Technical Report Documentation Page

1. Report No. FHWA/TX-97/1238-1F	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle PERMEABILITY OF COARSE MATRIX-HIGH BINDER MIXTURES AND ITS EFFECTS ON PERFORMANCE	5. Report Date April 1997
	6. Performing Organization Code
7. Author(s) Richard P. Izzo and Joe W. Button	8. Performing Organization Report No. Research Report 1238-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. Study No. 0-1238
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	13. Type of Report and Period Covered Final: April 1995 - March 1997
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Study Title: Permeability of Coarse Matrix-High Binder Mixtures and Its Effects on Performance

16. Abstract

The primary objective of this study is to evaluate permeability of coarse matrix-high binder (CMHB) mixtures in comparison with dense-graded mixtures and estimate the relative effects on pavement performance. Specific objectives include (1) developing a permeability test protocol, (2) comparing oxidative aging of CMHB and dense-graded mixtures, (3) comparing moisture susceptibility of CMHB and dense-graded mixtures, (4) monitoring field performance of CMHB field test pavements, and (5) suggesting methods to optimize performance of CMHB mixtures.

The scope of the laboratory work includes 3 aggregate types (limestone, sandstone, and siliceous) and 4 grades of asphalt cement. Engineering properties measured include permeability; stability; resistance to permanent deformation, water, and oxidation; voids in the mineral aggregate; and air void content.

Findings indicate CMHB mixtures are more permeable than dense-graded mixtures at similar air void contents; however, these differences are generally small and often statistically insignificant. Permeability of newly constructed CMHB pavements is often quite high, but usually decreases rapidly with traffic to acceptable levels. Flushing was the most common form of early CMHB pavement distress. However, this was usually explained by excessive asphalt above the optimum. Because of the coarse texture, even with some flushing the texture appeared comparatively good. TxDOT static creep testing did not conclusively establish that CMHB mixtures are less rut-susceptible than corresponding dense-graded mixtures. CMHB mixtures are generally more resistant to moisture damage and oxidative aging than dense-graded mixtures made using similar materials.

17. Key Words Asphalt, Pavements, Hot Mix Asphalt, Bituminous, Coarse Matrix-High Binder, Stone Matrix Asphalt, Permeability	18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 178	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PERMEABILITY OF COARSE MATRIX-HIGH BINDER MIXTURES AND ITS EFFECTS ON PERFORMANCE

by

Richard P. Izzo
Graduate Research Associate
Texas Transportation Institute

and

Joe W. Button
Research Engineer
Texas Transportation Institute

Research Report 1238-1F
Research Study Number 0-1238
Research Study Title: Permeability of Coarse Matrix-High Binder Mixtures and Its Effects on Performance

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

April 1997

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

Based on results of laboratory and field experiments, the following implementation concepts are recommended:

1. Compacted CMHB mixtures are more permeable than typical dense-graded mixtures fabricated using similar materials. Higher coarse aggregate content or larger maximum size stones in compacted asphalt mixtures will create fewer but larger voids than those in typical dense-graded mixtures at a given air void level. For example, asphalt mixtures made using fine sand and containing air voids up to 20% may exhibit very low permeability; whereas, large stone mixtures (>25 mm) containing 5% voids may exhibit significant permeability. The relatively high permeability of most newly placed CMHB mats should not normally present serious long-term pavement performance problems regarding damage by water and air (oxygen). The relatively thicker asphalt films in CMHB mixtures provide added protection from moisture damage and oxidative aging. After one year in service, the permeability of CMHB mixtures can be expected to decrease to acceptable levels. Higher initial permeability should not deter TxDOT from applying CMHB mixtures.

2. When placing CMHB as a surface course over flexible base, an impermeable layer (underseal and/or dense HMA) should be placed immediately beneath the CMHB. Because of its relatively higher permeability during the first year or two, water can leak into an unprotected base and, if it is susceptible to moisture damage, weaken the pavement structure.

3. A step-by-step procedure for measuring permeability of asphalt concrete mixtures was developed and is contained in Appendix F. This protocol exhibited excellent repeatability. It is not recommended that TxDOT routinely measure permeability of asphalt mixtures, including CMHB mixtures. However, the procedure is recommended for use in research and/or forensic studies.

4. Construction specifications for Item 340, Hot Mix Asphalt Concrete Pavement, requires design of mixtures at 4% air voids and allows 5% to 9% air voids at construction. Special Specification Item 3016, CMHB, requires design of mixtures at 3% air voids but also allows 5% to 9% air voids at construction. Since the air void tolerance allowed at construction is 1% larger for CMHB mixtures than for dense-graded mixtures, there can consequently be a greater negative effect on permeability, strength, stiffness, and stability of CMHB mixtures. Therefore, it may be desirable to modify the specifications for CMHB paving mixtures to allow 4% to 8% air voids at construction.

5. Construction specifications for CMHB paving mixtures should be modified to require more stringent field control of asphalt content to reduce the probability of flushing. Current specification wording that encourages the use of higher binder contents to achieve density should be modified.

6. Although the TxDOT static creep test did not conclusively demonstrate that CMHB mixtures are more resistant to rutting than dense-graded mixtures made using similar materials, the researchers believe that the coarse aggregate skeleton afforded by CMHB mixtures will prove to have superior rut resistance in subsequent field evaluations. (The authors believe that coarse-graded asphalt concrete mixtures like CMHB and SMA mixtures require a confining pressure which is not provided in the TxDOT creep protocol to fully mobilize their available shear strength.) Although not specifically addressed in this study, the relatively high asphalt film thickness in CMHB mixtures should be a positive attribute for reducing fatigue cracking. TxDOT should continue to apply CMHB mixtures to reduce rutting and cracking in asphalt concrete pavements.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT), or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation.

There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine, manufacture, design or composition of matter, or any new and useful improvement thereof, or any variety of plant which is or may be patentable under the patent laws of the United States of America or any foreign country.

ACKNOWLEDGMENT

Special thanks are extended to the following TxDOT personnel for supplying materials and mixture designs to produce CMHB and dense-graded asphalt paving mixtures in the laboratory.

Atlanta District - Mr. Miles R. Garrison
Materials and Tests Division - Mr. Johnny Lane and Mr. Earl Leaverton
Paris District - Mr. Bobby Jones

Appreciation is offered to the following TxDOT personnel for providing pavement cores for laboratory evaluation.

Atlanta District - Mr. Miles R. Garrison
Bryan District - Mr. Craig Hogan, Mr. Al Farrell, and Mr. David L. McCannon
Odessa District - Ms. Katherine C. Evans and Mr. Steve Smith

Mr. Maghsoud Tahmoressi served as Project Director on this study. His valuable advice and assistance in establishing a work plan and locating and evaluating the materials is gratefully acknowledged.

Laboratory testing at TTI was performed by Mr. Sidney Greer, Mr. Gene Schlieker, Mr. Lee Gustavus, and Mr. Richard Izzo.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

SUMMARY

STATEMENT OF THE PROBLEM

Through the years, many design and material alternatives have been suggested to produce rut-resistant pavements. Major rutting problems can only be addressed by ensuring adequate aggregate characteristics, such as gradation, maximum size, internal friction, and bond strength with asphalt (resistance to water damage).

TxDOT has developed a novel asphalt paving mixture called coarse matrix-high binder (CMHB) and an associated mixture design procedure. The concept strives to increase stone-on-stone contact of the largest stones in the mixture, thereby maximizing confined shear strength. The mixture is typically designed with 3% air voids. However, field experience indicated the CMHB mixture is more permeable than a conventional dense-graded mixture at similar air void contents. Researchers measured the permeability of CMHB mixtures in comparison to conventional mixtures.

Engineering judgment would contend that the thicker-than-usual asphalt films in the CMHB mixture should provide excellent protection from damage by oxidation and moisture. These perceptions need to be substantiated by controlled laboratory and field testing. Moisture susceptibility and aging resistance of CMHBs need to be evaluated and compared with conventional mixtures.

Several CMHB overlays have been placed in various locations around the state. Performance of selected CMHB overlays and any associated control sections (conventional dense-graded mixtures) should be monitored continuously throughout their useful lives to fully assess the cost effectiveness of this new type of paving mixture.

OBJECTIVES OF STUDY

The ultimate goal of this study is to provide TxDOT with an evaluation of CMHB mixtures. Specific objectives to reach this goal are:

- Develop or identify permeability test protocols suitable for measuring permeability of CMHB and dense-graded mixtures in the laboratory and in the field,
- Measure permeability of CMHB and dense-graded mixtures,
- Compare oxidative aging of CMHB and dense-graded mixtures,
- Compare moisture susceptibility of CMHB and dense-graded mixtures,
- Monitor field performance of CMHB field-test pavements and compare performance with control sections of conventional dense-graded mixtures, and
- Suggest methods to optimize performance of CMHB mixtures.

EXPERIMENT DESIGN

Researchers tested Type C (16 mm nominal maximum size) CMHB and corresponding Type C dense-graded mixtures made using similar materials. Three types of crushed aggregate and 4 grades of asphalt binder were used to fabricate asphalt concrete specimens. The aggregates included limestone from the Austin district, sandstone from Paris district, or siliceous gravel from the Atlanta district. The binders included AC-10, AC-20, AC-45P, and AC-20 modified with 3% latex.

Engineering properties of compacted mixtures at controlled air void contents included water permeability, stability, resistance to permanent deformation, moisture susceptibility, and age hardening susceptibility. Permeability was measured on laboratory-fabricated specimens as well as pavement cores. A modified TxDOT static creep test was conducted on all mixtures. The resilient modulus and indirect strength tests were performed on unaged, short-term and long-term aged specimens. Mixture aging was performed in accordance with Superpave requirements. Unaged and aged binders were tested to determine penetration and Superpave performance grade.

Researchers evaluated several existing CMHB pavements and, to the extent possible, compared them to pavements surfaced with conventional dense-graded mixtures. Construction parameters as well as subsequent pavement performance were surveyed. Nineteen pavement sites in 10 districts across the state of Texas were evaluated in the spring/summer of 1995 and 1996. Investigators used the SHRP field evaluation procedures to assess the condition the pavements.

A questionnaire was formulated and sent to all TxDOT districts to obtain subjective evaluations of construction and performance of CMHB pavements. Researchers visited several districts, either in person or by phone, to obtain detailed information.

CONCLUSIONS

- CMHB mixtures are more permeable than dense-graded mixtures made using similar materials. However, the magnitude of these differences is generally small and often statistically insignificant. This difference decreases with air void level.
- Permeability of CMHB and dense-graded mixtures increases almost linearly with air void content up to about 8%-10% air voids. Above 8%-10% air voids, however, permeability begins to level off or the slope of the curve rapidly decreases. This indicates that permeability increases only slightly as the air void content exceeds 8%.
- Permeability of 2 newly constructed CMHB pavements was relatively high; whereas, permeability of 2 other CMHB pavements exposed to 1 year of traffic was about 2 orders of magnitude lower and similar to that of dense-graded pavements. This indicates that, after 1 year of traffic, permeability should not be a concern.
- Following periods of precipitation, some CMHB pavements exhibited wet spots on the surface or drainage from the edge of the mat for up to 3 or 4 days after rainfall ceased. Permeabilities of cores drilled from such wet and dry areas were not significantly different.
- Field surveys revealed that flushing was the most common form of early pavement distress. However, this was usually explained by excessive asphalt above the optimum. Because of the coarse aggregate grading, even with some flushing, the pavement texture appeared comparatively good.

- The TxDOT static creep testing did not conclusively establish that CMHB mixtures are less rut-susceptible than corresponding dense-graded mixtures. (The authors believe that mixtures made with coarse materials like CMHB and SMA, which is not provided by the TxDOT creep protocol, require a confining pressure to fully mobilize their available shear strength.)
- CMHB mixtures are generally more resistant to moisture damage than dense-graded mixtures made using similar materials.
- CMHB mixtures are generally more resistant to oxidative aging than dense-graded mixtures made using similar materials.

RECOMMENDATIONS

- The relatively high permeability of newly placed CMHB mixtures should not present long-term pavement performance problems regarding damage by water and air (oxygen). TxDOT should continue to apply CMHB mixtures.
- When placing CMHB as a surface course over flexible base, an impermeable layer (underseal and/or dense HMA) should be placed immediately beneath the CMHB. Because of the CMHB's relatively higher permeability during the first year or two, water can leak into an unprotected base and, if it is susceptible to moisture damage, weaken the pavement structure.
- A procedure was developed to measure permeability of asphalt concrete mixtures and is contained in Appendix F. This protocol exhibited excellent repeatability. It is not recommended that TxDOT routinely measure permeability of asphalt mixtures. However, the procedure is recommended for use in research or forensic studies.
- Although the TxDOT static creep test did not conclusively demonstrate that CMHB mixtures are more resistant to rutting than dense-graded mixtures made using similar materials, the coarse aggregate skeleton provided by CMHB mixtures should prove its rut resistance in the field in subsequent evaluations. The relatively high asphalt film thickness in CMHB mixtures should be a positive attribute for reducing cracking. TxDOT should continue to apply CMHB mixtures to reduce rutting and cracking in

asphalt concrete pavements.

- Construction specifications for Item 340, Hot Mix Asphalt Concrete Pavement, requires design of mixtures at 4% air voids and allows 5% to 9% air voids at construction. Special Specification Item 3016, CMHB, requires design of mixtures at 3% air voids but also allows 5% to 9% air voids at construction. Since the air void tolerance allowed at construction is 1% further from the design value for CMHB mixtures than for dense-graded mixtures, there will be a greater negative effect on permeability, strength, stiffness, and stability of CMHB mixtures. Therefore, it may be desirable to modify the construction specifications for CMHB paving mixtures to allow 4% to 8% air voids at construction.
- Construction specifications for CMHB paving mixtures need to be modified to provide more stringent field control of asphalt content to reduce the probability of flushing.

CHAPTER I

INTRODUCTION

STATEMENT OF THE PROBLEM

Rutting of flexible pavements continues to be a problem. Many design and material alternatives have been suggested over the years to produce more rut-resistant pavements. These materials include both elastomeric and thermoplastic polymers, as well as fillers, stiffeners, and fibers, to increase the viscosity of the asphalt binder and thus the mass viscosity of the paving mixture. Stiffer asphalt binders can certainly contribute to the rut-resistance of a paving mixture but binder modification alone cannot be expected to solve a major rutting problem. Various mixture design changes have also been explored, including requiring angular aggregate, limiting rounded sand content, large-stone mixtures, additives and admixtures, and lower asphalt contents.

The Strategic Highway Research Program (SHRP) has developed a completely new set of asphalt binder specifications, test protocols, and mixture design procedures with the primary goal of improving asphalt pavement performance, including rutting. In the SHRP program, little consideration was given to aggregate gradation or quality. Major rutting problems can only be addressed by ensuring adequate aggregate characteristics such as gradation, maximum size, internal friction, and bond strength with asphalt (resistance to water damage).

The Texas Department of Transportation (TxDOT) has developed a novel asphalt paving mixture called coarse matrix-high binder (CMHB) and an associated mixture design procedure. The concept strives to increase stone-on-stone contact of the largest stones in the mixture thereby maximizing confined shear strength. The mixture is typically designed with 3% air voids. However, field experience indicated the CMHB mixture is more permeable than a conventional dense-graded mixture at similar air void contents. Testing needs to be performed to measure the permeability of CMHB mixtures in comparison to conventional mixtures.

Engineering judgment would contend that the thicker-than-usual asphalt films in the CMHB mixture should provide excellent protection from damage by oxidation and moisture.

These perceptions need to be substantiated by controlled laboratory and field testing. Moisture susceptibility and aging resistance of CMHBs needs to be evaluated and compared with conventional mixtures.

Several CMHB overlays have been placed in various locations around the state. Performance of selected CMHB overlays and any associated control sections (conventional dense-graded mixtures) should be monitored continuously throughout their useful lives to fully assess the cost effectiveness of this new type of paving mixture.

BACKGROUND ON CMHB MIXTURES

A CMHB paving mixture is a gap-graded, dense, crushed aggregate hot mixed asphalt with a large proportion of coarse aggregate and a rich asphalt cement/filler mastic. A CMHB is similar to a stone mastic asphalt mixture (SMA) but designed to eliminate the need for modified binders. The coarse aggregate forms a high stability structural skeleton and the asphalt cement, fine aggregate, and filler form a mastic which binds the structural skeleton together.

The following lists some of the characteristics of CMHB mixtures.

Reasons for Using CMHBs

- High stability - resists rutting (coarse stone skeleton),
- Good resistance to cracking - fatigue, thermal (thick asphalt films),
- Resists oxidation (thick asphalt films),
- Resists damage by water (thick asphalt films),
- Provides excellent surface friction (high percentage of coarse angular aggregate),
- Less sensitive to binder content than conventional mixes, and
- Ease of placement and compaction.

Impediments for Using CMHBs

- Higher initial cost than conventional mixes, and
- Lack of knowledge about long-term performance.

Hot Mix Technology

- Mix design air voids of about 3%,
- Gyratory compactor for preparation of mixture design specimens,
- Minimum of 85% crushed aggregates with adequate frictional properties,
- Coarse aggregate (plus 2 mm) content at 75% to 85%,
- Maximum aggregate size of 13 mm to 22 mm,
- Asphalt cement: AC-20 or harder, and
- When confined, mix stiffens under load from dilation due to coarse stone skeleton.

Production and Placement of CMHBs

- Less sensitive to construction difficulties (e.g., segregation).

OBJECTIVES OF STUDY

The ultimate goal of this study is to provide TxDOT with an evaluation of CMHB mixtures. Specific objectives used by the researchers to reach these goal are:

- Develop or identify permeability test protocols suitable for measuring permeability of CMHB and dense-graded mixtures in the laboratory and in the field,
- Measure permeability of CMHB and dense-graded mixtures,
- Compare oxidative aging of CMHB and dense-graded mixtures,
- Compare moisture susceptibility of CMHB and dense-graded mixtures,
- Monitor field performance of CMHB field test pavements and compare performance with control sections of conventional dense-graded mixtures, and
- Suggest methods to optimize performance of CMHB mixtures.

SCOPE OF STUDY

The scope of the laboratory work includes 3 aggregate types and 4 grades of asphalt cement. Engineering properties measured include permeability, stability, water susceptibility, age hardening susceptibility, voids in the mineral aggregate, and air void content. TxDOT static creep tests were conducted on all mixtures.

Nineteen pavement sites in 10 TxDOT districts were surveyed in the summers of 1995 and 1996. Information collected was used to evaluate ease of construction and short-term performance of CMHB overlays.

CHAPTER II
TECHNICAL LITERATURE REVIEW

The goal of this research was to evaluate the comparative performance of coarse matrix-high binder (CMHB) and dense-graded asphalt paving mixtures. The researchers used state-of-the-art testing equipment and a methodology developed for asphalt mixtures to evaluate the relative permeability of these mixtures. Relative susceptibility to permanent deformation (rutting), moisture damage, and aging were also measured. This chapter reviews selected publications concerning testing techniques and methodologies used for measuring permeability of asphalt mixtures, as well as the development of the SMA mixture, which is most comparable to the CMHB mixture.

PERMEABILITY

In 1856, a French waterworks engineer named D'Arcy experimentally demonstrated that the rate of flow of water in *clean sands* was proportional to the hydraulic gradient. Water and moisture travel through soils in response to an energy gradient. This gradient may be the force of gravity (elevation), capillary forces, and/or temperature or pressure differentials. The movement of water or moisture is treated as saturated or unsaturated flow. Saturated flow is the movement of free water using a hydraulic gradient supplied by elevation. Unsaturated flow is the movement of free water caused by energy gradients supplied by capillary forces, temperature differences, and osmotic pressure. The equation normally used for the computation of the flow of water through soils is based on those experiments conducted by D'Arcy and is commonly known as *Darcy's Law (1, 2)*.

Fluid flow can be described as *steady* or *unsteady*, which correspond to conditions that are constant or vary with time, respectively. Flow can also be described as *1*-, *2*-, or *3*-dimensional. One-dimensional flow is that in which all the fluid parameters, i.e., pressure, velocity, and temperature are constant in any cross section perpendicular to the direction of flow. Two-dimensional flow is characterized by fluid parameters which are equivalent in parallel planes. In 3-dimensional flow, the fluid parameters may vary in the 3-coordinate directions. Flow can also be described as *laminar*, *transition*, or *turbulent*. In laminar flow, the fluid theoretically flows in parallel layers without mixing. Turbulent flow involves random velocity fluctuations resulting in mixing of the fluid and internal energy dissipation. Transition flow occurs in situations between laminar and turbulent flow. These 3 states are illustrated in Figure 1, which shows how a hydraulic gradient with increasing velocity of flow. The hydraulic gradient, *i*, is known as the energy or *head loss, h,* per unit length, *l*, when flow is laminar. When flow becomes turbulent, a departure from this linear relationship will become apparent.

$$i = \frac{h}{l}$$

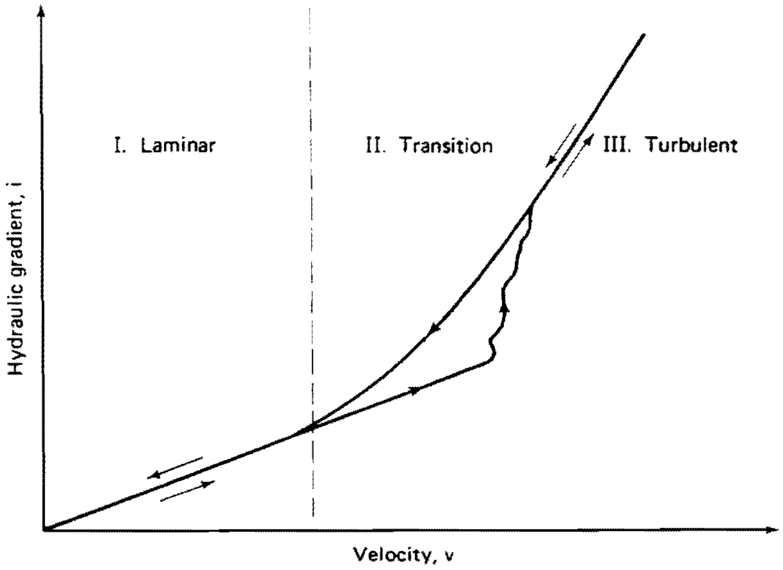

Figure 1. Zones for Laminar and Turbulent Flow.

Flow in most natural soils is small and considered laminar. Therefore, from Figure 1, it is known that velocity, *v*, is proportional to *i*.

$$v = k\,i$$

Incompressible steady flow reduces the law of conservation of mass to the equation of continuity,

$$q = v_1 A_1 = v_2 A_2 = constant$$

where q = rate of discharge (m^3/s),

v_1, v_2 = velocities at sections 1 and 2 (m/s), and

A_1, A_2 = cross-sectional areas at sections 1 and 2.

Using the equations mentioned above, Darcy's law is:

$$q = vA = k\,i\,A = k\frac{\Delta h}{L}A$$

where k = Darcy coefficient of permeability *(1)*.

Laboratory methodologies and procedures for measuring the coefficient of permeability of soils have been well established. The permeability constant, k, has been determined using permeameters through either constant-head or falling-head tests. A reliable test method utilizing a constant-head permeameter test has been established by the American Society for Testing and Materials (ASTM) and designated as ASTM D 2434-68 *(3)*. Internationally known researchers such as Cedergren, Taylor, and Terzaghi have utilized other reliable laboratory methods for directly determining the permeability constant, k, for soils *(4-6)*. Numerous charts and nomographs have been developed for estimating permeability *(2)*. However, laboratory methodologies and procedures for measuring the coefficient of permeability of porous media, such as asphalt concrete, have not been well established.

Several research studies have been performed utilizing different methodologies and procedures for measuring the permeability constant of asphalt paving mixtures. Permeability tests have been performed with either water or a gas (usually air). In the past, most researchers have used water for determining the permeability of asphalt mixtures. Darcy's Law has been most commonly used for computing this value; however, assumptions were made such that Darcy's Law would remain valid. These assumptions included full saturation of the test specimen prior to testing and laminar flow throughout testing.

McLaughlin and Goetz *(4)* initially developed an air permeameter because they believed the use of a gas would not require excessive pressures to obtain measurable flow values. They theorized that permeability values for their test specimens would be extremely low and that it would be difficult to force a measurable quantity of water through them. This system was capable of subjecting the test specimen to 3000 mm of mercury. However, their gas permeameter indicated that high pressures were not necessary. Therefore, a water permeability device was used with the same sample holder as that for the gas permeameter. The test specimen was sealed in the sample holder with hot asphalt cement. This was to insure that the only flow path would be through the specimen and parallel to its axis. The water permeameter was a falling-head type test. The data produced from these devices did not indicate any significant differences or effects of the type of medium used for the measurement of permeability *(4)*.

The U.S. Army Corps of Engineers Waterways Experiment Station *(5)* developed a device to measure relative permeability of open-graded friction courses. The design of the permeability device was similar to that of an outflow meter. However, the difference is that the outflow meter was designed to measure surface drainage capacities of dense-graded pavements and the permeability device was designed to measure the internal drainage capacities of open-graded pavements. This device was capable of performing both falling-head and constant-head permeability tests. The apparatus included a plastic standpipe with a 50.8 mm inside diameter and a 102 mm diameter baseplate. The baseplate had a foam rubber gasket on the bottom that contacted the pavement surface to provide a seal. This device was portable and adaptable to field testing. The test was conducted on 102 mm and 152 mm diameter samples. However, the Waterways Experiment Station reported the falling-head permeability as the "time to fall" for a certain head condition and the constant-head permeability as "flow rate." These values were not converted to traditional permeability units of cm/sec *(5, 6)*.

White *(5)* reported that the test results from the falling- and constant-head permeability tests were in "seemingly good agreement, as far as the relative display of permeability." He also indicated that the type of flow witnessed during field testing was different from what was occurring in the laboratory. In the laboratory, flow was occurring vertically *and* horizontally out the sides of the samples. In the field, flow of water occurred horizontally and then upward and out the pavement surface beyond the perimeter of the baseplate *(5)*.

Britton et al. *(6)* developed a permeability apparatus similar to that used by the Waterways Experiment Station for testing open-graded friction course materials. His permeameter consisted of a plastic standpipe with an inside diameter of 70 mm and a 178 mm diameter metal standpipe base. The primary difference in these 2 devices was a silicone sponge rubber gasket, developed as a seal between the standpipe base and the highly textured pavement surface, and compression springs, used to apply a load to the permeameter to improve the seal between the surfaces and eliminate surface flow. His device was also capable of performing both constant-head and falling-head tests. As with the Waterways device, results from his falling-head and constant-head tests were reported as "time to fall" and "flow rate," respectively. However, the coefficient of permeability was calculated in units of cm/sec *(6)*.

Gotolski et al. *(7)* performed permeability tests with air and water on sand-asphalt pavement (high void mixtures with low permeability). The results of their study indicated that the use of some type of flow rate device is warranted as an indicator of field compaction for asphalt concrete during construction. They showed that air flow rates were more sensitive indicators of degree of compaction than water flow rates for the densest pavements. No relationship was determined between field flow rates and air void contents.

The air permeability device used for the study was developed by the California Research Corporation *(7)*. It provided a rapid, non-destructive test of the density of asphalt pavements. A caulking gun device was sealed to the pavement by extruding grease around the perimeter of the area to be tested. An air chamber approximately 102 mm in diameter was formed on the pavement surface. Air pressure and flow rate were measured. The air flow was supplied by water pressure and the air flow rate was based on the time required for a known quantity of water to flow in a pipette. It is important to note that there was no circumferential confinement of the sample or area tested (on a pavement) and, thus, the flow path and actual area tested were indeterminate. Therefore, calculated values were based on flow rate rather than on permeability.

The water permeameter used for the study was developed by Johns-Manville Products Corporation *(7)*. This device consisted of a graduated cylinder and weights. The graduated cylinder was fastened to the pavement with a sealer material and weights were placed on a board that straddled the cylinder. Distilled water was used for testing and allowed to flow into the pavement for a minimum of 90 seconds to insure continuous flow.

Button *(8)* evaluated the permeability of asphalt surface seals (seal coat, slurry seal, and micro-surfacing). Falling-head permeability tests were performed using water with plexiglass permeameters. It is interesting to note that the seal coat specimens exhibited no permeability with a 200 mm head of water for 72 hours.

Several other research studies have evaluated the permeability of asphalt pavements. Basically, standard falling-head and/or constant-head permeability tests were performed and the devices used were rather simple. Detailed descriptions of these devices and methodologies are summarized in other publications *(9-14)*.

STONE MASTIC ASPHALT MIXTURES

Stone mastic asphalt (SMA) is a hot mix asphalt that was developed in Germany during the mid-1960s. The material is primarily known in Europe as "Splittmastixasphalt." It may also be referred to as Split Mastic, Grit Mastic, or Stone Filled Asphalt. The mixture is currently in use in Germany, Austria, Belgium, Holland, and the Scandinavian countries. SMA was originally developed to provide resistance to abrasion by studded tires and eventually used in high-traffic areas to resist permanent deformation. The surface texture is rough and provides good friction properties after the surface film of asphalt cement wears off due to traffic *(15, 16)*.

In the fall of 1990, the European Asphalt Study Tour, which included contractors, National Asphalt Pavement Association, The Asphalt Institute, Federal Highway Administration

(FHWA), and state highway agencies, was conducted to observe the quality of their roads. This group was most impressed with the performance of SMA mixtures and determined to introduce this mixture in the United States. In January 1991, the FHWA planned to support the construction of the first SMA test section in the U.S. in Michigan. This site was selected by the FHWA because the climatic conditions were similar to that in Europe and there was interest in SMA by the Michigan DOT and industry *(17)*.

Description of SMA Mixtures

SMA mixtures consist of a large proportion of coarse aggregate, fine aggregate, high filler content, asphalt cement with or without modifier, and sometimes a cellulose or mineral fiber. The current definition of SMA is:

> *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 agent (18).*

This specific definition was developed to signify the important characteristics of SMA that require particular attention. It was also developed to ensure that a mixture produced in the U.S. possesses these characteristics of the traditional SMA produced in Europe.

The principle of an SMA mixture is to have a greater amount of coarse aggregate than a dense-graded mixture fabricated from the same materials. The resulting superior stone-on-stone contact will produce a mixture that is less susceptible to permanent deformation (rutting). SMA specifications require high quality crushed coarse aggregate. Another specific quality of the SMA is the higher percentage of asphalt binder and mineral filler (dust or material passing the 0.075 mm sieve) which creates the mastic. A properly designed SMA mixture is both stable and workable *(19)*.

Mixture Design for SMA Mixtures

Aggregate Properties

The aggregate gradation specifications for SMA mixtures produce a gap-graded material that is significantly coarser than typical dense-graded mixtures. Generally, dense-graded mixtures produced throughout America have a nominal maximum aggregate size in the range of 19 mm to 12.5 mm. The typical overlay thickness of dense-graded hot mix lies in the range of 25 to 50 mm. Typically, in Sweden, nominal maximum aggregate sizes are 11.3 mm and 16 mm for SMA. Pavement thicknesses are generally 34 mm to 43 mm for a maximum size of 11.3 mm and 38 mm to 47 mm for a maximum size of 16 mm. The nominal maximum aggregate sizes for SMA produced in Germany are generally 5 mm, 8 mm, and 11.2 mm. Pavement thicknesses are typically 2 to 4 times the nominal maximum aggregate size. The Netherlands use nominal maximum aggregate sizes similar to that in Germany. Denmark uses sizes of approximately 8 mm, 11.2 mm, and 16 mm. To address road surface abrasion in their cold climate, Norway applies a maximum size of 16 mm and Finland uses a size of 20 mm *(20)*.

SMA mixtures typically have 20%-40% of the aggregate passing the 4.75 mm sieve and 15% to 35% passing the 2.36 mm sieve. These percentages vary according to the maximum aggregate size. The voids between the coarse aggregates are filled with the finer aggregate and binder *(20)*.

SMA mixtures contain approximately 10% minus 75 μm material. It has been shown that an increase in mineral filler has profound effects upon the performance of hot mix asphalt. Mineral fillers are beneficial, such that they stiffen the mixture at high temperatures but contribute less stiffening at low temperatures. They toughen the asphalt binder to resist cracking at low temperatures. However, not all mineral fillers have the same effect on HMA. Very fine (diameter less than the asphalt film thickness) mineral fillers may extend the asphalt cement making the mix appear to have an excessive asphalt content *(23)*. An insufficient quantity of mineral filler may yield a low effective viscosity of the mastic and result in premature rutting of the pavement *(19)*.

European SMA mixtures are generally made of 100% crushed materials. German engineers specify that 90% of the coarse aggregate is fractured. Natural sands with rounded particles are used sparingly and are usually less than or equal to 10% by total aggregate weight. The ratio of manufactured to natural sand is always greater or equal to 50% *(18, 20)*.

Common coarse aggregates used in European SMA mixtures are granite, basalt, gabbro, diabase, gneiss, porphyry, and quartzite. They specify that the aggregate particles have a cubic shape and rough surface texture to resist rutting, a certain hardness to resist fracture under heavy traffic loads, and low susceptibility to polishing and abrasion.

Germany and Sweden perform various quality tests on their aggregates. Aggregates in Germany are tested for fracture by impact, fracture by freezing and heat, resistance to expansion or degradation by water, and shape through the evaluation of flat and elongated particles. Aggregates in Sweden are tested using surface abrasion machines for both aggregates and mixtures, an impact device for fracture, and slotted sieves for particle shape. Neither Germany nor Sweden use the Los Angeles abrasion test *(20)*.

Several tests are performed in the U.S. to determine the durability of aggregates for dense-graded mixtures. AASHTO T 112 or ASTM C 142, "Clay Lumps and Friable Particles in Aggregates," require that the total amount of deleterious materials should not exceed 1% by weight. AASHTO T 176, "Plastic Fines in Graded Aggregates and Soils by Use of the Sand Equivalent Test," or ASTM D 2419, "Sand Equivalent Value of Soils and Fine Aggregate," establish a minimum sand equivalent value for the minus 4.75 mm sieve as 45. AASHTO T 104 or ASTM C 88, "Soundness of Aggregate by Use of Sodium Sulfate or Magnesium Sulfate," states that the sulfate soundness weight loss of the fine aggregate after 5 cycles should not exceed 15% using sodium sulfate and 20% when magnesium sulfate is used *(21, 17)*.

Asphalt Binder Properties

The asphalt binders used in Europe are typically 65, 80, or 85 penetration grade binders. A majority of northern European countries use 80 or 85 penetration grade binders; whereas, southern countries use a 65 penetration grade binder. In Germany, a 200 penetration grade binder is sometimes used with thin SMA layers composed of aggregate with a nominal maximum size of 5 mm. Generally, the penetration @ 25 °C, viscosity @ 135 °C, and softening point of binders are measured. There are no German or Swedish specifications for modified binders in SMA mixtures, but they have been used in some mixtures *(20)*.

SMA Mixture Design Methodologies

The objective of designing an asphalt paving mixture is to select and proportion the materials to attain the preferred properties in the completed project. It is intended to determine an economical blend and gradation of aggregates that meet the specifications and asphalt content to achieve:

- A durable pavement resistant to moisture and aging,
- Adequate stability to fulfill the demands of traffic without distortion or displacement,
- Adequate air voids in the compacted mixture for additional compaction under traffic without flushing, bleeding, or loss of stability. (However, air voids must be low enough to minimize damage by oxygen and moisture.), and
- Adequate workability to allow efficient placement without segregation *(23)*.

In Europe, the Marshall method of mixture design is typically used for designing SMA mixtures. Specifications that were established relative to the mixture design are based upon field performance and evaluation of material properties, i.e., gradation, asphalt binder content, and air voids. Optimal and minimum asphalt binder content specifications were established using the 50-blow Marshall design. Compaction with a greater number of blows is not recommended because it may produce an unacceptable amount of fractured aggregates. Throughout Europe hot mix is generally compacted using automatic Marshall hammers. A compaction temperature of 135 °C is used in Germany. In Sweden, compaction temperatures are in the range of 145 °C to 150 °C. Aging of loose mixtures or compacted specimens in an oven is not performed *(20)*.

