AN ABSTRACT OF THE THESIS OF

Wendy L. Allen for the degree of Doctor of Philosophy in Civil Engineering presented on May 18, 1993.

Title: Evaluation of the Environmental Conditioning System as a Water Sensitivity Test for Asphalt Concrete Mixtures

Redacted for Privacy

Abstract Approved: _________ ____________________
Ronald L. Terrel

The Environmental Conditioning System (ECS) was designed to evaluate the water sensitivity of asphalt concrete mixtures. The ECS subjects asphalt concrete specimens to a series of conditioning cycles including water flow, elevated and/or lowered temperature, and repeated axial loading. The purpose of this research was to: (1) evaluate the ECS test apparatus and procedure, and (2) determine whether the ECS can identify asphalt concrete mixtures that will perform well, or poorly, in the field with regard to water sensitivity.

Twelve primary field test sections were identified. For each section, specimens were prepared in the laboratory using the original mix design (or the mix design identified by extraction), and the original aggregates, asphalts, and admixtures. Specimens were tested using two procedures: the ECS and the Oregon State University (OSU) wheel tracker. Field cores were used to evaluate in-situ mixture performance. Nine additional mixtures that have historically experienced water damage were tested in a limited secondary test program.

Analyses were performed to determine the mixture properties that were significant in the prediction of mixture performance in the ECS. Mixture type was consistently the most significant predictor of ECS modulus ratio (change in mixture stiffness), degree of visual stripping, and binder migration, which were the performance indicators for water sensitivity evaluated in the ECS. Additional analysis indicated the existence of correlations among the ECS response variables. Significant correlations were found between the coefficient of water permeability and the degree of visual stripping; and between specimen deformation and the degree of visual

stripping and binder migration.

Mixture performance was compared between the ECS and the OSU wheel tracker and the field. Results indicate that the ECS test procedure can distinguish the relative performance of mixtures, with regard to water sensitivity, and mixture performance in the ECS correlates well with performance in the OSU wheel tracker. No correlation was found between mixture performance in the ECS and mixture performance in the field for the primary test sections. However, the primary field sections are relatively young, and water damage is expected to manifest itself in the future in those pavements identified as water sensitive by the ECS. The ECS predicted failure in the secondary mixtures which were identified as having had poor performance with regard to water sensitivity.

EVALUATION OF THE ENVIRONMENTAL CONDITIONING SYSTEM AS A WATER SENSITIVITY TEST FOR ASPHALT CONCRETE MIXTURES

by

Wendy L. Allen

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed May 18, 1993
Commencement June 1994

APPROVED:

Redacted for Privacy

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Date thesis is presented May 18, 1993

Typed by Wendy L. Allen and Teresa Culver

ACKNOWLEDGMENT

This research was made possible through a contract with the Strategic Highway Research Program (SHRP), Project A-003A: "Performance Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures." The University of California, Berkeley and Oregon State University were the major contributors to this contract.

The cooperation and efforts of Dr. R. Gary Hicks, Teresa Culver, and Gail Mathieson of Oregon State University; Mickey Hines of Elf Asphalt; the faculty and staff of the Richmond Field Station, University of California, Berkeley; and the staff of the Strategic Highway Research Program are gratefully acknowledged. In addition, the efforts of the transportation authorities from the states of Arizona, California, Colorado, Georgia, Louisiana, Minnesota, Mississippi, Oregon, Washington, and Wisconsin; the province of Alberta; the Asphalt Institute; and the Western Federal Lands Highway Division, Federal Highway Administration, are acknowledged. Without their cooperation this work could not have been completed. The statistical guidance of Charles Antle and Dave Thomas is also gratefully acknowledged.

I would like to extend my special thanks to Dr. Ron Terrel for his guidance and encouragement throughout the project. Special thanks also go to Chris Fagin, Larry Ilg and the others who helped in the specimen preparation process. The instruction and counsel of Abdulla Al-Joaib was invaluable in learning the ECS procedure, and the editorial comments of Paul Ryus contributed to the quality of the thesis. The efforts of the Graduate Committee; Dr. Jonathan Istok, Dr. W. Lee Schroeder, Dr. John Selker, and Dr. Benno Warkentin, are also gratefully acknowledged. Finally, I would like to thank my family for their support, and Alan Wieder for his patience.

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1 INTRODUCTION

Asphalt concrete paving mixtures are prone to several types of degradation that result from their exposure to the environment on the road surface. Degradation resulting from the effects of water and the combined effects of water and traffic are typically referred to as "water damage." Water damage manifests itself in a pavement structure through raveling, potholes, rutting, flushing, and loss of asphalt concrete layer stiffness. Asphalt concrete mixtures that exhibit water damage are typically referred to as "water sensitive."

1.1 Background

Water sensitivity involves three mechanisms within the asphalt concrete mixture: (1) a loss of adhesive strength between the asphalt binder and the aggregate, termed asphalt stripping, (2) a loss of cohesive strength and stiffness within the asphalt binder itself, and (3) aggregate degradation. Hicks (1991) and Terrel and Shute (1989) provide full bibliographies on the water sensitivity of asphalt concrete mixtures.

1.1.1 Theories of Adhesion

Loss of adhesion between the asphalt binder and the aggregate typically occurs when water gets between the asphalt film and the aggregate, breaking the bond between the two. The aggregate is left "stripped" of its asphalt film coating. Failure due to asphalt stripping occurs in two stages: the first is the stripping failure itself; the second is the failure of the pavement under the action of traffic. Excessive stripping is manifested by severe pavement deformation or rutting, potholes, or cracking and surface raveling (Hicks, 1991).

Adhesion of the asphalt binder to aggregate is related to the physical and chemical properties of the two materials and may be reduced by the presence of water. Several factors that affect adhesion between asphalt binder and aggregate are identified by Thelen (1958). These factors include: (a) interfacial tension between the asphalt cement and aggregate, (b) chemical composition of the asphalt cement and aggregate, (c) asphalt viscosity, (d) surface texture of the aggregate, (e) aggregate porosity, (f) aggregate cleanliness, and (g) aggregate moisture content and temperature at the time of mixing with the asphalt binder. Further discussion of adhesion between asphalt binder and aggregate is offered by Hicks (1991).

1.1.2 Theories of Cohesion

Cohesion within the an asphalt concrete mixture's binder matrix is influenced by factors such as the asphalt binder viscosity. The binder cohesion may be affected by water intrusion into the asphalt binder matrix, and saturation and perhaps expansion of the void system of the asphalt concrete mixture (Al-Swailmi, 1992). Tunnicliff and Root (1984) have documented asphalt concrete mixtures that increase in volume, or swell, due to water intrusion. This may cause elongation and weakening of the asphalt films that bind the aggregate matrix.

1.1.3 Aggregate Degradation

Aggregate degradation is a loss of integrity of the aggregate due to the effects of chemical and mechanical weathering, analogous to geological weathering. Water and temperature cycling are key components of weathering or aggregate degradation.

1.1.4 Laboratory Determination of Water Sensitivity

Several standard tests (Terrel and Shute, 1989 and Hicks, 1991) are currently used by transportation agencies to determine if a proposed asphalt concrete pavement mixture is water sensitive, and thus prevent placement of a mixture that will experience premature failure due to water damage. These tests are listed in Table 1.1. However, some dissatisfaction with the current standard tests has been expressed by several agencies.

Hicks (1991) surveyed 37 state and provincial transportation agencies about their methods for identifying water related asphalt concrete mixture problems. Thirty-three agencies use tests to evaluate water sensitivity of asphalt concrete mixtures. Arkansas (Hicks, 1991) expressed the opinion that an ideal test procedure should include saturated specimens subjected to confining pressures, heat, and pulse loading. Illinois (1991) indicated that better correlation is needed between laboratory and field performance. The Colorado Department of Transportation has experienced problems with pavements that pass the AASHTO T 283 test procedure in the laboratory, and yet experience water damage when placed in the field (Aschenbrener, 1993). Paul (1993) reports that the repeatability of the AASHTO T 283 test is variable. Several other agencies also expressed concern about the reproducibility of test results (Hicks, 1991). In addition, the AASHTO T 283 procedure does not address open-graded mixtures, which are frequently used in wet climates to provide a porous friction course for the pavement surface. The Environmental Condition System (ECS) was developed to improve upon existing tests for evaluating the water sensitivity of asphalt concrete mixtures and to address the concerns with current test methods.

The ECS was developed at Oregon State University (OSU) by Terrel and Al-Swailmi (1993) to evaluate the water sensitivity of asphalt concrete mixtures, and to provide an improved method for mixture acceptance with regard to water sensitivity during the mix design process. The ECS subjects asphalt mixture specimens to a series of conditioning cycles, including water flow, elevated and/or lowered temperature, and repeated axial loading. The equipment was developed as part of the Strategic Highway Research Program (SHRP) study on the behavior of asphalt concrete mixtures (Terrel and Al-Swailmi, 1993).

