mid-range along the trendline between non-modified and polymer modified mixes.

Finally, the relationship between strength and permeability is presented in Fig. 18. As seen in the figure, the two trendlines indicate a general shift in the sample's strength-permeability curve due to the effects of additives. Namely, the data for polymer and polymer+fiber modified samples clusters around the upper trendline, whereas the non-modified and fiber modified data fall on the lower trendline. This suggests that while fiber modification contributes to significant reduction in permeability, it offers relatively little increase in the strength of the specimen. On the other hand, the introduction of a SBS polymer modifier nearly doubled both the strength and permeability of the samples. When both polymer and fiber were used as modifiers, some additional strength improvements were observed but the permeability was found to decrease in comparison to a "polymer only" binder modifier

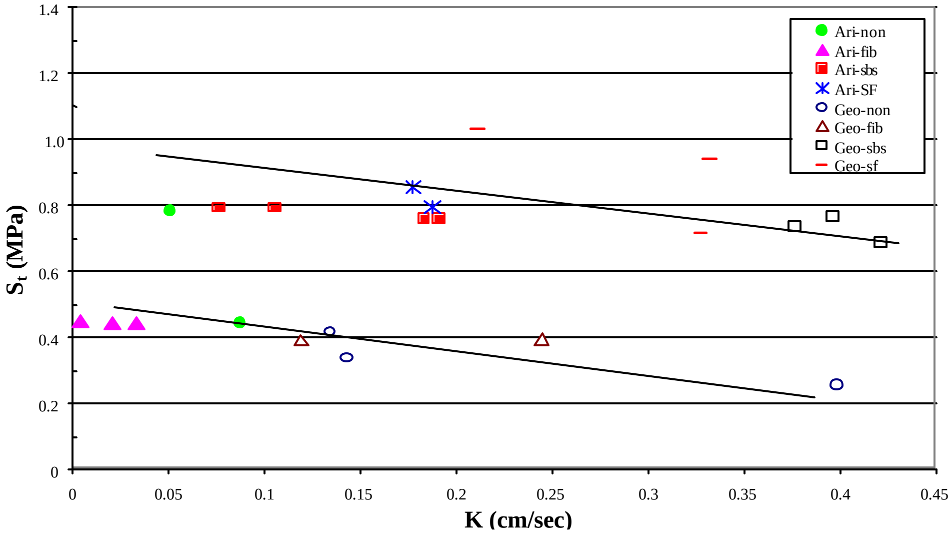


FIGURE 18 Strength versus permeability.

7. CONCLUSIONS

This report presents the results of a study on the effects of cellulose fiber and SBS polymer binder modifiers on strength and permeability of open-graded asphalt material. Four asphalt mixes were used in the study including Arizona, Georgia, Stone Matrix and an in-house mix. Standard 4-inch diameter cylindrical specimens were made using Marshall mix procedures. Permeability studies were conducted using a falling heading permeameter, and this determined the permeability coefficient and a non-Darcy parameter. Strength studies used indirect tension testing to determine the failure tensile stress and related elastic moduli. Permeability and strength behaviors were also investigated at elevated temperatures in the range 25-55^{o}C. Results of the study can be summarized as:

1.) The introduction of fiber modifiers led to minor improvement of the strength characteristics but produced a significant loss in permeability.

2.) The use of polymer modifiers nearly doubled both the strength and permeability of the samples.

3.) When both polymer and fiber modifiers were used, an additional strength improvement was observed but the permeability.
4.) The sample permeability increased with increasing temperature. This was caused by relocation of binder material within the pores.
5.) A repeat of elevated temperature testing on the same sample showed an upward shift in the permeability-temperature curve due to the repeated cycle. This could have important effects on roadway surfaces in warm climates during daily cyclic summer conditions.
6.) A significant decrease in tensile strength was found as the temperature was increased. Of course at the higher temperatures (55^{o}C) the material behavior is less elastic and more viscoelastic.
7.) The best compromise for the good strength/permeability characteristics was found by only using the polymer modifier.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

1. Thelan, E. and Howe, L., (1978) Porous Pavement, The Franklin Institute Press, Philadelphia, PA.

2. Diniz, E.V., (1980) Porous Pavement: Phase I, Design and Operational Criteria. Report EPA-600/2-80-135. Environmental Protection Agency.