Sample preparation procedures from the Marshall method have been adopted in Europe for the design of SMA mixtures. Stability and flow specifications can be used in the evaluation of SMA mixtures to estimate performance; however, they are not often used because the peak from the Marshall trace on SMA mixtures is not always well defined. Also, at times, the peak load occurs at very high flow values that are off the standard Marshall chart paper generally used. SMA mixture designs are based on specified air void levels and minimum asphalt binder contents. Design air void levels are lower than those used for dense-graded mixtures. This is due to the preponderance of coarse aggregates. There are no specifications for voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA) *(20)*.

In Germany, SMA mixtures are designed at a 3 ±1% air void level. In Sweden, SMA mixtures are designed close to 2% air voids for low traffic pavements and near 3% air voids for high traffic pavements. German specifications require mixtures to have an asphalt binder content of 6.5% to 7.5% (by mixture weight) for a nominal maximum aggregate size of 8 mm or greater and 7.0% to 8.0% for a nominal maximum aggregate size of 5 mm. Swedish specifications require mixtures to have an asphalt binder content in the range of 6.3% to 6.6%. In France, typical asphalt binder contents are between 6.3% and 6.8%. SMA mixtures have higher asphalt binder contents than dense-graded mixtures with the same type of aggregate and nominal maximum aggregate size *(20)*.

CHAPTER III

DESCRIPTION OF EXPERIMENTAL PROGRAM

Hot mix asphalt specimens were prepared and tested in the laboratory according to an experimental design developed to evaluate CMHB mixtures in terms of permeability and performance. Three different designs of the newly developed Type C CMHB mixture and 3 Type C dense-graded mixtures were chosen for this study. CMHB contains a majority of coarse aggregate which serves to establish stone-on-stone contact of the coarse stones and thus reduce the potential for permanent deformation (rutting). This structural skeleton will create larger air voids within the mixture and there is concern that this may lead to moisture damage and/or oxidative aging. Therefore, it is desirable to evaluate the permeabilities of CMHB mixtures in comparison to those of dense-graded mixtures. It is also relevant to investigate their relative performance, specifically, susceptibility to rutting, moisture damage, and oxidative aging.

Researchers tested corresponding CMHB and dense-graded mixtures made using similar materials. Three types of aggregate and 4 grades of asphalt cement were used to fabricate asphalt concrete specimens. The crushed aggregates included limestone from the Austin district, sandstone from the Paris district, and siliceous gravel from the Atlanta district. Gradings of these materials are given in Appendix E. The asphalt binders included AC-10, AC-20, and AC-45P, all supplied by Koch Materials Company. The researchers produced a fourth binder by modifying the AC-20 with 3% latex. These materials were used in a partial factorial laboratory experiment. Test procedures routinely used by TxDOT to evaluate the asphalt mixtures were used to evaluate the CMHB and dense-graded mixtures prepared in the laboratory.

EXPERIMENTAL DESIGN

The laboratory experimental design (Table 1) was developed to guide the testing program.

Table 1. Experimental Design for the Evaluation of Coarse Matrix-High Binder Hot Mix Asphalt Concrete[1].

Test Method	Aggregate											
	Siliceous, Atlanta				Sandstone, Paris				Limestone, Austin			
	AC-10	AC-20	AC-45P	Latex	AC-10	AC-20	AC-45P	Latex	AC-10	AC-20	AC-45P	Latex
Permeability, k		X		X						X		X
Tex-231-F	X	X	X	X	X	X	X	X	X	X	X	X
Tex-530-C		X	X			X	X			X	X	
Tex-531-C		X	X			X	X			X	X	
IDT @ 25 °C[3]		X	X							X	X	
M_R @ 25 °C[4]		X	X							X	X	
Hveem Stability[2]	X	X	X	X	X	X	X	X	X	X	X	X

[1] An 'X' in the chart indicates that 3 replicate tests will be performed on comparable CMHB and dense-graded mixtures.

[2] Hveem stability was only performed on the dense-graded mixtures.

[3, 4] Indirect tension tests (IDT) and resilient modulus tests (M_R) were performed on short-term and long-term aged specimens.

MATERIALS SELECTION AND ACQUISITION

Coarse Matrix-High Binder Mixtures

Three Type C (16 mm nominal maximum size) CMHB mixture designs were obtained from the Atlanta, Paris, and Austin districts. The Atlanta mixture design contained C-Rock, D-Rock, F-Rock, dry screenings, and hydrated lime. The Paris mixture design included C-Rock, D-Rock, unwashed screenings, and aglime. The Austin mixture design consisted of C-Rock, D-Rock, F-Rock, and dry screenings. Aggregate for the Atlanta mixture design was sampled at Texarkana Asphalt. Aggregate for the Paris mixture design was sampled at Buster Paving, Inc. Aggregate for the Austin mixture design was sampled at Colorado Materials Company. Sieve analyses were performed on the stockpile samples to ensure their conformity with their respective specifications. The mixture designs were verified through static creep properties, which are the primary factors that govern the CMHB mixture design as well as air void contents.

Dense-Graded Mixtures

A dense-graded TxDOT Item 340, Type C (16 mm nominal maximum size) mixture design was obtained from the Atlanta district. A dense-graded TxDOT Item 3778, Type C (16 mm nominal maximum size) mixture design was obtained from the Paris District. A dense-graded TxDOT Item 340-Specials, Type C (16 mm nominal maximum size) mixture design was obtained from the Austin District. The mixture design from the Atlanta District contained C-Rock, D-Rock, screenings, field sand, and hydrated lime. The mixture design from the Paris District included C-Rock, D-Rock, washed screenings, and field sand. The mixture design from the Austin District contained C-Rock, D-Rock, F-Rock, manufactured sand, and field sand. The aggregates were sampled at the same sites as mentioned above for the CMHB mixture designs. Sieve analyses were performed on the stockpile samples to ensure conformation with specifications. These mixture designs were verified through the fabrication of cylindrical specimens using the procured materials and testing to determine Hveem stability and air void content.

ASPHALT CONCRETE SAMPLE PREPARATION

Dry aggregates, blended to the appropriate grading, were heated in an oven to the specified temperature. Hot asphalt binder was added, and the mixtures were thoroughly blended. After blending, the materials containing AC-10 or AC-20 were placed in an oven at 121 °C for 2 hours. The blended materials containing AC-45P or AC-20 + latex were placed in an oven at 143 °C for 2 hours. The specimens containing AC-10 or AC-20 were prepared in accordance with standard TxDOT procedures. The specimens containing AC-45P or AC-20+latex were prepared at higher mixing and compaction temperatures due to their relatively higher viscosity.

Test specimens were fabricated using the Texas gyratory compactor and in accordance with the procedures specified in Tex-206-F. However, the aggregate blends for the CMHB specimens were prepared individually. The purpose of preparing the aggregate blends individually was to ensure that the proper gradation and asphalt content was achieved for each test specimen.

LABORATORY TESTS

Laboratory testing was conducted in accordance with Table 1. Permeability was measured on laboratory-fabricated specimens and pavement cores from various CMHB overlays throughout Texas. The TxDOT static creep test was modified slightly, as explained later in that subsection. The resilient modulus and indirect strength tests were performed on unaged, short-term and long-term aged specimens. Aging was performed in accordance with Superpave requirements. The asphalt binders were tested to determine penetration and Superpave performance grade. The following paragraphs provide a brief description of each test method.

Height and bulk specific gravity of all specimens (Tex-207-F) were measured. Alternative procedures for determining the bulk specific gravity, performed on selected specimens, included laboratory fabricated specimens and pavement cores. The alternative procedures included a protocol for measuring air void content of water permeable compacted asphalt mixtures using glass beads and Tex-207-F, "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens" (similar to ASTM D 1188). Three replicates of each test were conducted with exception to the modified version of the static creep test, where 2 replicates were conducted.

Permeability

A constant head water permeability test procedure was developed (Appendix F) which was similar to ASTM D 5084, Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. The test was performed using a water flow control panel and permeameter cell manufactured by Brainard-Killman located in Stone Mountain, Georgia. This particular testing apparatus was chosen for use in this evaluation because it is state of the art. The permeability control panel features pressure and vacuum gauges that provide accurate measurement of flow rate and volume. Upon complete saturation of the test specimen, maximum flow rate through the specimen is developed with no impedance from air bubbles. The required pressures are easily maintained with simple valving. The panel features digital gauges, precision regulators, and burettes. It is totally plumbed and easy to set up. The permeability cell features double drain lines at each end of the sample that aid in saturation and provide greater flexibility in controlling drainage.

The permeability tests were primarily performed with influent flows of 17 kPa. This inflow pressure was adequate to measure the time interval over which the flow occurred through typical asphalt concrete specimens. Greater pressures were used for specimens that exhibited no permeability at the 17 kPa inflow rate. The CMHB and dense-graded specimens were compacted to air void contents in the 3 ranges of 2-5%, >5-9%, and >9-15%, the purpose of which was to simulate pavements at terminal densification (after significant trafficking), after proper compaction during construction, and after inadequate compaction during construction. All tests were performed at 25 °C.

Texas DOT Static Creep

Static creep testing was performed in accordance with Tex-231-F. Cylindrical test specimens with a diameter of 102 mm and a height of approximately 50 mm were prepared in the laboratory. Each test specimen was capped with a plaster compound and special attention was given to minimize negative effects of the capping material. Prior to testing, each specimen was placed in an oven at 40 °C for 3 hours to reach the test temperature. Axial loading of specimens was accomplished using a MTS closed-loop system regulated using a Gardner GS-2000 controller which contains the pre-programmed test sequence and an automatic data acquisition apparatus.

Preconditioning of the test specimens included the application of 3 cycles with a 556 N square wave preload for 1-minute intervals followed by a 1-minute rest period after each cycle. This allowed the loading platens to achieve more uniform contact with the specimen. Following preconditioning, a 556 N load was applied for 1 hour. After 1 hour, the load was removed and the test specimen was allowed to rebound for 10 minutes. The applied load and resulting vertical deformations for each LVDT are monitored and recorded throughout the 1-hour loading period.

A modified version of the TxDOT creep test was employed. One modification involved an initial seating load of approximately 22-45 N (no seating load is normally used). Preconditioning included 3 cycles of a 556 N square wave preload for 1-minute intervals as well; however, the third cycle (only) was modified by using a 5-minute rest period instead of a 1-minute rest period. *Procedures following this were identical as mentioned in the preceding paragraph.* Pertinent data derived from each test includes the total axial strain, permanent strain, slope of the steady-state portion of the creep curve, and creep stiffness. CMHB test specimens were fabricated with 3±1% air voids and the dense-graded mixtures were fabricated with 4±1% air voids.

Moisture Susceptibility

Two tests (Tex-530-C & Tex-531-C) were performed to evaluate the moisture susceptibility of CMHB and dense-graded mixtures. Tex-530-C is a boiling water test and Tex-531-C is a modified Lottman test similar to ASTM D 4867.

Tex-530-C requires approximately 1000 gm of material for each mixture necessary for evaluation. A 200-gm batch of material is placed into boiling water which is maintained at a medium boil for 600 seconds. Then, the wet mix is placed onto a white paper towel adjacent to an unconditioned portion of the same mixture. The degree of stripping in percent is visually estimated while the mixture is wet and after the mixture has been allowed to air dry for 24 ± 2 hours.

Tex-531-C requires preparation of hot mixed asphalt specimens containing 7±1% air voids. Specimens designated for conditioning were vacuum saturated in water to fill 60%-80% of the voids. The saturated specimens were placed in a freezer for a minimum of 15 hours. Following freezing, the specimens were placed in a water bath at 60 °C for 24 hours. All specimens (unconditioned and conditioned) were then placed in a water bath at 25 °C for 3 to 4 hours. Then IDT strength of all specimens was measured at 25 °C. The tensile strength ratio (TSR) was determined by dividing the IDT strength of moisture-conditioned specimens by that of similar unconditioned specimens.

Indirect Tension (IDT)

Indirect tension testing was performed in accordance to Tex-226-F (or ASTM D 4123) at a temperature of 25 °C and at a loading rate of 51 mm per minute until complete failure occurred. Specimens were tested using an Instron machine with an adjustable frame which holds the specimen with its axis transverse to the crosshead. Two LVDT's mounted within the frame were used to measure the horizontal (diametral) deformation under load. This test was performed on the unconditioned specimens for Tex-531-C as well as similar (7±1% air voids) short-term and long-term aged specimens.

Resilient Modulus (M_R)

Resilient modulus testing in accordance to ASTM D 4123 was performed at a temperature of 25 °C utilizing a Retsina pneumatic apparatus. A diametral load was applied (magnitude dependent upon test temperature - typically 138 kPa to 517 kPa) was applied for a duration of 0.1 seconds while monitoring the diametral deformation perpendicular to the loaded plane. This test was performed on unaged, short-term aged, and long-term aged specimens.

CHAPTER IV

RESULTS & DISCUSSION

The laboratory tests described in Chapter 3 were performed to measure important engineering properties of Type C CMHB and dense-graded asphalt concrete mixtures. Findings from the laboratory experiments are discussed in this chapter. The data were analyzed through comparison of the averages of replicate tests as well as the rankings generated by Fisher's least significant difference (LSD) statistical procedure. Fisher's LSD test utilizes the analysis of variance (ANOVA) and the F-test.

MIXTURE DESIGNS

Mixture designs for the Type C CMHB and dense-graded mixtures along with aggregates and asphalt binders were obtained from TxDOT and used to fabricate test specimens with combined gradations and optimum asphalt contents specified in the mixture designs. The CMHB mixture designs were verified through the evaluation of air void content and static creep properties. The static creep properties include the stiffness, slope of the steady-state portion of the creep curve, and permanent strain. The dense-graded mixture designs were verified through the evaluation of air void content and the Hveem stability. Both tests were performed in replicates of 3 and average values reported. Individual test values are listed in the appendices.

Table 2 shows the optimum asphalt contents for the CMHB and dense-graded mixture designs with aggregate sources from Atlanta, Paris, and Austin. This table includes the difference in the optimum asphalt content between each mixture type as well. The asphalt content is greater for the CMHB mixtures in comparison to the dense-graded mixtures. The material exhibiting the greatest difference contains the siliceous aggregate from Atlanta; whereas, the design with the least difference contains the sandstone aggregate from Paris.

Table 2. Optimum Asphalt Content for the Atlanta, Paris, and Austin Mixture Designs.

AGGREGATE SOURCE	OPTIMUM ASPHALT CONTENT		
	MIXTURE TYPE		
	CMHB	Dense-graded	DIFFERENCE, +/-
ATLANTA	5.3	4.5	+0.8
PARIS	5.8	5.4	+0.4
AUSTIN	5.2	4.7	+0.5

Table 3 shows the combined aggregate gradations for the CMHB and dense-graded mixture designs for aggregates from Atlanta, Paris, and Austin. The combined gradations distinguish the CMHB from the dense-graded mixtures. Also listed in the table are the differences for each sieve size. Differences were quite large for the sieve sizes in the range of 9.5 mm to 2.00 mm. These large differences demonstrate the coarseness of the CMHB mixture. The differences at the 0.075 mm sieve were only 2% to 4%; however, this is relevant because a small increase in filler or dust can have a significant impact upon the performance of the asphalt mixture.

Table 4 lists the performance grade of the asphalt binders used in this study. The table breaks down the classification according to testing of the neat asphalt, TFOT residue, and the TFOT + PAV residue. Tabulated are either the highest or lowest temperatures at which the asphalt binders passed the required specification. The initial phase included testing of the neat asphalt with the DSR at high temperatures for the rheological properties. The DSR was also used to test the TFOT and TFOT + PAV residue. The BBR was utilized for testing the TFOT + PAV residue for creep stiffness and slope. AC-10 and AC-20 can sustain an average maximum 7-day temperature of 58 °C; whereas, AC-45P and AC-20+latex can sustain an average maximum 7-day temperature of 64 °C. The average minimum 7-day temperature found for these asphalt binders was -22 °C with exception to AC-45P which was -28 °C. It is interesting that modification improved the low temperature characteristics of the binder as well as the high temperature properties.

Table 3. Combined Aggregate Gradation in Percent Passing for Atlanta, Austin, and Paris Mixture Designs.

SIEVE SIZE, mm	COMBINED AGGREGATE GRADATION								
	SOURCE OF MIXTURE DESIGN								
	ATLANTA			PARIS			AUSTIN		
	CMHB	Dense-graded	Diff. +/-	CMHB	Dense-graded	Diff. +/-	CMHB	Dense-graded	Diff. +/-
22.4	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0
16.0	96.5	98.5	+2.0	99.8	99.8	0.0	100.0	100.0	0.0
9.5	60.1	80.7	+20.6	63.2	78.8	+15.6	61.2	79.0	+17.8
4.75	35.4	58.6	+23.2	35.5	49.9	+14.4	40.5	55.3	+14.8
2.00	19.8	39.4	+19.6	20.2	32.1	+11.9	20.3	33.3	+13.0
0.425	15.8	19.6	+3.8	13.4	21.0	+7.6	10.7	15.5	+4.8
0.180	15.0	9.2	-5.8	11.3	10.7	-0.6	8.3	8.1	-0.2
0.075	6.4	4.4	-2.0	7.1	3.2	-3.9	6.4	4.4	-2.0

Table 4. Superpave Performance Grades of Asphalt Binders.

Asphalt Binder	AC-10	AC-20	AC-45P	AC-20+latex
Performance Grade	PG 58-22	PG 58-22	PG 64-28	PG 64-22
Neat Asphalt Binder, Temperature meeting SHRP minimum $G^*/\sin\delta$ spec. of 1.00 kPa				
DSR	58	58	64	64
TFOT Residue, Temperature meeting SHRP minimum $G^*/\sin\delta$ spec. of 2.20 kPa				
DSR	58	64	70	64
TFOT/PAV Residue, Temperature meeting SHRP maximum $G^*\sin\delta$ spec. of 5000 kPa & maximum creep stiffness of 300 Mpa and minimum m-value of 0.30				
DSR	16	19	13	25
BBR	-12	-12	-18	-12

Figure 2 presents the Hveem stability for the dense-graded mixtures fabricated in the laboratory with AC-10, AC-20, AC-45P, or AC-20+latex. The specification for the Hveem stability is a minimum of 35 and is shown on the figure with a dark horizontal line. All of the dense-graded test specimens surpassed this minimum value thus complying with the specification. The dense-graded mixture designs were also verified through the evaluation of air void content. Test specimens were fabricated in the laboratory with the procured materials according to TxDOT specifications. Mixing and compaction temperatures were increased for the mixtures containing of polymer-modified asphalt binders. The air void content of the dense-graded test specimens for each mixture design were in the range of 4±1%, thus, meeting design specifications.

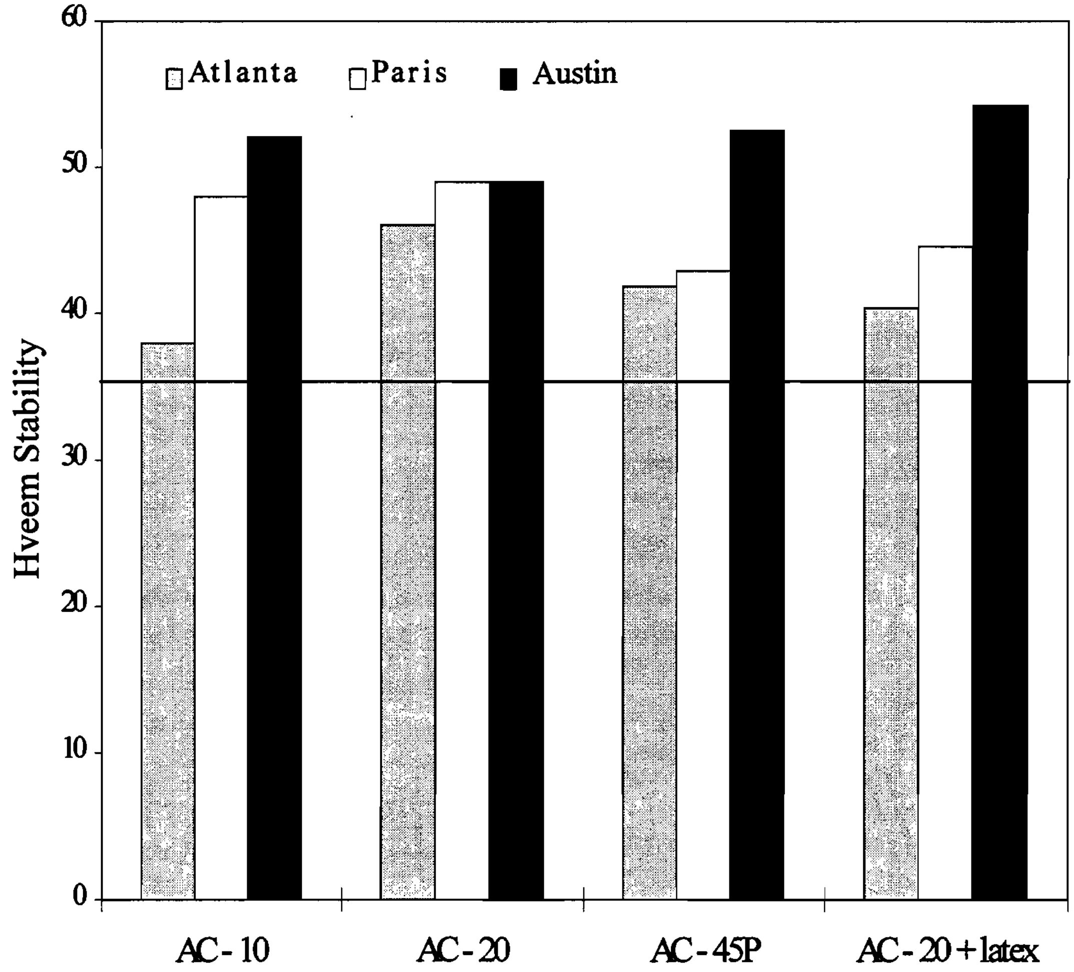

Figure 2. Hveem Stability of the Dense-graded Mixture Designs for Each Asphalt Binder.

Table 5 lists the static creep properties found for the CMHB mixtures of each mixture design used in this study. The 3 properties measured by this test are permanent strain, creep slope, and creep stiffness. This table shows the specifications employed for the test by TxDOT. Two of the 3 mixtures fabricated with AC-10 met the permanent strain criteria. However, all but one of the mixtures fabricated with AC-20, AC-45P, or AC-20+latex did not. This trend was not expected since the mixtures that did not meet the specification contained binders with higher viscosities. In most cases, the mixtures also did not meet the creep slope specification. All of the mixtures tested did meet the creep stiffness specification.

The CMHB mixture designs were also verified through the evaluation of air void content. Test specimens were fabricated in the laboratory with the procured materials according to TxDOT specifications. Mixing and compaction temperatures were increased for the mixtures containing polymer modified binders. The air void content of the CMHB test specimens for each mixture design were in the range of 3±1%, thus meeting design specifications.

PERMEABILITY

Laboratory Fabricated Test Specimens

Figures 3-7 show the permeability of CMHB and dense-graded mixtures as a function of the air void content. Figures 3 and 4 pertain to mixtures containing siliceous aggregate with AC-20 or AC-20+latex. Figures 5 and 6 apply to mixtures fabricated with limestone aggregate and AC-20, or AC-20+latex. Figure 7 represents the data collected for all the mixtures tested.

The permeability test results for both mixtures show a consistent increase as the air void content increased. This trend, of course, was expected. In all cases, it has been shown that the CMHB mixture is more permeable than corresponding dense-graded mixtures. However, the magnitude of this difference is small and has been statistically proven to be insignificant in some cases. Using Fisher's LSD, researchers determined that the difference among averages of replicate tests on specimens with air voids in the ranges of 2%-5% and >9% is insignificant for CMHB and dense-graded mixtures fabricated with limestone aggregate and AC-20 and AC-20+latex. However, the permeabilities of the CMHB and dense-graded limestone specimens

Table 5. Summary of TxDOT Static Creep Test Results for CMHB Mixtures.

MIXTURE DESIGN	ASPHALT BINDER	PERMANENT STRAIN, mm/mm	SLOPE, mm/mm/sec	CREEP STIFFNESS, kPa
SPECIFICATION	---	***< 6.00 x 10^{-4}***	***< 4.00 x 10^{-8}***	***> 41,400***
SILICEOUS, ATLANTA	AC-10	5.96 x 10^{-4}	3.74 x 10^{-8}	57841
	AC-20	6.93 x 10^{-4}	6.32 x 10^{-8}	59264
	AC-45P	8.26 x 10^{-4}	8.85 x 10^{-8}	58451
	LATEX	6.43 x 10^{-4}	3.73 x 10^{-8}	67013
SANDSTONE, PARIS	AC-10	6.97 x 10^{-4}	3.79 x 10^{-8}	54752
	AC-20	8.09 x 10^{-4}	6.19 x 10^{-8}	55597
	AC-45P	9.50 x 10^{-4}	8.39 x 10^{-8}	52705
	LATEX	8.18 x 10^{-4}	5.78 x 10^{-8}	52467
LIMESTONE, AUSTIN	AC-10	5.81 x 10^{-4}	4.22 x 10^{-8}	76306
	AC-20	6.39 x 10^{-4}	5.99 x 10^{-8}	71687
	AC-45P	7.65 x 10^{-4}	10.0 x 10^{-8}	68313
	LATEX	4.72 x 10^{-4}	4.13 x 10^{-8}	87643

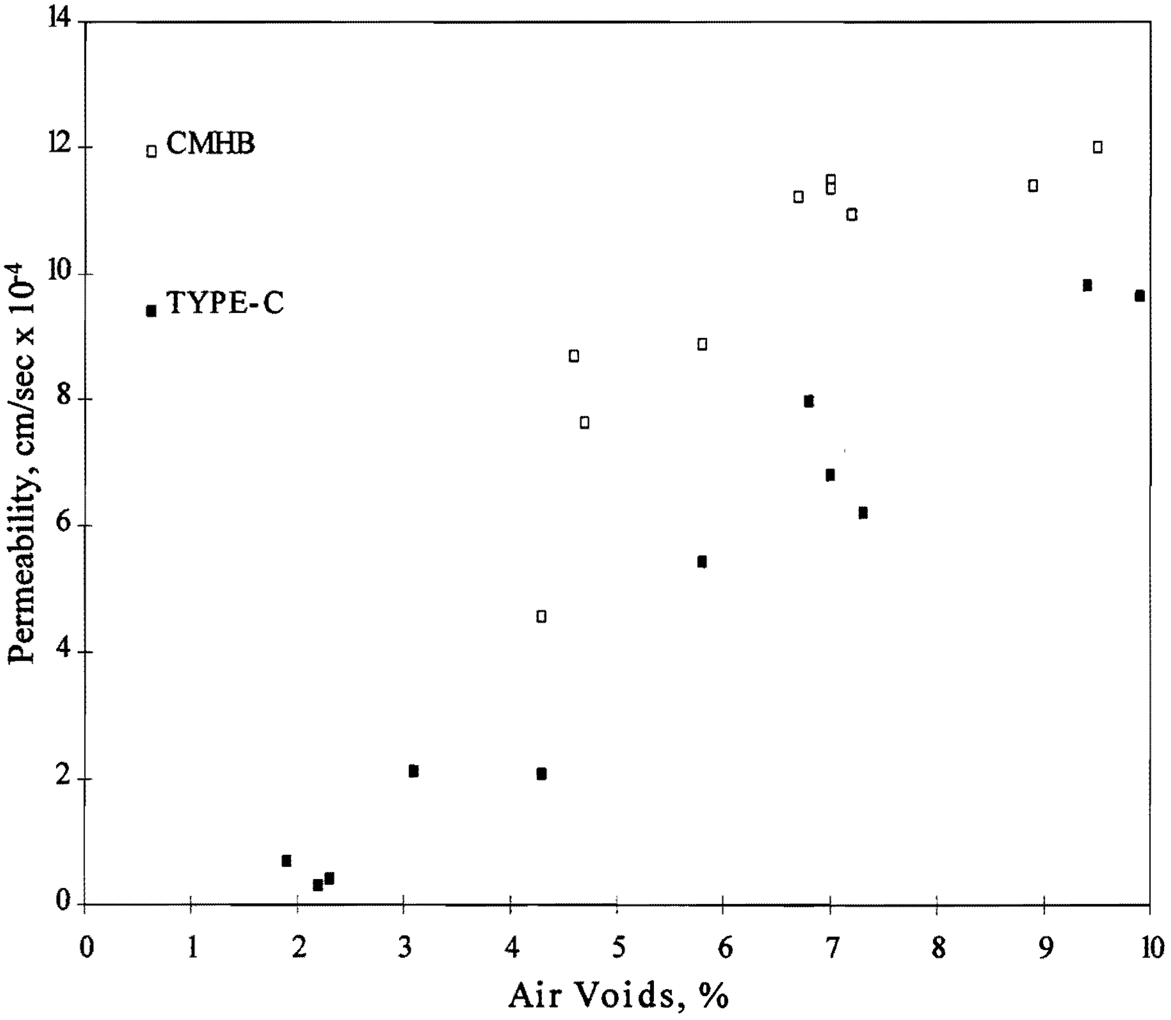

Figure 3. Permeability Values of Mixtures Comprised with Siliceous Aggregate and AC-20.

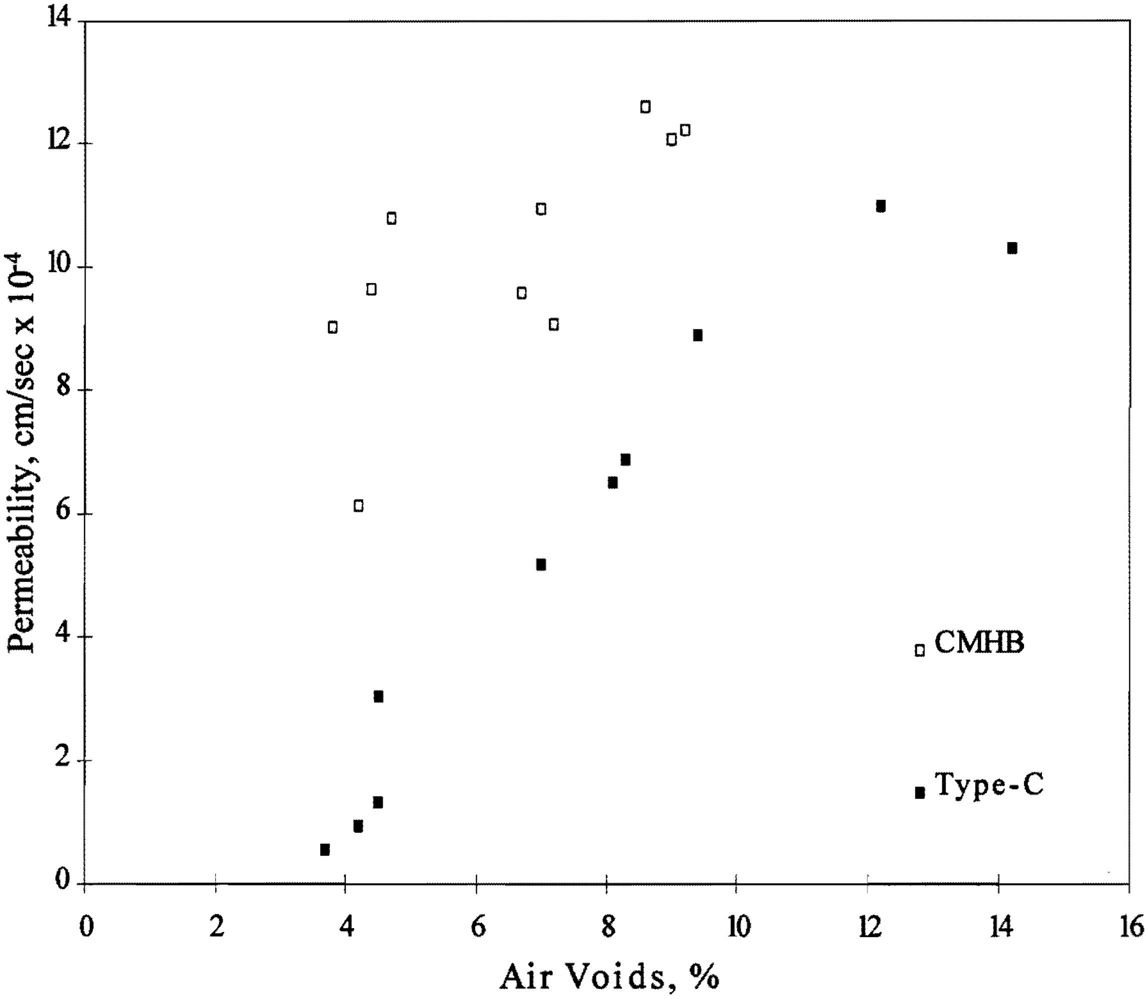

Figure 4. Permeability Values of Mixtures Comprised of Siliceous Aggregate and AC-20+latex.

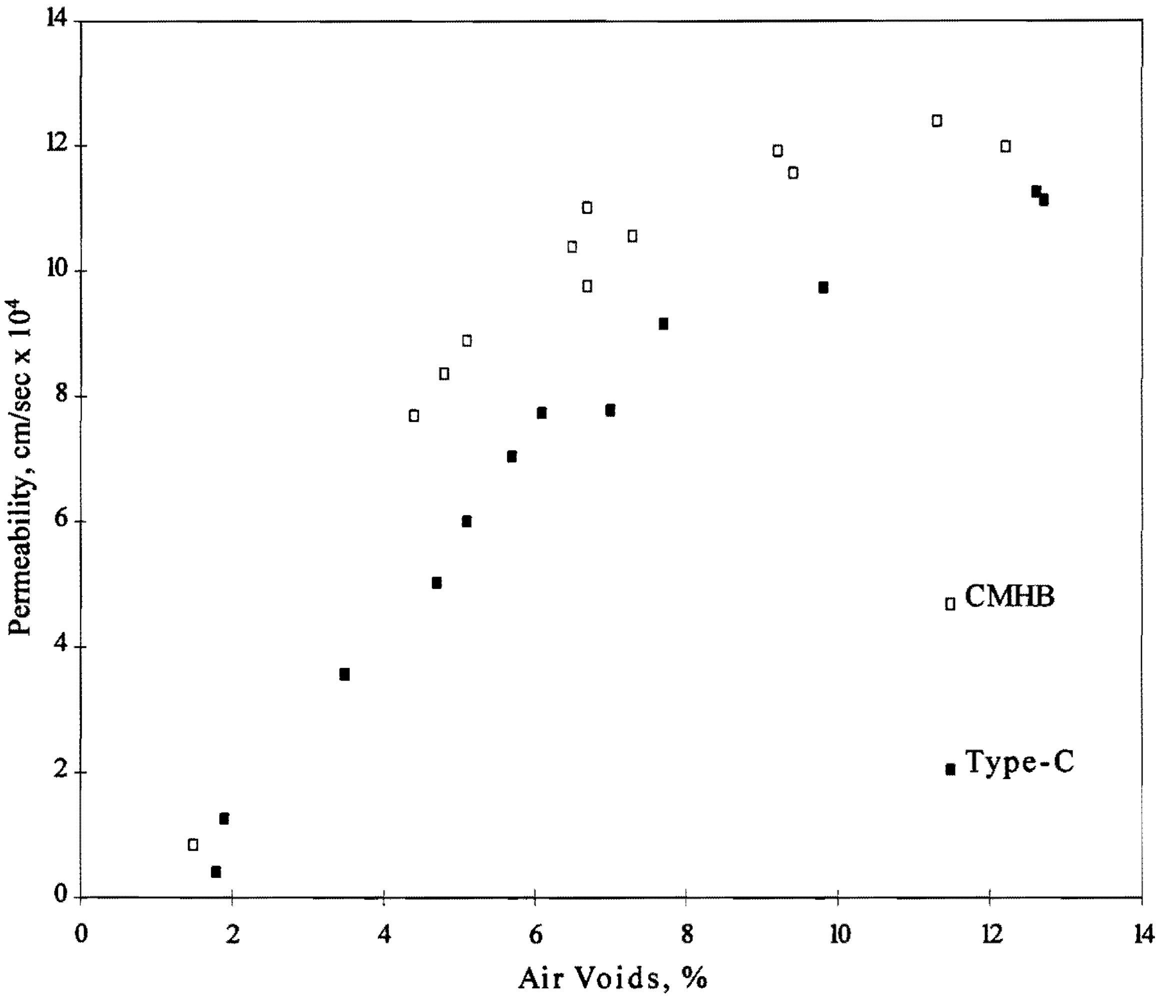

Figure 5. Permeability Values of Mixtures Comprised of Limestone Aggregate and AC-20.