The original SHRP program for evaluation of the water sensitivity of asphalt concrete mixtures included a laboratory testing phase for the development and evaluation of procedures and criteria designed to predict the performance of asphalt and aggregate mixtures subjected to water conditioning. A second phase was designed

Table 1.1. Standard tests for water sensitivity of asphalt concrete mixtures

Test Title	Test Designation
Indirect Tensile Test and/or Modulus Test with Lottman Conditioning	NCHRP 246
Indirect Tensile Test with Tunnicliff and Root Conditioning	NCHRP 274
Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage (Indirect Tensile Test with Modified Lottman Conditioning)	AASHTO T 283
Effect of Water on Bituminous Coated Aggregate--Quick Field Test (Boiling Water Tests)	ASTM D 3625
Effect of Water on Cohesion of Compacted Bituminous Mixtures (Immersion-Compression Tests)	AASHTO T 165, ASTM D 1075
Freeze-Thaw Pedestal Test	
Coating and Stripping of Bitumen-Aggregate Mixtures (Static Immersion Test)	AASHTO T 182, ASTM D 1664
Resistance of Compacted Bituminous Mixtures to Moisture Induced Damage (Conditioning with Stability Test)	AASHTO T 245

(after Terrel and Shute, 1989)

to verify that the techniques developed in the laboratory phase correlated with the performance of mixtures subjected to field conditions. An additional component was added to the experiment when the SHRP staff became concerned about the availability of original asphalt and aggregate materials and data from in-service field sections for the verification work. The extended program completed by Oregon State University for the SHRP investigation of the water sensitivity of asphalt concrete mixtures therefore was redesigned to include three phases: (1) laboratory development of procedures and criteria, (2) validation of the laboratory testing with accelerated laboratory "torture" tests (ALTs), and (3) field verification of both the laboratory testing program and the accelerated laboratory test. The work from phase one of the SHRP project is reported by Terrel and Al-Swailmi (1993); the work from phase two is reported by Scholz et al. (1993). This research includes the findings from the third phase, field verification program and additional information on the evaluation of the ECS test apparatus and procedure.

1.2 Objectives

The main goal of this reserach was to evaluate the predictive ability of the ECS apparatus with regard to water sensitivity of asphalt concrete mixtures using actual asphalt concrete mixtures from field test sections. To accomplish this goal the following objectives were formed:

1. Determine if a statistically significant correlation exists between the performance of an asphalt concrete mixture in the ECS test and the performance of the mixture in full scale field test sections, as described by the change in the mixture stiffness (ECS modulus), degree of visual stripping, and degree of binder migration.
2. Identify statistically significant correlations between the performance of mixtures in the ECS and the OSU wheel tracker, as a surrogate test for field performance.
3. Indicate which mixture parameters (e.g., air void level, initial ECS modulus, initial coefficient of air permeability, and initial coefficient of

water permeability) predict mixture performance in the ECS as described by the loss of mixture stiffness, degree of visual stripping, and degree of binder migration.

4. Identify the statistically significant correlations which exist between changes in mixture and specimen properties in the ECS test procedure (i.e., specimen deformation versus change in the coefficient of water permeability).
5. Evaluate the ECS flow apparatus for compliance with Darcy's law for both air and water flow to determine if the system is a valid constant-head permeameter.
6. Develop preliminary criteria for the use of ECS data in a mix design development program.
7. Recommend improvements to the ECS for implementation in future generations of the ECS apparatus.

This effort was the first opportunity for the ECS to test mixtures designed by the local authorities in whose jurisdictions the field sections were placed. Other asphalt-aggregate mixtures previously tested in the ECS development program were not from actual paving projects and were prepared according to mix designs developed for the SHRP program by the University of California, Berkeley.

2 EXPERIMENTAL PROGRAM

This chapter discusses the test program that was used to validate the ECS test equipment with materials and data from in-service field sections. Also included in this chapter are discussions of the ECS loading and flow systems. In particular, the calibration procedure used to investigate the ECS flow system, and the method for obtaining a preliminary precision statement for the values of coefficients of permeability for air and water calculated using the ECS data are discussed.

In 1990, OSU began acquiring materials from various agencies for use in the field validation of the ECS test procedure. As field sites with available materials were identified, and as early testing with the ECS progressed, a program of materials collection, specimen preparation and testing emerged. As data were collected, distress surveys of the in-place field sections indicated that due to their relatively recent placement, the sections were not showing any signs of water related distress. Modulus testing of field cores also indicated that the field mixtures were not displaying any loss of stiffness due to water damage. Nine additional mixtures were proposed for testing in the ECS that were combinations of asphalts and aggregates that had historically experienced severe water damage, or that were actual field cores from damaged pavements.

The completed testing program, therefore, included two phases: the primary testing program, which included an evaluation of twelve asphalt concrete mixtures and their performance in the ECS, the OSU wheel tracker and the field; and the secondary or extended program, which included evaluation of nine mixtures in the ECS that historically have had poor water sensitivity performance. The extended program mixtures did not have corresponding OSU wheel tracker specimens or field cores. In addition, as data from previous ECS testing was analyzed (Terrel and Al-Swailmi, 1993 and Scholz et al., 1993), various questions concerning the ECS test equipment and procedures were raised. In particular, the ECS modulus and proposed use of the ECS flow system as a permeameter were questioned.

2.1 Overview of Testing Program

2.1.1 Primary Test Program

Figure 2.1 presents an overview of the primary testing program. Specimens were subjected to one of three distinct treatments: the ECS, the OSU wheel tracker, or placement in the field. Each of the treatments consisted of a conditioning procedure unique to that system, and one or more testing techniques to evaluate the mixture performance.

The primary test program involved specimens manufactured by three different methods: laboratory kneading compactor, laboratory roller compactor, and field construction. Using the laboratory kneading compactor, specimens were manufactured for evaluation using the ECS procedure. Beam specimens were cut from large roller-compacted slabs for use in the OSU wheel tracker, and specimens were cored for use in the ECS. Field specimens were cored from field test sections for laboratory evaluation.

Seven performance modes were monitored: (1) triaxial resilient modulus as measured by the ECS, (2) change in the specimen's hydraulic conductivity or coefficient of water permeability, as measured in the ECS, (3) rut depth produced by the OSU wheel tracking device, (4) visual stripping evaluation after each test procedure, (5) binder migration evaluation after each test procedure, (6) MTS triaxial modulus, and (8) MTS diametral modulus. Table 2.1 summarizes this information. Test procedures are described more fully in Section 2.4.

Several performance criteria were required to allow correlation between the results from each specimen type and testing process. ECS-conditioned specimens were the only specimens to undergo full ECS modulus testing, which involves encasing the specimen in a latex membrane and testing within the ECS apparatus itself.

Field core specimens were tested only in the MTS apparatus. Due to the variable thickness of constructed layers, some of these specimens were tested in only

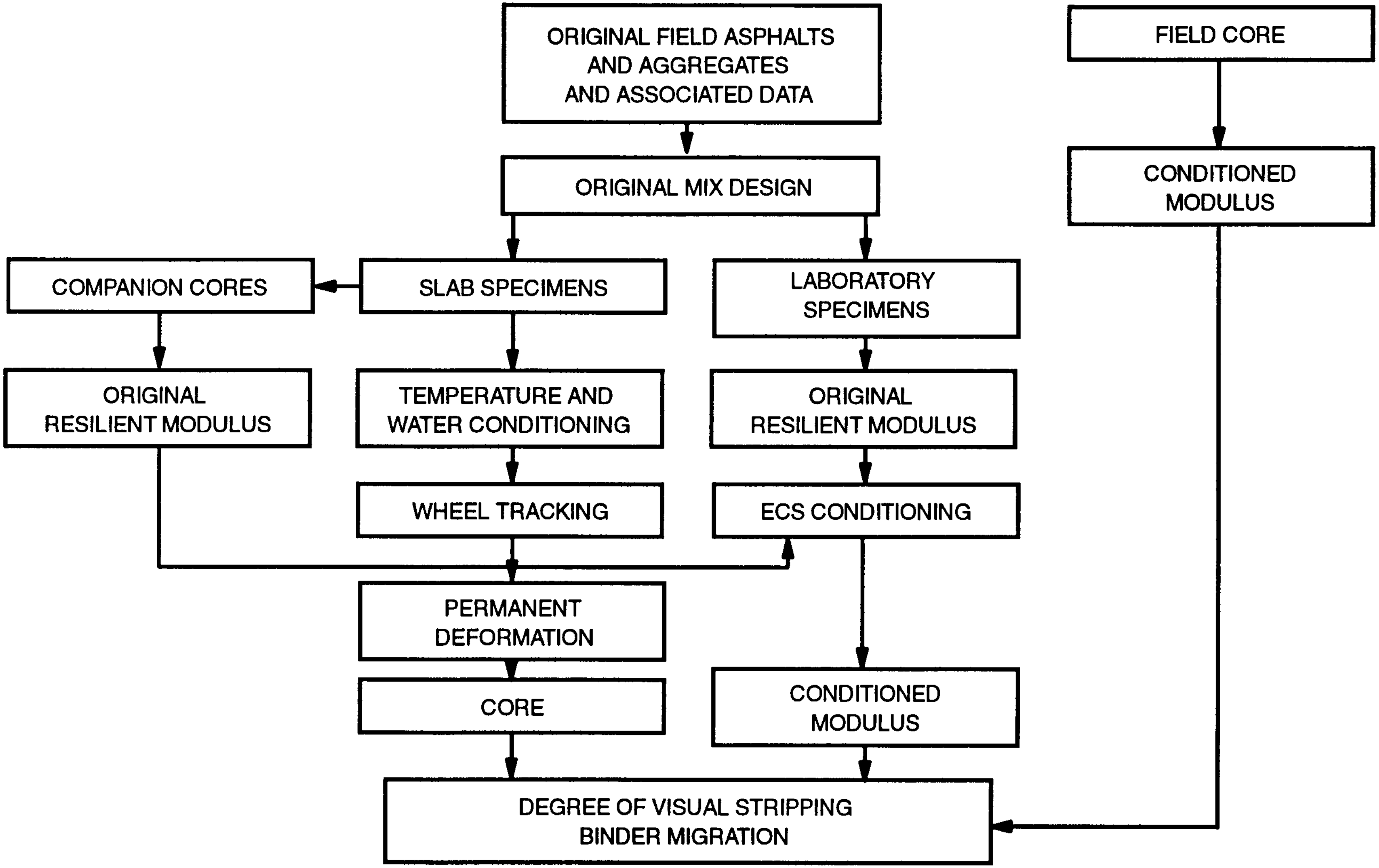


Figure 2.1. Field validation of water sensitivity, primary test program

Table 2.1. Specimen, test procedure, and performance mode identification

Specimen Preparation	Test Procedure	Performance Mode
Laboratory Kneading Compactor	ECS	ECS modulus Visual evaluation of stripping Visual evaluation of binder migration
Roller Compactor	ECS	ECS modulus Visual evaluation of stripping Visual evaluation of binder migration
Roller Compactor	OSU wheel tracker	Rut depth Visual evaluation of stripping Visual evaluation of binder migration
Field	Field exposure	MTS modulus Visual evaluation of stripping Visual evaluation of binder migration

the diametral mode (specimens significantly under 4.0 in. [102 mm] in height). If the specimen was nominally 4.0 in. (102 mm) high, it was tested in both the diametral and triaxial configurations.