3. Gemayel, C.A., and Mamlouk, M.S., (1988) Characterization of Hot-Mixed Open Graded Asphalt Mixtures. Transportation Research Record 1171, pp. 184-192.

4. Hicks, R.G., Gatch, D.R., Williamson, R., and Steward, J., (1979) Open-graded Emulsion Mixes for Use as Road Surfaces. Transportation Research Record 702, TRB, National Research Council, Washington D.C., pp. 64-72.

5. Majidzadeh, K. and Elmitiny, R., (1981) Development and Implementation of Pavement Drainage Design Guideline in Ohio. Report FHWA/OH-81/007. Ohio Department of Transportation, Columbus.

6. Qi, X. and Sebaaly P.E., (1995) Evaluation of Polymer- Modified Asphalt Concrete Mixtures, Journal of Materials in Civil Engineering, pp. 117-124.

7. Isenring, T., Harald, K., and Scazziga, I., (1990) Experience with Porous Asphalt in Switzerland, Transportation Research Record 1265, pp. 41-53.

8. Heystraeten, G.V. and Moraux, C., (1990) Ten Years Experience of Porous Asphalts in Belgium, Transportation Research Record 1265, pp. 34-40.

9. Kandhal, P.S. and Mallick, R.B., (1998) Open Graded Friction Course: State of the Practice, NCAT Report, No. 98-7.

10. Mallick, R. B., Kandhal, P. S., Cooley, L. A. and Watson, D. E., (2000) Design, Construction, and Performance of New-Generation Open-graded Friction Course, NCAT Report, No. 2000-01.

11. Mallick, R. B., Cooley, L. A., Teto, M. R., and Bradbury, R. L. (2001) An Evaluation of Factors Affecting Permeability of Superpave Designed Pavements, 80th TRB MeetingWashington D.C. Paper No. 01-2763

12. Bolzan, P.E., Nicholls, J.C., and Nuber, G.A., (2001) Searching for Superior Performing Porous Asphalt Wearing Courses, Proc. 80th TRB Meeting, Washington D.C.

13. Kanitpong, K., Benson, C. H. and Bahia, H. U., (2001) Hydraulic Conductivity (Permeability) of Laboratory Compacted Asphalt mixtures, Proc. 80th TRB Meeting, Washington, D.C.

14. Maupin, G. W., (2001) Asphalt Permeability Testing: Specimen Preparation and Testing Variability, Proc. 80th TRB Meeting, Washington, D.C.

15. Smith, R.W., Rice, J.M. and Spelman, S.R., (1974) Design of Open-Graded Asphalt Friction Courses. Report No.FHWA-RD-74-2, Federal Highway Administration.

16. Roberts, F.L., Kandhal, P.S., Brown, E.R., Lee, D. and Kennedy, T.W., (1996) Hot Mix Asphalt Materials, Mixture Design and Construction, NAPA Education Foundation, Lanlum, Maryland.

17. Hall, K.D., and Ng, H.G., (2001) Development of a Void Pathway Test for Investigating Void Interconnectivity in Compacted Hot-Mix Asphalt Concrete, Proc. 80th TRB Meeting, Washington D.C.

18. Dhalaan, M.A., (1982) Characterization and Design of Recycled Asphalt Concrete Mixtures Using Indirect Tensile Test Methods, Ph.D. Thesis, University of Texas, Austin.