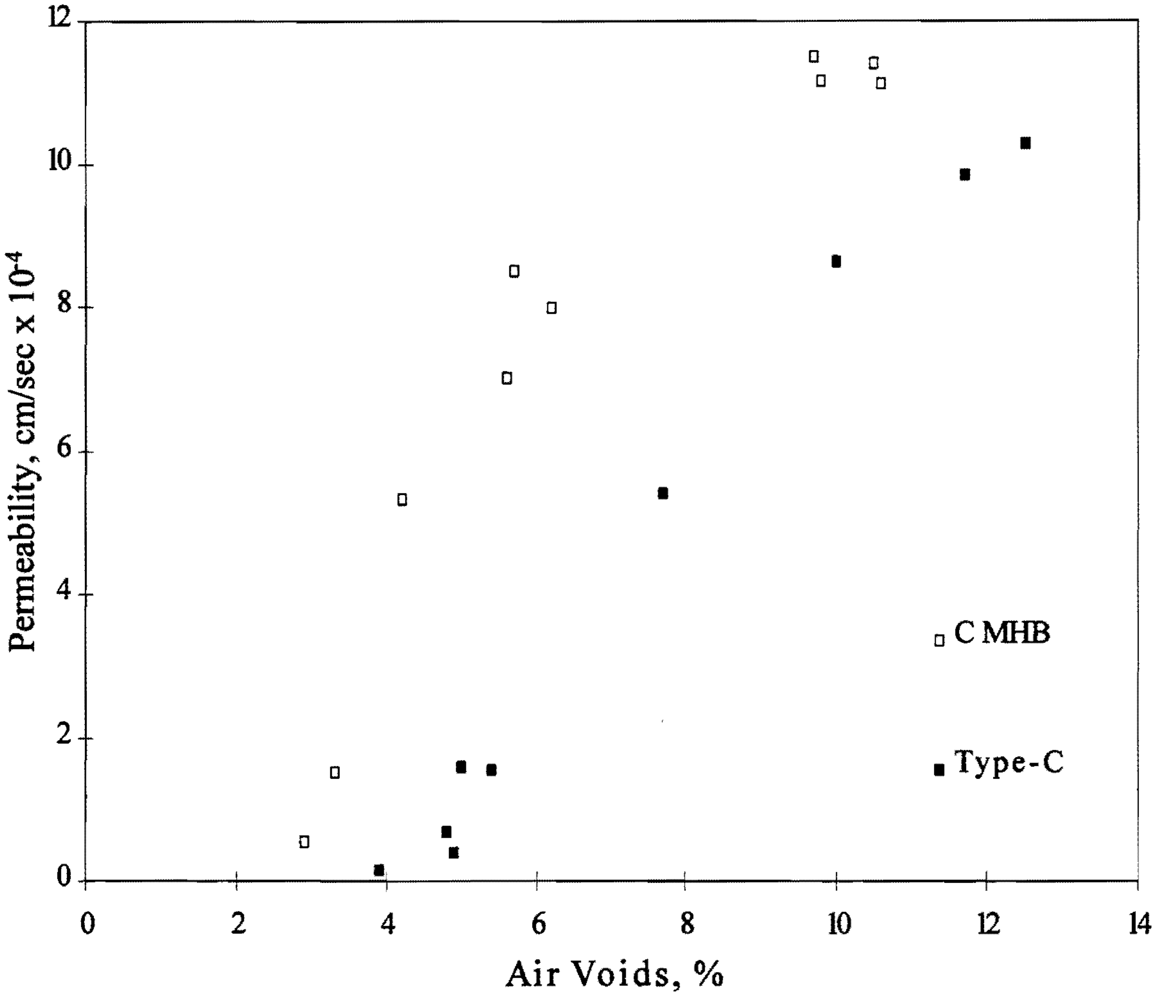

Figure 6. Permeability Values of Mixtures Comprised of Limestone Aggregate and AC-20+latex.

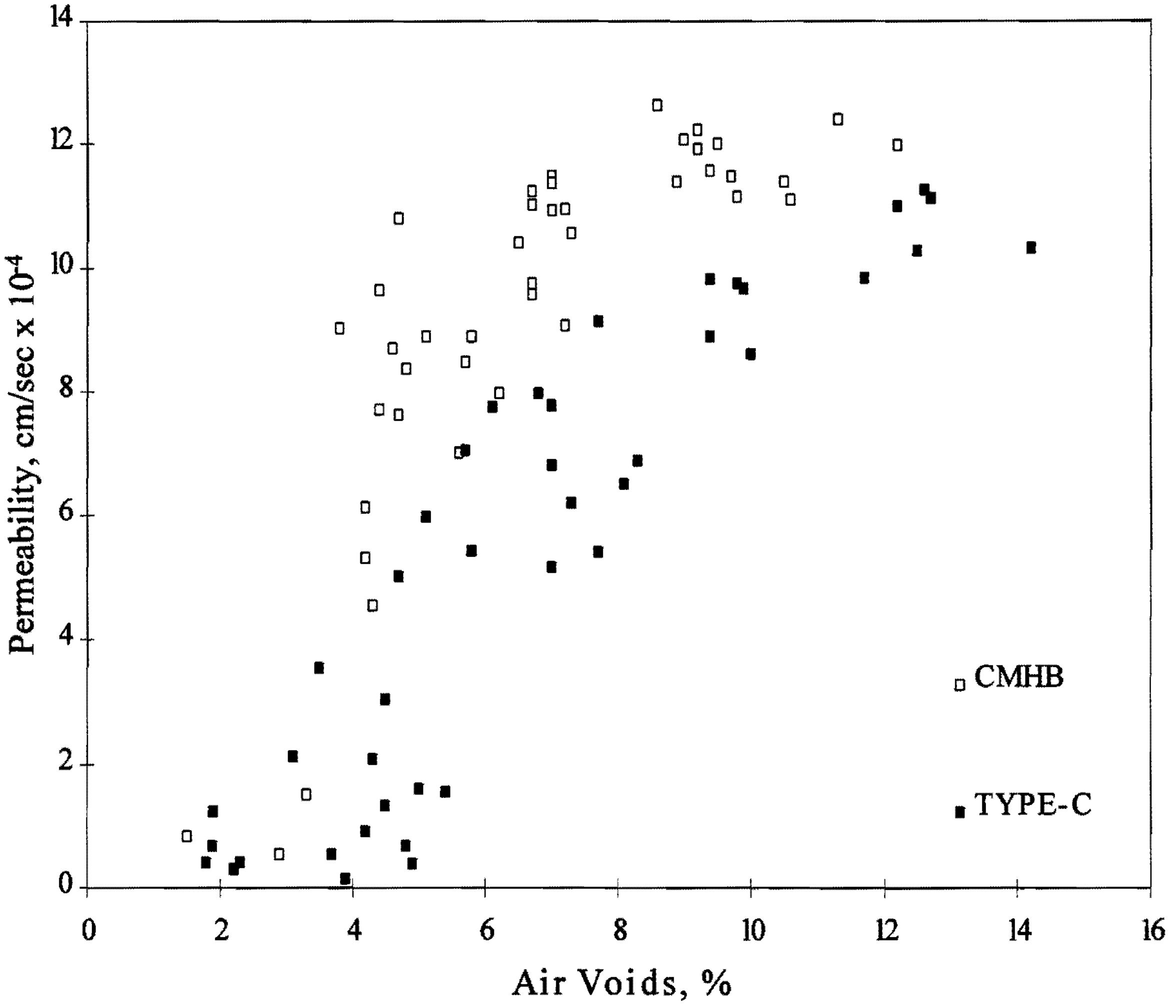

Figure 7. Permeability Values of All the Laboratory Fabricated Test Specimens.

with air voids in the middle range (>5%-9%) were found to be significantly different. Using Fisher's LSD, researchers found that permeability of CMHB and dense-graded mixtures composed of siliceous aggregate with AC- 20 or AC-20+latex with air voids in the range of 2%-5% and >5%-9% are significantly different. However, the permeability of CMHB and dense-graded mixtures of siliceous aggregate and AC-20 with voids exceeding 9% were not significantly different, but those with AC-20+latex at the same void level were significantly different. Fisher's LSD was performed at α=0.05.

The trend of the data has interesting as well as similar patterns in all cases. Permeability increases almost linearly with air void content and thus continues with a distinct incline to approximately 8%-10% air voids. Above 8%-10% air voids, however, permeability begins to level off or the curve begins to flatten out. This is an indication that the permeability increases only slightly as the air void content exceeds 10%.

One can also relate this trend to field compaction, which was the primary intention for fabricating the test specimens at a wide range of air voids. Often, newly constructed pavements contain air voids exceeding 8%. It has been shown that the permeability of the CMHB and dense-graded mixtures with air voids exceeding 8% differ consistently (but not statistically except in the mixtures containing siliceous aggregate and AC-20+latex). This can be expected due to the characteristics of the CMHB mixture in that it contains a greater percentage of coarse aggregate and forms a skeleton with stone-on-stone contact. However, as the pavement is subjected to traffic, the asphalt concrete densifies. Importantly, the permeability of the CMHB and dense-graded mixtures are similar at air void contents below 5%. Basically, with further densification, permeability of the CMHB and dense-graded pavements will approach similar values at similar voids. Therefore, once a CMHB pavement is fully compacted, it should have no greater permeability (or susceptibility to damage by water or air) than a similar dense-graded mixture.

Figure 8 depicts permeability for each mixture per void content range. Also included is the permeability for a seal coat and a plant mix seal. The seal coat permeability value was obtained from a study performed by Button *(8)*. He found that a new seal coat placed over an asphalt concrete pavement provided an impermeable surface cover.

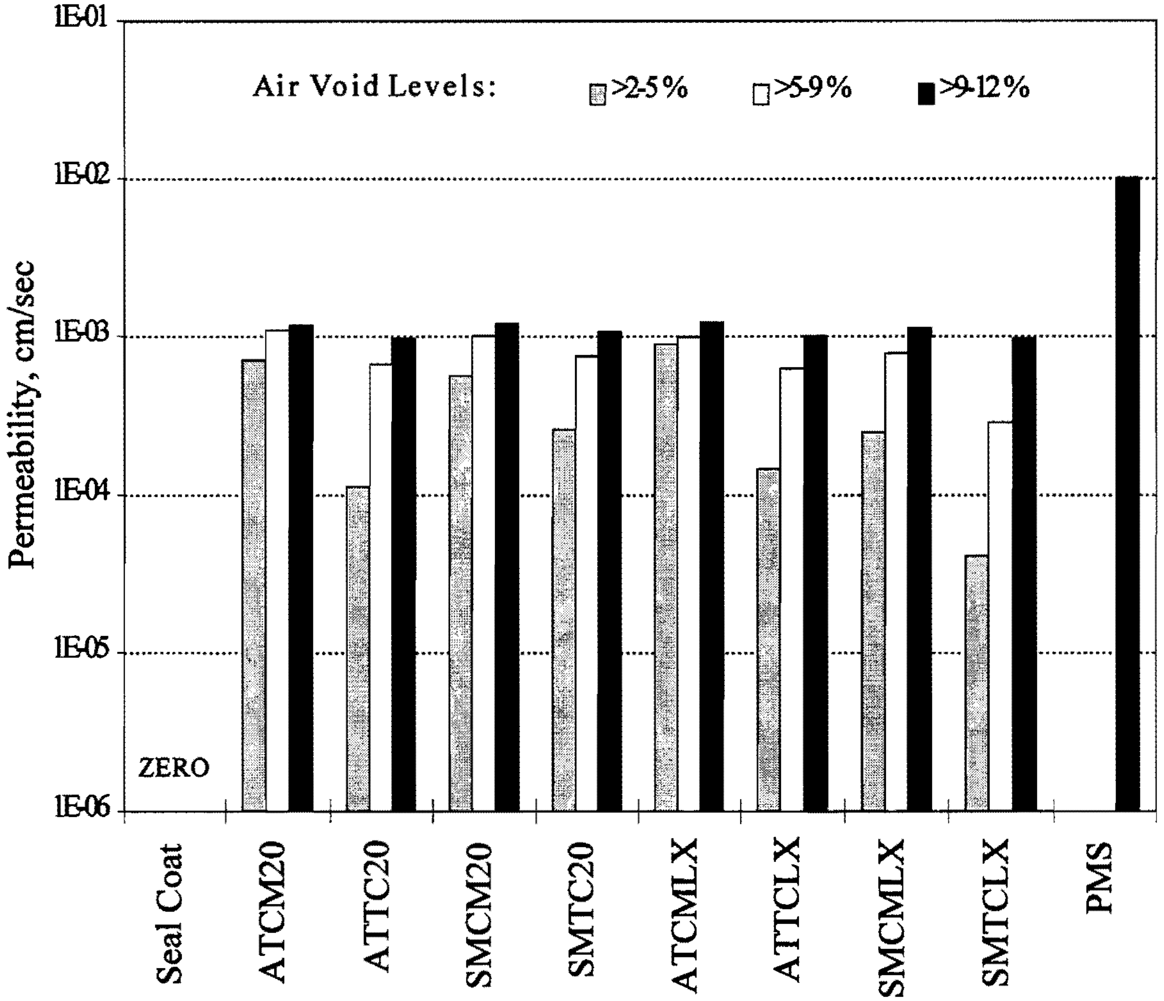

Figure 8. Scale of Permeability Values for Laboratory Fabricated, Seal Coat, and Plant Mix Sea Mixtures (PMS).

Legend

AT - Atlanta, Siliceous Aggregate

SM - Austin, Limestone Aggregate

CM - CMHB Mixture

TC - Dense-Graded Mixture

20 - AC-20

LX - AC-20+latex

The plant mix seal (PMS) was designed according to TxDOT specifications. No tests were conducted on this mixture to evaluate performance. The only purpose for testing the seal coat and PMS mixture was to determine lower and upper limits of permeability, respectively, for common paving materials to compare with the CMHB and dense-graded mixtures. Initially, 154 mm diameter PMS specimens were fabricated for testing with the constant-head permeability apparatus. However, permeability of the PMS mixture exceeded the capability of the apparatus, consequently, it was tested using a falling-head device. The falling-head device consisted of a 2-m graduated cylinder, 102-mm diameter cylindrical receptacle to enclose the specimen, and a catch basin for the water flowing through the specimen. Permeability of the PMS was approximately 10^{-2} cm/sec; whereas, permeability of the dense-graded and CMHB specimens were approximately 1 to 2 orders of magnitude lower. As expected, the CMHB and dense-graded specimens exhibited permeabilities exceeding that of the seal coat mix but lower than that of the PMS. Figure 8 clearly exhibits the relationship of permeability to air void content.

Figure 9 shows the permeability for mixtures saturated by 2 different methods. All of the test specimens were immersed in distilled water at room temperature for 24 hours. There was concern that this may not have been adequate and that vacuum saturation was required. Selected specimens were initially saturated for 24 hours then the permeability was measured. The specimens were air dried for approximately 1 week and then vacuum saturated to 60%-80% saturation and soaked for an additional 24 hours. Then permeability was measured again. There was concern that intense vacuum saturation might open pores in the specimen not previously open and thus increase permeability. Figure 9 indicates that vacuum saturation usually increased permeability but not to a large degree. According to Fisher's LSD, the difference in the permeabilities was not significant (α=0.05). This indicates that vacuum saturation is not necessary to achieve adequate saturation which reduces testing time and complexity of the experiment.

Pavement Field Core Test Specimens

Permeability of the field cores was found to be comparatively low. Testing of the field cores was more tedious than that for the laboratory fabricated test specimens. A few more

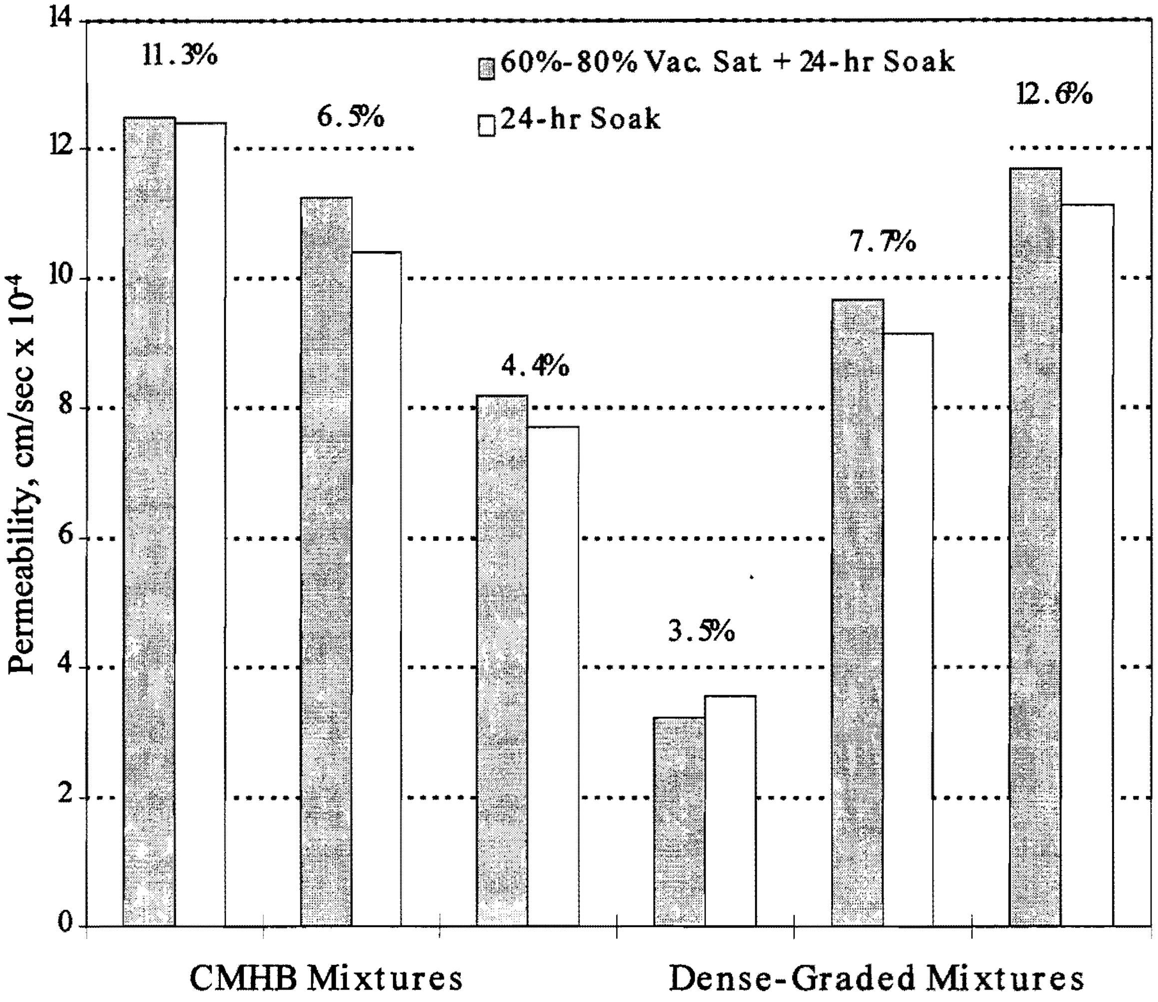

Figure 9. Evaluation of the Effects of Different Saturation Procedures on Permeability.

factors were involved and required attention. The technique used to separate the surface layer from the remainder of core was examined. Initially, researchers used a hammer and wedge to separate the surface layer following approximately 2 hours in an environmental chamber at 0 °C. The wedge was placed at the interface between the surface and adjacent layer in the core and struck sharply with the hammer. In most cases, the use of the hammer and wedge satisfactorily separated the cores. However, in a few cases, sawing was required. It is believed that sawing disturbs the in situ void structure of a specimen. Therefore, the sawn face was gently removed using an ice pick in an attempt to regain the in situ void structure, to the extent possible. The cut face of the core was placed on a hot plate for approximately 5-10 seconds and then systematically picked away. This process was repeated until no saw marks were evident. However, only a limited amount could be picked off because the original core heights were only about 60 mm.

Permeabilities of field cores drilled from 4 CMHB pavement sites in Texas were measured. Cores were obtained from DeBerry, Brenham, Odessa, and Bryan. The number of cores tested from each location varied. Individual results are tabulated in Appendix A. Figure 10 depicts the average permeability of the field cores along with their approximate time after construction as well as the inflow pressure used to measure the permeability. The values in parentheses near the location name along the x-axis are the average air void content of the cores.

Field cores from the Atlanta and Brenham districts were not permeable at the low pressure normally used and, therefore, were tested at higher inflow pressures (Figure 10). A pressure of 17 kPa was ordinarily used for these tests. Pressures of 276 kPa and 207 kPa were applied for the Atlanta and Brenham cores, respectively. Although these pressures are probably unrealistic, their sole purpose was to demonstrate that, even at much higher pressures, trafficked mixtures exhibit comparatively much lower permeabilities. The important factor is that cores from CMHB pavements exposed to 1 year of traffic exhibited permeabilities about 2 orders of magnitude lower (at 17 kPa pressure) than CMHB pavements recently constructed. Researchers determined that permeability of the cores after a year of construction was significantly different from those recently constructed (α=0.05).

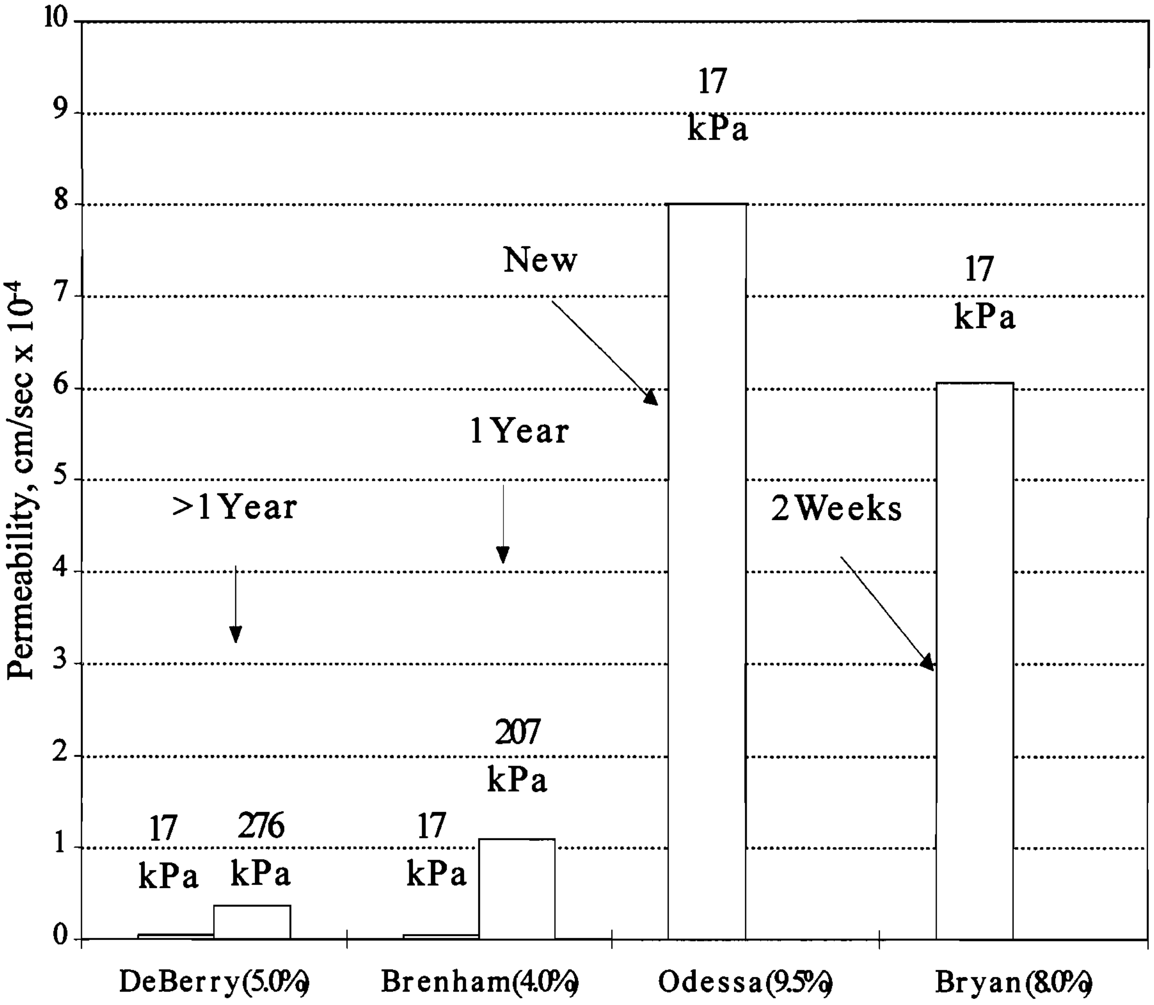

Figure 10. Permeability Values of Field Cores with Inflow Pressures and Time Since Construction.

Following periods of precipitation, some CMHB pavements exhibited wet spots for up to 3 or 4 days. This phenomenon was commonly witnessed by district personnel. New CMHB pavements in College Station and Abilene were observed to exhibit this phenomenon. Cores were extracted from wet and dry areas which were located and marked following rainfall on the previous day. Permeabilities of these cores from wet and dry areas were not significantly different according to Fisher's LSD (α=0.05). Sample data from College Station is shown in Figure 11.

Figure 12 shows air void contents of selected cores and laboratory fabricated test specimens for which the bulk specific gravities were determined using 3 different methods. The methods included the saturated surface dry (SSD) procedure (Tex-207-F, Part I), paraffin coating method (Tex-207-F, Part II), and a glass bead method. A brief description of these test methods is given in Chapter 3. These 3 specific gravity tests were performed to evaluate the values provided by the commonly used SSD method on relatively high-void mixtures such as a newly constructed CMHB overlay. The higher coarse aggregate content in a CMHB will create fewer, larger voids than those in a typical dense-graded mixture at a given air void content. Therefore, water can more readily penetrate these voids during submersion and promptly run out when the specimen is withdrawn. This, of course, will result in an erroneously low air void measurement.

Surprisingly, the paraffin coating method yielded consistently lower air voids than the SSD method, but they were not significantly different, according to Fisher's LSD. The SSD procedure was performed before permeability testing and the paraffin method was performed after permeability testing and air drying. It is believed that the specimens used in the paraffin method may have still contained water. Conversely, the bead method provided significantly higher air voids than the SSD method where, in some cases, the difference was approximately twice the SSD or paraffin coating measurement. The bead method is relatively new and designed specifically for very large specimens. Additional work is needed to fully comprehend the effects of bead size and methodology with different sizes and types of mixtures. The results obtained by the bead method were statistically different from those obtained by the SSD and paraffin coating method.

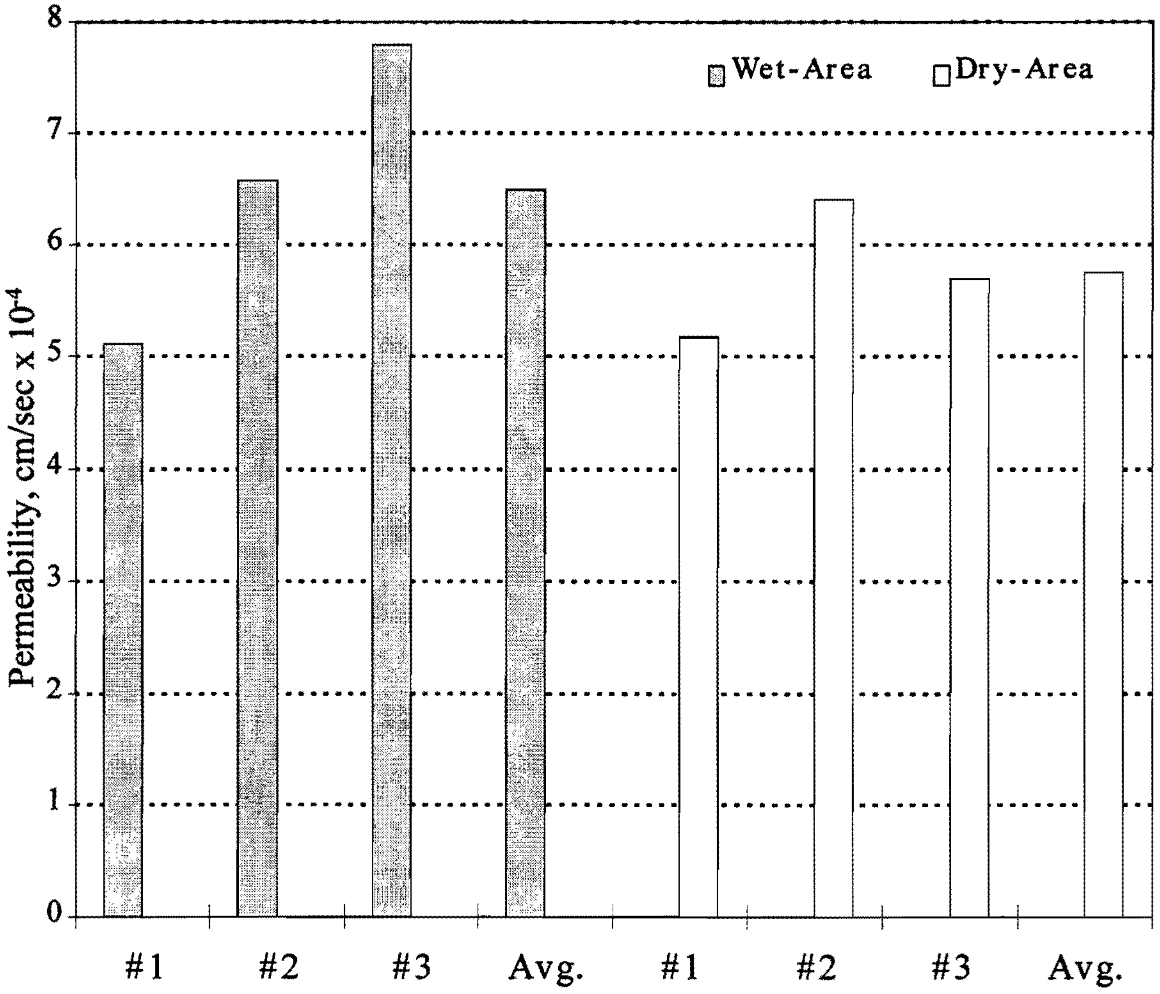

Figure 11. Permeability Values of Cores Extracted from Wet and Dry Areas in College Station.

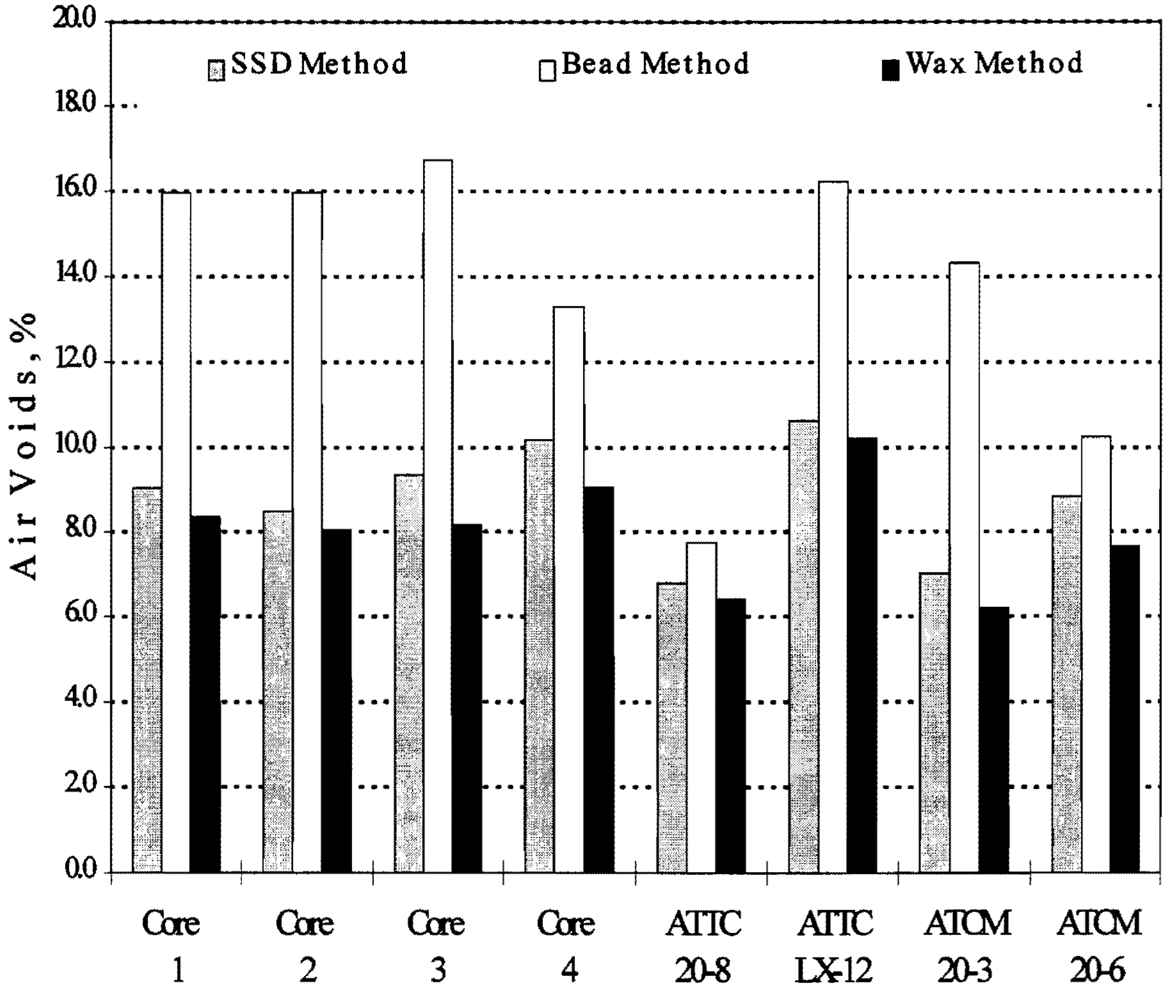

Figure 12. Measurement of Air Void Content through Different Methodologies.

Legend

AT - Atlanta, Siliceous Aggregate

TC - Dense-Graded Mixture

CM - CMHB Mixture

20 - AC-20

LX - AC-20+latex

- Sample Number

TxDOT STATIC CREEP TEST

The TxDOT creep test and associated criteria were developed specifically for the evaluation of CMHB mixtures. Nevertheless, the test procedure should be valid for comparative evaluations of dense-graded mixtures; however, the specification criteria may not be valid. Test results for the CMHB and dense-graded mixtures are listed in Tables 5 and 6, respectively. Related materials specifications are also shown. These data were generated from a modified creep test procedure. The test procedure was slightly altered as discussed in Chapter 3. The test performed with the original procedure yielded illogical results such as negative

Table 6. Summary of TxDOT Static Creep Test Results for Dense-Graded Mixtures.

MIXTURE DESIGN	ASPHALT BINDER	PERMANENT STRAIN, mm/mm	SLOPE, mm/mm/sec	CREEP STIFFNESS, kPa
SPECIFICATION	---	***< 6.00 x 10^{-4}***	***< 4.00 x 10^{-8}***	***> 41,400***
SILICEOUS, ATLANTA	AC-10	5.71 x 10^{-4}	3.44 x 10^{-8}	62149
	AC-20	6.05 x 10^{-4}	5.88 x 10^{-8}	70019
	AC-45P	9.82 x 10^{-4}	9.69 x 10^{-8}	49723
	LATEX	9.57 x 10^{-4}	8.17 x 10^{-8}	49571
SANDSTONE, PARIS	AC-10	4.87 x 10^{-4}	3.24 x 10^{-8}	70843
	AC-20	6.45 x 10^{-4}	5.60 x 10^{-8}	65824
	AC-45P	9.13 x 10^{-4}	1.00 x 10^{-7}	54987
	LATEX	8.67 x 10^{-4}	7.84 x 10^{-8}	53108
LIMESTONE, AUSTIN	AC-10	5.59 x 10^{-4}	3.64 x 10^{-8}	78405
	AC-20	5.13 x 10^{-4}	6.81 x 10^{-8}	91363
	AC-45P	1.06 x 10^{-4}	1.23 x 10^{-7}	51843
	LATEX	4.77 x 10^{-4}	2.30 x 10^{-8}	88174

permanent strains. This occurred several times such that minor procedural changes were required to eliminate this problem. (Since this study began, TxDOT modified their standard procedure to eliminate this problem.)