In order to develop stiffness ratios for field mixture performance evaluation with field cores, diametral and triaxial modulus data from laboratory roller and kneading-compacted specimens with similar air void values were used. The modulus values for the laboratory specimens were related to air void levels using a linear regression. Then, using the air void level for the field core, an unconditioned modulus for the field core was estimated from the laboratory data. All specimens were evaluated for the degree of visual stripping and binder migration, regardless of specimen type or testing procedure. These procedures are described later in this chapter.

In order to bracket the air voids of specimens from the field and determine the effect of air voids on the performance of mixtures in the ECS, specimens were compacted so that the widest possible range of air voids was obtained. This was accomplished with the laboratory kneading compactor. Four compaction levels were attempted: low, medium, high, and dense. The method for producing these levels is discussed in Section 2.3.3. Roller-compacted specimens were targeted at 8.0 percent air voids to match the previous work with roller-compacted specimens conducted at OSU. However, due to limited amounts of available material, and the natural variability in the specimens produced due to the mixing and compaction procedures used, some of the beam specimens do not meet the 8.0 percent voids criterion.

2.1.2 Secondary Test Program

The nine additional mixtures tested at the end of the program received only ECS testing. Four of the mixtures were known to have failed in the field. Another four mixtures were made with an asphalt-aggregate combination that was known to be susceptible to water damage, with variation in air voids and the addition of an anti-strip agent in one mixture, and lime in another. The last mixture was designated as

The Asphalt Institute "non stripping" mixture and should provide good performance with regard to water sensitivity.

2.2 Selection of Field Sites

2.2.1 Primary Mixtures

Twelve field sites were selected for evaluation with the ECS test procedure. Sites were selected on the basis of availability of: a minimum of 300 lbs (136 kg) of usable blended aggregate, 3 gallons (11.4 l) of asphalt cement, required admixtures, mix design information, and cooperation from the presiding authority for field coring. In addition, at least two sites were selected from each of the four environmental zones that have been designated by SHRP. The sites were chosen to be as old as possible to allow several seasons of natural environmental conditioning to the pavements.

Forty agencies, including 23 state materials laboratories, The Asphalt Institute and Chicago Testing Labs, the University of Texas, the University of Nevada at Reno, and others were contacted either by phone or questionnaire, to request information on the availability of retained materials and their willingness to cooperate in this testing program. The response to these questionnaires, and related telephone conversations, illustrated the lack of retained materials available from most projects.

The need for retained asphalt and aggregate restricted the field sections that were available. The SHRP project provided several Special Pavement Studies (SPS) and General Pavement Studies (GPS) sites that had materials stored in the Materials Reference Library (MRL) in Austin, Texas. The MRL also provided material from three of the four National Cooperative Highway Research Program's (NCHRP's) Asphalt-Aggregate Mixture Analysis Study (AAMAS) test sections constructed during the second phase of that project (Von Quintus et al., 1991). The use of the AAMAS sites required the cooperation of the host state as these pavements are not actively being researched by others at this time and are under the authority of the local jurisdiction. The remaining projects were provided by the Oregon Department of

Transportation (ODOT) and the Western Federal Lands Highway Division (WFLHD) of the Federal Highway Administration (FHWA).

Table 2.2 lists the names of the twelve sites selected, the three-letter site designator used in this document, the governing agency for the site, and any local mixture designation used. Table 2.3 lists the route number, construction date, and environmental zone for each site. Figure 2.2 indicates the approximate locations of the selected sites.

Sites with retained materials constructed prior to 1989 were unavailable. It is not common practice to retain materials from a paving job unless an existing research program is in place, in which case the materials are typically used for the purposes of that project.

Table 2.4 summarizes the asphalt type and source, aggregate type and source, and admixtures for each site. Table 2.5 indicates how the pavement was placed (i.e., as an overlay), the layer thickness, the number of lifts and the lift thickness. More information on the individual mix designs is given in Section 2.3.

In order to qualify the mixture performance in the field, distress information was requested from SHRP (for the SPS sites), and from the local state agency for the other pavement sections. In the case of WA1, Ron Terrel (1992) performed manual distress surveys. For the SHRP test sections, the manual distress surveys were performed in accordance to the SHRP protocol. Other manual distress surveys were performed according to the procedures of the agency conducting the test. A standard survey procedure was not available due to geographical and training considerations. The SHRP protocol requires the person performing the survey to be trained in the procedure.

Rutting and other signs of asphalt stripping were the distress types that were evaluated in the distress surveys of the test sections.

2.2.2 Secondary Mixtures

Table 2.6 gives the site designations, governing agency, admixtures, and compaction method for the nine additional mixtures tested in the secondary ECS

Table 2.2. Field site identification

Site	Governing Agency	Mixture Designation
Alberta, SPS-5 (AB5)	SHRP	
Arizona, SPS-5 (AZ5)	SHRP	Arizona DOT 3/4-in. modified
California, AAMAS Batch (CAB)	CALTRANS	CALTRANS Type "A" mix
California, AAMAS Drum (CAD)	CALTRANS	CALTRANS Type "A" mix
California, GPS-6b (CAG)	SHRP	
Georgia, AAMAS (GAA)	Georgia DOT	Georgia DOT "B" mix
Minnesota, SPS-5 (MN5)	SHRP	
Mississippi, SPS-5 (MS5)	SHRP	Mississippi DOT Surface SC-1 (Type 8)
Rainier, Oregon (OR1)	Oregon DOT	Oregon DOT "B" mix
Bend-Redmond, Oregon (OR2)	Oregon DOT	Oregon DOT open-graded "F" mix
Mount Baker, Washington (WA1)	WFLHD	Polymer modified
Wisconsin, AAMAS (WIA)	Wisconsin DOT	Recycled

Table 2.3. Field site locations

Site	Route Number	Construction Date	Environmental Zone
AB5	Highway 16 from Edson to E of Jct HW 32, Alberta, Canada, MP: 38.54, westbound	1990	Dry-Freeze
AZ5	Interstate 8 near Casa Grande, AZ, MP: 159.01, eastbound	1990	Dry-No Freeze
CAB	State Route 395 north of Doyle, CA	1989	Dry-Freeze
CAD	State Route 395 north of Doyle, CA	1989	Dry-Freeze
CAG	Interstate 8 west of El Centro, CA, MP: 25.50, eastbound	1991	Dry-No Freeze
GAA	U.S. 76 approximately 3 miles west of Hiawassee, GA	1989	Wet-No Freeze
MN5	U.S. 2, two miles east of Shelvin, MN, MP: 98, eastbound	1990	Wet-Freeze
MS5	Route 55 in Yazoo County, MS	1990	Wet-No Freeze
OR1	Highway 30 southeast of Rainier, OR	1990	Wet-No Freeze
OR2	U.S. 97 east of Redmond, OR	1990	Dry-Freeze
WA1	Highway 542 at Mt. Baker winter recreation area, uphill lane, ≈ 1/2 mile from chair lift	1990	Wet-Freeze
WIA	U.S. 51 from Jct Highway 60 north to Poynette city limits	1989	Wet-Freeze