10. APPENDICES

APPENDIX A: MIX VOLUMETRIC PROPERTY TEST DATA

Bulk Specific Gravity

Non-Modified	No.	Dry(g)	Dry, Coated(g)	In Water(g)	BSG	TMD	VTM(%)
Arizona	1	1161.9	1163.3	630.3	2.19	2.52	13.3
	2	1146.4	1147.9	617.6	2.17	2.52	14.0
	3	1150.0	1151.0	625.5	2.19	2.52	13.0
	Ave.				2.18	2.52	13.4
SMA	1	1145.3	1146.5	640.5	2.27	2.54	10.7
	2	1152.1	1153.4	650.6	2.30	2.54	9.6
	3	1144.7	1146.3	645.3	2.29	2.54	9.8
	Ave.				2.29	2.54	10.0
Georgia	1	1102.1	1103.5	565.3	2.05	2.51	18.2
	2	1082.7	1084.2	554.3	2.05	2.51	18.4
	3	1143.1	1144.9	588.8	2.06	2.51	17.9
	4	1114.2	1117.8	586.0	2.11	2.51	16.0
	Ave.				2.07	2.51	17.6
Fiber-Modified	**No.**	**Dry(g)**	**Dry, Coated(g)**	**In Water(g)**	**BSG**	**TMD**	**VTM(%)**
Arizona	1	1146.7	1147.6	622.8	2.19	2.52	13.2
	2	1163.2	1164.5	633.8	2.20	2.52	12.8
	3	1158.7	1159.5	632.5	2.20	2.52	12.6
	4	1158.9	1162.7	630.2	2.19	2.52	13.1
	Ave.				2.19	2.52	12.9
SMA	1	1162.9	1164.4	655.6	2.29	2.54	9.8
	2	1164.7	1167.0	656.1	2.29	2.54	9.9
	3	1171.1	1173.7	662.9	2.30	2.54	9.3
	Ave.				2.29	2.54	9.7
Georgia	1	1149.4	1150.7	590.6	2.06	2.51	18.1
	2	1160.9	1162.4	599.8	2.07	2.51	17.6
	3	1149.4	1151.1	593.7	2.07	2.51	17.6
	Ave.				2.06	2.51	17.8
SBS-Modified	**No.**	**Dry(g)**	**Dry, Coated(g)**	**In Water(g)**	**BSG**	**TMD**	**VTM(%)**
Arizona	1	1129.7	1131.2	607.4	2.16	2.52	14.2
	2	1141.3	1143.6	615.1	2.17	2.52	14.0
	3	1122.7	1124.9	600.1	2.15	2.52	14.8
	4	1139.5	1143	605.2	2.13	2.52	15.4
	Ave.				2.15	2.52	14.6
SMA	1	1148.4	1152.0	640.9	2.26	2.54	11.0
	2	1139.1	1141.1	624.9	2.21	2.54	12.8
	3	1150.5	1151.9	637.5	2.24	2.54	11.7
	Ave.				2.24	2.54	11.8
Georgia	1	1136.3	1140.4	596.6	2.10	2.51	16.2
	2	1145.7	1150.6	601	2.10	2.51	16.3
	3	1141.1	1144.4	593.2	2.08	2.51	17.1
	Ave.				2.10	2.51	16.5
SBS+Fiber-Modified	**No.**	**Dry(g)**	**Dry, Coated(g)**	**In Water(g)**	**BSG**	**TMD**	**VTM(%)**
Arizona	1	1153.8	1155.1	628.3	2.20	2.52	12.9
	2	1092.2	1092.9	593.4	2.19	2.52	13.1
	3	1145.1	1146.7	619.9	2.18	2.52	13.5
	Ave.				2.19	2.52	13.2
SMA	1	1159.3	1163.1	658.6	2.31	2.54	8.9
	2	1132.1	1133.8	638.9	2.29	2.54	9.7
	3	1169.0	1171.3	658.6	2.29	2.54	9.9
	Ave.				2.30	2.54	9.5
Georgia	1	1070.9	1073.5	546.9	2.04	2.51	18.6
	2	1131.5	1137.2	591.6	2.09	2.51	16.6
	3	1135.7	1140.9	599.8	2.12	2.51	15.6
	4	1132.5	1136.6	604.5	2.14	2.51	14.6
	Ave.				2.10	2.51	16.4