In most cases, permanent strains for the CMHB mixtures were less than or similar to those for corresponding dense-graded mixtures. Statistical analyses using Fisher's LSD showed that the permanent strains for CMHB and dense-graded mixtures composed of siliceous aggregate and AC-10, AC-20, or AC-45P were statistically equivalent except for those fabricated with AC-20+latex. Fisher's LSD also showed that the permanent strains for all mixtures composed of limestone to be statistically equivalent. The permanent strains for CMHB and dense-graded mixtures containing sandstone and AC-20, AC-45P, or AC-20+latex were not significantly different. A majority of the CMHB and dense-graded mixtures did not meet the TxDOT specification for permanent strain.

Examination of the raw data indicated that the slopes of the steady-state portion of the creep curves for the CMHB mixtures were generally less than those for the corresponding dense-graded mixtures. However, the creep slopes for the CMHB mixtures fabricated using siliceous or sandstone aggregates with AC-10 or AC-20 as well as mixtures with limestone and AC-10 were greater than those for their corresponding dense-graded mixtures. CMHB mixtures containing the modified binders, except for that containing limestone and AC-20+latex, yielded lower creep slopes than their corresponding dense-graded mixtures. Using Fisher's LSD, researchers determined that the creep slopes for all corresponding CMHB and dense-graded mixtures were statistically equivalent. Overall, more than half the mixtures did not meet the TxDOT specification for creep slope.

From the raw data, creep stiffness of the CMHB mixtures was generally less than the stiffness of the corresponding dense-graded mixtures. However, there were 3 exceptions where the opposite occurred: siliceous aggregate plus either modified binder and limestone with AC-45P. This general trend was expected because the CMHB mixtures contain more binder (higher film thicknesses) than the dense-graded mixtures. All of the mixtures tested met TxDOT's creep stiffness specification. Using Fisher's LSD, researchers determined that, in most cases, the average creep stiffness for CMHB and dense-graded mixtures are not significantly different among similar aggregate types. However, the stiffness of the CMHB mixture composed of limestone and AC-45P is significantly greater than its corresponding dense-graded mixture.

TxDOT static creep testing did not conclusively prove that the CMHB mixtures were less rut-susceptible than their corresponding dense-graded mixtures. Unconfined uniaxial creep tests are typically performed to estimate relative rut-susceptibility because of their simplicity, reproducibility, and efficiency.

Little et al. *(25)* showed that uniaxial creep testing, in general, is normally sufficient for prioritizing HMA mixtures according to their relative resistance to permanent deformation. They demonstrated that a realistic evaluation of the rut resistance of SMA mixtures required a confining pressure to simulate actual field conditions. It should be noted that CMHB mixtures are similar to SMA mixtures and that such a confining pressure is required to mobilize the available shear strength in the coarse stone-to-stone skeleton of the mixture.

MOISTURE SUSCEPTIBILITY

Effect of Water On Bituminous Paving Mixtures

Figure 13 depicts the amount of stripping visually estimated from the tests performed in accordance with Tex-530-C. The visual inspection of the relative stripping after the boiling tests indicated that the CMHB mixtures were consistently less affected than the dense-graded mixtures. The mixtures composed of the siliceous aggregate exhibited less stripping which is attributable to the hydrated lime in that mixture. Fisher's LSD indicated that the difference between averages of replicate tests for corresponding CMHB and dense-graded mixtures fabricated with similar materials was significantly different at $\alpha=0.05$.

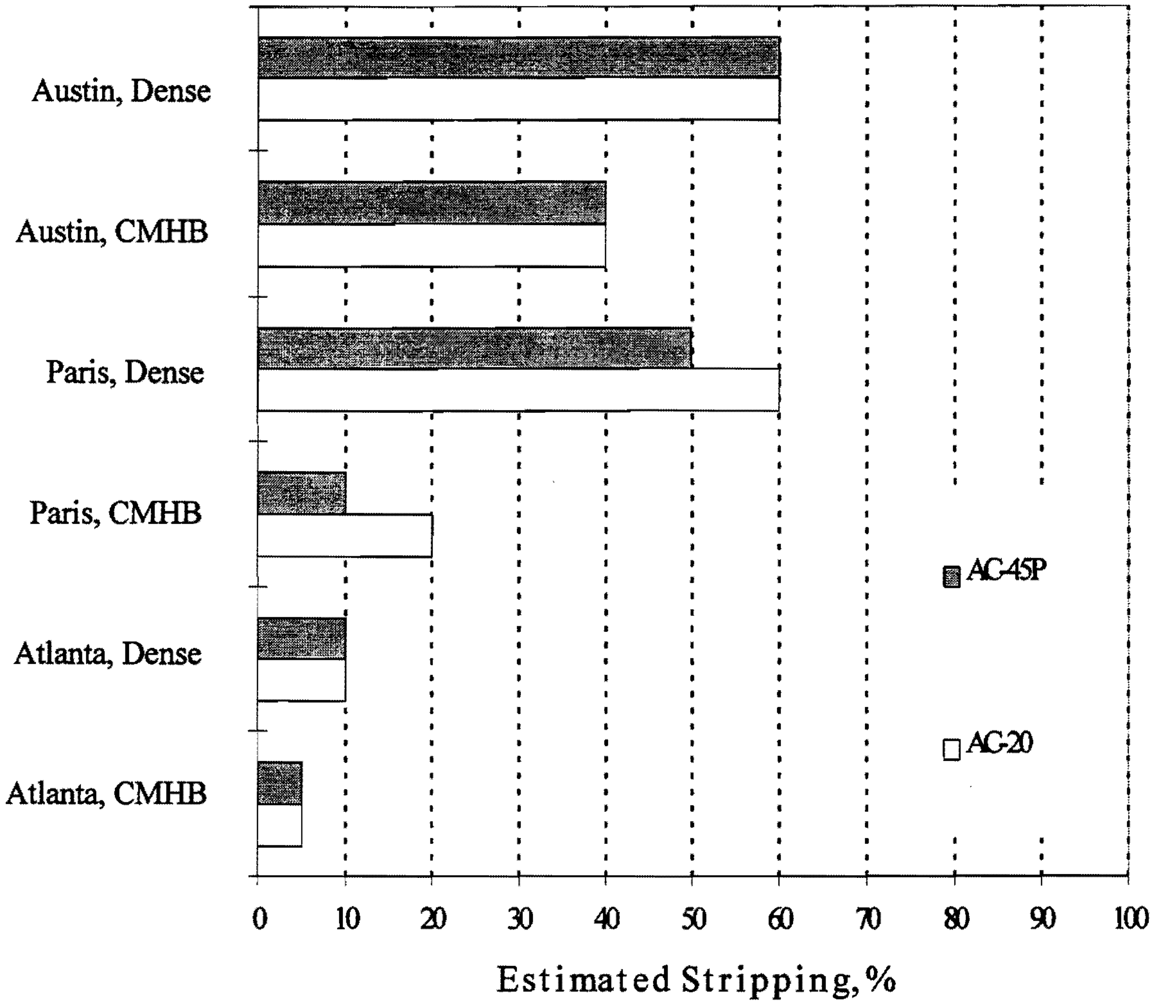

Figure 13. Estimated Visual Percent Stripping from Tex-530-C.

Prediction of Moisture-Induced Damage Using Molded Specimens

Figures 14 and 15 compare the indirect tensile strength of the conditioned and unconditioned CMHB and dense-graded specimens. These results were used to compute tensile strength ratios (TSR) for mixtures composed of siliceous, sandstone, or limestone aggregate with AC-20 or AC-45P (Table 7).

Table 7. TSR Values for Mixtures Tested According to Tex-531-C.

Asphalt Binder	Atlanta, Siliceous		Paris, Sandstone		Austin, Limestone	
	CMHB	Dense-graded	CMHB	Dense-graded	CMHB	Dense-graded
AC-20	83	85	57	50	68	57
AC-45P	90	86	83	68	81	96

In most cases, the CMHB mixtures exhibited higher TSR values than their corresponding dense-graded mixtures. This trend was expected due to the higher binder film thicknesses in the CMHB mixtures as well as the higher mastic content created by the high filler content and binder. The higher binder film thickness provides improved coating of the aggregate and thus protection from moisture.

The CMHB mixture containing limestone and AC-45P gave a lower TSR than its corresponding dense-graded mixture. The conditioned, dense-graded test specimens composed of these materials had a significantly lower air void content which probably contributed to the higher indirect tensile strength. Tensile strength is very sensitive to and inversely proportional to the air void content. Although these air voids are within the specified range (7±1%) for testing, small differences in air void content can still significantly affect the IDT strength, which was apparently the case here. The TSR values for both mixtures with the siliceous aggregate are relatively high. Both siliceous mixtures contained hydrated lime which likely contributed to these high TSR values. The air void content of the specimens are listed in

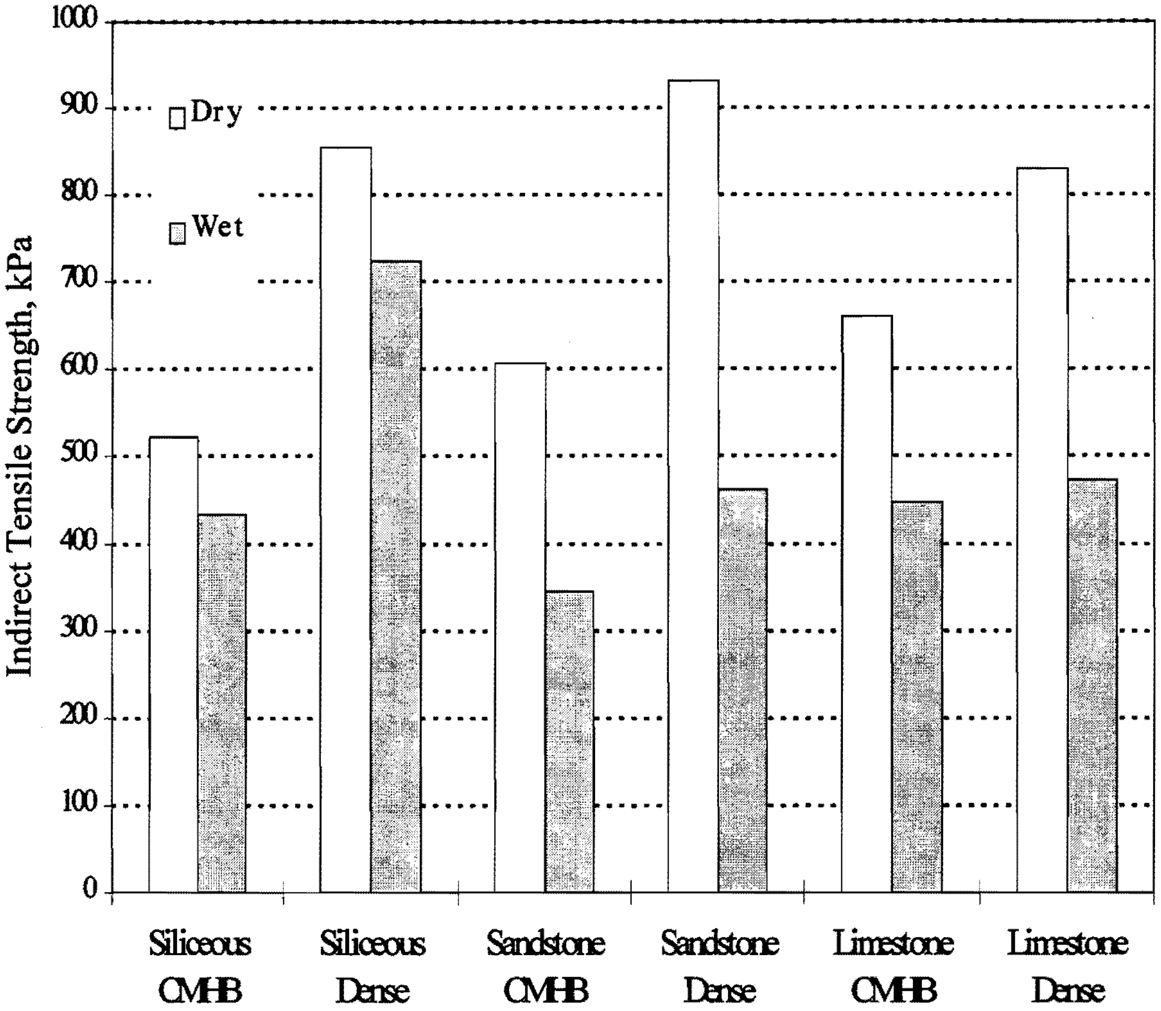

Figure 14. Results of Tex-531-C Tests on CMHB and Dense-graded Mixture Specimens Composed of AC-20 (25 °C).

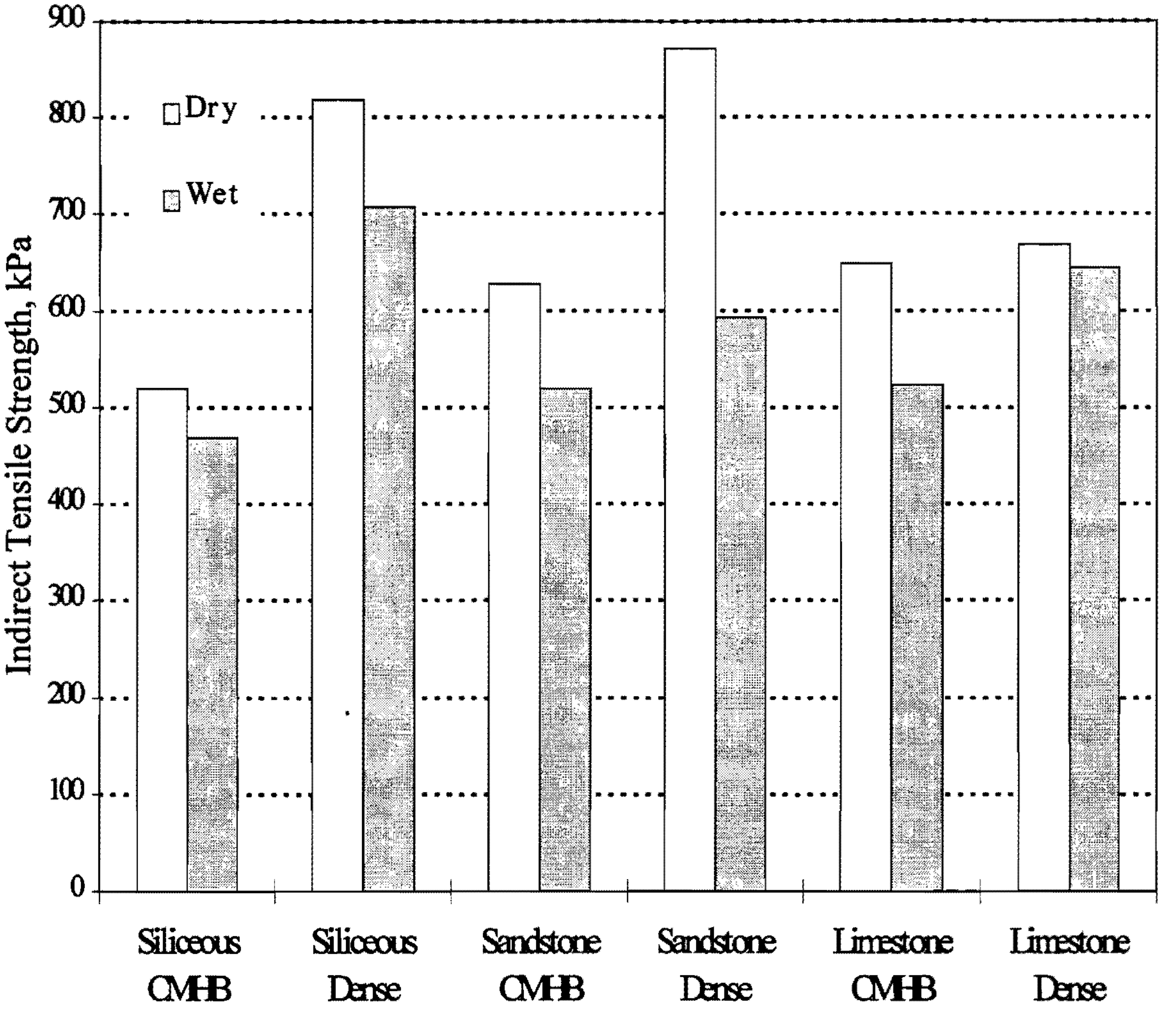

Figure 15. Results of Tex-531-C Tests on CMHB and Dense-graded Mixture Specimens Composed of AC-45P (25 °C).

Appendix B along with the moisture susceptibility data.

Fisher's LSD demonstrated that the TSRs for corresponding CMHB and dense-graded mixtures composed of siliceous, sandstone, or limestone with AC-20 are not significantly different (α=0.05). Further, the TSRs for corresponding CMHB and dense-graded mixtures containing siliceous or limestone aggregate with AC-45P were not significantly different. However, the corresponding CMHB and dense-graded mixtures containing sandstone and AC-45P were significantly different.

SHRP SHORT-TERM AND LONG-TERM AGING

Laboratory prepared CMHB and dense-graded mixtures (compacted to 7±1% air voids) containing similar materials were exposed to short-term and long-term aging. Properties before and after aging were measured to determine the relative effects. Binders from unaged and aged specimens were extracted and their properties were comparatively examined.

Mixture Evaluation

Results from individual aging tests are provided in Appendix D. Figures 16-19 summarize the indirect tensile strength and resilient modulus of non-aged, short-term, and long-term aged mixtures. The dense-graded mixtures exhibited higher tensile strengths and resilient moduli than corresponding CMHB mixtures subjected to short-term and long-term aging. This is an indication that the dense-graded mixtures are more susceptible to oxidative aging than comparable CMHB mixtures. The relatively higher asphalt film thickness of CMHB mixtures allows less aging than in the dense-graded mixtures. From a practical standpoint, aged CMHB pavements should resist cracking better than dense-graded mixtures made using similar materials.

The raw data indicated tensile strengths of unaged CMHB mixtures are consistently lower than those of corresponding dense-graded mixtures. However, Fisher's LSD (α=0.05) indicated that tensile strengths for the unaged CMHB and dense-graded mixtures containing limestone and AC-20 or AC-45P are statistically equivalent. Fisher's LSD showed that the tensile strength of long-term aged CMHB mixture containing siliceous aggregate with AC-45P is significantly lower than that for corresponding dense-graded mixtures. Tensile strengths of

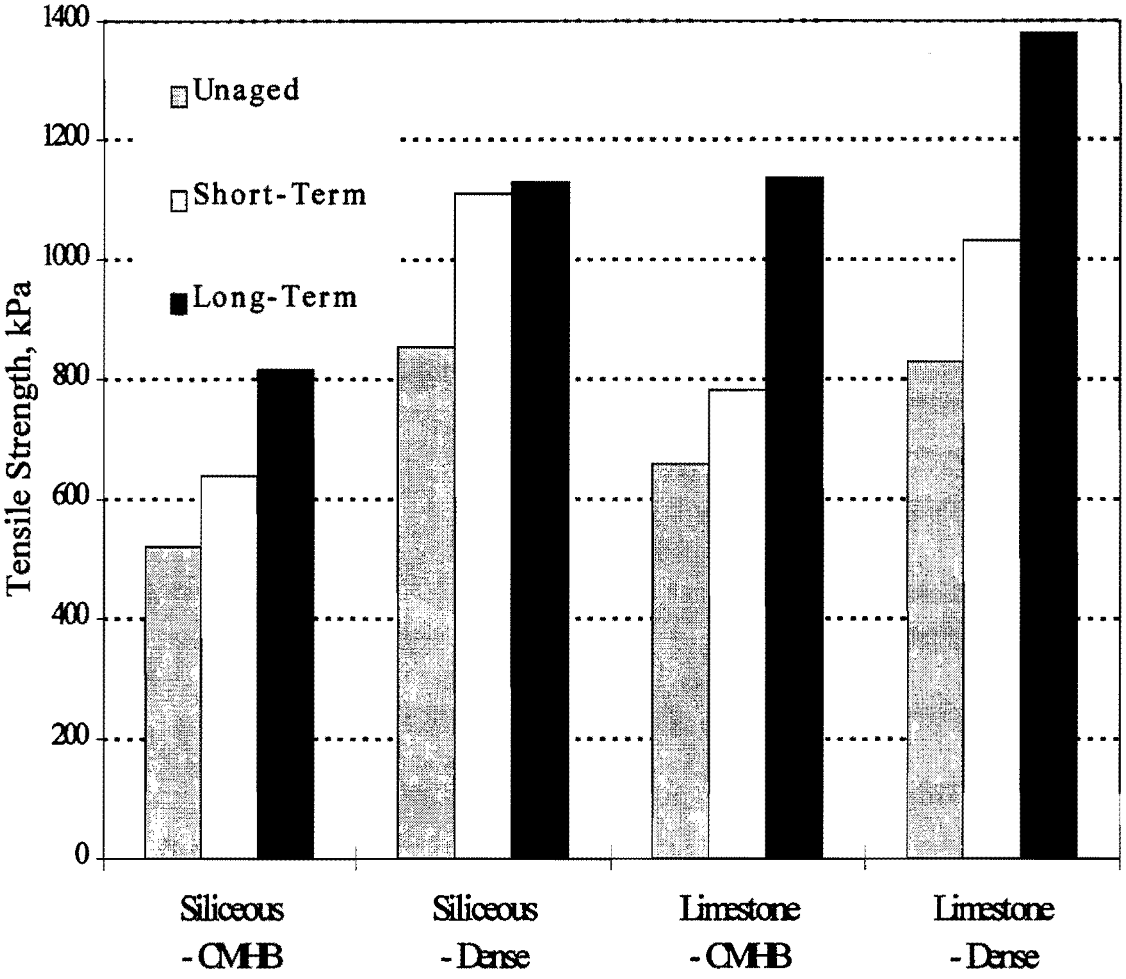

Figure 16. Indirect Tensile Strength of Short-Term and Long-Term Aged Specimens with AC-20.

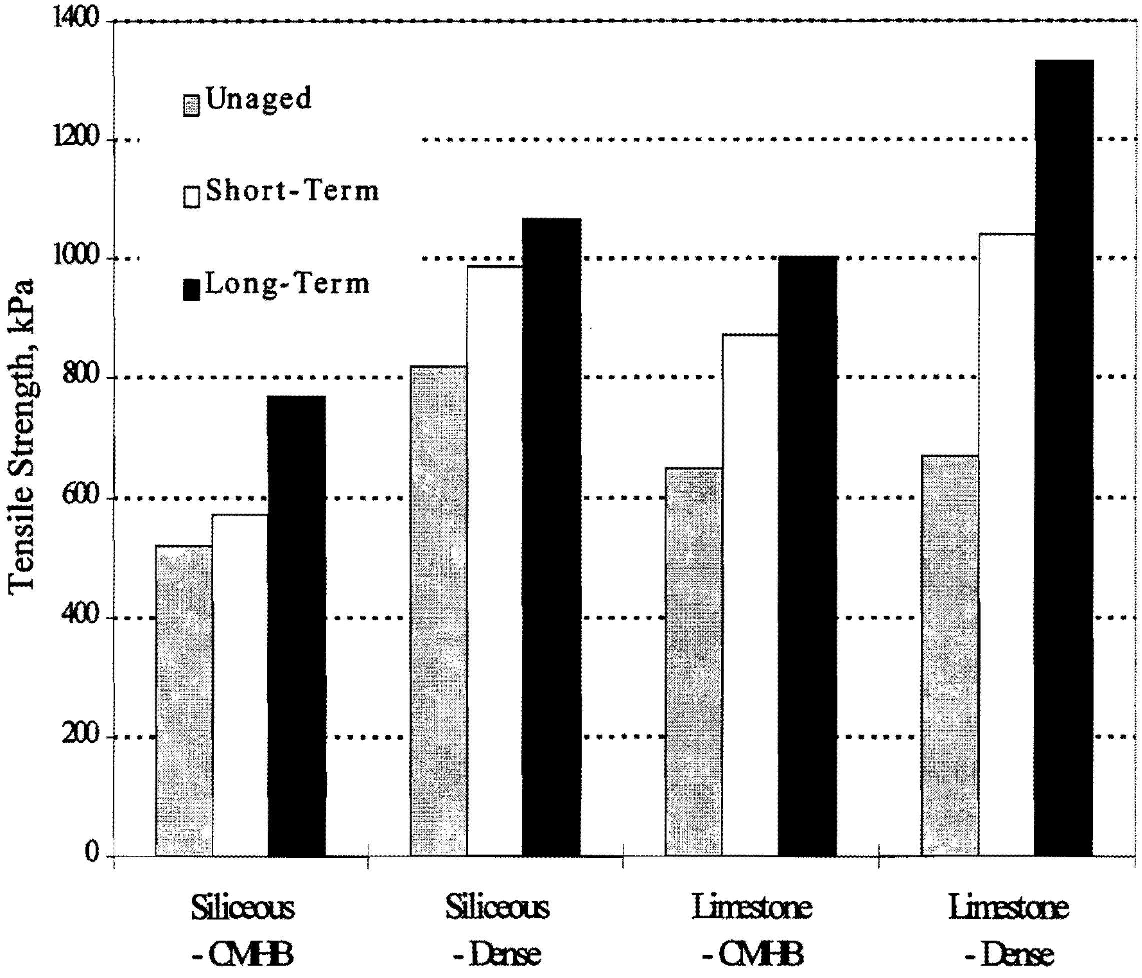

Figure 17. Indirect Tensile Strength of Short-Term and Long-Term Aged Specimens with AC-45P.

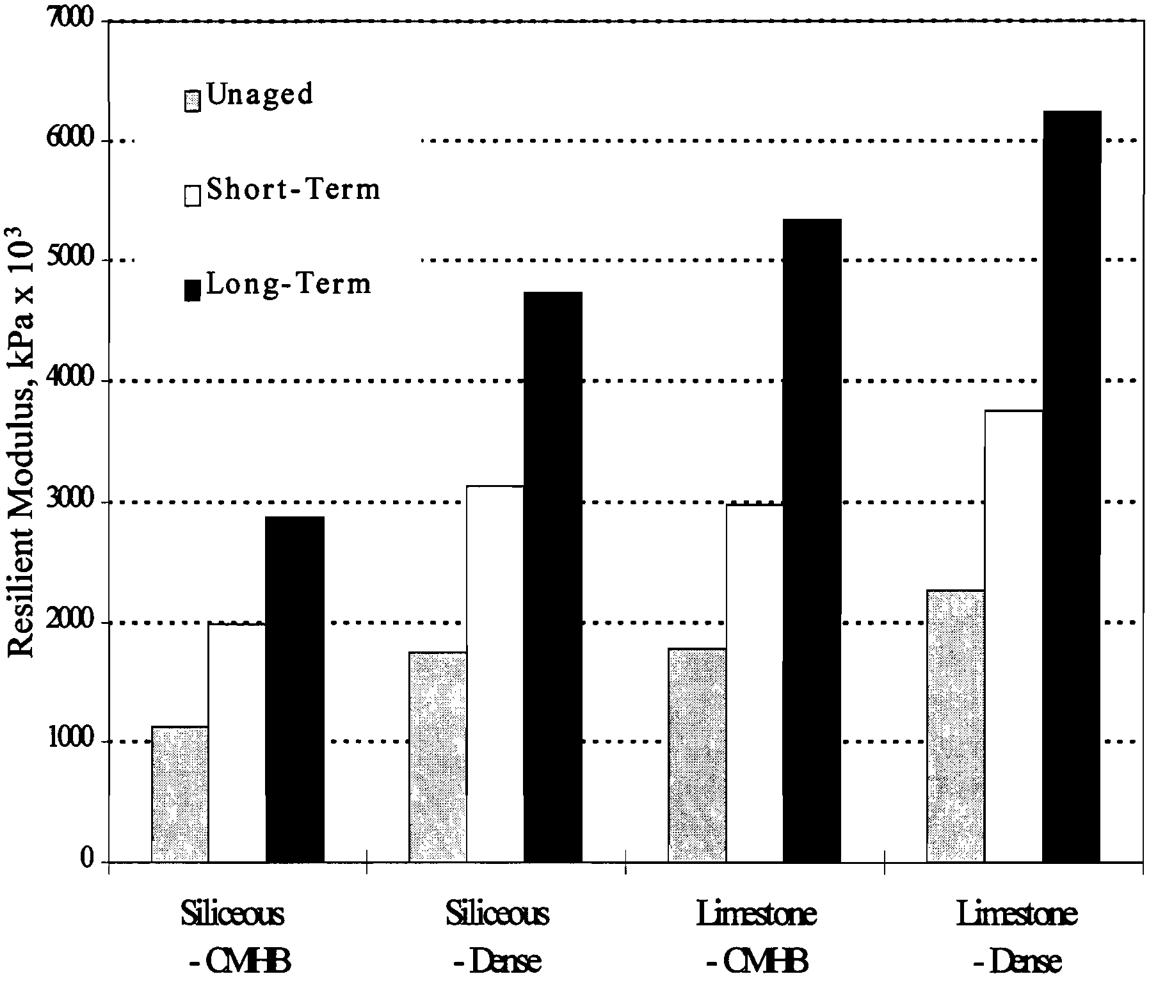

Figure 18. Resilient Modulus of Short-Term and Long-Term Aged Specimens with AC-20.

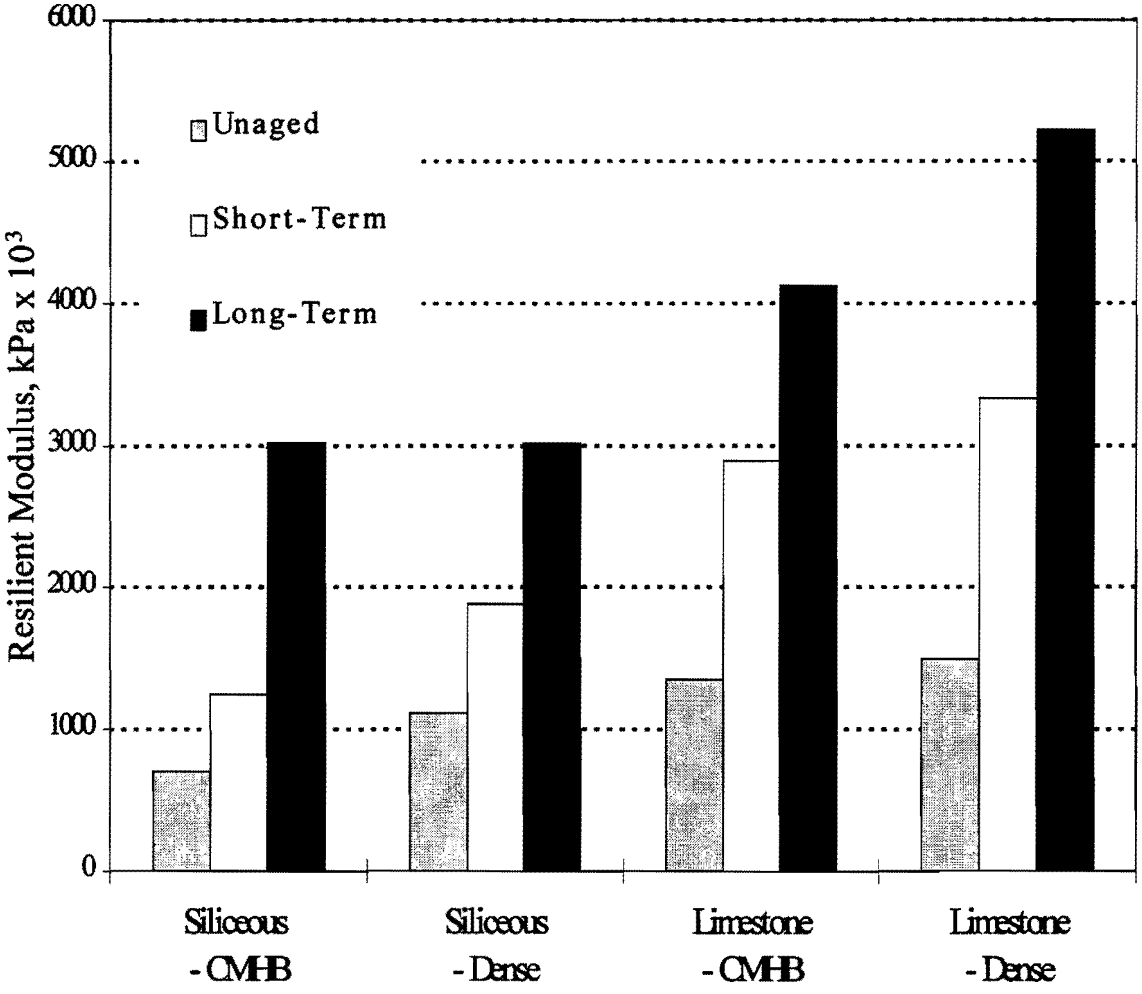

Figure 19. Resilient Modulus of Short-Term and Long-Term Aged Specimens with AC-45P.

short-term and long-term aged CMHB mixtures composed of limestone aggregate with AC-45P are also significantly lower than the comparable dense-graded mixtures. Fisher's LSD indicated that tensile strengths for the remaining mixtures are statistically equivalent.

Generally, resilient moduli of the unaged CMHB mixtures are lower than those for comparable dense-graded mixtures. Fisher's LSD showed that resilient moduli of the unaged CMHB and dense-graded mixtures containing limestone and AC-45P are statistically equivalent. Fisher's LSD showed that resilient modulis of corresponding short-term and long-term aged mixtures are statistically equivalent. However, the resilient moduli of the long-term aged CMHB mixtures containing limestone and AC-45P were found to be significantly different from those for corresponding dense-graded mixtures.

Tensile strengths and resilient moduli of the unaged and aged CMHB mixtures were generally lower than those of corresponding dense-graded mixtures. However, it must be noted that compaction to 7±1% air voids may not have yielded uniform affects on these two types of mixtures since the CMHB mixtures were designed at 3% air voids and the dense-graded mixtures were designed at 4% air voids. Therefore, less compactive effort was required to achieve 7±1% air voids for the CMHB mixtures than for the dense-graded mixtures. To examine the effects of compaction, CMHB and dense-graded specimens containing limestone or siliceous aggregate with AC-20 were fabricated at design air voids and subjected to indirect tensile and resilient modulus testing. Table 8 lists the tensile strengths and resilient moduli for these unaged mixtures as well as the percent increase in each material property. As expected, the tensile strengths and resilient moduli increased in 7 out of 8 instances. Consequently, the dense-graded mixtures may have had an advantage over the CMHB mixtures during aging and moisture susceptibility comparisons.

Table 8. Tensile Strength and M_R for Siliceous and Limestone Mixtures with AC-20 at Different Air Voids.

Parameter Measured	Siliceous Aggregate w/ AC-20					
	CMHB			Dense-graded		
Air Voids, %	7±1%	3±1%	% Increase	7±1%	4±1%	% Increase
Tensile Strength, kPa	522	596	14.2	855	953	11.5
M_R, kPa x 10^3	1124	1195	6.3	1752	1600	-8.7
	Limestone Aggregate w/ AC-20					
Air Voids, %	7±1%	3±1%	% Increase	7±1%	4±1%	% Increase
Tensile Strength, kPa	660	968	46.7	830	1126	35.7
M_R, kPa x 10^3	1776	2454	38.2	2264	3060	35.2

Binder Evaluation

Complex moduli (G^*) of extracted and recovered unaged and aged binders for the CMHB and dense-graded mixtures are listed in Table 9. In all cases, G^* values for the AC-20 from the CMHB mixtures are lower than those from corresponding dense-graded mixtures. In most cases, G^* values for AC-45P from the CMHB mixtures are lower than those from corresponding dense-graded mixtures. This is further evidence that CMHB mixtures are less susceptible to aging than comparable dense-graded mixtures.