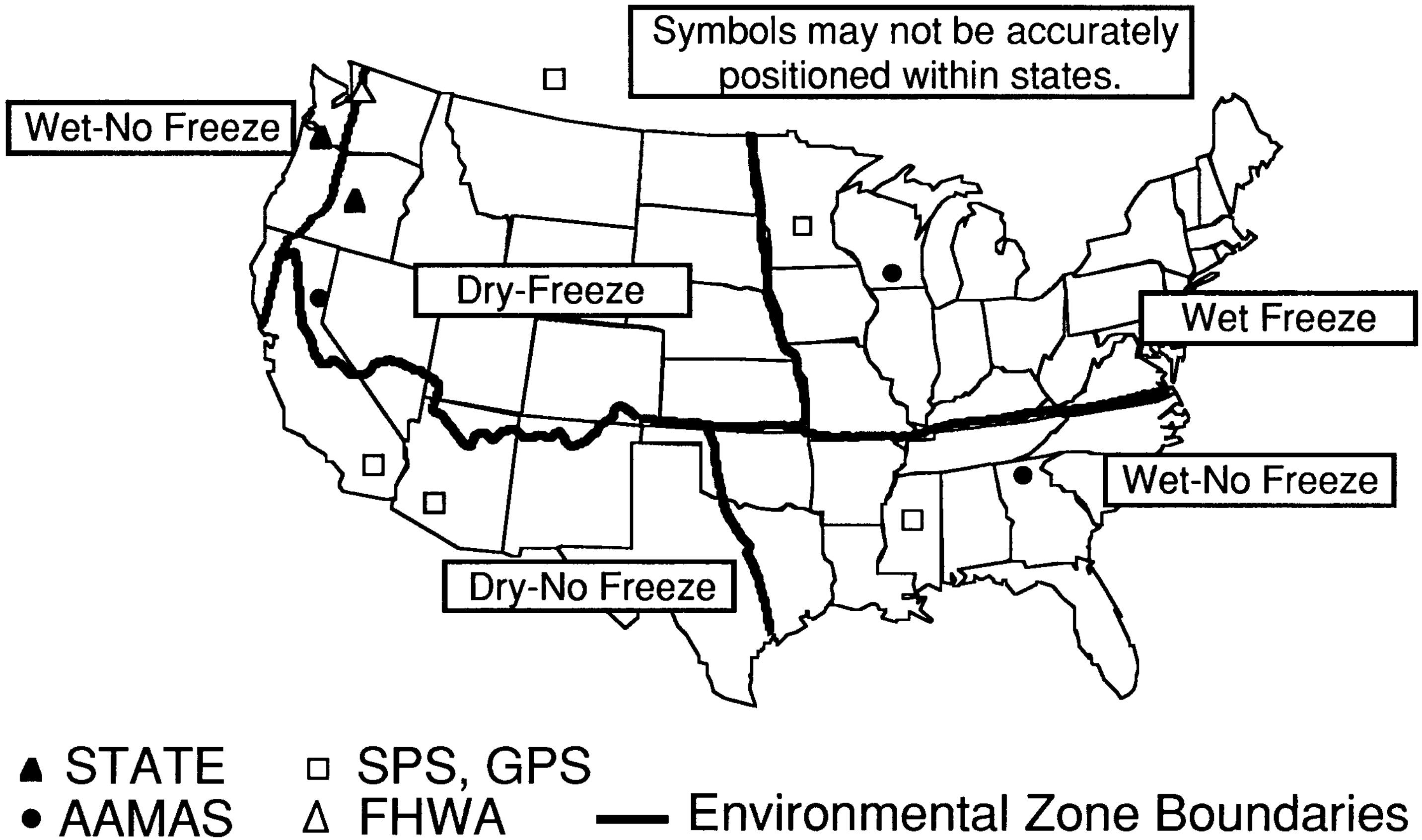


Figure 2.2. Primary field sites

Table 2.4. Field site material identification

Site	Asphalt Type	Asphalt Source	Aggregate Type	Admixtures
AB5	150-200A	Esso Edmonton, AB	NA[1]	None
AZ5	AC-40	Chevron USA Richmond, CA	NA	Type II Portland Cement
CAB	AR-4000	Shell Oil Martinez, CA	Crushed gravel	None
CAD	AR-4000	Shell Oil Martinez, CA	NA	None
CAG		NA	NA	None
GAA	AC-30	Amoco Oil Co. Trumull-Fulco Atlanta, GA	Crushed granite with high mica content	Hydrated Lime
MN5	85-100	NA	NA	None
MS5	AC-30	Southland	Limestone	Anti-strip
OR1	AC-15	McCall Asphalt Portland, OR	NA	None
OR2	PAC-20	Albina Asphalt Portland, OR	NA	Polymer, Anti-strip, Hydrated Lime, Flyash
WA1	PMA-60	Chevron USA Richmond Beach, WA	NA	Polymer
WIA	AC-5	Koch Asphalt Co.	New: Crushed gravel	None

[1] Information not available

Table 2.5. Field site construction information

Site	Construction Type	Normal Layer Thickness (in.)	Number of Lifts	Nominal Lift Thickness (in.)	Comments
AB5	Overlay on AC	5	3	2	
AZ5	Overlay on AC	5	3	2	
CAB	Overlay on AC	4.5[1]	3[1]	1.5[1]	
CAD	Overlay on AC	4.4[1]	3[1]	1.5[1]	
CAG	Overlay on AC	3.5	2	1.75	
GAA	Overlay on AC	4[1]	1[1]	4[1]	
MN5	Overlay on AC	5	3	1.75	
MS5	Overlay on AC	5	3	2 in. surface 2.5 in. binder	Density out of specification
OR1	Reconstruction	2	1	2	Gradation out of specification
OR2	Reconstruction	2	1	2	
WA1	Reconstruction	4	1	4	
WIA	Recycled overlay on AC	4	1	4	

[1] From visual inspection of field cores.

Table 2.6. Additional mixtures, secondary test program

Site	Governing Agency	Specimen Compaction Method	Admixtures
Arizona Slurry Seal (AZF)	Arizona DOT	Field core	Unknown
Colorado A (COA)	The Asphalt Institute (TAI)	Gyratory compaction	0.5% anti-strip
Colorado B (COB)	TAI	Gyratory compaction	None
Colorado C (COC)	TAI	Gyratory compaction	None
Colorado E (COE)	TAI	Gyratory compaction	1% lime
Georgia Field (GAF)	SHRP	Gyratory compaction	None
Louisiana Field (LAF)	Louisiana Department of Transportation	Field core	0.5% anti-strip
The Asphalt Institute Non-Stripping Mixture (TAI)	TAI	Gyratory compaction	None
Wyoming (WYO)	WFLHD	Kneading compaction	None

testing program. These mixture specimens were prepared by the governing agencies and shipped to OSU for ECS testing. Several of the mixtures were prepared using the gyratory compactor (see Table 2.6). The specimens from Louisiana (LAF) and Arizona (AZF) were field cores.

2.3 Specimen Preparation

The primary testing program involved specimens manufactured by three methods and tested by one or more of four test procedures. Specimens were fabricated using one of the following: (1) the laboratory kneading compactor, (2) the laboratory roller compactor, or (3) in-place field compaction at the test section site. Laboratory-compacted specimens were manufactured at OSU; field cores were obtained from cooperating agencies as discussed previously. Specimen identification codes are defined in Figure 2.3. All specimens from the secondary test program were prepared by others using the laboratory kneading or gyratory compactor, or field compaction.

2.3.1 Laboratory Aggregate Preparation

The specimens manufactured at OSU were made from mix designs obtained by SHRP from the agency responsible for the paving of the site. Original aggregate, asphalt, and admixtures were obtained and processed prior to mixing and compacting the specimens. Original aggregate from each site typically arrived in 5-gallon (19-l) drums or 50-lb (23-kg) bags. Though several were nominally mixed to the correct gradation, the aggregates were re-sieved and recombined as described below according to protocols for aggregate processing developed by SHRP in order to eliminate any potential for segregation during shipping and handling.

The aggregates were sieved for 5 minutes in batches of approximately 10 lbs (4.5 kg) and separated on the 1-1/2-, 1-, 3/4-, 1/2-, and 3/8-in. (38.1-, 25.4-, 19.05-, 12.7-, and 9.525-mm) screens and on the US sieves No. 4 and 30. Each fraction was

Example Code: AB5R806

AB5 = 3 place site designator (i.e., AB5 = Alberta SPS-5)
R = compaction method
K = kneading compactor
R = rolling wheel compactor
F = field compacted
8 = compaction effort
L = low, kneading compactor
M = medium, kneading compactor
H = high, kneading compactor
D = dense, kneading compactor
8 = 8%, roller compactor
F = field compacted
06 = specimen number in group

Note: Specimens prepared from the nine additional mixtures tested were designated by their three place site designation and a number (i.e., LAF01)

Figure 2.3. Specimen identification code

then treated as a separate source bin for recombination. The aggregate passing the No. 4 and retained on the No. 30, and the aggregate passing the No. 30 were wet sieved to obtain an accurate grain size distribution of those portions.

The aggregate was recombined using a least sum of error squared method to produce gradations which match either the job mix formula (JMF) for a given project, or gradations from extractions (Extr), if available. Table 2.7 summarizes the gradations used for the twelve test sections. Plots of the gradations are presented in Appendix A. The aggregates were batched into quantities for preparation of 4.0 in. by 4.0 in. (102 mm by 102 mm) kneading compactor specimens, approximately 4.23 lb (1920 grams), or 24.0 in. by 24.0 in. by 4.0 in. (610 mm by 610 mm by 102 mm) roller- compacted slabs, approximately 195 lbs (88.5 kg).

Dry admixtures required were weighed and added to the aggregate dry, prior to the heating required for mixing. If hydrated lime was the admixture, the combined aggregate and lime were stirred until an uniform color was noted and then lightly sprayed with tap water while stirring continued. Water was added and stirring continued until the aggregate became damp. Excess wetting was avoided. Portland cement and flyash were stirred into the aggregate without the addition of water. Admixtures used are summarized in Table 2.8.