TMD: Theoretical Maximum Density ⏩ **BSG**: Bulk Specific Gravity ⏩ **VTM:** Void in Total Mix

APPENDIX B: PERMEABILITY COEFFICIENT TEST DATA

Non-modified

Arizona

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.0574	0.8169
	2	0.0437	0.8759
	3		
Ave.		**0.0506**	**0.8464**
Unc.		**0.0134**	**1.1745**
2	1	0.2692	0.3440
	2	0.1090	0.7068
	3	0.0929	0.7581
Ave.		**0.1010**	**0.6030**
Unc.		**0.0091**	**0.2554**
3	1	0.0815	0.7212
	2	0.1006	0.6213
	3	0.0793	0.7143
Ave.		**0.0871**	**0.6856**
Unc.		**0.0133**	**0.0631**
none	1		
	2	No Sample	
	3		
Ave.			
Unc.			

Georgia

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.4519	0.4759
	2	0.2882	0.6617
	3	0.4532	0.4529
Ave.		**0.3978**	**0.5302**
Unc.		**0.1074**	**0.1296**
2	1	0.3165	0.4665
	2	0.3745	0.4828
	3	0.2556	0.5832
Ave.		**0.3155**	**0.5108**
Unc.		**0.0673**	**0.0715**
3	1	0.1489	0.6341
	2	0.1017	0.7741
	3	0.1510	0.6186
Ave.		**0.1339**	**0.6756**
Unc.		**0.0315**	**0.0969**
4	1	0.1529	0.4190
	2	0.1362	0.4670
	3	0.1384	0.4540
Ave.		**0.1425**	**0.4467**
Unc.		**0.0103**	**0.0281**

Fiber Modified

Arizona

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.0709	0.6502
	2	0.0345	0.9252
	3	0.0321	0.9119
Ave.		**0.0333**	**0.9186**
Unc.		**0.0019**	**0.2149**
2	1		
	2	0.0191	0.8673
	3	0.0167	0.9176
Ave.		**0.0119**	**0.5950**
Acc.		**0.5838**	**0.0000**
3	1	0.0138	1.3149
	2	0.0153	1.1589
	3	0.0044	1.6558
Ave.		**0.0112**	**1.3765**
Unc.		**0.0067**	**0.2876**
4	1	0.0262	0.7823
	2	0.0191	0.8673
	3	0.0167	0.9176
Ave.		**0.0207**	**0.8557**
Unc.		**0.0000**	**0.0056**

Georgia

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.1284	0.7192
	2	0.1267	0.7098
	3	0.1018	0.7937
Ave.		**0.1190**	**0.7409**
Unc.		**0.0169**	**0.0520**
2	1	0.1950	0.6406
	2	0.2344	0.5484
	3	0.1982	0.6050
Ave.		**0.1966**	**0.5980**
Unc.		**0.0303**	**0.0526**
3	1	0.2334	0.4963
	2	0.2572	0.4473
	3	0.2418	0.4619
Ave.		**0.2441**	**0.4685**
Unc.		**0.0137**	**0.0285**
none	1		
	2	No Sample	
	3		
Ave.		**0.0000**	**0.0000**
Unc.		**0.0000**	**0.0000**

SBS Modified

Arizona

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.1600	0.5363
	2	0.1680	0.5168
	3	0.2210	0.4126
Ave.		**0.1830**	**0.4886**
Unc.		**0.0375**	**0.0753**
2	1	0.0740	0.5606
	2	0.0790	0.5242
	3	0.0760	0.5374
Ave.		**0.0763**	**0.5407**
Acc.		**0.0209**	**0.0000**
3	1	0.2000	0.4848
	2	0.1980	0.4911
	3	0.1750	0.5382
Ave.		**0.1910**	**0.5047**
Unc.		**0.0157**	**0.0330**
4	1	0.1007	0.5962
	2	0.1098	0.5693
	3	0.1066	0.5632
Ave.		**0.1057**	**0.5762**
Unc.		**0.0000**	**0.0052**