The G^* values of a few recovered aged AC-45P binders were lower than values for their corresponding virgin binders. AC-45P contains polymer. It appears that exposure to heat during aging or exposure to heat and trichloroethylene during extraction or a combination of these factors caused break down of the polymer which resulted in binder softening that offset the hardening due to aging.

Fisher's LSD indicated that G^* values for the short-term and long-term aged CMHB and corresponding dense-graded mixtures for each material are statistically equivalent at test temperatures of 60 °C and 40 °C. However, G^* values of recovered binders tested at 10 °C were significantly different.

Penetration values for recovered unaged and aged binders from CMHB and dense-graded mixtures are compared in Figure 20. Retained penetrations for the binders from the CMHB mixtures are greater than those from corresponding dense-graded mixtures. This indicates that the CMHB mixtures are less susceptible to oxidative aging than comparable dense-graded mixtures.

It was anticipated that the retained penetration for the binders from the long-term aged mixtures would always be significantly lower than those from the short-term aged mixtures. However, Figure 20 reveals that the binders did not uniformly follow this trend. In some cases, no additional aging was detected by measuring penetration. This is probably due to inherent variability caused by extraction and recovery procedures.

Table 9. Complex Shear Modulus of Recovered Asphalt Binder from Short-Term and Long-Term Aged Specimens.

Temperature °C	Complex Shear Modulus (G*), kPa					
	Unaged	Short-Term	Long-Term	Unaged	Short-Term	Long-Term
	AC-20, CMHB, Austin, Limestone			AC-20, Dense-Graded, Austin, Limestone		
60	1.04	7.88	12.7	1.04	10.1	14.4
40	47.8	280	347	47.8	296	384
10	11,900	26,700	31,600	11,900	30,400	34,500
	AC-45P, CMHB, Austin, Limestone			AC-45P, Dense-Graded, Austin, Limestone		
60	2.24	15.7	23.3	2.24	19.4	25.5
40	54.1	100	187	54.1	141	198
10	8,600	7,510	12,600	8,600	8,000	15,000
	AC-20, CMHB, Atlanta, Siliceous			AC-20, Dense-Graded, Atlanta, Siliceous		
60	1.04	1.32	10.4	1.04	4.76	14.7
40	47.8	37.7	261	47.8	251	394
10	11,900	8,290	25,100	11,900	15,900	31,900
	AC-45P, CMHB, Atlanta, Siliceous			AC-45P, Dense-Graded, Atlanta, Siliceous		
60	2.24	5.97	9.71	2.24	6.33	13.9
40	54.1	41.7	123	54.1	138	152
10	8,600	3,400	12,000	8,600	11,000	12,000

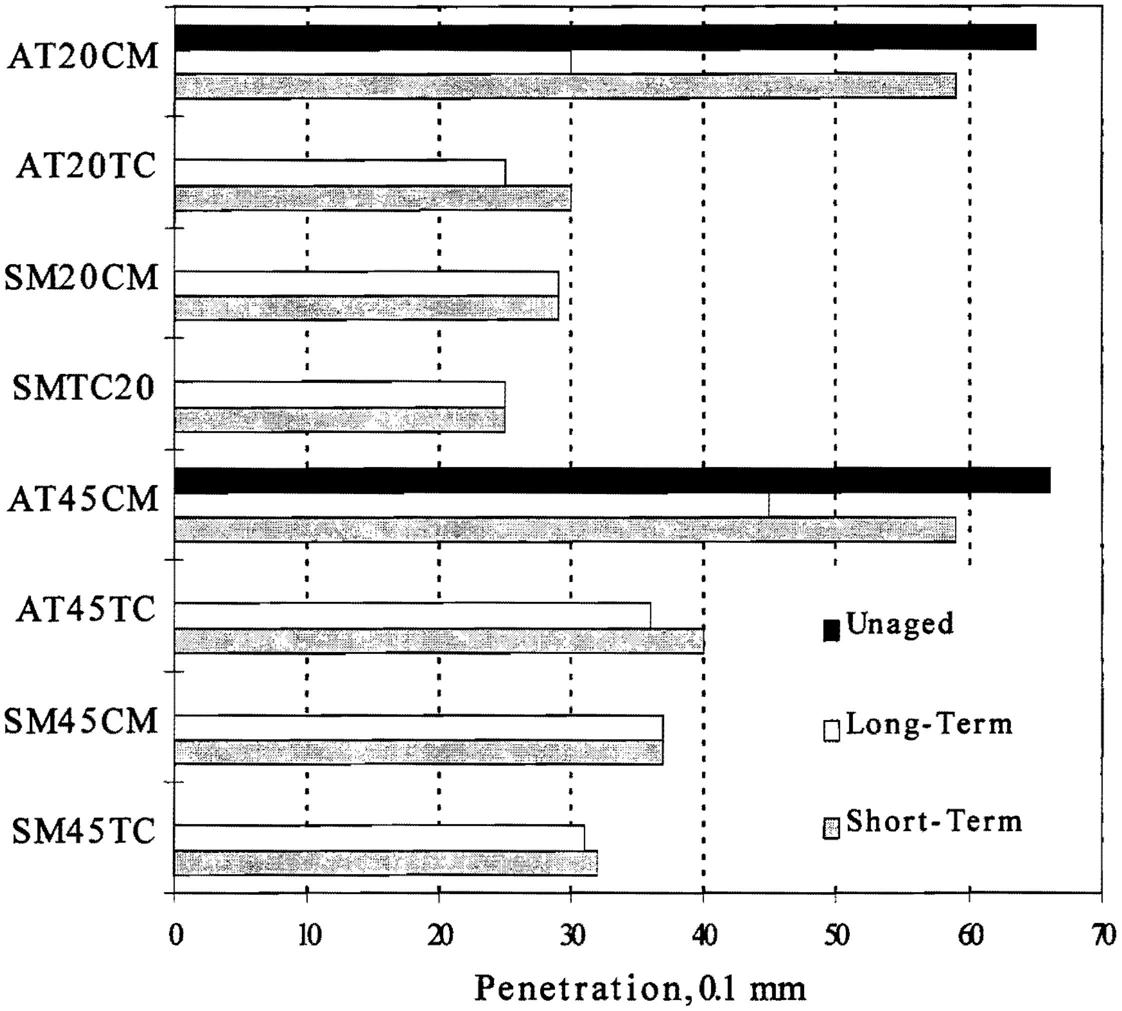

Figure 20. Penetration of Recovered Asphalt Binder from Short-Term and Long-Term Aging.

Legend

AT - Atlanta, Siliceous Aggregate

SM - Austin, Limestone Aggregate

20 - AC-20

45 - AC-45P

CM - CMHB Mixture

TC - Dense-Graded Mixture

CHAPTER V

FIELD STUDIES OF CMHB PAVEMENTS

The primary objective of this element of work was to evaluate several existing CMHB pavements, to the extent possible, in comparison to pavements surfaced with conventional dense-graded mixtures. Construction parameters as well as subsequent pavement performance were surveyed. Nineteen pavement sites in 10 districts across the state of Texas were evaluated in the spring/summer of 1995 and 1996 (Table 10). Only 1 of the CMHB pavements evaluated had a companion dense-graded control pavement for direct comparison. Researchers used the SHRP performance evaluation procedures (24) to evaluate the pavements.

A questionnaire (Appendix G) was formulated and sent to each TxDOT district to obtain subjective evaluations of construction and performance of CMHB pavements. Researchers visited personnel in several districts, either in person or by phone, to obtain detailed information.

CONSTRUCTION

Comments from TxDOT Area Engineers and Laboratory Supervisors regarding construction of these CMHB mixtures are summarized in this subsection. No particular construction difficulties were noted. Placement of a CMHB mat was reported by most engineers to be no different than placing a dense-graded mixture. Handworking (raking) was significantly more difficult for CMHB mixtures; that is, it was almost impossible to obtain a smooth finish when raking or luting. Therefore, raking should be kept to an absolute minimum. Feathering a CMHB mat was difficult because of the coarseness of the mix.

Segregation was not normally a problem; most engineers reported less segregation than with typical dense-graded mixes. Because of the gradation of CMHB mixtures, they should be less susceptible to segregation than typical dense-graded mixtures. Further, with the coarse texture of the mat, segregation is more difficult to detect.

Table 10. Description of Test Pavements Surveyed.

District	No. Sections Surveyed	Highway Location	Thickness & Mix Type	Traffic, ADT-1995	Control Section
Abilene	1	US83	37 mm, C	8050	No
Amarillo	1	IH40	63 mm, C	9900	No
Atlanta	3	US79	50 mm, C with AC-10	5600	No
			50 mm, C with AC-20	5600	No
			50 mm, C AC-15TR	5600	No
Austin	4	Spur 1825	38 mm, C	3500	No
		US290 + Control	50 mm, C	15,000	Yes, Ty C
		SH45	50 mm, C	light	No
Bryan	1	US290	42 mm, C	11,300	No
Childress	1	US287	56 mm, C	3500	No
El Paso	2	FM659	38 mm, C	5400	No
Odessa	3	FM1882	--, F	14,500	No
		US385	--, C	1950	No
		Loop 350	--, C	16,500	No
Waco	2	US84	38 mm, C	--	No
		Loop 340	--, C	--	No
Wichita Falls	1	US287	50 mm, C	13,950	No

Most engineers reported that adequate compaction of CMHB mixtures was as easy or easier to attain than that for dense-graded mixtures with equivalent maximum size aggregate. During compaction, a CMHB mat does not "roll down" (that is, decrease in height) as much as a dense-graded mixture. This indicates that the CMHB mixture immediately behind the paver is closer to its densest configuration than a similar dense-graded mixture. Some engineers noted a faster drop in temperature which was attributed to the comparatively more open texture of the CMHB mat.

Most engineers noted that a newly placed CMHB overlay was permeable to water. In many cases, the CMHB mat would hold water for 3 or 4 days after rainfall ceased. This was manifested by slow drainage of water out of the lower side of the mat for a few days after rainfall ceased. Further, wet areas on the pavement surface were often apparent (usually in the wheel path) for a few days after the last rainfall. These wet areas decreased in size with time and traffic, both of which served to dry the pavement. On occasion, in high-traffic areas, these wet areas exhibited foaming at the pavement surface. In lower trafficked areas, the wet areas may leave temporary stains on the pavement surface after drying. These phenomena associated with CMHB pavements usually disappeared after a year or two of traffic and, thus, subsequent densification of the mat.

PERFORMANCE

Generally, after 2 or more years in service, all CMHB pavements were performing well. Some flushing in the wheelpaths of certain pavements was noted (Table 11), but this was usually explained by excessive asphalt above the optimum selected for the mixture design. It should be pointed out that even with some flushing, surface textures of the CMHB mixtures appeared to be fairly good, in most instances. In 1996, the CMHB mixture on U.S. 290 near Austin showed significantly less cracking than its corresponding Type C, dense-graded Control section. This is likely due to the relatively higher asphalt film thicknesses in the CMHB mixture. Rutting resistance of CMHB mixtures generally appears to be excellent. The total area of significant flushing, rutting, and cracking in all the CMHB pavements evaluated (Figure 21) demonstrated that flushing is, by far, the most significant visible surface distress.

Table 11. Summary of Pavement Distresses for a Typical 164 m Pavement Section.

District	Highway Location	1995 Survey			1996 Survey		
		Flushing[2] (m^2)	Rutting[3] (depth) (area)	L+T Cracking[4] (m)	Flushing[2] (m^2)	Rutting[3] (depth) (area)	L+T Cracking[4] (m)
Abilene	US83	0	3 mm 0 m	11	0	3 mm 0 m	37
Amarillo	IH40	98L 65M	3 mm 0 m	0	124L --	6 mm 7 m	0
Atlanta US79	AC-10	9L	12 mm 93 m	0	14L	16 mm 130 m	0
	AC-20	10L	12 mm 93 m	0	15L	25 mm 139 m	0
	AC-15TR	0	6 mm 25 m	0	0	6 mm 25 m	0
Austin	Spur 1825	0	2 mm 0 m	8	0	2 mm 0 m	10
	US290	0	2 mm 0 m	0	0	2 mm 0 m	0
	US290-Control	0	3 mm 0 m	30	0	3 mm 0 m	39
	SH45	1L	5 mm 0 m	0	2L	5 mm 0 m	0
Bryan	US290	15L	5 mm 0 m	0	29L	6mm 28 m	0
Childress	US287	114L 3M	6 mm 24 m	0	68L 1M	6 mm 7 m	0

Table 11. (Continued)

El Paso	FM659 fly ash	47L 26M 327H	2 mm 0 m	0	47L 26M 327H	2 mm 0 m	0
	FM659 baghouse fines	0	0	0	0	0	0
Odessa	IH20	1L 12M 1H	3 mm 0 m	0	6L 14M --	3 mm 0 m	0
	US385	0	2 mm 0 m	0	14L	5 mm 0 m	0
	Loop 250	108L	3 mm 0 m	0	12L 1M	3 mm 0 m	0
Waco	US84[1]	0	0	0	167L	2 mm 0 m	0
	Loop 340[1]	0	0	0	0	5 mm 0 m	100
Wichita Falls	US287	279L	6 mm 14 m	0	167L 112M	6 mm 70 m	0

[1] Newly constructed pavement at the time of the 1995 survey.

[2] Low, medium, or high severity flushing are indicated by L, M, and H, respectively.

[3] Rutting shows maximum depth and estimated total area containing rut depths of 6 mm or greater.

[4] L+T Cracking = Longitudinal and transverse cracking.

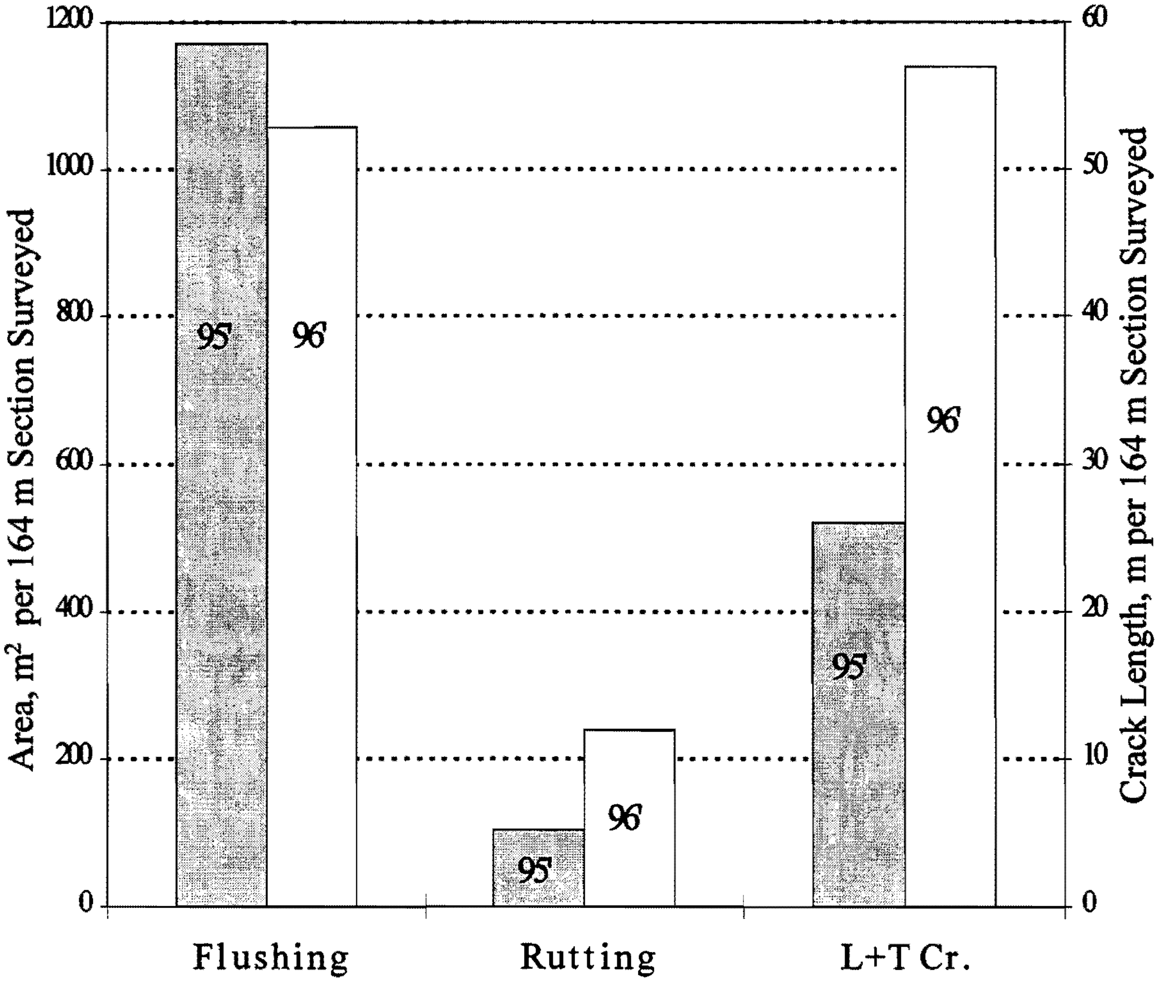

Figure 21. Summary of Total Pavement Distresses Surveyed at all the CMHB Site Locations.

CMHB paving mixtures and QC/QA specifications were implemented by TxDOT about the same time. CMHB mixture designs are rather harsh, rut resistant mixtures and, thus, may sometimes require more compaction energy than comparable dense-graded mixtures. QC/QA specifications penalize the contractor if he does not achieve a certain specified density. Some contractors, attempting to avoid this penalty, have apparently added asphalt above the optimum to achieve the required density. It is believed this action may be one of the main contributors to the flushing CMHB pavements observed in this study.

Most engineers were pleased with the relative performance of the CMHB mixtures and planned to use them in the future. Some are concerned about their comparatively high permeability during the first year or two after construction.

In the Atlanta district, short sections of CMHB mixtures containing AC-10, AC-20, or AC-15TR (tire rubber) were placed end to end. After 2 years in service, the section containing tire rubber was exhibiting significantly less flushing and somewhat less rutting than the unmodified sections. (Based on surfacial evidence, researchers believe the rutting was occurring in pavement layers beneath the CMHB layer.)

Raveling was observed in two 164-m test sections in the Odessa district which totaled 192 m^2. No other raveling was observed.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Laboratory experiments were performed to evaluate CMHB mixtures in comparison to corresponding dense-graded mixtures made using similar materials. Laboratory tests included water permeability, stability, and resistance to permanent deformation, moisture, and oxidative aging. Field surveys to assess short-term performance of existing CMHB overlays were conducted on nineteen pavement sites in 10 districts. Based on the findings of these studies, the following conclusions and recommendations are tendered.

CONCLUSIONS

1. CMHB mixtures are more permeable than dense-graded mixtures made using similar materials at similar air void levels. However, the magnitude of these differences is generally small and often statistically insignificant. This difference decreases with air void level.

2. Permeability of CMHB and dense-graded mixtures increases almost linearly with air void content up to about 8%-10% air voids. Above 8%-10% air voids, however, permeability begins to level off or the slope of the curve rapidly decreases. This indicates that permeability increases only slightly as the air void content exceeds 8%.

3. Permeability of 2 newly constructed CMHB pavements was relatively high; whereas, permeability of 2 other CMHB pavements exposed to 1 year of traffic was about 2 orders of magnitude lower and similar to that of dense-graded pavements. This indicates that, after 1 year of traffic, permeability should not be a concern.

4. Following periods of precipitation, some CMHB pavements exhibited wet spots on the surface or drainage from the edge of the mat for up to 3 or 4 days after rainfall ceased. Permeabilities of cores drilled from such wet and dry areas were not significantly different.

5. Field surveys revealed that flushing was the most common form of early CMHB pavement distress. TxDOT engineers asserted that flushing was often explained by excessive asphalt above the optimum. Because of the coarse aggregate grading, even with some flushing the pavement texture appeared comparatively good.

6. TxDOT static creep testing did not conclusively establish that CMHB mixtures are less rut-susceptible than corresponding dense-graded mixtures. (The authors believe that coarse materials like CMHB and SMA, which is not provided by the TxDOT creep protocol, mixtures require a confining pressure to fully mobilize their available shear strength.)

7. CMHB mixtures are generally more resistant to moisture damage than dense-graded mixtures made using similar materials.

8. CMHB mixtures are generally more resistant to oxidative aging than dense-graded mixtures made using similar materials.

RECOMMENDATIONS

1. The relatively high permeability of newly placed CMHB mixtures should not present long-term pavement performance problems regarding damage by water and air (oxygen). TxDOT should continue to apply CMHB mixtures.

2. When placing CMHB as a surface course over flexible base, an impermeable layer (underseal and/or dense HMA) should be placed immediately beneath the CMHB. Because of the CMHB's relatively higher permeability during the first year or two, water can leak into an unprotected base and, if it is susceptible to moisture damage, weaken the pavement structure.

3. A procedure was developed to measure permeability of asphalt concrete mixtures and is contained in Appendix F. The protocol exhibited excellent repeatability. It is not recommended that TxDOT routinely measure permeability of asphalt mixtures. However, the procedure is recommended for use in research or forensic studies.

4. Although the TxDOT static creep test did not conclusively demonstrate that CMHB mixtures are more resistant to rutting than dense-graded mixtures made using similar materials, the coarse aggregate skeleton provided by CMHB mixtures should prove its rut resistance in the field in subsequent evaluations. The relatively high asphalt film thickness in CMHB mixtures should be a positive attribute for reducing cracking. TxDOT should continue to apply CMHB mixtures to reduce rutting and cracking in asphalt concrete pavements.

5. Construction specifications for Item 340, Hot Mix Asphalt Concrete Pavement, requires design of mixtures at 4% air voids and allows 5% to 9% air voids at construction. Special Specification Item 3016, CMHB, requires design of mixtures at 3% air voids but also allows 5% to 9% air voids at construction. Because the air voids allowed at construction are 1% further from the design value for CMHB mixtures than for dense-graded mixtures, there will be a greater negative effect on permeability, strength, stiffness, and stability of CMHB mixtures. Therefore, it may be desirable to modify the construction specifications for CMHB paving mixtures to allow 4% to 8% air voids at construction.

6. Construction specifications for CMHB paving mixtures need to be modified to provide more stringent field control of asphalt content to reduce the probability of flushing.

REFERENCES

1. Holtz, R.D. and Kovacs, W.D. *An Introduction to Geotechnical Engineering*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1981.
2. Ridgeway, H.H. *Pavement Subsurface Drainage Systems*. NCHRP Synthesis No. 96, National Cooperative Highway Research Program, Transportation Research Board, Washington, D.C., November 1982.
3. American Society for Testing and Materials. *1992 Annual Book of ASTM Standards*. Section 4--Volume 04.03, 1916 Race Street, Philadelphia, PA, 19103-1187, 1992.
4. McLaughlin, J.F. and Goetz, W.H. *Permeability, Void Content, and Durability of Bituminous Concrete*. Proceedings, Highway Research Board, Vol. 34, 1955.
5. White, T.D. *Construction and Evaluation of Airfield PFC in the United States*. Proceedings, International Symposium on Porous Asphalt, Amsterdam, June 1976, Studie Centrum Wegenbouw, Record 2, pp 136-160, 1977.
6. Britton, S.C., Gallaway, B.M., and R.L. Tomasini. *Performance of Open-Graded Friction Courses*. Texas Transportation Institute, FHWA/TX-79/28+234-IF, College Station, TX, June 1979.
7. Gotolski, W.H., Ciesielski, S.K., and Sandvig, L.D. *Asphaltic Concrete Pavement and Permeability*. Pennsylvania State University, Hpr-1/3, ITEM 7, STATE 625, January 1967.
8. Button, J.W. *Permeability of Asphalt Surface Seals and Their Effect on Aging of Underlying Asphalt Concrete*. Foundation for Pavement Rehabilitation and Maintenance Research, Washington, D.C., May 1994.
9. Crockford, W.W., Makunike, D., Davison, R.R., Scullion, T., and Billiter, T.C. *Recycling Crumb Rubber Modified Asphalt Pavements*. Texas Transportation Institute, Research Report 1333-1F, College Station, TX, November 1994.
10. Barenberg, E.J. and Brown, D. *Modeling of Effects of Moisture and Drainage on NJDOT Flexible Pavement Systems*. New Jersey Department of Transportation, FHWA/NJ-83/009, April 1981.

11. Kozlov, G.S. *Improved Drainage and Frost Action Criteria for New Jersey Pavement Design. Volume III. Road Subsurface Drainage Design, Construction and Maintenance Guide for Pavements. Final Report.* New Jersey Department of Transportation, FHWA/NJ-84/015, March 1984.
12. Kumar, A. and Goetz, W.H. *Laboratory Measurement of Permeability of Compacted Asphalt Mixtures.* Transportation Research Record, National Research Council, Washington, D.C., 1977.
13. Los Angeles County Department of Public Works. *Permeability of Asphalt Concrete.* Materials Engineering Division, June 1993.
14. Gemayel, C.A. and Mamlouk, M.S. *Characterization of Hot-Mixed Open-Graded Asphalt Mixtures.* Transportation Research Board, National Research Council, Washington, D.C., 1992.
15. Brown, E.R. and Manglorkar, H. *Evaluation of Laboratory Properties of SMA Mixtures.* National Center for Asphalt Technology, Report No. 93-5, Auburn University, AL, October 1993.
16. Rademaker, M. *Evaluation of Stone Matrix Asphalt.* Illinois Department of Transportation, FHWA/IL/PR-121, January 1996.
17. Brown, E.R. *Experience with Stone Matrix Asphalt in the United States.* National Center for Asphalt Technology, Report No. 93-4, Auburn University, AL, March 1992.
18. Carpenter, S.H. *Stone Matrix Asphalt (SMA) Mixtures.* Illinois Transportation Research Center, Project IB-H1, July 1994.
19. Anderson, D.A. *Influence of Fines on Performance on Asphalt Concrete Mixtures.* Pennsylvania Transportation Institute, Pennsylvania State University, University Park, PA, 1996.
20. Stuart, K.D. *Stone Mastic Asphalt (SMA) Mixture Design.* U.S. Department of Transportation, Federal Highway Administration, FHWA-RD-92-006, VA, March 1992.

21. American Association of State Highway and Transportation Officials. *Standard Specifications for Transportation Materials and Methods of Sampling and Testing.* Part II, Methods of Sampling and Testing, 444 North Capital Street, N.W., Suite 225, Washington D.C., 20001, 1993.

22. Asphalt Institute. *Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types.* Manual Series No. 2 (MS-2), Lexington, KY, 40512-4052, 1990

23. Boynton, R.S., *Chemistry and Technology of Lime and Limestone,* Second Edition, John Wiley & Sons, Inc., New York City, NY, 1980.

24. SHRP, "Distress Identification Manual for the Long-Term Pavement Performance Project," Report No. SHRP-P-338, Strategic Highway Research Program, National Research Council, Washington, D.C., 1993.

25. Little, D.N. and Youssef, H., *Improved ACP Mixture Design: Development and Verification*, Report No. FHWA/TX-92/1170-1F, Texas Transportation Institute, Texas A&M University, College Station, TX, 1992.