2.3.2 Laboratory Asphalt Preparation

Asphalt materials obtained from the MRL and other sources typically arrived in 1- or 5-gallon (4- or 19-l) pails. For ease of use, each large pail was broken down into 1-quart (0.95-l) containers following the SHRP protocols for dividing asphalt. Four penetration tins of asphalt were also obtained at this time for viscosity test samples. These samples were sent to the ODOT bituminous laboratory in Salem, Oregon for standard viscosity testing. Mixing and compaction temperatures were based on these data. The mixing temperature corresponds to the temperature at which the asphalt being used has a viscosity of 170 ± 20 centiStokes (0.26 in^2/s). The compaction temperature corresponds to the temperature at which the asphalt being used has a viscosity of 665 ± 80 centiStokes (1.03 in^2/s). Table 2.9 presents the

Table 2.7. Aggregate gradations, primary mixtures

Sieve Size	AB5		AZ5		CAB			CAD			CAG		GAA		
	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF	Extr (Target)	Mix Blend	JMF Blend	Extr (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF	Extr (Target)	Mix Blend
1 "	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 "	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	92.0	89.0	89.0
1/2 "	92.0	92.0	93.0	93.0	97.0	92.0	92.0	97.0	99.0	99.0	96.0	96.0	77.0	70.0	70.0
3/8 "	80.0	82.0	78.0	78.0	85.0	88.0	87.0	85.0	85.0	86.0	83.0	83.0	68.0	62.0	61.9
1/4 "	--	--	63.0	--	--	--	--	--	--	--	--	--	--	--	--
No. 4	60.0	60.8	58.0	56.9	61.0	64.0	61.0	61.0	61.0	61.0	60.0	59.9	54.0	52.0	51.1
No. 8	48.0	46.4	46.0	46.4	47.0	52.0	52.4	47.0	53.0	51.6	49.0	47.6	38.0	39.0	37.1
No. 10	--	--	43.0	--	--	--	--	--	--	--	--	--	--	--	--
No. 16	37.0	36.8	34.0	36.7	35.0	41.0	41.0	35.0	39.0	39.1	38.0	38.2	26.0	26.0	26.8
No. 30	30.0	30.0	32.0	22.2	25.0	31.0	30.8	25.0	27.0	28.0	25.0	26.0	19.0	19.0	19.5
No. 40	--	--	16.0	--	--	--	--	--	--	--	--	--	--	--	--
No. 50	20.0	20.3	11.0	10.4	16.0	20.0	20.2	16.0	18.0	18.3	13.0	14.9	13.0	14.0	15.1
No. 100	12.4	12.2	5.0	3.9	10.0	13.0	13.0	10.0	11.0	11.8	6.0	7.7	9.0	10.0	11.4
No. 200	7.8	7.6	2.9	2.0	8.0	9.0	8.3	8.0	8.0	7.6	3.0	3.2	5.0	7.0	7.5

Table 2.7. Aggregate gradations, primary mixtures (continued)

Sieve Size	MN5		MS5		OR1		OR2		WA1		WIA		
	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF (Target)	Mix Blend	JMF	Extr (Target)	Mix Blend
1 "	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
3/4 "	100.0	100.0	100.0	100.0	97.0	97.0	93.0	93.0	100.0	100.0	100.0	100.0	100.0
5/8 "	96.0	--	--	--	--	--	--	--	--	--	--	--	--
1/2 "	83.0	83.0	100.0	100.0	81.0	81.0	68.0	68.0	97.2	97.0	98.0	97.0	97.0
3/8 "	75.0	74.0	96.0	96.0	--	70.0	43.0	43.0	86.7	87.0	90.0	83.0	83.0
1/4 "	--	--	--	--	58.0	--	26.0	--	--	--	--	--	--
No. 4	64.0	63.0	65.0	64.7	--	51.9	--	22.9	54.4	54.0	69.0	58.0	58.4
No. 8	--	53.7	47.0	48.1	--	36.0	--	13.3	34.3	36.7	53.0	42.0	42.4
No. 10	51.0	--	--	--	32.0	--	12.0	--	--	--	--	--	--
No. 16	--	42.4	--	39.1	--	26.5	--	9.2	--	25.9	--	34.0	32.2
No. 30	--	27.0	25.9	25.4	--	18.7	--	7.1	18.5	17.7	23.0	25.0	24.6
No. 40	19.0	--	--	--	13.0	--	6.0	--	15.1	--	--	--	--
No. 50	--	13.8	10.9	8.8	--	13.3	--	5.5	--	12.6	--	17.0	17.4
No. 100	--	8.5	--	4.9	--	9.7	--	4.4	--	9.3	--	11.5	10.7
No. 200	5.0	5.9	4.6	3.7	4.7	7.0	3.7	3.5	5.4	6.9	9.4	6.0	6.9

Table 2.8. Asphalt and admixture contents, primary mixtures

Site	Asphalt Content[1]	Admixture Content
AB5	5.4 Job Mix Formula (JMF)	
AZ5	4.7 JMF	2% Type II Portland cement[2]
CAB	5.61 Extraction (Extr)	
CAD	4.54 Extr	
CAG	5.21 JMF	
GAA	4.33 Extr	1.0% Lime[2]
MN5	5.60 JMF	
MS5	5.90 JMF	0.3% Anti-strip[3]
OR1	5.20 JMF	
OR2	5.80 JMF	0.62% Lime[2] 1.0% Flyash[2] 0.25% Anti-strip[3]
WA1	5.21 JMF	Polymer[3]
WIA	3.16 New Extr 5.30 total	45% RAP 55% New Aggregate

[1] By total weight of mix
[2] By weight of aggregate
[3] By weight of asphalt

Table 2.9. Asphalt viscosity data and mixing and compaction temperatures

Site	Absolute Viscosity at 60°C (Poises)	Kinematic Viscosity at 135°C (cS)	Mix Temperature (°C)	Compaction Temperature (°C)
AB5	774	229	141	117
AZ5	4140	411	151	128
CAB	2050	286	151	127
CAD	2050	286	151	127
CAG	1180	278	144	120
GAA	3150	528	157	132
MN5	608	223	141	116
MS5	3670	592	160	134
OR1	1620	224	140	118
OR2	2230[1]	581[1]	160	134
WA1	70[2]	656	163	136
WIA	392	187	137	112

[1] Original asphalt, no anti-strip
[2] Penetration at 60°C

viscosity data and mixing and compaction temperatures for each of the original twelve asphalts.

2.3.3 Laboratory Mixing and Compaction

Two mixing processes were used to prepare laboratory specimens for the primary test mixtures. Individual 4.0 in. by 4.0 in. (102 mm by 102 mm) specimens were mixed using protocols developed by SHRP based upon ASTM D 1561-81a (ASTM, 1990) (Appendix B). Large slabs were mixed using protocols developed for the roller-compacted test specimens (Appendix C). Eight individual specimens and one large slab were manufactured for each of the 12 test mixtures, with the exception of the CAB mixture, for which there was not enough original material to construct a test slab.

Individual specimens were prepared by first heating the aggregate and mixing equipment for at least four hours to the mixing temperature. The asphalt was heated for two hours until it reached mixing temperature. The aggregate was poured into a mixing bowl and asphalt was added to the heated aggregate to the nearest 0.1 grams. Asphalt contents for each mixture are reported in Table 2.8. Mixing was completed within four minutes in a Cox mechanical mixer, after which the mixture was spread into metal baking pans for short-term aging. At the time of mixing, an extra specimen was mixed for use as a Rice Maximum Specific gravity sample (ASTM D 2041-90; ASTM, 1990). Details on the specimen preparation method are provided in Appendix B.

The loose mixture was heated in a forced-draft oven set to 275°F (135°C) for four hours in order to promote "short-term aging," a simulation of the aging which occurs in asphalt mixtures prior to compaction. The mixture was stirred every hour during this period to expose the mixture to air to promote uniform aging. At the end of the short-term aging, the loose mixture was removed from the oven and allowed to cool between 12 and 24 hours at room temperature. This departure from the standard SHRP procedure reported in Appendix B was required due to time constraints. Mixtures are typically not allowed to cool before heating for compaction begins.

Two hours prior to compaction, the mixture was returned to an oven set to the compaction temperature. The mixture was then compacted with a Cox kneading compactor in accordance with ASTM D-1561-81a (ASTM, 1990). The kneading compactor was set to one of four levels as shown in Table 2.10. Two specimens were prepared at each compaction level.

After compaction, the specimens were placed in a forced-draft oven set at 140°F (60°C) for 1-1/2 to 2 hours and then subjected to a 12,600-lb (56.1-kN) static "leveling" load. Following leveling, the specimens were allowed to cool 12 to 24 hours at room temperature before being extruded from the compaction molds. The specimens were then labeled, placed in zip-lock plastic bags, and stored at 59°F (15°C) until testing.

Preparation of the large slabs for use in the OSU wheel tracker involved a variation from the above process summarized in Table 2.11, with a detained description in Appendix C. The slab preparation process is shown schematically in Figure 2.4. Again, the aggregate and asphalt were preheated to mixing temperature, the aggregate overnight in a forced-draft oven and the asphalt for two hours prior to mixing. The mixer used was a conventional electrically-powered concrete mixer modified to include infrared propane heaters to preheat the mixer bowl prior to mixing as well as to reduce heat loss during the mixing process. Enough mixture for a single slab, typically 190-210 lb (86-95 kg), was mixed at one time. Once the aggregate and asphalt were both placed in the mixer, mixing continued for four minutes.

After mixing, the loose mixture was placed in a 275°F (135°C) oven for four hours to simulate short term aging. The mixture was stirred every hour. At the completion of the aging process, the mixture was placed in the preheated mold and allowed to cool to compaction temperature before being compacted to a predetermined density using a small steel wheel compactor with tandem rollers (e.g., a sidewalk compactor). The compactor used at OSU weighs approximately 3260 lb (1480 kg). The compacted slab was then allowed to cool overnight (approximately 16 hours) before being removed from the mold.

Two beam specimens, 19.0 in. by 6.5 in. by 4.0 in. (480 mm by 165 mm by 102 mm), for use in the OSU wheel tracker, were sawn from the compacted slab.