Georgia

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.3730	0.4553
	2	0.3680	0.4436
	3	0.3880	0.4241
Ave.		**0.3763**	**0.4410**
Unc.		**0.0118**	**0.0178**
2	1	0.4638	0.4043
	2	0.4440	0.4157
	3	0.3550	0.5236
Ave.		**0.4209**	**0.4479**
Unc.		**0.0656**	**0.0745**
3	1	0.4330	0.4541
	2	0.3380	0.5580
	3	0.4170	0.7868
Ave.		**0.3960**	**0.5996**
Unc.		**0.0576**	**0.1926**
none	1		
	2	No Sample	
	3		
Ave.		**0.0000**	**0.0000**
Unc		**0.0000**	**0.0000**

Fiber-SBS Modified

Arizona

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.1673	0.43
	2	0.187	0.59
	3		
Ave.		**0.1772**	**0.5055**
Unc.		**0.0193**	**0.7178**
2	1	0.0944	0.612
	2	0.0938	0.6051
	3		
Ave.		**0.0941**	**0.6086**
Unc.		**0.0006**	**0.8434**
3	1	0.169	0.6299
	2	0.205	0.5382
	3		
Ave.		**0.1870**	**0.5841**
Unc.		**0.0353**	**0.8144**
none	1		
	2	No Sample	
	3		
Ave.		**0.0000**	**0.0000**
Unc.		**0.0000**	**0.0000**

Georgia

Specimen No.	Trial No.	k (cm/sec)	m
1	1	0.3510	0.3971
	2	0.3430	0.4051
	3	0.2880	0.48
Ave.		**0.3273**	**0.4272**
Unc.		**0.0388**	**0.0513**
2.2	1	0.3129	0.4541
	2	0.3175	0.4466
	3	0.3651	0.3855
Ave.		**0.3318**	**0.4287**
Unc.		**0.0269**	**0.0426**
3	1	0.218	0.4582
	2	0.208	0.4666
	3	0.208	0.47
Ave.		**0.2113**	**0.4649**
Unc.		**0.0065**	**0.0069**
4	1	0.1900	0.5061
	2	0.2000	0.4997
	3		
Ave.		**0.1950**	**0.5029**
Unc.		**0.1561**	**0.4024**

Unc: Uncertainty ▶▶ **Ave**: Average ▶▶ **k**: Permeability coefficient ▶▶ **m**: Non-Darcy parameter

APPENDIX C: INDIRECT STRENGTH TEST DATA

Arizona

Non modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	0.783		0.445	-	0.614
E (Elastic modulus) [MPa]	5.4			-	5.4
n (Poisson's ratio)	0.516			-	0.5160
k (Permeability) [cm/s]	0.0506	0.101	0.0871	-	0.0796
m (Non Darcy parameter)	0.8464	0.603	0.6856	-	0.7117
VTM [%]	13.3	14.0	13.0	-	13.4

Fiber modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	0.44	0.45		0.44	0.443
E (Elastic modulus) [MPa]	16.0			9.1	12.6
n (Poisson's ratio)	0.772			0.268	0.5200
k (Permeability) [cm/s]	0.0333	0.0041	0.0112	0.0207	0.0173
m (Non Darcy parameter)	0.9186	1.6405	1.3765	0.8557	1.1978
VTM [%]	13.2	12.8	12.6	13.1	12.9

SBS modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	0.758	0.793	0.758	0.793	0.776
E (Elastic modulus) [MPa]	22.8	29.3	19.2	17.8	22.3
n (Poisson's ratio)	0.448	0.498	0.365	0.237	0.387
k (Permeability) [cm/s]	0.1830	0.0763	0.1910	0.1057	0.1390
m (Non Darcy parameter)	0.4886	0.5407	0.5047	0.5762	0.5276
VTM [%]	14.2	14.0	14.8	15.4	14.6