APPENDIX A

RESULTS OF PERMEABILITY TESTS

Table A1. Summary of Permeability Test Results.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATCM20-1	6.23	4.3	51.7	17.2	5	15	4.24	4.57E-04
	6.23	4.3	51.7	17.2	5	15	4.24	4.57E-04
	6.23	4.3	51.7	17.2	5	15	4.26	4.55E-04
	6.23	4.3	51.7	17.2	5	15	4.25	4.56E-04
	6.23	4.3	51.7	17.2	5	15	4.23	4.58E-04
	6.23	4.3	51.7	17.2	20	10	4.22	4.59E-04
	6.23	4.3	51.7	17.2	20	10	4.24	4.57E-04
Average								***4.57E-04***
ATCM20-2	6.38	5.8	51.7	17.2	5	15	2.24	8.86E-04
	6.38	5.8	51.7	17.2	5	15	2.23	8.90E-04
	6.38	5.8	51.7	17.2	5	15	2.17	9.14E-04
	6.38	5.8	51.7	17.2	5	15	2.27	8.74E-04
	6.38	5.8	51.7	17.2	5	15	2.26	8.78E-04
	6.38	5.8	51.7	17.2	20	10	2.21	8.98E-04
	6.38	5.8	51.7	17.2	20	10	2.23	8.90E-04
Average								***8.90E-04***
ATCM20-3	6.30	7	51.7	17.2	5	15	1.68	1.17E-03
	6.30	7	51.7	17.2	5	15	1.66	1.18E-03
	6.30	7	51.7	17.2	5	15	1.73	1.13E-03
	6.30	7	51.7	17.2	5	15	1.73	1.13E-03
	6.30	7	51.7	17.2	5	15	1.67	1.17E-03
	6.30	7	51.7	17.2	20	10	1.74	1.13E-03
	6.30	7	51.7	17.2	20	10	1.72	1.14E-03
Average								***1.15E-03***
ATCM20-4	6.33	7.2	51.7	17.2	5	15	1.75	1.12E-03
	6.33	7.2	51.7	17.2	5	15	1.82	1.08E-03
	6.33	7.2	51.7	17.2	5	15	1.83	1.07E-03
	6.33	7.2	51.7	17.2	5	15	1.82	1.08E-03
	6.33	7.2	51.7	17.2	5	15	1.78	1.10E-03
	6.33	7.2	51.7	17.2	20	10	1.77	1.11E-03
	6.33	7.2	51.7	17.2	20	10	1.8	1.09E-03
Average								***1.09E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATCM20-5	5.71	4.6	51.7	17.2	5	15	2	8.88E-04
	5.71	4.6	51.7	17.2	5	15	2.06	8.62E-04
	5.71	4.6	51.7	17.2	5	15	2.04	8.70E-04
	5.71	4.6	51.7	17.2	5	15	2.07	8.58E-04
	5.71	4.6	51.7	17.2	5	15	2.03	8.74E-04
	5.71	4.6	51.7	17.2	20	10	2.06	8.62E-04
	5.71	4.6	51.7	17.2	20	10	2.02	8.79E-04
Average								***8.70E-04***
ATCM20-6	6.18	8.9	51.7	17.2	5	15	1.63	1.18E-03
	6.18	8.9	51.7	17.2	5	15	1.67	1.15E-03
	6.18	8.9	51.7	17.2	5	15	1.75	1.10E-03
	6.18	8.9	51.7	17.2	5	15	1.68	1.14E-03
	6.18	8.9	51.7	17.2	5	15	1.69	1.14E-03
	6.18	8.9	51.7	17.2	20	10	1.71	1.12E-03
	6.18	8.9	51.7	17.2	20	10	1.67	1.15E-03
Average								***1.14E-03***
ATCM20-7	6.10	6.7	51.7	17.2	5	15	1.66	1.14E-03
	6.10	6.7	51.7	17.2	5	15	1.73	1.10E-03
	6.10	6.7	51.7	17.2	5	15	1.71	1.11E-03
	6.10	6.7	51.7	17.2	5	15	1.7	1.12E-03
	6.10	6.7	51.7	17.2	5	15	1.65	1.15E-03
	6.10	6.7	51.7	17.2	20	10	1.68	1.13E-03
	6.10	6.7	51.7	17.2	20	10	1.69	1.12E-03
Average								***1.12E-03***
ATCM20-8	6.26	7	51.7	17.2	5	15	1.69	1.15E-03
	6.26	7	51.7	17.2	5	15	1.68	1.16E-03
	6.26	7	51.7	17.2	5	15	1.72	1.13E-03
	6.26	7	51.7	17.2	5	15	1.71	1.14E-03
	6.26	7	51.7	17.2	5	15	1.74	1.12E-03
	6.26	7	51.7	17.2	20	10	1.75	1.11E-03
	6.26	7	51.7	17.2	20	10	1.69	1.15E-03
Average								***1.14E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATCM20-9	5.85	4.7	51.7	17.2	5	15	2.39	7.61E-04
	5.85	4.7	51.7	17.2	5	15	2.41	7.55E-04
	5.85	4.7	51.7	17.2	5	15	2.35	7.74E-04
	5.85	4.7	51.7	17.2	5	15	2.36	7.71E-04
	5.85	4.7	51.7	17.2	5	15	2.4	7.58E-04
	5.85	4.7	51.7	17.2	20	10	2.41	7.55E-04
	5.85	4.7	51.7	17.2	20	10	2.36	7.71E-04
Average								***7.63E-04***
ATCM20-12	6.39	9.5	51.7	17.2	5	15	1.62	1.23E-03
	6.39	9.5	51.7	17.2	5	15	1.68	1.18E-03
	6.39	9.5	51.7	17.2	5	15	1.65	1.20E-03
	6.39	9.5	51.7	17.2	5	15	1.65	1.20E-03
	6.39	9.5	51.7	17.2	5	15	1.67	1.19E-03
	6.39	9.5	51.7	17.2	20	10	1.66	1.20E-03
	6.39	9.5	51.7	17.2	20	10	1.65	1.20E-03
Average								***1.20E-03***
ATTC20-1	6.11	4.3	51.7	17.2	5	15	9.27	2.05E-04
	6.11	4.3	51.7	17.2	5	15	9.08	2.09E-04
	6.11	4.3	51.7	17.2	5	15	9.1	2.09E-04
	6.11	4.3	51.7	17.2	5	15	9.22	2.06E-04
	6.11	4.3	51.7	17.2	5	15	9.19	2.07E-04
	6.11	4.3	51.7	17.2	20	10	9.14	2.08E-04
	6.11	4.3	51.7	17.2	20	10	9.04	2.10E-04
Average								***2.08E-04***
ATTC20-2	6.39	5.8	51.7	17.2	5	15	3.6	5.52E-04
	6.39	5.8	51.7	17.2	5	15	3.7	5.37E-04
	6.39	5.8	51.7	17.2	5	15	3.72	5.34E-04
	6.39	5.8	51.7	17.2	5	15	3.61	5.50E-04
	6.39	5.8	51.7	17.2	5	15	3.66	5.43E-04
	6.39	5.8	51.7	17.2	20	10	3.67	5.41E-04
	6.39	5.8	51.7	17.2	20	10	3.61	5.50E-04
Average								***5.44E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTC20-3	6.22	3.1	51.7	17.2	5	15	9.01	2.15E-04
	6.22	3.1	51.7	17.2	5	15	9.15	2.11E-04
	6.22	3.1	51.7	17.2	5	15	9.06	2.13E-04
	6.22	3.1	51.7	17.2	5	15	9.22	2.10E-04
	6.22	3.1	51.7	17.2	5	15	9.17	2.11E-04
	6.22	3.1	51.7	17.2	20	10	9.12	2.12E-04
	6.22	3.1	51.7	17.2	20	10	9.05	2.14E-04
Average								***2.12E-04***
ATTC20-4	6.09	2.3	51.7	17.2	5	15	45.64	4.14E-05
	6.09	2.3	51.7	17.2	5	15	45.37	4.17E-05
	6.09	2.3	51.7	17.2	5	15	45.44	4.16E-05
	6.09	2.3	51.7	17.2	5	15	45.68	4.14E-05
	6.09	2.3	51.7	17.2	5	15	45.4	4.17E-05
	6.09	2.3	51.7	17.2	20	10	45.55	4.15E-05
	6.09	2.3	51.7	17.2	20	10	45.6	4.15E-05
Average								***4.15E-05***
ATTC20-5	5.75	2.2	51.7	17.2	5	15	57.57	3.11E-05
	5.75	2.2	51.7	17.2	5	15	61.35	2.91E-05
	5.75	2.2	51.7	17.2	5	15	60.56	2.95E-05
	5.75	2.2	51.7	17.2	5	15	62.71	2.85E-05
	5.75	2.2	51.7	17.2	5	15	59.68	3.00E-05
	5.75	2.2	51.7	17.2	20	10	59.01	3.03E-05
	5.75	2.2	51.7	17.2	20	10	62.3	2.87E-05
Average								***2.96E-05***
ATTC20-6	5.67	1.9	51.7	17.2	5	15	26.03	6.77E-05
	5.67	1.9	51.7	17.2	5	15	25.48	6.91E-05
	5.67	1.9	51.7	17.2	5	15	25.57	6.89E-05
	5.67	1.9	51.7	17.2	5	15	25.8	6.83E-05
	5.67	1.9	51.7	17.2	5	15	25.66	6.87E-05
	5.67	1.9	51.7	17.2	20	10	25.6	6.88E-05
	5.67	1.9	51.7	17.2	20	10	25.75	6.84E-05
Average								***6.86E-05***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTC20-7	5.89	7	51.7	17.2	5	15	2.72	6.73E-04
	5.89	7	51.7	17.2	5	15	2.67	6.86E-04
	5.89	7	51.7	17.2	5	15	2.64	6.94E-04
	5.89	7	51.7	17.2	5	15	2.7	6.78E-04
	5.89	7	51.7	17.2	5	15	2.7	6.78E-04
	5.89	7	51.7	17.2	20	10	2.7	6.78E-04
	5.89	7	51.7	17.2	20	10	2.66	6.89E-04
Average								***6.82E-04***
ATTC20-8	6.22	6.8	51.7	17.2	5	15	2.43	7.95E-04
	6.22	6.8	51.7	17.2	5	15	2.44	7.92E-04
	6.22	6.8	51.7	17.2	5	15	2.46	7.86E-04
	6.22	6.8	51.7	17.2	5	15	2.42	7.99E-04
	6.22	6.8	51.7	17.2	5	15	2.4	8.05E-04
	6.22	6.8	51.7	17.2	20	10	2.39	8.09E-04
	6.22	6.8	51.7	17.2	20	10	2.42	7.99E-04
Average								***7.98E-04***
ATTC20-9	6.10	7.3	51.7	17.2	5	15	3.05	6.21E-04
	6.10	7.3	51.7	17.2	5	15	3.04	6.24E-04
	6.10	7.3	51.7	17.2	5	15	3.06	6.19E-04
	6.10	7.3	51.7	17.2	5	15	3.1	6.11E-04
	6.10	7.3	51.7	17.2	5	15	3.07	6.17E-04
	6.10	7.3	51.7	17.2	20	10	3.01	6.30E-04
	6.10	7.3	51.7	17.2	20	10	3.03	6.26E-04
Average								***6.21E-04***
ATTC20-11	6.25	9.9	51.7	17.2	5	15	2.04	9.52E-04
	6.25	9.9	51.7	17.2	5	15	1.99	9.76E-04
	6.25	9.9	51.7	17.2	5	15	2.04	9.52E-04
	6.25	9.9	51.7	17.2	5	15	2.02	9.62E-04
	6.25	9.9	51.7	17.2	5	15	2	9.71E-04
	6.25	9.9	51.7	17.2	20	10	1.97	9.86E-04
	6.25	9.9	51.7	17.2	20	10	2.03	9.57E-04
Average								***9.65E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTC20-12	6.35	9.4	51.7	17.2	5	15	2.02	9.77E-04
	6.35	9.4	51.7	17.2	5	15	2.02	9.77E-04
	6.35	9.4	51.7	17.2	5	15	1.99	9.92E-04
	6.35	9.4	51.7	17.2	5	15	2.02	9.77E-04
	6.35	9.4	51.7	17.2	5	15	1.97	1.00E-03
	6.35	9.4	51.7	17.2	20	10	2.01	9.82E-04
	6.35	9.4	51.7	17.2	20	10	2.04	9.68E-04
Average								***9.82E-04***
SMCM20-1	6.48	6.5	51.7	17.2	5	15	1.96	1.03E-03
	6.48	6.5	51.7	17.2	5	15	1.98	1.02E-03
	6.48	6.5	51.7	17.2	5	15	1.93	1.04E-03
	6.48	6.5	51.7	17.2	5	15	1.95	1.03E-03
	6.48	6.5	51.7	17.2	5	15	1.91	1.05E-03
	6.48	6.5	51.7	17.2	20	10	1.89	1.07E-03
	6.48	6.5	51.7	17.2	20	10	1.9	1.06E-03
Average								***1.04E-03***
SMCM20-2	6.30	5.1	51.7	17.2	5	15	2.18	8.98E-04
	6.30	5.1	51.7	17.2	5	15	2.21	8.86E-04
	6.30	5.1	51.7	17.2	5	15	2.18	8.98E-04
	6.30	5.1	51.7	17.2	5	15	2.2	8.90E-04
	6.30	5.1	51.7	17.2	5	15	2.22	8.82E-04
	6.30	5.1	51.7	17.2	20	10	2.2	8.90E-04
	6.30	5.1	51.7	17.2	20	10	2.2	8.90E-04
Average								***8.90E-04***
SMCM20-3	6.43	7.3	51.7	17.2	5	15	1.91	1.05E-03
	6.43	7.3	51.7	17.2	5	15	1.87	1.07E-03
	6.43	7.3	51.7	17.2	5	15	1.87	1.07E-03
	6.43	7.3	51.7	17.2	5	15	1.9	1.05E-03
	6.43	7.3	51.7	17.2	5	15	1.87	1.07E-03
	6.43	7.3	51.7	17.2	20	10	1.92	1.04E-03
	6.43	7.3	51.7	17.2	20	10	1.89	1.06E-03
Average								***1.06E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMCM20-4	6.44	6.7	51.7	17.2	5	15	1.81	1.11E-03
	6.44	6.7	51.7	17.2	5	15	1.81	1.11E-03
	6.44	6.7	51.7	17.2	5	15	1.85	1.08E-03
	6.44	6.7	51.7	17.2	5	15	1.82	1.10E-03
	6.44	6.7	51.7	17.2	5	15	1.84	1.09E-03
	6.44	6.7	51.7	17.2	20	10	1.8	1.11E-03
	6.44	6.7	51.7	17.2	20	10	1.8	1.11E-03
Average								***1.10E-03***
SMCM20-5	5.91	6.8	51.7	17.2	5	15	1.87	9.82E-04
	5.91	6.8	51.7	17.2	5	15	1.93	9.52E-04
	5.91	6.8	51.7	17.2	5	15	1.88	9.77E-04
	5.91	6.8	51.7	17.2	5	15	1.9	9.67E-04
	5.91	6.8	51.7	17.2	5	15	1.86	9.88E-04
	5.91	6.8	51.7	17.2	20	10	1.86	9.88E-04
	5.91	6.8	51.7	17.2	20	10	1.88	9.77E-04
Average								***9.76E-04***
SMCM20-6	5.92	4.8	51.7	17.2	5	15	2.24	8.21E-04
	5.92	4.8	51.7	17.2	5	15	2.19	8.40E-04
	5.92	4.8	51.7	17.2	5	15	2.17	8.48E-04
	5.92	4.8	51.7	17.2	5	15	2.16	8.51E-04
	5.92	4.8	51.7	17.2	5	15	2.2	8.36E-04
	5.92	4.8	51.7	17.2	20	10	2.22	8.28E-04
	5.92	4.8	51.7	17.2	20	10	2.19	8.40E-04
Average								***8.38E-04***
SMCM20-7	5.76	1.5	51.7	17.2	5	15	21.23	8.43E-05
	5.76	1.5	51.7	17.2	5	15	21.51	8.32E-05
	5.76	1.5	51.7	17.2	5	15	21.2	8.44E-05
	5.76	1.5	51.7	17.2	5	15	21.39	8.36E-05
	5.76	1.5	51.7	17.2	5	15	21.35	8.38E-05
	5.76	1.5	51.7	17.2	20	10	21.47	8.33E-05
	5.76	1.5	51.7	17.2	20	10	21.19	8.44E-05
Average								***8.39E-05***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMCM20-8	5.81	4.4	51.7	17.2	5	15	2.34	7.72E-04
	5.81	4.4	51.7	17.2	5	15	2.36	7.65E-04
	5.81	4.4	51.7	17.2	5	15	2.32	7.79E-04
	5.81	4.4	51.7	17.2	5	15	2.36	7.65E-04
	5.81	4.4	51.7	17.2	5	15	2.33	7.75E-04
	5.81	4.4	51.7	17.2	20	10	2.36	7.65E-04
	5.81	4.4	51.7	17.2	20	10	2.34	7.72E-04
Average								***7.71E-04***
SMCM20-9	6.39	9.2	51.7	17.2	5	15	1.68	1.18E-03
	6.39	9.2	51.7	17.2	5	15	1.71	1.16E-03
	6.39	9.2	51.7	17.2	5	15	1.65	1.20E-03
	6.39	9.2	51.7	17.2	5	15	1.66	1.20E-03
	6.39	9.2	51.7	17.2	5	15	1.65	1.20E-03
	6.39	9.2	51.7	17.2	20	10	1.65	1.20E-03
	6.39	9.2	51.7	17.2	20	10	1.68	1.18E-03
Average								***1.19E-03***
SMCM20-10	6.38	9.4	51.7	17.2	5	15	1.69	1.17E-03
	6.38	9.4	51.7	17.2	5	15	1.72	1.15E-03
	6.38	9.4	51.7	17.2	5	15	1.74	1.14E-03
	6.38	9.4	51.7	17.2	5	15	1.73	1.15E-03
	6.38	9.4	51.7	17.2	5	15	1.72	1.15E-03
	6.38	9.4	51.7	17.2	20	10	1.72	1.15E-03
	6.38	9.4	51.7	17.2	20	10	1.68	1.18E-03
Average								***1.16E-03***
SMCM20-11	6.68	12.3	51.7	17.2	5	15	1.72	1.21E-03
	6.68	12.3	51.7	17.2	5	15	1.77	1.17E-03
	6.68	12.3	51.7	17.2	5	15	1.75	1.19E-03
	6.68	12.3	51.7	17.2	5	15	1.76	1.18E-03
	6.68	12.3	51.7	17.2	5	15	1.7	1.22E-03
	6.68	12.3	51.7	17.2	20	10	1.71	1.21E-03
	6.68	12.3	51.7	17.2	20	10	1.72	1.21E-03
Average								***1.20E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMCM20-12	6.74	11.3	51.7	17.2	5	15	1.68	1.25E-03
	6.74	11.3	51.7	17.2	5	15	1.67	1.25E-03
	6.74	11.3	51.7	17.2	5	15	1.7	1.23E-03
	6.74	11.3	51.7	17.2	5	15	1.74	1.20E-03
	6.74	11.3	51.7	17.2	5	15	1.7	1.23E-03
	6.74	11.3	51.7	17.2	20	10	1.67	1.25E-03
	6.74	11.3	51.7	17.2	20	10	1.65	1.27E-03
Average								***1.24E-03***
SMTC20-1	6.25	5.1	51.7	17.2	5	15	3.26	5.96E-04
	6.25	5.1	51.7	17.2	5	15	3.22	6.03E-04
	6.25	5.1	51.7	17.2	5	15	3.26	5.96E-04
	6.25	5.1	51.7	17.2	5	15	3.24	6.00E-04
	6.25	5.1	51.7	17.2	5	15	3.27	5.94E-04
	6.25	5.1	51.7	17.2	20	10	3.21	6.05E-04
	6.25	5.1	51.7	17.2	20	10	3.24	6.00E-04
Average								***5.99E-04***
SMTC20-2	6.24	3.5	51.7	17.2	5	15	5.46	3.55E-04
	6.24	3.5	51.7	17.2	5	15	5.39	3.60E-04
	6.24	3.5	51.7	17.2	5	15	5.41	3.59E-04
	6.24	3.5	51.7	17.2	5	15	5.51	3.52E-04
	6.24	3.5	51.7	17.2	5	15	5.47	3.55E-04
	6.24	3.5	51.7	17.2	20	10	5.49	3.53E-04
	6.24	3.5	51.7	17.2	20	10	5.48	3.54E-04
Average								***3.55E-04***
SMTC20-3	6.25	6.1	51.7	17.2	5	15	2.54	7.65E-04
	6.25	6.1	51.7	17.2	5	15	2.48	7.83E-04
	6.25	6.1	51.7	17.2	5	15	2.53	7.68E-04
	6.25	6.1	51.7	17.2	5	15	2.53	7.68E-04
	6.25	6.1	51.7	17.2	5	15	2.51	7.74E-04
	6.25	6.1	51.7	17.2	20	10	2.47	7.87E-04
	6.25	6.1	51.7	17.2	20	10	2.5	7.77E-04
Average								***7.74E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMTC20-4	6.35	5.7	51.7	17.2	5	15	2.84	6.94E-04
	6.35	5.7	51.7	17.2	5	15	2.8	7.04E-04
	6.35	5.7	51.7	17.2	5	15	2.77	7.12E-04
	6.35	5.7	51.7	17.2	5	15	2.79	7.07E-04
	6.35	5.7	51.7	17.2	5	15	2.8	7.04E-04
	6.35	5.7	51.7	17.2	20	10	2.77	7.12E-04
	6.35	5.7	51.7	17.2	20	10	2.82	6.99E-04
Average								***7.05E-04***
SMTC20-5	5.94	7.7	51.7	17.2	5	15	2.01	9.19E-04
	5.94	7.7	51.7	17.2	5	15	2.01	9.19E-04
	5.94	7.7	51.7	17.2	5	15	2.06	8.96E-04
	5.94	7.7	51.7	17.2	5	15	1.99	9.28E-04
	5.94	7.7	51.7	17.2	5	15	2.01	9.19E-04
	5.94	7.7	51.7	17.2	20	10	2.04	9.05E-04
	5.94	7.7	51.7	17.2	20	10	2.02	9.14E-04
Average								***9.14E-04***
SMTC20-6	5.92	7	51.7	17.2	5	15	2.38	7.73E-04
	5.92	7	51.7	17.2	5	15	2.36	7.79E-04
	5.92	7	51.7	17.2	5	15	2.33	7.89E-04
	5.92	7	51.7	17.2	5	15	2.36	7.79E-04
	5.92	7	51.7	17.2	5	15	2.35	7.82E-04
	5.92	7	51.7	17.2	20	10	2.4	7.66E-04
	5.92	7	51.7	17.2	20	10	2.36	7.79E-04
Average								***7.78E-04***
SMTC20-7	5.78	1.8	51.7	17.2	5	15	14.24	1.26E-04
	5.78	1.8	51.7	17.2	5	15	14.33	1.25E-04
	5.78	1.8	51.7	17.2	5	15	14.4	1.25E-04
	5.78	1.8	51.7	17.2	5	15	14.25	1.26E-04
	5.78	1.8	51.7	17.2	5	15	14.3	1.26E-04
	5.78	1.8	51.7	17.2	20	10	14.27	1.26E-04
	5.78	1.8	51.7	17.2	20	10	14.33	1.25E-04
Average								***1.26E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMTC20-8	5.73	1.9	51.7	17.2	5	15	42.24	4.21E-05
	5.73	1.9	51.7	17.2	5	15	41.73	4.26E-05
	5.73	1.9	51.7	17.2	5	15	42.76	4.16E-05
	5.73	1.9	51.7	17.2	5	15	43.34	4.11E-05
	5.73	1.9	51.7	17.2	5	15	42.7	4.17E-05
	5.73	1.9	51.7	17.2	20	10	43.01	4.14E-05
	5.73	1.9	51.7	17.2	20	10	42.66	4.17E-05
Average								***4.17E-05***
SMTC20-9	5.89	4.7	51.7	17.2	5	15	3.64	5.02E-04
	5.89	4.7	51.7	17.2	5	15	3.69	4.96E-04
	5.89	4.7	51.7	17.2	5	15	3.64	5.02E-04
	5.89	4.7	51.7	17.2	5	15	3.62	5.05E-04
	5.89	4.7	51.7	17.2	5	15	3.65	5.01E-04
	5.89	4.7	51.7	17.2	20	10	3.64	5.02E-04
	5.89	4.7	51.7	17.2	20	10	3.67	4.98E-04
Average								***5.01E-04***
SMTC20-10	6.53	12.6	51.7	17.2	5	15	1.76	1.15E-03
	6.53	12.6	51.7	17.2	5	15	1.83	1.11E-03
	6.53	12.6	51.7	17.2	5	15	1.82	1.11E-03
	6.53	12.6	51.7	17.2	5	15	1.82	1.11E-03
	6.53	12.6	51.7	17.2	5	15	1.79	1.13E-03
	6.53	12.6	51.7	17.2	20	10	1.79	1.13E-03
	6.53	12.6	51.7	17.2	20	10	1.8	1.13E-03
Average								***1.13E-03***
SMTC20-12	6.47	12.7	51.7	17.2	5	15	1.76	1.14E-03
	6.47	12.7	51.7	17.2	5	15	1.83	1.10E-03
	6.47	12.7	51.7	17.2	5	15	1.79	1.12E-03
	6.47	12.7	51.7	17.2	5	15	1.84	1.09E-03
	6.47	12.7	51.7	17.2	5	15	1.81	1.11E-03
	6.47	12.7	51.7	17.2	20	10	1.77	1.14E-03
	6.47	12.7	51.7	17.2	20	10	1.85	1.09E-03
Average								***1.11E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMTC20-13	6.27	9.8	51.7	17.2	5	15	1.98	9.84E-04
	6.27	9.8	51.7	17.2	5	15	2.06	9.45E-04
	6.27	9.8	51.7	17.2	5	15	2.02	9.64E-04
	6.27	9.8	51.7	17.2	5	15	1.91	1.02E-03
	6.27	9.8	51.7	17.2	5	15	2.01	9.69E-04
	6.27	9.8	51.7	17.2	20	10	1.98	9.84E-04
	6.27	9.8	51.7	17.2	20	10	2.04	9.55E-04
Average								***9.74E-04***
ATCMLX-1	5.58	4.4	51.7	17.2	5	15	1.8	9.63E-04
	5.58	4.4	51.7	17.2	5	15	1.8	9.63E-04
	5.58	4.4	51.7	17.2	5	15	1.8	9.63E-04
	5.58	4.4	51.7	17.2	5	15	1.78	9.74E-04
	5.58	4.4	51.7	17.2	5	15	1.8	9.63E-04
	5.58	4.4	51.7	17.2	20	10	1.78	9.74E-04
	5.58	4.4	51.7	17.2	20	10	1.83	9.47E-04
Average								***9.64E-04***
ATCMLX-2	5.71	3.8	51.7	17.2	5	15	1.95	9.10E-04
	5.71	3.8	51.7	17.2	5	15	2	8.87E-04
	5.71	3.8	51.7	17.2	5	15	1.95	9.10E-04
	5.71	3.8	51.7	17.2	5	15	1.97	9.01E-04
	5.71	3.8	51.7	17.2	5	15	2.01	8.83E-04
	5.71	3.8	51.7	17.2	20	10	1.94	9.15E-04
	5.71	3.8	51.7	17.2	20	10	1.94	9.15E-04
Average								***9.03E-04***
ATCMLX-3	5.69	4.2	51.7	17.2	5	15	2.9	6.09E-04
	5.69	4.2	51.7	17.2	5	15	2.87	6.16E-04
	5.69	4.2	51.7	17.2	5	15	2.86	6.18E-04
	5.69	4.2	51.7	17.2	5	15	2.9	6.09E-04
	5.69	4.2	51.7	17.2	5	15	2.91	6.07E-04
	5.69	4.2	51.7	17.2	20	10	2.87	6.16E-04
	5.69	4.2	51.7	17.2	20	10	2.89	6.11E-04
Average								***6.12E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATCMLX-4	5.92	4.7	51.7	17.2	5	15	1.68	1.09E-03
	5.92	4.7	51.7	17.2	5	15	1.73	1.06E-03
	5.92	4.7	51.7	17.2	5	15	1.69	1.09E-03
	5.92	4.7	51.7	17.2	5	15	1.74	1.06E-03
	5.92	4.7	51.7	17.2	5	15	1.7	1.08E-03
	5.92	4.7	51.7	17.2	20	10	1.69	1.09E-03
	5.92	4.7	51.7	17.2	20	10	1.75	1.05E-03
Average								***1.08E-03***
ATCMLX-5	5.97	7	51.7	17.2	5	15	1.65	1.13E-03
	5.97	7	51.7	17.2	5	15	1.7	1.09E-03
	5.97	7	51.7	17.2	5	15	1.68	1.10E-03
	5.97	7	51.7	17.2	5	15	1.72	1.08E-03
	5.97	7	51.7	17.2	5	15	1.7	1.09E-03
	5.97	7	51.7	17.2	20	10	1.7	1.09E-03
	5.97	7	51.7	17.2	20	10	1.73	1.07E-03
Average								***1.09E-03***
ATCMLX-6	6.02	6.7	51.7	17.2	5	15	1.94	9.64E-04
	6.02	6.7	51.7	17.2	5	15	1.92	9.74E-04
	6.02	6.7	51.7	17.2	5	15	2	9.35E-04
	6.02	6.7	51.7	17.2	5	15	1.97	9.49E-04
	6.02	6.7	51.7	17.2	5	15	1.97	9.49E-04
	6.02	6.7	51.7	17.2	20	10	1.95	9.59E-04
	6.02	6.7	51.7	17.2	20	10	1.92	9.74E-04
Average								***9.57E-04***
ATCMLX-7	6.27	7.2	51.7	17.2	5	15	1.53	1.27E-03
	6.27	7.2	51.7	17.2	5	15	157	1.24E-05
	6.27	7.2	51.7	17.2	5	15	1.58	1.23E-03
	6.27	7.2	51.7	17.2	5	15	1.57	1.24E-03
	6.27	7.2	51.7	17.2	5	15	162	1.20E-05
	6.27	7.2	51.7	17.2	20	10	1.49	1.31E-03
	6.27	7.2	51.7	17.2	20	10	1.53	1.27E-03
Average								***9.08E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATCMLX-9	6.53	8.6	51.7	17.2	5	15	1.56	1.30E-03
	6.53	8.6	51.7	17.2	5	15	1.64	1.24E-03
	6.53	8.6	51.7	17.2	5	15	1.61	1.26E-03
	6.53	8.6	51.7	17.2	5	15	1.63	1.25E-03
	6.53	8.6	51.7	17.2	5	15	1.59	1.28E-03
	6.53	8.6	51.7	17.2	20	10	1.62	1.25E-03
	6.53	8.6	51.7	17.2	20	10	1.62	1.25E-03
Average								***1.26E-03***
ATCMLX-10	6.65	9.2	51.7	17.2	5	15	1.72	1.20E-03
	6.65	9.2	51.7	17.2	5	15	1.72	1.20E-03
	6.65	9.2	51.7	17.2	5	15	1.68	1.23E-03
	6.65	9.2	51.7	17.2	5	15	1.7	1.22E-03
	6.65	9.2	51.7	17.2	5	15	1.69	1.22E-03
	6.65	9.2	51.7	17.2	20	10	1.63	1.27E-03
	6.65	9.2	51.7	17.2	20	10	1.7	1.22E-03
Average								***1.22E-03***
ATCMLX-11	6.56	9	51.7	17.2	5	15	1.64	1.24E-03
	6.56	9	51.7	17.2	5	15	1.69	1.21E-03
	6.56	9	51.7	17.2	5	15	1.72	1.18E-03
	6.56	9	51.7	17.2	5	15	1.71	1.19E-03
	6.56	9	51.7	17.2	5	15	1.71	1.19E-03
	6.56	9	51.7	17.2	20	10	1.7	1.20E-03
	6.56	9	51.7	17.2	20	10	1.65	1.23E-03
Average								***1.21E-03***
ATTCLX-1	5.70	3.7	51.7	17.2	5	15	32.67	5.42E-05
	5.70	3.7	51.7	17.2	5	15	32.25	5.49E-05
	5.70	3.7	51.7	17.2	5	15	31.63	5.60E-05
	5.70	3.7	51.7	17.2	5	15	31.68	5.59E-05
	5.70	3.7	51.7	17.2	5	15	32.05	5.52E-05
	5.70	3.7	51.7	17.2	20	10	31.79	5.57E-05
	5.70	3.7	51.7	17.2	20	10	32.3	5.48E-05
Average								***5.52E-05***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTCLX-2	5.71	4.5	51.7	17.2	5	15	5.84	3.04E-04
	5.71	4.5	51.7	17.2	5	15	5.85	3.03E-04
	5.71	4.5	51.7	17.2	5	15	5.9	3.01E-04
	5.71	4.5	51.7	17.2	5	15	5.92	3.00E-04
	5.71	4.5	51.7	17.2	5	15	5.8	3.06E-04
	5.71	4.5	51.7	17.2	20	10	5.77	3.07E-04
	5.71	4.5	51.7	17.2	20	10	5.81	3.05E-04
Average								***3.04E-04***
ATTCLX-3	5.79	4.2	51.7	17.2	5	15	19.51	9.22E-05
	5.79	4.2	51.7	17.2	5	15	19.45	9.25E-05
	5.79	4.2	51.7	17.2	5	15	19.55	9.21E-05
	5.79	4.2	51.7	17.2	5	15	19.47	9.24E-05
	5.79	4.2	51.7	17.2	5	15	19.51	9.22E-05
	5.79	4.2	51.7	17.2	20	10	19.45	9.25E-05
	5.79	4.2	51.7	17.2	20	10	19.52	9.22E-05
Average								***9.23E-05***
ATTCLX-4	5.79	4.5	51.7	17.2	5	15	13.47	1.33E-04
	5.79	4.5	51.7	17.2	5	15	13.6	1.32E-04
	5.79	4.5	51.7	17.2	5	15	13.44	1.34E-04
	5.79	4.5	51.7	17.2	5	15	13.5	1.33E-04
	5.79	4.5	51.7	17.2	5	15	13.52	1.33E-04
	5.79	4.5	51.7	17.2	20	10	13.49	1.33E-04
	5.79	4.5	51.7	17.2	20	10	13.55	1.33E-04
Average								***1.33E-04***
ATTCLX-5	6.13	7	51.7	17.2	5	15	3.75	5.08E-04
	6.13	7	51.7	17.2	5	15	3.67	5.19E-04
	6.13	7	51.7	17.2	5	15	3.65	5.22E-04
	6.13	7	51.7	17.2	5	15	3.68	5.17E-04
	6.13	7	51.7	17.2	5	15	3.69	5.16E-04
	6.13	7	51.7	17.2	20	10	3.64	5.23E-04
	6.13	7	51.7	17.2	20	10	3.67	5.19E-04
Average								***5.18E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTCLX-6	6.08	8.1	51.7	17.2	5	15	2.89	6.54E-04
	6.08	8.1	51.7	17.2	5	15	2.91	6.49E-04
	6.08	8.1	51.7	17.2	5	15	2.92	6.47E-04
	6.08	8.1	51.7	17.2	5	15	2.91	6.49E-04
	6.08	8.1	51.7	17.2	5	15	2.91	6.49E-04
	6.08	8.1	51.7	17.2	20	10	2.89	6.54E-04
	6.08	8.1	51.7	17.2	20	10	2.9	6.51E-04
Average								***6.50E-04***
ATTCLX-7	6.08	8.3	51.7	17.2	5	15	2.77	6.83E-04
	6.08	8.3	51.7	17.2	5	15	2.76	6.85E-04
	6.08	8.3	51.7	17.2	5	15	2.71	6.98E-04
	6.08	8.3	51.7	17.2	5	15	2.73	6.93E-04
	6.08	8.3	51.7	17.2	5	15	2.76	6.85E-04
	6.08	8.3	51.7	17.2	20	10	2.76	6.85E-04
	6.08	8.3	51.7	17.2	20	10	2.74	6.90E-04
Average								***6.88E-04***
ATTCLX-9	6.54	12.2	51.7	17.2	5	15	1.87	1.09E-03
	6.54	12.2	51.7	17.2	5	15	1.87	1.09E-03
	6.54	12.2	51.7	17.2	5	15	1.82	1.12E-03
	6.54	12.2	51.7	17.2	5	15	1.85	1.10E-03
	6.54	12.2	51.7	17.2	5	15	1.8	1.13E-03
	6.54	12.2	51.7	17.2	20	10	1.88	1.08E-03
	6.54	12.2	51.7	17.2	20	10	1.84	1.10E-03
Average								***1.10E-03***
ATTCLX-11	6.68	14.2	51.7	17.2	5	15	2.02	1.03E-03
	6.68	14.2	51.7	17.2	5	15	2	1.04E-03
	6.68	14.2	51.7	17.2	5	15	2.04	1.02E-03
	6.68	14.2	51.7	17.2	5	15	1.99	1.04E-03
	6.68	14.2	51.7	17.2	5	15	2	1.04E-03
	6.68	14.2	51.7	17.2	20	10	2.01	1.03E-03
	6.68	14.2	51.7	17.2	20	10	2.02	1.03E-03
Average								***1.03E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATTCLX-12	6.20	9.4	51.7	17.2	5	15	2.2	8.75E-04
	6.20	9.4	51.7	17.2	5	15	2.13	9.04E-04
	6.20	9.4	51.7	17.2	5	15	2.16	8.92E-04
	6.20	9.4	51.7	17.2	5	15	2.21	8.72E-04
	6.20	9.4	51.7	17.2	5	15	2.16	8.92E-04
	6.20	9.4	51.7	17.2	20	10	2.19	8.79E-04
	6.20	9.4	51.7	17.2	20	10	2.12	9.09E-04
Average								***8.89E-04***
SMCMLX-1	5.71	6.2	51.7	17.2	5	15	2.22	7.99E-04
	5.71	6.2	51.7	17.2	5	15	2.25	7.88E-04
	5.71	6.2	51.7	17.2	5	15	2.19	8.10E-04
	5.71	6.2	51.7	17.2	5	15	2.22	7.99E-04
	5.71	6.2	51.7	17.2	5	15	2.2	8.06E-04
	5.71	6.2	51.7	17.2	20	10	2.26	7.85E-04
	5.71	6.2	51.7	17.2	20	10	2.22	7.99E-04
Average								***7.98E-04***
SMCMLX-2	5.85	3.3	51.7	17.2	5	15	11.84	1.54E-04
	5.85	3.3	51.7	17.2	5	15	12.08	1.51E-04
	5.85	3.3	51.7	17.2	5	15	12.12	1.50E-04
	5.85	3.3	51.7	17.2	5	15	12.04	1.51E-04
	5.85	3.3	51.7	17.2	5	15	11.99	1.52E-04
	5.85	3.3	51.7	17.2	20	10	12.15	1.50E-04
	5.85	3.3	51.7	17.2	20	10	12.06	1.51E-04
Average								***1.51E-04***
SMCMLX-3	6.96	5.7	51.7	17.2	5	15	2.56	8.44E-04
	6.96	5.7	51.7	17.2	5	15	2.53	8.54E-04
	6.96	5.7	51.7	17.2	5	15	2.56	8.44E-04
	6.96	5.7	51.7	17.2	5	15	2.54	8.51E-04
	6.96	5.7	51.7	17.2	5	15	2.53	8.54E-04
	6.96	5.7	51.7	17.2	20	10	2.55	8.48E-04
	6.96	5.7	51.7	17.2	20	10	2.56	8.44E-04
Average								***8.49E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMCMLX-4	5.94	5.6	51.7	17.2	5	15	2.62	7.04E-04
	5.94	5.6	51.7	17.2	5	15	2.67	6.91E-04
	5.94	5.6	51.7	17.2	5	15	2.6	7.10E-04
	5.94	5.6	51.7	17.2	5	15	2.65	6.97E-04
	5.94	5.6	51.7	17.2	5	15	2.6	7.10E-04
	5.94	5.6	51.7	17.2	20	10	2.66	6.94E-04
	5.94	5.6	51.7	17.2	20	10	2.61	7.07E-04
Average								***7.02E-04***
SMCMLX-5	6.38	10.5	51.7	17.2	5	15	1.74	1.14E-03
	6.38	10.5	51.7	17.2	5	15	1.73	1.15E-03
	6.38	10.5	51.7	17.2	5	15	1.75	1.13E-03
	6.38	10.5	51.7	17.2	5	15	1.73	1.15E-03
	6.38	10.5	51.7	17.2	5	15	1.74	1.14E-03
	6.38	10.5	51.7	17.2	20	10	1.77	1.12E-03
	6.38	10.5	51.7	17.2	20	10	1.73	1.15E-03
Average								***1.14E-03***
SMCMLX-6	6.39	10.6	51.7	17.2	5	15	1.82	1.09E-03
	6.39	10.6	51.7	17.2	5	15	1.78	1.12E-03
	6.39	10.6	51.7	17.2	5	15	1.81	1.10E-03
	6.39	10.6	51.7	17.2	5	15	1.77	1.12E-03
	6.39	10.6	51.7	17.2	5	15	1.78	1.12E-03
	6.39	10.6	51.7	17.2	20	10	1.76	1.13E-03
	6.39	10.6	51.7	17.2	20	10	1.78	1.12E-03
Average								***1.11E-03***
SMCMLX-7	6.41	9.7	51.7	17.2	5	15	1.74	1.14E-03
	6.41	9.7	51.7	17.2	5	15	1.71	1.16E-03
	6.41	9.7	51.7	17.2	5	15	1.76	1.13E-03
	6.41	9.7	51.7	17.2	5	15	1.72	1.16E-03
	6.41	9.7	51.7	17.2	5	15	1.71	1.16E-03
	6.41	9.7	51.7	17.2	20	10	1.73	1.15E-03
	6.41	9.7	51.7	17.2	20	10	1.77	1.13E-03
Average								***1.15E-03***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMCMLX-8	6.36	9.8	51.7	17.2	5	15	1.75	1.13E-03
	6.36	9.8	51.7	17.2	5	15	1.79	1.10E-03
	6.36	9.8	51.7	17.2	5	15	1.83	1.08E-03
	6.36	9.8	51.7	17.2	5	15	1.77	1.12E-03
	6.36	9.8	51.7	17.2	5	15	1.79	1.10E-03
	6.36	9.8	51.7	17.2	20	10	1.71	1.16E-03
	6.36	9.8	51.7	17.2	20	10	1.77	1.12E-03
Average								***1.11E-03***
SMCMLX-9	5.73	4.2	51.7	17.2	5	15	3.31	5.38E-04
	5.73	4.2	51.7	17.2	5	15	3.35	5.32E-04
	5.73	4.2	51.7	17.2	5	15	3.4	5.24E-04
	5.73	4.2	51.7	17.2	5	15	3.35	5.32E-04
	5.73	4.2	51.7	17.2	5	15	3.33	5.35E-04
	5.73	4.2	51.7	17.2	20	10	3.34	5.33E-04
	5.73	4.2	51.7	17.2	20	10	3.31	5.38E-04
Average								***5.33E-04***
SMCMLX-10	6.34	2.9	51.7	17.2	5	15	35.37	5.57E-05
	6.34	2.9	51.7	17.2	5	15	35.41	5.56E-05
	6.34	2.9	51.7	17.2	5	15	35.56	5.54E-05
	6.34	2.9	51.7	17.2	5	15	35.25	5.59E-05
	6.34	2.9	51.7	17.2	5	15	35.12	5.61E-05
	6.34	2.9	51.7	17.2	20	10	35.2	5.60E-05
	6.34	2.9	51.7	17.2	20	10	35.52	5.55E-05
Average								***5.57E-05***
SMTCLX-1	5.83	7.7	51.7	17.2	5	15	3.37	5.37E-04
	5.83	7.7	51.7	17.2	5	15	3.33	5.44E-04
	5.83	7.7	51.7	17.2	5	15	3.41	5.31E-04
	5.83	7.7	51.7	17.2	5	15	3.35	5.41E-04
	5.83	7.7	51.7	17.2	5	15	3.36	5.39E-04
	5.83	7.7	51.7	17.2	20	10	3.34	5.42E-04
	5.83	7.7	51.7	17.2	20	10	3.3	5.49E-04
Average								***5.40E-04***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMTCLX-2	6.17	10	51.7	17.2	5	15	2.24	8.56E-04
	6.17	10	51.7	17.2	5	15	2.21	8.67E-04
	6.17	10	51.7	17.2	5	15	2.24	8.56E-04
	6.17	10	51.7	17.2	5	15	2.19	8.75E-04
	6.17	10	51.7	17.2	5	15	2.22	8.63E-04
	6.17	10	51.7	17.2	20	10	2.25	8.52E-04
	6.17	10	51.7	17.2	20	10	2.22	8.63E-04
Average								***8.62E-04***
SMTCLX-3	5.82	5.4	51.7	17.2	5	15	11.8	1.53E-04
	5.82	5.4	51.7	17.2	5	15	11.58	1.56E-04
	5.82	5.4	51.7	17.2	5	15	11.6	1.56E-04
	5.82	5.4	51.7	17.2	5	15	11.42	1.58E-04
	5.82	5.4	51.7	17.2	5	15	11.7	1.55E-04
	5.82	5.4	51.7	17.2	20	10	11.8	1.53E-04
	5.82	5.4	51.7	17.2	20	10	11.71	1.55E-04
Average								***1.55E-04***
SMTCLX-4	5.94	5.6	51.7	17.2	5	15	11.54	1.60E-04
	5.94	5.6	51.7	17.2	5	15	11.62	1.59E-04
	5.94	5.6	51.7	17.2	5	15	11.51	1.60E-04
	5.94	5.6	51.7	17.2	5	15	11.63	1.59E-04
	5.94	5.6	51.7	17.2	5	15	11.5	1.60E-04
	5.94	5.6	51.7	17.2	20	10	11.69	1.58E-04
	5.94	5.6	51.7	17.2	20	10	11.49	1.61E-04
Average								***1.60E-04***
SMTCLX-6	5.67	4.9	51.7	17.2	5	15	44.26	3.98E-05
	5.67	4.9	51.7	17.2	5	15	44.47	3.97E-05
	5.67	4.9	51.7	17.2	5	15	44.16	3.99E-05
	5.67	4.9	51.7	17.2	5	15	44.21	3.99E-05
	5.67	4.9	51.7	17.2	5	15	44.31	3.98E-05
	5.67	4.9	51.7	17.2	20	10	44.13	4.00E-05
	5.67	4.9	51.7	17.2	20	10	44.25	3.99E-05
Average								***3.98E-05***

Table A1. Continued.