Table 2.10. Compaction levels

Compaction Effort	Seating Load	Compaction Pressure
Low	20 blows @ 250 psi (1724 kPa)	150 blows @ 150 psi (1034 kPa)
Medium	20 blows @ 250 psi (1724 kPa)	150 blows @ 300 psi (2067 kPa)
High	20 blows @ 250 psi (1724 kPa)	150 blows @ 500 psi (3445 kPa)
Dense	20 blows @ 250 psi (1724 kPa)	200 blows @ 500 psi (3445 kPa)

Table 2.11. Summary of specimen preparation procedure for roller compacted slabs

Step	Description
1	Calculate the quantity of materials (asphalt and aggregate) needed based on the volume of the mold, the theoretical maximum (Rice) specific gravity of the mixture, and the desired percent air voids. Batch weights ranged between 190 and 210 lbs (86 and 95 kN) at an air void content of 8.0±1.0%.
2	Prepare the asphalt and aggregate for mixing.
3	Heat the materials to the mixing temperature for the asphalt (170 ± 20 cS). Mixing temperatures ranged between 279 and 320°F (137 and 163°C).
4	Mix the asphalt and aggregate for four (4) minutes in a conventional concrete mixer fitted with infrared propane burners and preheated to the mixing temperature for the asphalt.
5	Age the mixture at 275°F (135°C) in a forced-draft oven for four (4) hours, stirring the mixture every hour, to represent the amount of aging which occurs in the mixing plant.
6	Assemble and preheat the compaction mold using heat lamps.
7	Place the mixture in the compaction mold and level it using a rake. Avoid segregation of the mixture.
8	Compact the mixture when it reaches the compaction temperature using a rolling wheel compactor until the desired density is obtained. This is determined by the thickness of the specimen (the only volumetric dimension that can be varied during compaction for a set width and length of slab). Steel channels with depth equal to the thickness of the specimen prevent over-compaction of the mixture. Compaction temperatures (based on 665 ± 80 cS) ranged between 234 and 271°F (112 and 136°C).
9	Allow the compacted mixture to cool to room temperature (≈16 hours).
10	Disassemble the mold and remove the slab. Dry cut (saw) two (2) beams for the OSU wheel tracker. Dry cut four (4) cores for the ECS. Retain material for Rice specific gravity test.

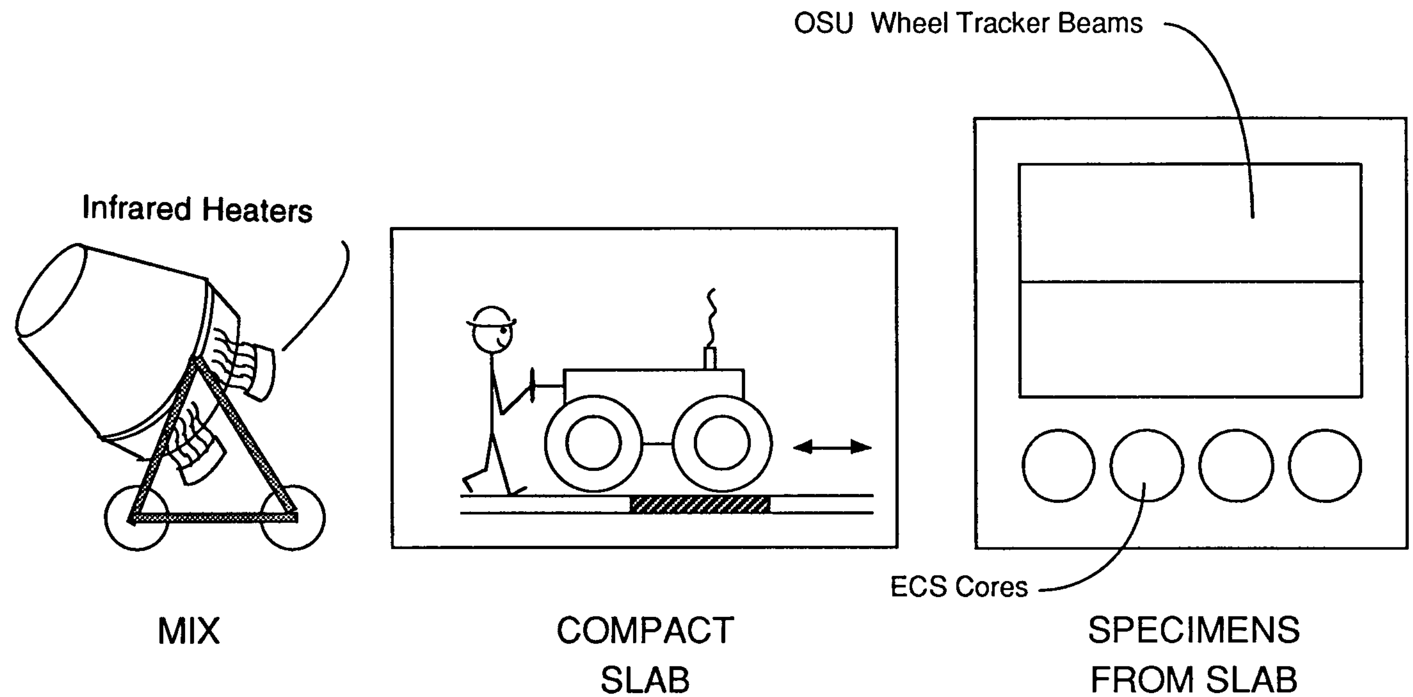


Figure 2.4. Schematic of the specimen preparation process for roller compacted slabs

Four 4.0 in. high by 4.0 in. diameter (102 mm by 102 mm) cores were dry cored using a 4.0-in. (102 mm) inside diameter diamond core bit for testing in the ECS apparatus. A sample of the mixture was retained for the Rice specific gravity test.

2.3.4 Field Cores

The governing agency for each of the original twelve sites was requested to take cores from the site during 1990 and 1991 as the sites were identified. Arizona SPS-5 was the first site to be cored in January 1991. Table 2.12 indicates the approximate coring date of each site. Eight cores were requested from each site, four from the outside wheel path and four from between the wheel paths. Field specimens tested for this effort are identified in Table 2.13.

Several state agencies cored the pavements themselves, while others allowed the regional SHRP contractor to arrange for coring. Four-in. (102-mm) diameter, dry-cored specimens were originally requested. All agencies concerned responded that dry coring was not possible, so all the cores were taken with water-cooled core rigs. The GAA pavement was originally cored in the field with a 6-in. (150-mm) core bit and later recored at OSU with preferably a dry coring machine, or alternatively, a wet coring machine if the sample was too tall for the dry coring setup. The CAB and CAD samples were cored to 3.75 in. (95.2 mm) diameter in the field.

When the cores arrived at OSU they were unwrapped and allowed to dry at room temperature for seven days before proceeding. After drying, cores were visually evaluated to determine the lift containing the test mixture within the core. Data provided by the local agency and the SHRP regional contractors typically allowed for determination of the portion of the core that contained the mixture under investigation. In one case, GAA, the mixture of interest is the base for a 2-in. (51-mm) surface wearing course. The OR1 mixture is also the base lift of the surface course, and has an 2-in. (51-mm) open-graded wearing surface on top of it. In all other cases, the mixture being studied was the topmost layer or layers in the pavement, depending on the number of lifts used to place the mixture. In some cases, if it was difficult to identify the lift containing the appropriate mixture, specimens made from the mixture

Table 2.12. Coring dates for primary field sites

Site	Coring Date
AB5	May 1991
AZ5	January 14, 1991
CAB	August 1991
CAD	August 1991
CAG	October 1991[1], September 1992[2]
GAA	April 1991
MN5	December 12, 1991
MS5	June 1991
OR1	June 4, 1992
OR2	September 16, 1991
WA1	September 1, 1992
WIA	September 19, 1991

[1] Cores 1-16
[2] Cores 17-28

Table 2.13. Specimen identification for field cores

Site	Between Wheel Path	Outside Wheel Path
AB5	AB5F01 AB5F02B AB5F01B AB5F04 AB5F02 AB5F06 AB5F06B	AB5F09 AB5F11 AB5F10 AB5F12
AZ5	AZ5F01 AZ5F07 AZ5F02 AZ5F08 AZ5F04 AZ5F10 AZ5F05 AZ5F11	AZ5F03 AZ5F09 AZ5F06 AZ5F12
CAB	CABF01 CABF04 CABF02 CABF05 CABF03 CABF06	CABF07 CABF12 CABF08 CABF13 CABF09 CABF14 CABF10 CABF15 CABF11 CABF16
CAD	CADF01 CADF04 CADF02 CADF05 CADF03 CADF06	CADF07 CADF12 CADF08 CADF13 CADF09 CADF14 CADF10 CADF15 CADF11 CADF16
CAG	CAGF01 CAGF05 CAGF19 CAGF02 CAGF06 CAGF20 CAGF03 CAGF17 CAGF21 CAFG04 CAGF18 CAGF22	CAGF07 CAGF12 CAGF24 CAGF08 CAGF13 CAGF25 CAGF09 CAGF14 CAGF26 CAGF10 CAGF15 CAGF27 CAGF11 CAGF16 CAGF28 CAGF23
GAA	GAAF01B GAAF04B GAAF02B GAAF05B GAAF03B GAAF06B	GAAF01A GAAF04A GAAF02A GAAF05A GAAF03A GAAF06A
MN5	MN5F18 MN5F21 MN5F22 MN5F23 MN5F24 MN5F26	MN5F01 MN5F03 MN5F06 MN5F07 MN5F08 MN5F15
MS5	MS5F01 MS5F05 MS5F03 MS5F07	MS5F02 MS5F06 MS5F04 MS5F08
OR1	OR1F03 OR1F09 OR1F04 OR1F10	OR1F01 OR1F07[1] OR1F02 OR1F08[1] OR1F05[1] OR1F11 OR1F06[1] OR1F12
OR2	OR2F09 OR2F10 OR2F11 OR2F12	OR2F01 OR2F05 OR2F02 OR2FO6 OR2F03 OR2F07 OR2F04 OR2F08

Table 2.13. Specimen identification for field cores (continued)

Site	Between Wheel Path		Outside Wheel Path	
WA1	WA1F01	WA1F04	WA1F07	WA1F10
	WA1F02	WA1F05	WA1F08	WA1F11
	WA1F03	WA1F06	WA1F09	WA1F12
WIA	WIAF01	WIAF04	WIAF07	WIAF11
	WIAF02	WIAF05	WIAF08	WIAF12
	WIAF03	WIAF06	WIAF09	WIAF13
			WIAF10	WIAF14

[1] Inside wheel path

in the laboratory were cut in half to give a reference for identifying the mixture in the field core.