SBS+Fiber modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	0.856		0.793	-	0.825
E (Elastic modulus) [MPa]	19.1	23.8	17.6	-	20.2
n (Poisson's ratio)	0.330		0.242	-	0.286
k (Permeability) [cm/s]	0.1772	0.0941	0.187	-	0.1528
m (Non Darcy parameter)	0.5055	0.6086	0.5841	-	0.5661
VTM [%]	12.9	13.1	13.5	-	13.2

SMA

Non modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]		0.509		-	0.509
E (Elastic modulus) [MPa]				-	
n (Poisson's ratio)				-	
k (Permeability) [cm/s]	-	-	-	-	-
m (Non Darcy parameter)	-	-	-	-	-
VTM [%]	10.7	9.6	9.8	-	10.0

Fiber modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	0.626	0.575		-	0.601
E (Elastic modulus) [MPa	318.5			-	318.5
n (Poisson's ratio)	0.212			-	0.2120
k (Permeability) [cm/s]	-	-	-	-	-
m (Non Darcy parameter)	-	-	-	-	-
VTM [%]	9.8	9.9	9.3	-	9.7

SBS modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	1.06	1.057	0.998	-	1.038
E (Elastic modulus) [MPa	371.6	339.3	489.9	-	400.3
n (Poisson's ratio)	0.118	0.394	0.384	-	0.2987
k (Permeability) [cm/s]	-	-	-	-	-
m (Non Darcy parameter)	-	-	-	-	-
VTM [%]	11.0	12.8	11.7	-	11.8

SBS+Fiber modified

Sample number	1	2	3	4	Ave
S_t (Strength) [MPa]	1.36	1.311	1.135	-	1.269
E (Elastic modulus) [MPa	706.4	696.0	698.5	-	700.3
n (Poisson's ratio)	0.179	0.586	-0.039	-	0.2420
k (Permeability) [cm/s]	-	-	-	-	-
m (Non Darcy parameter)	-	-	-	-	-
VTM [%]	8.9	9.7	9.0	-	9.2

Georgia

Non modified

Sample number	**1**	**2**	**3**	**4**	**Ave**
S_t (Strength) [MPa]	0.257		0.416	0.338	0.337
E (Elastic modulus) [MPa]	1.5			11.3	6.4
n (**Poisson's ratio)**					
k (Permeability) [cm/s]	0.3978	0.3155	0.1339	0.1425	0.2474
m (Non Darcy parameter)	0.5302	0.5108	0.6756	0.4467	0.5408
VTM [%]	18.2	18.4	17.9	16.0	17.6

Fiber modified

Sample number	**1**	**2**	**3**	**4**	**Ave**
S_t (Strength) [MPa]	0.391		0.395	-	0.393
E (Elastic modulus) [MPa]	6.0			-	6.0
n (**Poisson's ratio)**			0	-	0.0000
k (Permeability) [cm/s]	0.1190	0.1966	0.2441	-	0.1866
m (Non Darcy parameter)	0.7409	0.5980	0.4685	-	0.6025
VTM [%]	18.1	17.6	17.6	-	17.8

SBS modified

Sample number	**1**	**2**	**3**	**4**	**Ave**
S_t (Strength) [MPa]	0.734	0.685	0.763	0.734	0.729
E (Elastic modulus) [MPa]	17.0	11.7	25.2	19.7	18.4
n (**Poisson's ratio)**				0	0.0000
k (Permeability) [cm/s]	0.3763	0.4209	0.3960		0.3977
m (Non Darcy parameter)	0.4410	0.4479	0.5996		0.4962
VTM [%]	16.2	16.3	17.1	14.6	16.1

SBS+Fiber modified

Sample number	**1**	**2**	**3**	**4**	**Ave**
S_t (Strength) [MPa]	0.714	0.939	1.027		0.893
E (Elastic modulus) [MPa]	14.7	25.5	25.5		21.9
n (**Poisson's ratio)**				0	0.0000
k (Permeability) [cm/s]	0.3273	0.3318	0.2113	0.1950	0.2664
m (Non Darcy parameter)	0.4272	0.4287	0.4649	0.5029	0.4559
VTM [%]	18.6	16.6	15.6	14.6	16.4