Sample ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
SMTCLX-7	5.70	4.8	51.7	17.2	5	15	25.61	6.92E-05
	5.70	4.8	51.7	17.2	5	15	25.8	6.87E-05
	5.70	4.8	51.7	17.2	5	15	25.85	6.86E-05
	5.70	4.8	51.7	17.2	5	15	25.74	6.89E-05
	5.70	4.8	51.7	17.2	5	15	25.53	6.94E-05
	5.70	4.8	51.7	17.2	20	10	25.6	6.93E-05
	5.70	4.8	51.7	17.2	20	10	25.8	6.87E-05
Average								***6.90E-05***
SMTCLX-8	6.18	11.7	51.7	17.2	5	15	1.97	9.76E-04
	6.18	11.7	51.7	17.2	5	15	1.96	9.81E-04
	6.18	11.7	51.7	17.2	5	15	1.97	9.76E-04
	6.18	11.7	51.7	17.2	5	15	1.95	9.86E-04
	6.18	11.7	51.7	17.2	5	15	1.91	1.01E-03
	6.18	11.7	51.7	17.2	20	10	1.95	9.86E-04
	6.18	11.7	51.7	17.2	20	10	1.98	9.71E-04
Average								***9.83E-04***
SMTCLX-9	5.67	3.9	51.7	17.2	5	15	116.65	1.51E-05
	5.67	3.9	51.7	17.2	5	15	120.32	1.47E-05
	5.67	3.9	51.7	17.2	5	15	118.96	1.48E-05
	5.67	3.9	51.7	17.2	5	15	121.4	1.45E-05
	5.67	3.9	51.7	17.2	5	15	112.69	1.56E-05
	5.67	3.9	51.7	17.2	20	10	119.45	1.48E-05
	5.67	3.9	51.7	17.2	20	10	120.63	1.46E-05
Average								***1.49E-05***
SMTCLX-10	6.28	12.5	51.7	17.2	5	15	1.89	1.03E-03
	6.28	12.5	51.7	17.2	5	15	1.91	1.02E-03
	6.28	12.5	51.7	17.2	5	15	1.91	1.02E-03
	6.28	12.5	51.7	17.2	5	15	1.9	1.03E-03
	6.28	12.5	51.7	17.2	5	15	1.87	1.04E-03
	6.28	12.5	51.7	17.2	20	10	1.92	1.02E-03
	6.28	12.5	51.7	17.2	20	10	1.91	1.02E-03
Average								***1.03E-03***

AT - Atlanta, Siliceous Aggregate	CM - CMHB Mixture	20 - AC-20
SM - Austin, Limestone Aggregate	TC - Dense-Graded Mixture	LX - AC-20+Latex
# - Sample Number		

Table A2. Summary of Permeability Test Results for Cores Extracted from Various CMHB Sites Throughout Texas.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
BRYAN								
BRY-1	4.28	11.5	7.5	2.5	5	15	1.58	8.43E-04
	4.28	11.5	7.5	2.5	5	15	1.56	8.54E-04
	4.28	11.5	7.5	2.5	5	15	1.56	8.54E-04
	4.28	11.5	7.5	2.5	5	15	1.57	8.48E-04
	4.28	11.5	7.5	2.5	5	15	1.59	8.38E-04
	4.28	11.5	7.5	2.5	20	10	1.60	8.32E-04
	4.28	11.5	7.5	2.5	20	10	1.58	8.43E-04
Average								***8.44E-04***
BRY-2	4.00	8.8	7.5	2.5	5	15	1.94	6.40E-04
	4.00	8.8	7.5	2.5	5	15	1.90	6.54E-04
	4.00	8.8	7.5	2.5	5	15	1.91	6.51E-04
	4.00	8.8	7.5	2.5	5	15	1.95	6.37E-04
	4.00	8.8	7.5	2.5	5	15	1.94	6.40E-04
	4.00	8.8	7.5	2.5	20	10	1.94	6.40E-04
	4.00	8.8	7.5	2.5	20	10	1.92	6.47E-04
Average								***6.44E-04***
BRY-3	4.19	5.7	7.5	2.5	5	15	2.22	5.86E-04
	4.19	5.7	7.5	2.5	5	15	2.22	5.86E-04
	4.19	5.7	7.5	2.5	5	15	2.23	5.84E-04
	4.19	5.7	7.5	2.5	5	15	2.20	5.92E-04
	4.19	5.7	7.5	2.5	5	15	2.19	5.94E-04
	4.19	5.7	7.5	2.5	20	10	2.20	5.92E-04
	4.19	5.7	7.5	2.5	20	10	2.21	5.89E-04
Average								***5.89E-04***
BRY-4	4.29	6.0	7.5	2.5	5	15	3.81	3.50E-04
	4.29	6.0	7.5	2.5	5	15	3.84	3.47E-04
	4.29	6.0	7.5	2.5	5	15	3.91	3.41E-04
	4.29	6.0	7.5	2.5	5	15	3.87	3.45E-04
	4.29	6.0	7.5	2.5	5	15	3.90	3.42E-04
	4.29	6.0	7.5	2.5	20	10	3.85	3.46E-04
	4.29	6.0	7.5	2.5	20	10	3.83	3.48E-04
Average								***3.46E-04***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ODESSA								
ODSA-I	3.42	8.5	7.5	2.5	5	15	1.8	5.90E-04
	3.42	8.5	7.5	2.5	5	15	1.75	6.07E-04
	3.42	8.5	7.5	2.5	5	15	1.74	6.11E-04
	3.42	8.5	7.5	2.5	5	15	1.77	6.00E-04
	3.42	8.5	7.5	2.5	5	15	1.75	6.07E-04
	3.42	8.5	7.5	2.5	20	10	1.81	5.87E-04
	3.42	8.5	7.5	2.5	20	10	1.77	6.00E-04
Average								***6.00E-04***
ODSA-II	5.35	9	7.5	2.5	5	15	2.14	7.76E-04
	5.35	9	7.5	2.5	5	15	2.15	7.73E-04
	5.35	9	7.5	2.5	5	15	2.06	8.07E-04
	5.35	9	7.5	2.5	5	15	2.13	7.80E-04
	5.35	9	7.5	2.5	5	15	2.16	7.69E-04
	5.35	9	7.5	2.5	5	15	2.1	7.91E-04
	5.35	9	7.5	2.5	20	10	2.11	7.88E-04
	5.35	9	7.5	2.5	20	10	2.11	7.88E-04
Average								***7.85E-04***
ODSA-III	5.24	9.352	7.5	2.5	5	15	1.79	9.10E-04
	5.24	9.352	7.5	2.5	5	15	1.81	9.00E-04
	5.24	9.352	7.5	2.5	5	15	1.79	9.10E-04
	5.24	9.352	7.5	2.5	5	15	1.8	9.05E-04
	5.24	9.352	7.5	2.5	5	15	1.85	8.80E-04
	5.24	9.352	7.5	2.5	5	15	1.78	9.15E-04
	5.24	9.352	7.5	2.5	20	10	1.76	9.25E-04
	5.24	9.352	7.5	2.5	20	10	1.77	9.20E-04
Average								***9.08E-04***
ODSA-6	4.88	10.18	7.5	2.5	5	15	1.66	9.14E-04
	4.88	10.18	7.5	2.5	5	15	1.65	9.20E-04
	4.88	10.18	7.5	2.5	5	15	1.67	9.09E-04
	4.88	10.18	7.5	2.5	5	15	1.72	8.83E-04
	4.88	10.18	7.5	2.5	5	15	1.68	9.04E-04
	4.88	10.18	7.5	2.5	20	10	1.65	9.20E-04
	4.88	10.18	7.5	2.5	20	10	1.68	9.04E-04
Average								***9.08E-04***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
BRENHAM								
BRM-1SH	1.72	4.39	35	30	5	15	0	0
	1.72	4.39	35	30	5	15	0	0
	1.72	4.39	35	30	5	15	0	0
	1.72	4.39	35	30	5	15	0	0
	1.72	4.39	35	30	5	15	0	0
	1.72	4.39	35	30	20	10	0	0
	1.72	4.39	35	30	20	10	0	0
Average								***0***
BRM-2SH	1.76	5.14	35	30	5	15	2.57	2.13E-04
	1.76	5.14	35	30	5	15	2.67	2.05E-04
	1.76	5.14	35	30	5	15	2.71	2.02E-04
	1.76	5.14	35	30	5	15	2.68	2.04E-04
	1.76	5.14	35	30	5	15	2.49	2.20E-04
	1.76	5.14	35	30	20	10	2.53	2.16E-04
	1.76	5.14	35	30	20	10	2.64	2.07E-04
Average								***2.10E-04***
BRM-3SH	1.76	3.89	35	30	5	15	23.64	2.31E-05
	1.76	3.89	35	30	5	15	22.4	2.44E-05
	1.76	3.89	35	30	5	15	22.73	2.41E-05
	1.76	3.89	35	30	5	15	22.85	2.39E-05
	1.76	3.89	35	30	5	15	23.04	2.37E-05
	1.76	3.89	35	30	20	10	22.15	2.47E-05
	1.76	3.89	35	30	20	10	22.37	2.45E-05
Average								***2.41E-05***
BRM-4SH	1.50	3.3	35	30	5	15	0	0
	1.50	3.3	35	30	5	15	0	0
	1.50	3.3	35	30	5	15	0	0
	1.50	3.3	35	30	5	15	0	0
	1.50	3.3	35	30	5	15	0	0
	1.50	3.3	35	30	20	10	0	0
	1.50	3.3	35	30	20	10	0	0
Average								***0***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
BRENHAM CONTINUED								
BRM-5SH	1.50	4.39	35	30	5	15	0	0
	1.50	4.39	35	30	5	15	0	0
	1.50	4.39	35	30	5	15	0	0
	1.50	4.39	35	30	5	15	0	0
	1.50	4.39	35	30	5	15	0	0
	1.50	4.39	35	30	20	10	0	0
	1.50	4.39	35	30	20	10	0	0
Average								***0***
BRM-1IWP	1.30	4.06	35	30	5	15	2.47	1.64E-04
	1.30	4.06	35	30	5	15	2.56	1.58E-04
	1.30	4.06	35	30	5	15	2.41	1.68E-04
	1.30	4.06	35	30	5	15	2.52	1.60E-04
	1.30	4.06	35	30	5	15	2.44	1.66E-04
	1.30	4.06	35	30	20	10	2.43	1.66E-04
	1.30	4.06	35	30	20	10	2.49	1.62E-04
Average								***1.63E-04***
BRM-4IWP	1.91	3.47	35	30	5	15	0	0
	1.91	3.47	35	30	5	15	0	0
	1.91	3.47	35	30	5	15	0	0
	1.91	3.47	35	30	5	15	0	0
	1.91	3.47	35	30	5	15	0	0
	1.91	3.47	35	30	20	10	0	0
	1.91	3.47	35	30	20	10	0	0
Average								***0***
BRM-5IWP	1.89	4.06	35	30	5	15	6.54	9.00E-05
	1.89	4.06	35	30	5	15	6.59	8.93E-05
	1.89	4.06	35	30	5	15	6.72	8.76E-05
	1.89	4.06	35	30	5	15	6.63	8.88E-05
	1.89	4.06	35	30	5	15	6.69	8.80E-05
	1.89	4.06	35	30	20	10	6.7	8.79E-05
	1.89	4.06	35	30	20	10	6.57	8.96E-05
Average								***8.87E-05***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
BRENHAM CONTINUED								
BRM-6IWP	1.89	3.76	35	30	5	15	8.95	6.56E-05
	1.89	3.76	35	30	5	15	9.1	6.45E-05
	1.89	3.76	35	30	5	15	9.11	6.45E-05
	1.89	3.76	35	30	5	15	9.05	6.49E-05
	1.89	3.76	35	30	5	15	9.15	6.42E-05
	1.89	3.76	35	30	20	10	9.19	6.39E-05
	1.89	3.76	35	30	20	10	9.09	6.46E-05
Average								***6.46E-05***
BRM-7IWP	1.76	3.09	35	30	5	15	0	0
	1.76	3.09	35	30	5	15	0	0
	1.76	3.09	35	30	5	15	0	0
	1.76	3.09	35	30	5	15	0	0
	1.76	3.09	35	30	5	15	0	0
	1.76	3.09	35	30	20	10	0	0
	1.76	3.09	35	30	20	10	0	0
Average								***0***
ATLANTA								
ATL-1	2.26	2	45	40	5	15	0	0
	2.26	2	45	40	5	15	0	0
	2.26	2	45	40	5	15	0	0
	2.26	2	45	40	5	15	0	0
	2.26	2	45	40	5	15	0	0
	2.26	2	45	40	20	10	0	0
	2.26	2	45	40	20	10	0	0
Average								***0***
ATL-2	2.14	2	45	40	5	15	0	0
	2.14	2	45	40	5	15	0	0
	2.14	2	45	40	5	15	0	0
	2.14	2	45	40	5	15	0	0
	2.14	2	45	40	5	15	0	0
	2.14	2	45	40	20	10	0	0
	2.14	2	45	40	20	10	0	0
Average								***0***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATLANTA CONTINUED								
ATL-3	2.15	1.9	45	40	5	15	0	0
	2.15	1.9	45	40	5	15	0	0
	2.15	1.9	45	40	5	15	0	0
	2.15	1.9	45	40	5	15	0	0
	2.15	1.9	45	40	5	15	0	0
	2.15	1.9	45	40	20	10	0	0
	2.15	1.9	45	40	20	10	0	0
Average								***0***
ATL-4	2.26	3.8	45	40	5	15	0	0
	2.26	3.8	45	40	5	15	0	0
	2.26	3.8	45	40	5	15	0	0
	2.26	3.8	45	40	5	15	0	0
	2.26	3.8	45	40	5	15	0	0
	2.26	3.8	45	40	20	10	0	0
	2.26	3.8	45	40	20	10	0	0
Average								***0***
ATL-7	2.01	3	45	40	5	15	0	0
	2.01	3	45	40	5	15	0	0
	2.01	3	45	40	5	15	0	0
	2.01	3	45	40	5	15	0	0
	2.01	3	45	40	5	15	0	0
	2.01	3	45	40	20	10	0	0
	2.01	3	45	40	20	10	0	0
Average								***0***
ATL-8	2.25	6.8	45	40	5	15	0	0
	2.25	6.8	45	40	5	15	0	0
	2.25	6.8	45	40	5	15	0	0
	2.25	6.8	45	40	5	15	0	0
	2.25	6.8	45	40	5	15	0	0
	2.25	6.8	45	40	20	10	0	0
	2.25	6.8	45	40	20	10	0	0
Average								***0***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATLANTA CONTINUED								
ATL-9	2.06	3	45	40	5	15	0	0
	2.06	3	45	40	5	15	0	0
	2.06	3	45	40	5	15	0	0
	2.06	3	45	40	5	15	0	0
	2.06	3	45	40	5	15	0	0
	2.06	3	45	40	20	10	0	0
	2.06	3	45	40	20	10	0	0
Average								***0***
ATL-12	2.51	5.7	35	30	5	15	18.57	4.20E-05
	2.51	5.7	35	30	5	15	18.75	4.16E-05
	2.51	5.7	35	30	5	15	19.02	4.10E-05
	2.51	5.7	35	30	5	15	18.89	4.13E-05
	2.51	5.7	35	30	5	15	18.43	4.23E-05
	2.51	5.7	35	30	20	10	18.62	4.19E-05
	2.51	5.7	35	30	20	10	18.95	4.11E-05
Average								***4.16E-05***
ATL-14	2.47	5.5	35	30	5	15	23.11	3.33E-05
	2.47	5.5	35	30	5	15	22.96	3.35E-05
	2.47	5.5	35	30	5	15	22.75	3.38E-05
	2.47	5.5	35	30	5	15	22.87	3.36E-05
	2.47	5.5	35	30	5	15	22.99	3.34E-05
	2.47	5.5	35	30	20	10	23.12	3.33E-05
	2.47	5.5	35	30	20	10	23.02	3.34E-05
Average								***3.35E-05***
ATL-15	2.12	2.3	45	40	5	15	0	0
	2.12	2.3	45	40	5	15	0	0
	2.12	2.3	45	40	5	15	0	0
	2.12	2.3	45	40	5	15	0	0
	2.12	2.3	45	40	5	15	0	0
	2.12	2.3	45	40	20	10	0	0
	2.12	2.3	45	40	20	10	0	0
Average								***0***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
ATLANTA CONTINUED								
ATL-17	2.11	2.1	45	40	5	15	0	0
	2.11	2.1	45	40	5	15	0	0
	2.11	2.1	45	40	5	15	0	0
	2.11	2.1	45	40	5	15	0	0
	2.11	2.1	45	40	5	15	0	0
	2.11	2.1	45	40	20	10	0	0
	2.11	2.1	45	40	20	10	0	0
Average								***0***
ATL-18	2.24	4.3	45	40	5	15	0	0
	2.24	4.3	45	40	5	15	0	0
	2.24	4.3	45	40	5	15	0	0
	2.24	4.3	45	40	5	15	0	0
	2.24	4.3	45	40	5	15	0	0
	2.24	4.3	45	40	20	10	0	0
	2.24	4.3	45	40	20	10	0	0
Average								***0***
ATL-19	1.97	4.9	45	40	5	15	0	0
	1.97	4.9	45	40	5	15	0	0
	1.97	4.9	45	40	5	15	0	0
	1.97	4.9	45	40	5	15	0	0
	1.97	4.9	45	40	5	15	0	0
	1.97	4.9	45	40	20	10	0	0
	1.97	4.9	45	40	20	10	0	0
Average								***0***
ATL-20	2.11	4.9	45	40	5	15	0	0
	2.11	4.9	45	40	5	15	0	0
	2.11	4.9	45	40	5	15	0	0
	2.11	4.9	45	40	5	15	0	0
	2.11	4.9	45	40	5	15	0	0
	2.11	4.9	45	40	20	10	0	0
	2.11	4.9	45	40	20	10	0	0
Average								***0***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
COLLEGE STATION								
2-WET	3.35		5	2.5	5	20	3.47	5.13E-04
	3.35		5	2.5	5	20	3.41	5.22E-04
	3.35		5	2.5	5	20	3.44	5.18E-04
	3.35		5	2.5	5	20	3.51	5.07E-04
	3.35		5	2.5	5	20	3.46	5.15E-04
	3.35		5	2.5	20	5	3.54	5.03E-04
	3.35		5	2.5	20	5	3.55	5.02E-04
Average								***5.12E-04***
3-WET	3.12		5	2.5	5	20	2.5	6.65E-04
	3.12		5	2.5	5	20	2.59	6.42E-04
	3.12		5	2.5	5	20	2.5	6.65E-04
	3.12		5	2.5	5	20	2.51	6.62E-04
	3.12		5	2.5	5	20	2.55	6.52E-04
	3.12		5	2.5	20	5	2.52	6.60E-04
	3.12		5	2.5	20	5	2.54	6.54E-04
Average								***6.57E-04***
1-WET	3.89		5	2.5	5	20	2.61	7.92E-04
	3.89		5	2.5	5	20	2.68	7.71E-04
	3.89		5	2.5	5	20	2.62	7.89E-04
	3.89		5	2.5	5	20	2.66	7.77E-04
	3.89		5	2.5	5	20	2.63	7.86E-04
	3.89		5	2.5	20	5	2.69	7.69E-04
	3.89		5	2.5	20	5	2.69	7.69E-04
Average								***7.79E-04***
5-DRY	3.39		5	2.5	5	20	3.42	5.27E-04
	3.39		5	2.5	5	20	3.45	5.22E-04
	3.39		5	2.5	5	20	3.5	5.15E-04
	3.39		5	2.5	5	20	3.48	5.18E-04
	3.39		5	2.5	5	20	3.51	5.14E-04
	3.39		5	2.5	20	5	3.52	5.12E-04
	3.39		5	2.5	20	5	3.52	5.12E-04
Average								***5.17E-04***

Table A2. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Inflow (cc)	Outflow (cc)	Time (sec)	Permeability (cm/sec)
COLLEGE STATION CONTINUED								
4D	3.73		5	2.5	5	20	2.97	6.69E-04
	3.73		5	2.5	5	20	2.97	6.69E-04
	3.73		5	2.5	5	20	3.13	6.35E-04
	3.73		5	2.5	5	20	3.17	6.27E-04
	3.73		5	2.5	5	20	3.13	6.35E-04
	3.73		5	2.5	20	5	3.16	6.29E-04
	3.73		5	2.5	20	5	3.18	6.25E-04
Average								***6.41E-04***
6D	2.74		5	2.5	5	20	2.53	5.76E-04
	2.74		5	2.5	5	20	2.61	5.59E-04
	2.74		5	2.5	5	20	2.53	5.76E-04
	2.74		5	2.5	5	20	2.57	5.67E-04
	2.74		5	2.5	5	20	2.53	5.76E-04
	2.74		5	2.5	20	5	2.6	5.61E-04
	2.74		5	2.5	20	5	2.58	5.65E-04
Average								***5.69E-04***

Table A3. Summary of Permeability Test Results for Test Specimens with Different Saturation Procedures.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Time (sec)	Permeability 60%-80% (cm/sec)	Permeability 24 Hr. (cm/sec)
SMCM20-1	6.48	6.5	7.5	2.5	1.75	1.15E-03	1.03E-03
	6.48	6.5	7.5	2.5	1.82	1.11E-03	1.02E-03
	6.48	6.5	7.5	2.5	1.84	1.09E-03	1.04E-03
	6.48	6.5	7.5	2.5	1.78	1.13E-03	1.03E-03
	6.48	6.5	7.5	2.5	1.79	1.13E-03	1.05E-03
	6.48	6.5	7.5	2.5	1.79	1.13E-03	1.07E-03
	6.48	6.5	7.5	2.5	1.77	1.14E-03	1.06E-03
Average						1.12E-03	1.04E-03
SMCM20-12	6.74	11.3	7.5	2.5	1.69	1.24E-03	1.25E-03
	6.74	11.3	7.5	2.5	1.67	1.25E-03	1.25E-03
	6.74	11.3	7.5	2.5	1.67	1.25E-03	1.23E-03
	6.74	11.3	7.5	2.5	1.68	1.25E-03	1.20E-03
	6.74	11.3	7.5	2.5	1.65	1.27E-03	1.23E-03
	6.74	11.3	7.5	2.5	1.69	1.24E-03	1.25E-03
	6.74	11.3	7.5	2.5	1.68	1.25E-03	1.27E-03
Average						1.25E-03	1.24E-03
SMCM20-8	5.81	4.4	7.5	2.5	2.23	8.10E-04	7.72E-04
	5.81	4.4	7.5	2.5	2.22	8.14E-04	7.65E-04
	5.81	4.4	7.5	2.5	2.23	8.10E-04	7.79E-04
	5.81	4.4	7.5	2.5	2.21	8.17E-04	7.65E-04
	5.81	4.4	7.5	2.5	2.18	8.29E-04	7.75E-04
	5.81	4.4	7.5	2.5	2.18	8.29E-04	7.65E-04
	5.81	4.4	7.5	2.5	2.20	8.21E-04	7.72E-04
Average						8.18E-04	7.71E-04
SMTC20-2	6.24	3.5	7.5	2.5	6.08	3.19E-04	3.55E-04
	6.24	3.5	7.5	2.5	6.09	3.19E-04	3.60E-04
	6.24	3.5	7.5	2.5	5.97	3.25E-04	3.59E-04
	6.24	3.5	7.5	2.5	5.98	3.24E-04	3.52E-04
	6.24	3.5	7.5	2.5	6.01	3.23E-04	3.55E-04
	6.24	3.5	7.5	2.5	6.05	3.21E-04	3.53E-04
	6.24	3.5	7.5	2.5	5.99	3.24E-04	3.54E-04
Average						3.22E-04	3.55E-04

Table A3. Continued.

Core ID	Height (cm)	Voids (%)	Confining Pressure (kPa)	Input Pressure (kPa)	Time (sec)	Permeability 60%-80% (cm/sec)	Permeability 24 Hr. (cm/sec)
SMTC20-5	5.94	7.7	7.5	2.5	1.88	9.82E-04	9.19E-04
	5.94	7.7	7.5	2.5	1.91	9.67E-04	9.19E-04
	5.94	7.7	7.5	2.5	1.92	9.62E-04	8.96E-04
	5.94	7.7	7.5	2.5	1.92	9.62E-04	9.28E-04
	5.94	7.7	7.5	2.5	1.92	9.62E-04	9.19E-04
	5.94	7.7	7.5	2.5	1.93	9.57E-04	9.05E-04
	5.94	7.7	7.5	2.5	1.91	9.67E-04	9.14E-04
Average						9.65E-04	9.14E-04
SMTC20-10	6.53	12.6	7.5	2.5	1.77	1.15E-03	1.15E-03
	6.53	12.6	7.5	2.5	1.72	1.18E-03	1.11E-03
	6.53	12.6	7.5	2.5	1.72	1.18E-03	1.11E-03
	6.53	12.6	7.5	2.5	1.76	1.15E-03	1.11E-03
	6.53	12.6	7.5	2.5	1.75	1.16E-03	1.13E-03
	6.53	12.6	7.5	2.5	1.72	1.18E-03	1.13E-03
	6.53	12.6	7.5	2.5	1.71	1.19E-03	1.13E-03
Average						1.17E-03	1.13E-03

** The confining & input pressure values were identical to the other permeability test specimens.

SM - Austin, Limestone Aggregate

CM - CMHB Mixture

- Sample Number

TC - Dense-Graded Mixture

20 - AC-20

APPENDIX B

RESULTS OF TxDOT CREEP TESTS

Table B1. Summary of Modified TxDOT Creep Test Results.

Aggregate/ Mix Type	Asphalt Binder	Creep Stiffness (kPa)	Total Strain (cm/cm)	Permanent Strain (cm/cm)	Slope (cm/cm-sec)
Austin Dense	AC-10	86016	8.29E-04	4.86E-04	4.57E-08
		70794	1.02E-03	6.32E-04	2.70E-08
	Average	***78405***	***9.25E-04***	***5.59E-04***	***3.64E-08***
	AC-20	68457	1.06E-03	7.75E-04	1.09E-07
		114268	6.29E-04	2.51E-04	2.70E-08
	Average	***91363***	***8.44E-04***	***5.13E-04***	***6.81E-08***
	AC-45P	53477	1.34E-03	1.06E-03	1.70E-07
		50209	1.39E-03	1.06E-03	7.50E-08
	Average	***51843***	***1.36E-03***	***1.06E-03***	***1.23E-07***
	AC-20+latex	88174	8.17E-04	4.77E-04	2.30E-08
		92534	1.18E-03	-1.56E-04	2.54E-08
	Average**	***88174***	***8.17E-04***	***4.77E-04***	***2.30E-08***
Austin CMHB	AC-10	79853	8.99E-04	5.57E-04	5.84E-08
		72759	9.82E-04	6.04E-04	2.60E-08
	Average	***76306***	***9.41E-04***	***5.81E-04***	***4.22E-08***
	AC-20	72373	9.78E-04	6.19E-04	8.38E-08
		71001	1.01E-03	6.59E-04	3.60E-08
	Average	***71687***	***9.94E-04***	***6.39E-04***	***5.99E-08***
	AC-45P	63480	1.12E-03	8.42E-04	1.50E-07
		73145	9.83E-04	6.87E-04	5.10E-08
	Average	***68313***	***1.05E-03***	***7.65E-04***	***1.00E-07***
	AC-20+latex	83155	8.53E-04	5.85E-04	6.86E-08
		92131	7.64E-04	3.59E-04	1.40E-08
	Average	***87643***	***8.09E-04***	***4.72E-04***	***4.13E-08***

Table B1. Continued.

Aggregate/ Mix Type	Asphalt Binder	Creep Stiffness (kPa)	Total Strain (cm/cm)	Permanent Strain (cm/cm)	Slope (cm/cm-sec)
Atlanta Dense	AC-10	66431	1.08E-03	5.22E-04	4.57E-08
		57868	1.21E-03	6.20E-04	2.30E-08
	Average	***62149***	***1.14E-03***	***5.71E-03***	***3.44E-08***
	AC-20	58261	1.23E-03	7.58E-04	9.65E-08
		81777	8.77E-04	4.52E-04	2.10E-08
	Average	***70019***	***1.05E-03***	***6.05E-04***	***5.88E-08***
	AC-45P	41088	1.71E-03	1.10E-03	1.40E-07
		58358	1.24E-03	8.62E-04	5.40E-08
	Average	***49723***	***1.48E-03***	***9.82E-04***	***9.69E-08***
	AC-20+latex	49623	1.40E-03	9.50E-04	1.14E-07
		49520	1.45E-03	9.63E-04	4.90E-08
	Average	***49571***	***1.43E-03***	***9.57E-04***	***8.17E-08***
Atlanta CMHB	AC-10	55331	1.28E-03	5.37E-04	4.57E-08
		60350	1.18E-03	6.55E-04	2.90E-08
	Average	***57841***	***1.23E-03***	***5.96E-04***	***3.74E-08***
	AC-20	59950	1.19E-03	6.97E-04	9.14E-08
		58578	1.20E-03	6.89E-04	3.50E-08
	Average	***59264***	***1.19E-03***	***6.93E-04***	***6.32E-08***
	AC-45P	59971	1.19E-03	7.91E-04	1.22E-07
		56931	1.27E-03	8.60E-04	5.50E-08
	Average	***58451***	***1.23E-03***	***8.26E-04***	***8.85E-08***
	AC-20+latex	77102	9.25E-04	4.87E-04	4.06E-08
		56924	1.25E-03	7.99E-04	3.40E-08
	Average	***67013***	***1.09E-03***	***6.43E-04***	***3.73E-08***

Table B1. Continued.

Aggregate/ Mix Type	Asphalt Binder	Creep Stiffness (kPa)	Total Strain (cm/cm)	Permanent Strain (cm/cm)	Slope (cm/cm-sec)
Paris Dense	AC-10	60715	1.18E-03	6.09E-04	5.59E-08
		80970	8.85E-04	3.65E-04	9.00E-09
	Average	***70843***	***1.03E-03***	***4.87E-04***	***3.24E-08***
	AC-20	54173	1.32E-03	8.24E-04	9.40E-08
		77475	9.27E-04	4.65E-04	1.80E-08
	Average	***65824***	***1.12E-03***	***6.45E-04***	***5.60E-08***
	AC-45P	50705	1.42E-03	1.00E-03	1.60E-07
		59268	1.21E-03	8.21E-04	4.00E-08
	Average	***54987***	***1.32E-03***	***9.13E-04***	***1.00E-07***
	AC-20+latex	54738	1.31E-03	8.89E-04	1.12E-07
		51477	1.40E-03	8.45E-04	4.50E-08
	Average	***53108***	***1.35E-03***	***8.67E-04***	***7.84E-08***
Paris CMHB	AC-10	49533	1.43E-03	7.77E-04	5.59E-08
		59971	1.19E-03	6.17E-04	2.00E-08
	Average	***54752***	***1.31E-03***	***6.97E-04***	***3.79E-08***
	AC-20	58220	1.23E-03	7.43E-04	7.87E-08
		52973	1.34E-03	8.75E-04	4.50E-08
	Average	***55597***	***1.28E-03***	***8.09E-04***	***6.19E-08***
	AC-45P	55724	1.28E-03	8.79E-04	1.17E-07
		49685	1.45E-03	1.02E-03	5.10E-08
	Average	***52705***	***1.37E-03***	***9.50E-04***	***8.39E-08***
	AC-20+latex	50671	1.39E-03	8.37E-04	7.37E-08
		54263	1.30E-03	7.98E-04	4.20E-08
	Average	***52467***	***1.34E-03***	***8.18E-04***	***5.78E-08***

** - The average consists only of the first set of test values due to the negative permanent strain measured for the second test specimen.