Several sites had cores which exhibited debonding between lifts within the overlay or between the overlay and the existing pavement. Where lifts within the overlay itself were debonding, the cores were cut so that the test specimen did not include this potentially weak layer.

Once the correct portion of the core was identified, the samples were trimmed to remove the excess pavement from the bottom of the specimen. The preferred sample height was 4.0 in. (102 mm), but several of the pavements had lifts significantly less than this. The OR2 pavement lift was nominally 2 in. (51 mm); after trimming, many of these specimens were under 2 in. (51 mm) in height. If the mixture layer was thick enough to allow it, the top 0.25 in. (6.4 mm) was also removed. This removed overly oxidized or consolidated material and material that might be contaminated with typical roadway substances. All specimen trimming used a carbon dioxide (CO_2) cooled, dry-cut, diamond blade saw to prevent introducing additional moisture into the specimens. After trimming, the samples were labelled, bagged, and stored at 59°F (15°C) until further testing.

2.4 Testing Procedures

Each program (ECS, OSU wheel tracking, and field) employed specimen conditioning which subjected the specimen to water damage. Afterwards, rutting (OSU wheel tracker) or modulus measurements (ECS and field) were made, and the degree of stripping and binder migration were visually evaluated.

However, before the specimens were subjected to the ECS and OSU wheel tracking procedures, a series of tests to establish the original volumetric and stiffness properties of the specimen were required. These tests were conducted on all of the 4.0 in. high by 4.0 in. diameter (102 mm by 102 mm) cylindrical specimens and all beam specimens for the OSU wheel tracker, with the exception of modulus testing, which is not performed on beam specimens prior to testing with the OSU wheel tracker.

Field cores were subjected to the volumetric and stiffness tests after they had been removed from the pavement and trimmed. Data from corresponding laboratory specimens were used to estimate the original unconditioned properties of the field cores.

This section briefly describes the testing performed prior to the ECS and OSU wheel tracking procedures, the ECS, and OSU wheel tracker test procedures, and the degree of visual stripping and binder migration evaluations. The treatment that field cores undergo within the pavement test section is not described, as it is self-evident. Detailed test methods are provided in Appendices B, C, D, and E.

2.4.1 Volumetric Properties

All specimens were measured for thickness and bulk specific gravity (G_{MB}). Specimen height was measured in three places at approximate one-third points around the perimeter of the specimen; and the specimen thickness was taken as the average of those measurements. The bulk specific gravity was calculated by weighing the specimen (1) dry, (2) wrapped in Parafilm, and finally (3) wrapped in Parafilm while submerged in a water bath (temperature 77°F [25°C]). The bulk specific gravity was calculated as:

$$G_{MB} = \frac{Wt_A}{(Wt_C - Wt_W) - \left(\frac{Wt_C - Wt_A}{0.9}\right)} \tag{2.1}$$

where
Wt_A = weight of dry sample in air (gr),
Wt_C = weight of sample coated in Parafilm in air (gr),
Wt_W = weight of sample coated in Parafilm and submerged in water (gr), and
0.9 = specific gravity of parafilm at 25°C (77°F).

Two samples of loose mixture were used to determine the theoretical maximum specific gravity G_{MM} (Rice specific gravity); one from the kneading compaction efforts and one from material left over in the sawing process for the wheel tracker beams.

The percent air voids (V_v) in each specimen was determined using the theoretical maximum and bulk specific gravities. The V_v values were calculated by the equation:

$$V_v = \left(1 - \frac{G_{MB}}{G_{MM}}\right) * 100 \tag{2.2}$$

Field cores which have been wet will retain some undetermined amount of water. The measurement of bulk specific gravity and calculation of air voids may therefore be somewhat inaccurate for these specimens. Maximum bulk specific gravities from laboratory-mixed specimens were used when calculating the air voids of field specimens.

2.4.2 Diametral Resilient Modulus

Diametral resilient modulus (ASTM D 4123-82; ASTM, 1990) testing was used to screen sets of laboratory cores prior to testing in the ECS and for final stiffness testing of rutted beam cores and field sections. Diametral modulus testing was performed on a closed loop hydraulic system (manufactured by MTS Systems Corporation [MTS]) run by computer software that performs the test and calculates each specimen's modulus value.

Each specimen was placed in an environmental cabinet at 77°F (25°C) for at least four hours prior to testing. The diametral modulus test was performed in accordance with ASTM D 4123-82 (ASTM, 1990). A static load of 10 lbs (44 N) was applied to restrain the specimen in the test apparatus. A pulse load was then applied for 0.1 seconds, followed by a 0.9-second resting phase. The pulse load was increased until a constant strain condition of 100 μ-strain was maintained. The computer software then recorded three consecutive pulse loads of data and calculated the diametral modulus from the average of those values. The specimen was then unloaded, rotated 90° within the diametral yoke, and retested. If the two calculated values of diametral modulus were within 10 percent of the average of the two values, the average was reported as the diametral modulus of the specimen. If they differed by more then 10 percent from their average, the specimen was retested.

The diametral resilient modulus was calculated using the following equation (ASTM D 4123-82; ASTM, 1990):

$$\text{Diametral } M_R = \frac{(v_{RT} + 0.27) * P}{(\Delta H_T * t)} \qquad (2.3)$$

where M_R = resilient modulus (psi),
v_{RT} = total resilient poisson's ratio (taken as 0.35 for asphalt concrete at 25°C (77°F)
P = repeated load (pounds),
ΔH_T = total recoverable horizontal deformation (inches), and
t = specimen height (inches).

The automated data acquisition system used for this testing was developed by Scholz and Ab-Wahab (1992). In addition to monitoring the linear variable differential transducers (LVDTs) and load cell outputs, the computer program also displayed them graphically and calculated an approximate modulus value in real time. The data from the last three pulses were saved to hard disk for subsequent calculation of the modulus and for hard copy output.

2.4.3 Triaxial Resilient Modulus

Each of the specimens nominally 4.0 in. (102 mm) in height was also tested in the triaxial configuration with the MTS apparatus to determine resilient modulus. This test was performed with a 30.0-lb (134-N) static load. The pulse loading was increased until either 100 μ-strain or 40.0 psi (275 kPa) of loading was reached. The computer software then calculated a triaxial resilient modulus value. Next, the specimen was further loaded until the second condition was reached, and the modulus was calculated again. The constant stress and constant strain readings were taken to compare the ECS resilient modulus values, which were taken at constant stress, and the to resilient modulus values generated by the aging group, which were taken at constant strain.

2.4.4 ECS Test

The test procedure for the ECS involves inducing and monitoring the water damage to a 4.0 in. high by 4.0 in. diameter (102 mm by 102 mm) asphalt concrete specimen. The specimen may be prepared with either the kneading or gyratory compactor, or by coring from a roller compacted slab or field section. The procedure for the ECS is briefly described in Table 2.14. The formal test protocol for the ECS procedure is given in Appendix D. Specimens tested with the ECS are identified in Tables 2.15 and 2.16. All ECS testing discussed in this document was performed using the dual prototype ECS constructed at OSU, unless otherwise noted.

Figure 2.5 shows a schematic of the equipment used to perform the ECS test procedure. The system consists of three components: (1) the environmental chamber with controlled temperature, (2) a fluid conditioning system which is essentially a constant head permeameter with the fluid being either air or water, and (3) a computer-controlled loading and data acquisition system to monitor the triaxial resilient modulus of the test specimen.

The ECS test quantitatively assesses the effect of water on the stiffness and permeability of an asphalt-aggregate mixture. Prior to testing with the ECS, specimens undergo testing for volumetric properties and for diametral and triaxial resilient modulus, as described previously in this chapter. Following this testing, the dry (unconditioned) specimen was then encased in a latex rubber membrane and placed within the ECS. With the specimen in the ECS test frame the dry (unconditioned) ECS modulus and coefficient of air permeability were determined. The modulus test performed by the ECS is a triaxial resilient modulus test with no confining pressure (i.e., $\sigma_2 = \sigma_3 = 0$). The loading, a true haversine waveform having a duration of 0.1 s followed by a dwell time of 0.9 s, was targeted to be 40 psi (275 kPa) for the primary test program. Testing for the nine additional secondary mixtures took place at 100 μ-strain, according to updated ECS test procedures. Sufficient loading was applied to the specimen to ensure a constant stress or strain condition before an ECS modulus value was calculated. Discussion of the permeability test procedure follows in Section 2.5.