APPENDIX C

RESULTS OF MOISTURE SUSCEPTIBILITY TESTS

Table C1. Summary of Indirect Tensile Strength Results for Unconditioned Test Specimens.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strength kPa
			1	7.1	483
Atlanta	CMHB	AC-20	2	6.0	565
			3	7.3	517
			Average	***6.8***	***522***
			1	6.3	876
Atlanta	Dense	AC-20	2	6.0	855
			3	6.2	834
			Average	***6.2***	***855***
			1	7.3	703
Austin	CMHB	AC-20	2	7.9	641
			3	7.5	634
			Average	***7.6***	***660***
			1	6.4	869
Austin	Dense	AC-20	2	7.4	772
			3	6.4	848
			Average	***6.7***	***830***
			1	6.4	489
Atlanta	CMHB	AC-45P	2	6.9	483
			3	6.6	586
			Average	***6.6***	***519***
			1	6.6	731
Atlanta	Dense	AC-45P	2	6.5	834
			3	5.9	889
			Average	***6.3***	***818***
			1	7.9	641
Austin	CMHB	AC-45P	2	7.9	627
			3	7.8	676
			Average	***7.9***	***648***

Table C1. Continued.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strength kPa
			1	8.1	627
Austin	Dense	AC-45P	2	8.2	676
			3	8.0	703
			Average	***8.1***	***669***
Paris	CMHB	AC-20	1	7.3	600
			2	7.4	614
			3	7.4	607
			Average	***7.4***	***607***
Paris	Dense	AC-20	1	7.0	931
			2	6.4	931
			3	6.7	931
			Average	***6.7***	***931***
Paris	CMHB	AC-45P	1	7.1	614
			2	6.9	627
			3	7.2	641
			Average	***7.2***	***627***
Paris	Dense	AC-45P	1	6.8	944
			2	7.4	800
			3	7.0	872
			Average	***7.1***	***872***

Table C2. Summary of Indirect Tensile Strength Ratios for One-Day Cycle Test Specimens.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strengt kPa	TSR
Atlanta	CMHB	AC-20	1	6.8	427	
			2	7.0	441	
			3	6.9	434	
			Average	***6.9***	***434***	***83***
Atlanta	Dense	AC-20	1	6.5	717	
			2	6.2	731	
			3	6.4	724	
			Average	***6.4***	***724***	***85***
Austin	CMHB	AC-20	1	7.0	455	
			2	7.2	441	
			3	7.1	448	
			Average	***7.1***	***448***	***68***
Austin	Dense	AC-20	1	6.6	545	
			2	6.8	400	
			3	6.7	472	
			Average	***6.7***	***472***	***57***
Atlanta	CMHB	AC-45P	1	6.1	462	
			2	6.0	476	
			3	6.1	469	
			Average	***6.1***	***469***	***90***
Atlanta	Dense	AC-45P	1	6.2	669	
			2	6.6	745	
			3	6.4	707	
			Average	***6.4***	***707***	***86***
Austin	CMHB	AC-45P	1	7.5	510	
			2	6.7	538	
			3	7.1	524	
			Average	***7.1***	***524***	***81***

Table C2. Continued.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strengt kPa	TSR
Austin	Dense	AC-45P	1	6.6	669	
			2	5.9	620	
			3	6.3	645	
			Average	***6.3***	***645***	***96***
Paris	CMHB	AC-20	1	6.5	345	
			2	7.1	345	
			3	6.8	345	
			Average	***6.8***	***345***	***57***
Paris	Dense	AC-20	1	8.2	**	
			2	7.2	462	
			3	7	462	
			Average	***7.1***	***462***	***50***
Paris	CMHB	AC-45P	1	6.5	503	
			2	6.6	538	
			3	6.6	520	
			Average	***6.6***	***520***	***83***
Paris	Dense	AC-45P	1	7.5	503	
			2	6.8	683	
			3	7.2	593	
			Average	***7.2***	***593***	***68***

** Test specimen broke during the thawing process.

APPENDIX D

RESULTS OF OXIDATIVE AGING TESTS

Table D1. Summary of Indirect Tensile Strength Results for Short-Term Aged Test Specimen

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strength kPa	Percent Increase
Atlanta	CMHB	AC-20	1	8.1	648	24.2
			2	7.5	600	15.0
			3	6.6	669	28.2
			Average	***7.4***	***639***	***22.5***
Atlanta	Dense	AC-20	1	6.7	1013	18.5
			2	6.4	1117	30.6
			3	6.5	1200	40.3
			Average	***6.5***	***1110***	***29.8***
Austin	CMHB	AC-20	1	7.8	793	20.2
			2	7.7	820	24.4
			3	8.1	731	10.8
			Average	***7.9***	***781***	***18.5***
Austin	Dense	AC-20	1	6.6	1138	37.1
			2	6.5	1117	34.6
			3	7.6	834	0.6*
			Average	***6.9***	***1030***	***35.9***
Atlanta	CMHB	AC-45P	1	7.1	641	23.5
			2	6.9	572	10.2
			3	6.9	503	-3.1*
			Average	***7.0***	***572***	***16.8***
Atlanta	Dense	AC-45P	1	6.9	1013	23.9
			2	7.3	938	14.6
			3	7.0	1007	23.0
			Average	***7.1***	***986***	***20.5***
Austin	CMHB	AC-45P	1	7.5	924	42.6
			2	7.4	841	29.8
			3	7.0	848	30.9
			Average	***7.3***	***871***	***34.4***
Austin	Dense	AC-45P	1	7.1	979	46.4
			2	7.1	1013	51.5
			3	6.7	1131	69.1
			Average	***7.0***	***1041***	***55.7***

* Not included in average

Table D2. Summary of Indirect Tensile Strength Results for Long-Term Aged Test Specime

Aggregate	Mixture	Binder	Sample No.	Air Voids %	Tensile Strengt kPa	Percent Increase
Atlanta	CMHB	AC-20	1	6.2	841	61.2
			2	6.5	841	61.2
			3	6.5	765	46.7
			Average	***6.4***	***816***	***56.4***
Atlanta	Dense	AC-20	1	7.7	1103	29.0
			2	7.3	1179	37.9
			3	8.1	1110	29.8
			Average	***7.7***	***1131***	***32.3***
Austin	CMHB	AC-20	1	7.9	1075	63.1
			2	7.7	1213	84.0
			3	7.6	1124	70.4
			Average	***7.7***	***1138***	***72.5***
Austin	Dense	AC-20	1	7.2	1206	45.4
			2	6.6	1420	71.2
			3	6.8	1510	82.0
			Average	***6.9***	***1379***	***66.2***
Atlanta	CMHB	AC-45P	1	6.2	834	60.6
			2	6.4	820	58.0
			3	6.8	655	26.1
			Average	***6.5***	***770***	***48.2***
Atlanta	Dense	AC-45P	1	7.3	938	14.6
			2	7.1	1138	39.0
			3	6.6	1124	37.4
			Average	***7.0***	***1066***	***30.3***
Austin	CMHB	AC-45P	1	8.2	965	48.9
			2	7.9	993	53.2
			3	7.5	1055	62.8
			Average	***7.9***	***1004***	***55.0***
Austin	Dense	AC-45P	1	6.5	1303	94.8
			2	6.8	1351	102.1
			3	6.0	1344	101.0
			Average	***6.4***	***1333***	***99.3***

Table D3. Summary of Resilient Moduli Results for Short-Term Aged Test Specimens.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	M_R kPa x 10^3	Percent Increase
Atlanta	CMHB	AC-20	1	8.1	2028	80.4
			1		1958	74.2
			2	7.5	1952	73.6
			2		1688	50.1
			3	6.6	2278	102.6
			3		1989	76.9
			Average	***7.4***	***1982***	***76.3***
Atlanta	Dense	AC-20	1	6.7	3332	90.2
			1		3068	75.2
			2	6.4	3162	80.5
			2		3426	95.6
			3	6.5	3009	71.8
			3		2829	61.5
			Average	***6.5***	***3138***	***79.1***
Austin	CMHB	AC-20	1	7.8	2796	57.4
			1		2698	51.9
			2	7.7	3468	95.2
			2		3617	103.6
			3	8.1	2664	50.0
			3		2587	45.7
			Average	***7.9***	***2972***	***67.3***
Austin	Dense	AC-20	1	6.6	3838	69.5
			1		3838	69.5
			2	6.5	4235	87.1
			2		3888	71.8
			3	7.6	3313	46.4
			3		3389	49.7
			Average	***6.9***	***3750***	***65.7***
Atlanta	CMHB	AC-45P	1	7.1	1338	90.4
			1		1364	94.1
			2	6.9	1555	121.3
			2		1233	75.4
			3	6.9	1051	49.6
			3		974	38.6
			Average	***7.0***	***1252***	***78.2***

Table D3. Continued.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	M_R kPa x 10^3	Percent Increase
Atlanta	Dense	AC-45P	1	6.9	1861	66.7
			1		1779	59.4
			2	7.3	1787	60.2
			2		1748	56.6
			3	7.0	2096	87.8
			3		2074	85.9
			Average	***7.1***	***1891***	***69.4***
Austin	CMHB	AC-45P	1	7.5	3223	138.7
			1		3149	133.2
			2	7.4	2436	80.4
			2		2529	87.3
			3	7.0	3124	131.3
			3		2897	114.5
			Average	***7.3***	***2893***	***114.2***
Austin	Dense	AC-45P	1	7.1	3251	116.8
			1		3243	116.3
			2	7.1	3054	103.7
			2		3159	110.7
			3	6.7	3583	139.0
			3		3671	144.8
			Average	***7.0***	***3327***	***121.9***

Table D4. Summary of Resilient Moduli Results for Long-Term Aged Test Specimens.

Aggregate	Mixture	Binder	Sample No.	Air Voids %	M_R kPa x 10^3	Percent Increase
Atlanta	CMHB	AC-20	1	6.2	3214	185.8
			1		2966	163.8
			2	6.5	3034	169.9
			2		2896	157.5
			3	6.5	2459	118.7
			3		2654	136.0
			Average	***6.4***	***2870***	***155.3***
Atlanta	Dense	AC-20	1	7.7	5333	204.5
			1		4242	142.2
			2	7.3	4179	138.6
			2		4344	148.0
			3	8.1	5420	209.4
			3		4896	179.5
			Average	***7.7***	***4736***	***170.4***
Austin	CMHB	AC-20	1	7.9	5318	199.4
			1		4782	169.3
			2	7.7	5649	218.1
			2		5843	229.0
			3	7.6	4933	177.7
			3		5540	211.9
			Average	***7.7***	***5344***	***200.9***
Austin	Dense	AC-20	1	7.2	6555	189.6
			1		5257	132.3
			2	6.6	6337	180.0
			2		6535	188.7
			3	6.8	6329	179.6
			3		6377	181.7
			Average	***6.9***	***6232***	***175.3***
Atlanta	CMHB	AC-45P	1	6.2	2321	230.3
			1		2041	190.5
			2	6.4	1943	176.6
			2		1929	174.6
			3	6.8	1618	130.3
			3		1612	129.4
			Average	***6.5***	***1911***	***171.9***

Table D4. Continued

Aggregate	Mixture	Binder	Sample No.	Air Voids %	M_R kPa x 10^3	Percent Increase
Atlanta	Dense	AC-45P	1	7.3	3412	205.7
			1		2695	141.5
			2	7.1	2971	166.2
			2		2762	147.5
			3	6.6	3070	175.1
			3		3189	185.8
			Average	***7.0***	***3016***	***170.3***
Austin	CMHB	AC-45P	1	8.2	3965	193.6
			1		4016	197.4
			2	7.9	3980	194.7
			2		4127	205.6
			3	7.5	3897	188.6
			3		4736	250.7
			Average	***7.9***	***4120***	***205.1***
Austin	Dense	AC-45P	1	6.5	5294	253.1
			1		4651	210.2
			2	6.8	5270	251.4
			2		5263	251.0
			3	6.0	5026	235.2
			3		5778	285.4
			Average	***6.4***	***5214***	***247.7***

APPENDIX E

GRADATIONS OF AGGREGATES USED IN STUDY

Table E1. Gradations of Aggregates Used in the CMHB, Atlanta Mixture Design.

Sieve Size	C-Rock	D-Rock	Field Sand	Texas Lime
25.4 mm	100.0	100.0	100.0	100.0
19.0 mm	99.3	100.0	100.0	100.0
16.0 mm	90.2	100.0	100.0	100.0
9.5 mm	14.3	82.0	100.0	100.0
4.75 mm	8.1	37.0	100.0	100.0
2.00 mm	4.9	8.0	100.0	100.0
425 μm	3.6	1.0	99.8	100.0
180 μm	2.9	0.6	96.6	100.0
75 μm	1.9	0.4	26.0	100.0
Job Mix Formula	36.0	50.0	11.5	2.5

Table E2. Gradations of Aggregates Used in the CMHB, Paris Mixture Design.

Sieve Size	C-Rock	D-Rock	Dry Screenings	Ag Lime
25.4 mm	100.0	100.0	100.0	100.0
19.0 mm	100.0	100.0	100.0	100.0
16.0 mm	99.5	100.0	100.0	100.0
9.5 mm	28.3	89.7	100.0	100.0
4.75 mm	2.5	37.8	100.0	100.0
2.00 mm	1.2	7.0	68.7	100.0
425 μm	1.1	1.9	39.0	100.0
180 μm	1.1	1.6	28.1	98.0
75 μm	0.6	0.8	12.3	80.7
Job Mix Formula	47.0	30.0	17.5	5.5

Table E3. Gradations of Aggregates Used in the CMHB, Austin Mixture Design.

Sieve Size	C-Rock	D-Rock	F-Rock	Dry Screenings
25.4 mm	100.0	100.0	100.0	100.0
19.0 mm	100.0	100.0	100.0	100.0
16.0 mm	99.9	100.0	100.0	100.0
9.5 mm	5.6	66.4	100.0	99.9
4.75 mm	1.5	6.3	70.1	99.5
2.00 mm	1.3	2.1	12.0	88.3
425 µm	1.3	2.0	4.8	47.2
180 µm	1.2	1.9	4.3	34.6
75 µm	1.0	1.6	3.8	26.0
Job Mix Formula	35.0	17.0	30.0	18.0

Table E4. Gradations of Aggregates Used in the Dense-Graded, Atlanta Mixture Design.

Sieve Size	C-Rock	D-Rock	Dry Screenings	Field Sand	Texas Lime
25.4 mm	100.0	100.0	100.0	100.0	100.0
19.0 mm	99.3	100.0	100.0	100.0	100.0
16.0 mm	90.2	100.0	100.0	100.0	100.0
9.5 mm	14.3	82.0	100.0	100.0	100.0
4.75 mm	8.1	37.0	98.1	99.9	100.0
2.00 mm	4.9	8.0	69.0	99.8	100.0
425 µm	3.6	1.0	24.3	99.3	100.0
180 µm	2.9	0.6	10.6	37.4	100.0
75 µm	1.9	0.4	3.1	16.1	100.0
Job Mix Formula	15.0	36.0	40.0	2.5	1.5

Table E5. Gradations of Aggregates Used in the Dense-Graded, Paris Mixture Design.

Sieve Size	C-Rock	D-Rock	Washed Screenings	Field Sand
25.4 mm	100.0	100.0	100.0	100.0
19.0 mm	100.0	100.0	100.0	100.0
16.0 mm	99.5	100.0	100.0	98.9
9.5 mm	28.3	89.7	100.0	98.2
4.75 mm	2.5	18.8	96.7	97.4
2.00 mm	1.2	3.0	60.9	96.3
425 µm	1.1	1.9	30.4	95.2
180 µm	1.1	1.6	18.2	35.5
75 µm	0.6	0.8	5.2	10.3
Job Mix Formula	25.0	30.0	35.0	10.0

Table E6. Gradations of Aggregates Used in the Dense-Graded, Austin Mixture Design.

Sieve Size	C-Rock	D-Rock	F-Rock	Manufact. Sand	Field Sand
25.4 mm	100.0	100.0	100.0	100.0	100.0
19.0 mm	100.0	100.0	100.0	100.0	100.0
16.0 mm	99.9	100.0	100.0	100.0	100.0
9.5 mm	5.6	66.4	100.0	100.0	100.0
4.75 mm	1.5	6.3	70.1	100.0	99.9
2.00 mm	1.3	2.1	12.0	74.4	99.8
425 µm	1.3	2.0	4.8	21.3	75.4
180 µm	1.2	1.9	4.3	10.8	33.3
75 µm	1.0	1.6	3.8	5.8	13.4
Job Mix Formula	13.0	26.0	25.0	25.0	11.0

Table E7. Optimum Asphalt Content for All Mixture Designs.

Aggregate Source	Optimum Asphalt Content	
	Mixture Type	
	CMHB	Dense Graded
Atlanta	5.3	4.5
Paris	5.8	5.4
Austin	5.2	4.7

APPENDIX F

PERMEABILITY TEST PROCEDURE

Permeability Test Procedure

Please refer to Figures 22 and 23 for delineation of valve and port lettering.

A. Preparation of Equipment

1. Supply air to the panel.
2. Adjust master regulator A to approximately 40-50 psi. This is an ample supply of pressure for determining the permeability of compacted bituminous materials.
3. Position all valves on the panel and chamber to either CLOSED, OFF, or VENT.
4. Adjust regulator L in first, second, and third position to zero.
5. Connect line from port Q in the first position to quick connector 15.
6. Connect line from port Q in the second position to valve 10.
7. Connect line from port Q in the third position to valve 12.

B. Deairing Water

1. Fill water tank.
    a. Turn valve D to vent position
    b. Turn valve E to fill position. Fill the water tank to approximately 3/4 of its capacity.
    c. Move valve E to the OFF position when the desired capacity has been achieved.

2. Turn valve D to vacuum
    a. Turn in-line valve to pump.
    b. Turn pump on. Allow the vacuum gauge C reach 29 in Hg and let it continue vacuuming for approximately 30 minutes.
    c. Close in-line valve.

   d. Turn pump off. The water in the tank will remain vacuumed as long as valve D is either in the VACUUM or PRESSURE position. It is best to this when testing for the day has been completed such that deaired water will be available the next day for testing. This is primarily for the testers convenience.

C. Filling the Burettes and Pipettes (from the de-aired water tank)

1. Turn valve D to PRESSURE position.
2. Valve E should be turned to the OFF position.
3. Start with the burette and pipette in the third position of the control panel.
   a. Turn valve P to OFF position.
   b. Turn valve M to VENT position. It is essential that valve M is turned to VENT and not left on PRESSURE. If the pressure being applied to the top of the burette is greater than 10 psi being applied to the top of the water tank, water will flow out of the burette and back into the tank. The water tank is designed for a pressure of 20 psi, such that a pressure greater than this will over pressurize the tank.
   c. Turn valve N to either BURETTE, PIPETTE, or BOTH position.
   d. Fill the burette, pipette, or both by turning valve O to H2O position. It is essential to carefully monitor the rise of the water level in the burette or pipette, such that it is not overfilled. A burette or pipette that is overfilled will cause water to leak out of valve M behind the panel board. This must be avoided because water may enter regulator L and damage it.
4. Repeat steps 3 (a-d) to fill the burettes and pipettes in the first and second position.

D. Flushing Air from Lines

1. At this point, valve M should be in the VENT position, valve N should be in either the BURETTE, PIPETTE, or BOTH setting, valve O should be in OFF position, and valve P should be in the OFF position.

2. This procedure will start with the line in the second position, but it is not necessary to start here. It can start with the first or third position. This is based on preference only.
3. Turn valve K to REGULATOR 2.
4. Apply a pressure of approximately 1 to 1.5 psi, which is more than adequate for flushing the air from the line.
5. Turn valve M in the second position to PRESSURE.
6. Turn valve P to the ON position.
7. Slowly open valve 10 on the cell to flush air from the line, valve 10, and the bottom pedestal.
8. Close valve 10 when the line appears to be free of air.
9. Turn valve P to OFF.
10. Turn valve M to VENT. At this point the air in the line of the second position has been flushed.
11. Release the pressure by adjusting valve K.
12. Repeat steps 3 and 4 for the third position.
13. Turn valve M to the PRESSURE position in the third position of the panel.
14. Turn valve P to the ON position.
15. Slowly open valve 12 on the cell to flush air from the line, valve 12, and spiral tube to the top cap.
16. Close valve 12 when the line appears to be free of air.
17. Turn valve P to OFF.
18. Turn M to VENT. At this point the air in the line of the third position has been flushed; Release the pressure by adjusting valve K.
19. Repeat steps 3 and 4 for the first position.
20. Turn valve M to the pressure position in the first position of the panel.
21. Slowly open valve P until water appears on the connecting line to the cell.
22. Turn valve P to OFF.
23. Turn valve M to VENT. At this point the air in the line of the first position has been flushed.

24. Make sure that valves P, O, and N are in the OFF position and M is in the VENT position for each position of the panel.

E. Placement of Specimen in Permeability Cell

1. Seal the rubber membrane to the base pedestal with 2 "O" rings. Allow an ample amount of membrane such that it can be securely sealed to the top pedestal.
2. Place the specimen on the lower pedestal. If porous stones are in use then they must be placed before and on top of the specimen, as well as be fully saturated. Importantly the permeability of the stones must be known such that a true permeability of the specimen is determined and not of the porous stones.
3. Place the cap inside the rubber membrane and on top of the specimen.
4. Seal the membrane to the top pedestal with 2 "O" rings.
5. Align the specimen such that it lies in the middle of both pedestals if the diameter is less than 152.4 mm.
6. Connect male quick connector to female quick connector 16 on top of the cell, this will vent the cell.
7. Set the top of the triaxial cell in place.
8. Tighten the three tie rods by hand, applying approximately the same pressure.
9. Disconnect the line from connector Q in the first position and connect it to connector G.
10. Turn valve F to the FILL position. Tap water is sufficient for the purpose of filling the chamber and application of the confining pressure.
11. Quickly remove the male quick connector 16 on top of cell when water starts to flow out.
12. Turn valve F to the OFF position.
13. Disconnect the line from connector G and connect it to connector Q of the first position.
14. Check to ensure that all burettes or pipettes or both have water in operating level. If not, refill. All valves on the panel and cell should be CLOSED, OFF, or in the VENT position.

F. Saturation

1. Turn valve K to REGULATOR 1. The proceeding steps are going to establish a confining pressure in the cell outside the specimen.
2. Adjust cell pressure to 5 psi by turning REGULATOR L in the first position. Five psi is normally a sufficient *confining pressure* and is at the engineer's discretion. This pressure can be less or greater. Unlike soils, this pressure can be greater because it will not damage the specimen.
3. Turn valve M in the first position to PRESSURE.
4. Turn valve N in the first position to BOTH.
5. Valve O in the first position ought to be in the OFF position.
6. Turn valve P in the first position to the ON position.
7. Turn valve K to REGULATOR 2. The display reading should be 0 psi.
8. Turn valve M in the second position to VENT.
9. Turn valve N in the second position to BOTH.
10. Valve O in the second position ought to be in the OFF position.
11. Turn valve P in the second position to the ON position.
12. Open valve 10 and 11.
13. Close valve 11 when water starts flowing out.
14. Turn valve P in the second position to the OFF position.
15. Turn valve K to REGULATOR 3.
16. Repeat steps 8 through 11 with the valves in the third position.
17. Open valves 12 and 13.
18. Close valve 13 when water starts flowing out.
19. Close valves 10 and 12.
20. Turn autoload valve R to the ON position. The autoload feature maintains a pressure difference between regulators 1 and 2. This is used when forcing saturation and a set pressure difference needs to be maintained between the forcing pressure and confining pressure. However, this differential may only be necessary for soils where the specimen can be damaged.

21. Turn valve K to regulator 2.
22. Adjust the pressure to 10 psi. Once again, this pressure is at the engineer's discretion and not a set standard. This pressure will vary among specimens. Specimens that are less permeable will require a higher pressure to force saturation.
23. Turn valve M in the second position to PRESSURE position.
24. Turn valve N in the second position to BOTH position.
25. Valve O in the second position is in the OFF position.
26. Turn valve P in the second position to the ON position.
27. Turn valve K to regulator 3. The display should read 0 pressure.
28. Repeat steps 23 through 26 for valves in the third position of the panel.
29. At this point the system is ready to start forcing saturation.
30. Make sure there is plenty of water in the burette and pipette of the second position of the panel. Make sure that the burette and pipette of the third position of the panel contain a small amount of water or are partially drained, such that water will be forced from the burette and pipette of the second position to the that of the third position.
31. Start saturation by opening valves 12 and 10. Water will flow (the speed will depend on the permeability of the specimen) from the second burette and pipette through the specimen and into the third burette and pipette. It is essential to NOT let the water completely drain out of the burette and pipette of the second position of the panel, such that air will be forced into the specimen and thus the purpose of this procedure is defeated. Also, it is essential to NOT overfill the burette and pipette of the third position of the panel, as mentioned in section C.
32. Refill the burette and pipette of the second position and drain the burette and pipette of the third position. Follow the steps in section C for refilling. To drain the burette and pipette follow the steps in section C except for turning valve O to the DRAIN position instead of H20 position.
33. Repeat this process at least 3 times. Once again, this is not a standard and will depend on the permeability of the specimen. Repeat this until there is a consistent flow within the burettes and pipettes and that no air bubbles are seen in the lines, which there should not be if properly flushed.

34. Upon completion of forcing saturation, refill the pipette and drain the burette of the second position. Also, drain the burette and pipette of the third position, but not completely. Perhaps to the 24 or 25 marking on the pipette. The specimen is now fully saturated and ready for testing.

G. Testing

1. Testing will immediately follow saturation.
2. Turn valve P to OFF position of both the second and third position of the panel.
3. Turn valve M to VENT position of both the second and third position of the panel.
4. Turn valve K to regulator 2.
5. Adjust the pressure to 2.5 psi. Once again, this is not a standard pressure to measure permeability but was chosen as a convenient pressure for measurement. This pressure will allow an adequate amount of time to record the time of flow within the pipette.
6. Turn valve K to regulator 3. This is to check that the pressure is 0 psi.
7. Turn valve M to PRESSURE position of both the second and third position of the panel.
8. Turn valve P to ON position of both the second and third position of the panel.
9. It is necessary to record the time of flow of the water within the pipette of both the second and third position of the panel. First, this will be performed with the pipette in the second position and then with the pipette in the third position.
10. Choose two markings within the pipette. It is recommended to choose 5 and 20. There will be time to start the stop watch at the number 5 marking as water flows from the zero marking towards the 25 marking. Once again, these are suggestions only and not standardized. Also, do not let the water completely drain out of the pipette as air will be forced into the specimen.
11. Record the time that it takes for the water to flow from marking 5 to 20 on the pipette. Please refer to Figure 3 which displays a sample data sheet.

12. Perform this 5 times, which is once again a suggestion. Three times may be enough.
13. Perform this with the pipette in the third position to verify full saturation of the specimen. The times should be similar if not the same as that with the times found with the pipette in the second position of the panel.

H. Following Testing

1. Turn valve P to OFF position of the first, second, and third position of the panel.
2. Turn valve M to VENT position of the first, second, and third position of the panel.
3. Turn valve K to position 2.
4. Adjust regulator L of the second position of the panel to 0 psi.
5. Turn valve K to REGULATOR 1.
6. Adjust regulator L of the first position of the panel to 0 psi.
7. Drain all the burettes and pipettes of the first, second, and third position of the panel.
8. Disconnect line from port Q.
9. Disconnect line from quick connector 15 of the permeability cell.
10. The following steps pertain to draining the chamber. Connect one end of the transparent (clear) line to port G and the other end of that line to quick connector 16 on top of the cell.
12. Connect another line to quick connector 15 as an outlet for the water in the cell and direct it towards or into the drain of a sink.
13. Turn valve F to FORCE DRAIN.
14. Turn valve F to OFF when all of the water has drained from the cell.
15. Remove the specimen.
16. Dry the areas that are wet within the cell and area of the panel and properly store all equipment such.

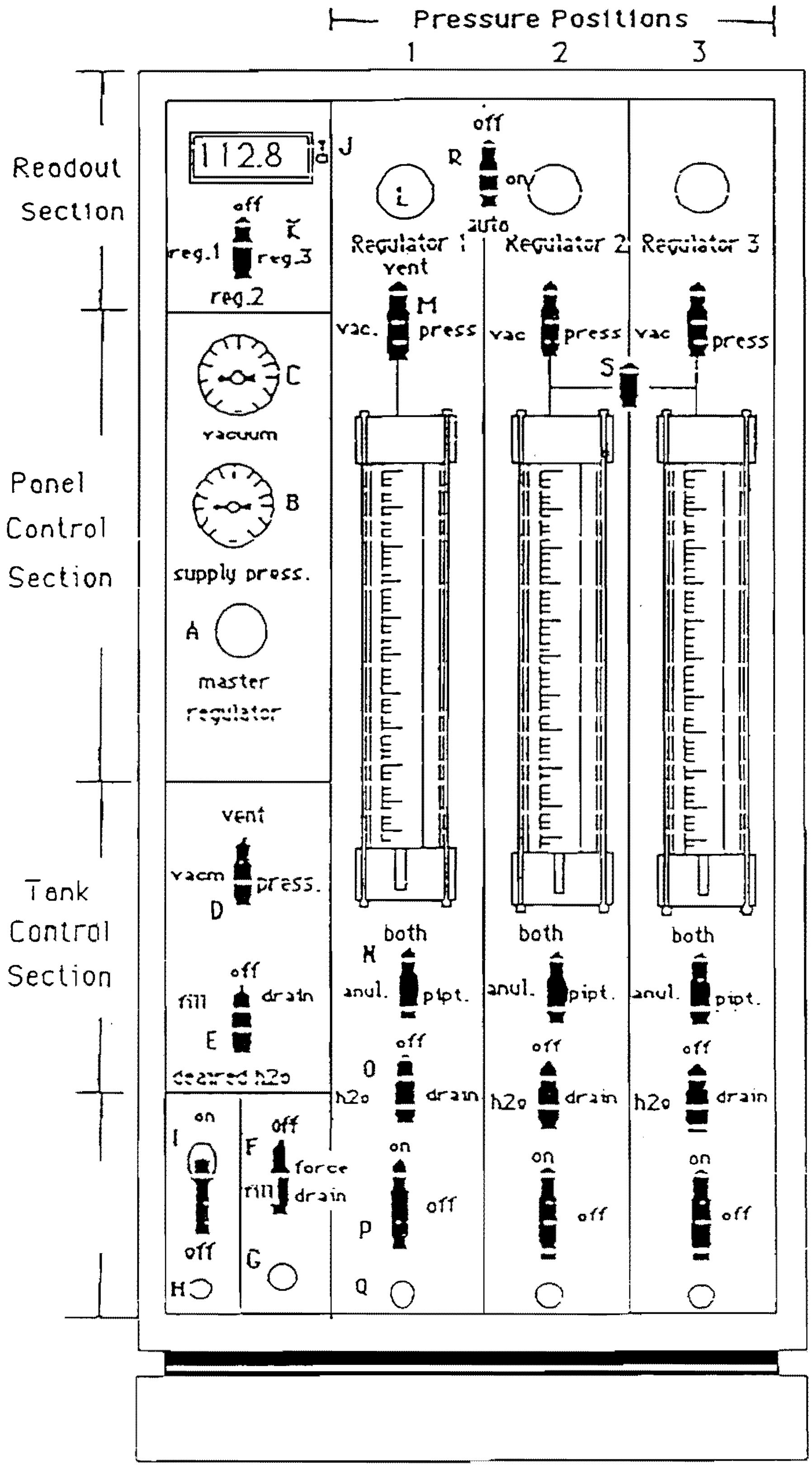

Figure 22. Schematic Diagram of the Pressure Control Panel.

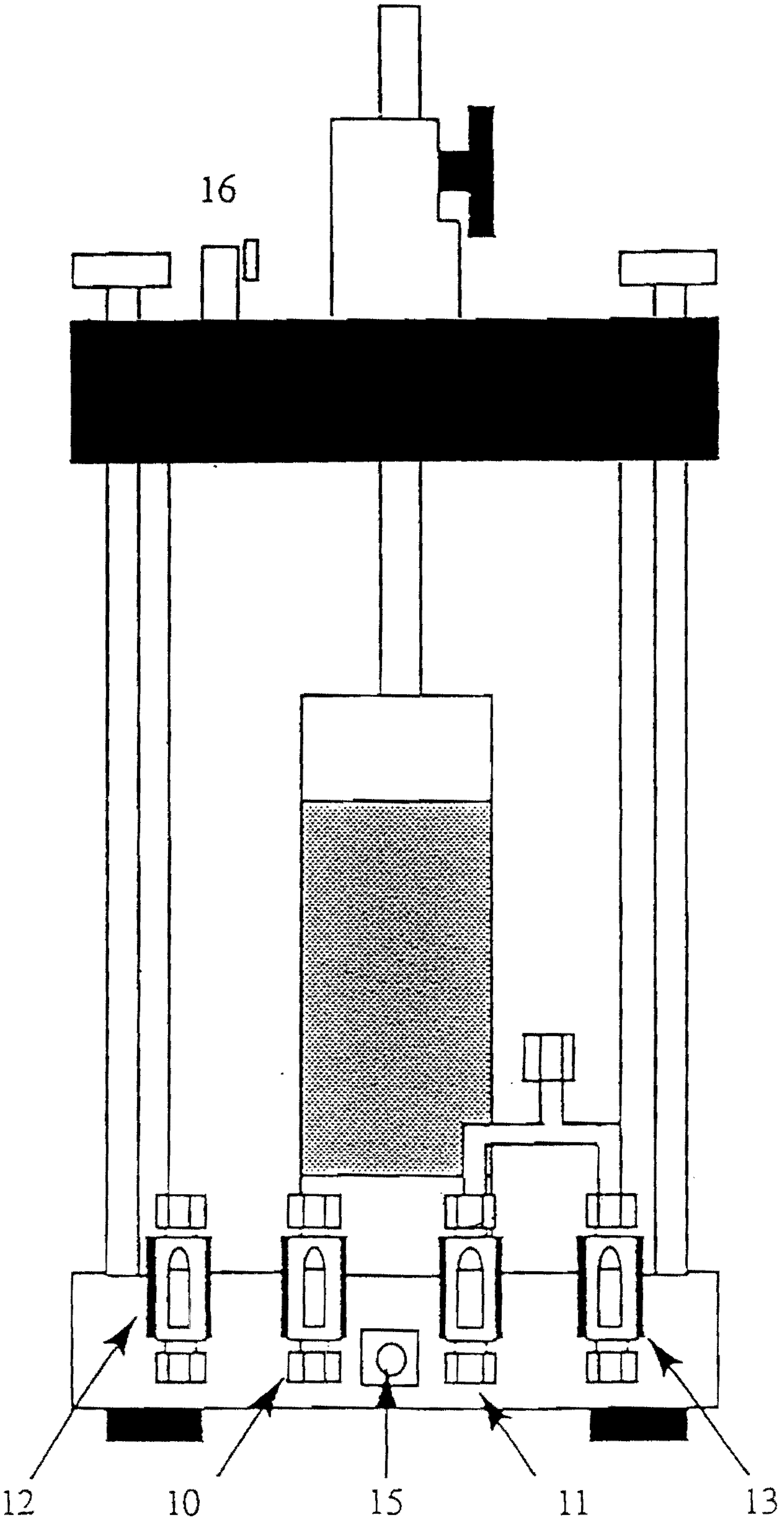

Figure 23. Schematic Diagram of the Permeability Cell.

APPENDIX G

QUESTIONNAIRE USED TO SURVEY TxDOT DISTRICTS

QUESTIONNAIRE FOR RESEARCH STUDY 1238

Permeability of CMHB Mixtures and Its Effect on Performance

The objective of Research Study 1238 is to provide the Department with an evaluation of coarse matrix-high binder asphalt mixtures. Properties of CMHB mixes will be measured and compared with dense-graded mixes. Properties to be measured include: permeability, water susceptibility, resistance to short-term and long-term aging, and creep properties. Limestone, sandstone, and siliceous aggregates will be studied. Please answer the following questions to the best of your knowledge by July 31, 1995. If you have any questions or comments about the questionnaire, please call Joe Button at Texas Transportation Institute (409) 845-9965. You may fax your response to (409) 845-0278 or mail to the following address: Joe Button, Texas Transportation Institute, Texas A&M University, College Station, TX 77843-3135.

I understand from Mr. Maghsoud Tahmoressi that your district constructed at least one CMHB pavement last year. Preferably, this questionnaire should be completed by someone familiar with the design, mixing, placement, and compaction of the CMHB mixture.

1. In what district are you located? ____________ Today's Date: ____________
   Please provide your name, title, and phone number.

2. Please give exact location of CMHB pavement.

   Highway No. -
   County -
   Control Section No. -
   Construction Project No. -
   No. Lanes in each direction -

3. Please provide a copy of the CMHB mixture design.

   How thick was the CMHB layer placed?

   What was the average (approximate) air void content of the compacted CMHB layer?

4. What was the approximate date of construction of the CMHB layer?

5. Briefly describe old pavement substrate.

   Layer 1 (old surface) -
   Layer 2 -
   Layer 3 -
   Layer 4 -

6. Describe condition of old pavement surface (before placement of the CMHB).

   a. Cracking type (longitudinal, transverse, alligator, random)
   b. Cracking severity -
   c. Approximate rut depth -

7. Was an end-to-end Control section (dense-graded mix) placed using similar aggregates and asphalt and with similar substrates?
   If so, please describe. Item 340 or 3063, etc., Type ______

8. How did placement of the CMHB compare with the Control mix or typical dense-graded mixes?

9. How did compaction of the CMHB compare with the Control mix or typical dense-graded mixes?

10. Did the CMHB mix experience any segregation? Any worse than usual with dense-graded mixtures? Was it attributed to the CMHB grading or to the contractor's operation or equipment?

11. Did you experience any construction difficulties that you associated with the CMHB mixture?

12. What type of mixing equipment was used? (Drum plant or batch plant)

13. What type of compaction equipment was used? (Vibratory, pneumatic, and/or steel wheel roller) Was the rolling sequence or pattern different for CMHB than for typical dense-graded mix? Was it successful?

14. What is the level of traffic on this section of roadway?

    ADT (1995 & 2015)
    Truck in ADT, % -
    ATHWLD -
    Tandem axles in ATHWLD -
    Equivalent 18 kip axle loads expected in 20 yr design life -
    Speed limit, mph -

15. Condition survey summary for CMHB pavement - Date: ____________

    Rut depth (in or mm) -
    Cracking (slight, moderate, or severe) -
    Raveling (slight, moderate, or severe) -
    Flushing (slight, moderate, or severe) -
    Patching (slight, moderate, or severe) -