Table 2.14. Summary of the ECS test procedure

Step	Description
1	Prepare test specimens as per SHRP protocol (Appendix B).
2	Determine the geometric and volumetric properties of the specimen.
3	Encapsulate specimen in silicon sealant and latex rubber membrane; allow to cure overnight (24 hours).
4	Place the specimen in the ECS load frame; determine air permeability.
5	Determine unconditioned (dry) triaxial resilient modulus.
6	Vacuum condition specimen (subject to vacuum of 20 in. [508 mm] Hg for 10 minutes).
7	Wet specimen by pulling distilled water through specimen for 30 minutes using a 20 in. (508 mm) Hg vacuum.
8	Determine unconditioned water permeability.
9	Heat the specimen to 140°F (60°C) for six (6) hours, under repeated loading. This is a hot cycle.
10	Cool the specimen to 77°F (25°C) for at least four (4) hours. Measure triaxial resilient modulus and water permeability.
11	Repeat steps 9 and 10 for two (2) more hot cycles.
12	Cool the specimen to 0°F (-18°C) for six (6) hours, without repeated loading. This is a freeze cycle.
13	Heat the specimen to 77°F (25°C) for at least four (4) hours and measure the triaxial resilient modulus and the water permeability.
14	Split the specimen and perform a visual evaluation of stripping and binder migration.
15	Plot the ECS resilient modulus ratio.

(after Scholz et al., 1993)

Table 2.15. Test plan for the ECS testing of primary mixtures

Specimen Number	Specimen Code	Site	Replicate
1	AB5R803	AB5	
2	AB5R804		
3	AB5KL01		
4	AB5KM03		
5	AB5KH06		
6	AB5KD08		
7	AZ5R804	AZ5	AZ5R803
8	AZ5R805		
9	AZ5KL01		
10	AZ5KM04		
11	AZ5KH05		
12	AZ5KH06		
	AZ5KD07		
13	CABKL02	CAB	
14	CABKM12		
15	CABKM14		
16	CABKD05		CABKH04
17	CADR804	CAD	
18	CADR806		
19	CADKL02		
20	CADKM04		
21	CADKD07		
22	CADKD08		CADKH05
23	CAGR803	CAG	
24	CAGR805		
25	CAGKL01		
26	CAGKM04		
27	CAGKD06		
28	CAGKD07		
29	GAAR803	GAA	
30	GAAR806		
31	GAAKL12		
32	GAAKM11		
33	GAAKH04		
34	GAAKD01		

Table 2.15. Test plan for the ECS testing of primary mixtures (continued)

Specimen Number	Specimen Code	Site	Replicate
35	MN5R804	MN5	
36	MN5R806		MN5R803
37	MN5KL03		
38	MN5KM05		
39	MN5KD08		
40	MN5KD09		
41	MS5R804	MS5	
42	MS5R805		
43	MS5KL03		
44	MS5KM04		
45	MS5KH07		
46	MS5KD08		
47	OR1R803	OR1	OR1R804
48	OR1R806		
49	OR1KL02		
50	OR1KM04		
51	OR1KH07		
52	OR1KD08		
53	OR2R803	OR2	OR2R804
54	OR2R806		OR2KL02
55	OR2KL01		OR2KD09
56	OR2KH05		
57	OR2KH06		
58	OR2KD08		
59	WA1R804	WA1	
60	WA1R805		
61	WA1KL20		
62	WA1KL21		WA1KM22
63	WA1KD07		
64	WA1KD26		WA1KD27
65	WIAR804	WIA	
66	WIAR805		
67	WIAKL01		
68	WIAKM08		
69	WIAKH15		
70	WIAKD19		WIAKD18

Table 2.16. Test plan for ECS testing of additional secondary mixtures

Specimen Number	Specimen Code	Mixture
1 2 3	AZF06 AZF07 AZF08	AZ5
4 5 6	COA05 COA22 COA33	COA
7 8 9	COB27 COB31 COB34	COB
10 11	COC12 COC16	COC
12 13	COE26 COE32	COE
14 15	GAF04 GAF05	LAF
16 17	LAF01 LAF03	GAF
18 19	TAI09 TAI39	TAI
20 21	WYO02 WYO05	WYO

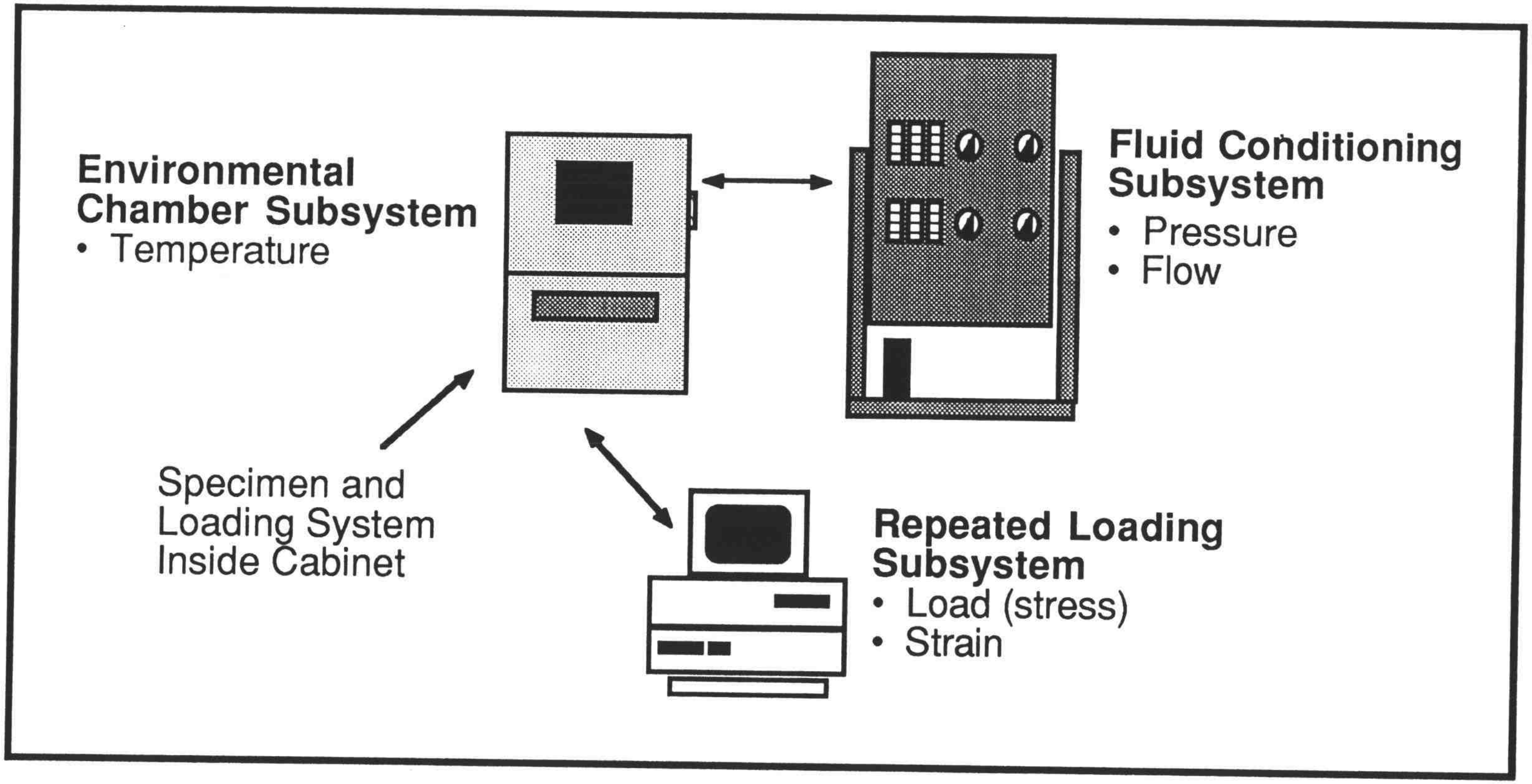


Figure 2.5. Schematic of the environmental conditioning system (ECS)

Some air was removed from the specimen by applying a partial vacuum of 20 in. (508 mm) Hg to the specimen outlet. The specimen was then "wetted" by pulling distilled water through the specimen under the action of the 20 in. (508 mm) Hg vacuum for 30 minutes. In the case of impermeable specimens, very little or no water may have infiltrated the specimen during the wetting procedure. Upon completion of the wetting process, the coefficient of water permeability of the specimen was determined. The specimen was then subjected to one of two programs of thermal conditioning cycles.

Specimens which came from No-Freeze environmental zones, were subjected to three "hot" cycles by heating the specimens to 140°F (60°C) for six hours. During this time each specimen was subjected to repeated loading of approximately 200 lbs (890 N) and distilled water flow of 2-5 ccm. Between cycles, each specimen was brought to 77°F (25°C) for at least four hours and tested for ECS modulus and the coefficient of water permeability. All ECS modulus testing took place with the specimens at 77°F (25°C).

Specimens which originated in Freeze environmental zones were subjected to an additional "Freeze" cycle at the end of the third hot cycle. This cycle cooled specimens to 0°F (-18°C) for six hours, without repeated loading, but with 2-5 ccm water flow. After a specimen was brought to 77°F (25°C) for at least four hours, the ECS modulus and the coefficient of water permeability were again measured.
At the completion of the three or four conditioning cycles, the membrane was removed from the specimen and the specimen was split diameterally using the MTS hydraulic loading system. A visual evaluation of stripping and binder migration was made from the two split faces of the specimen.

2.4.5 OSU Wheel Tracking Test

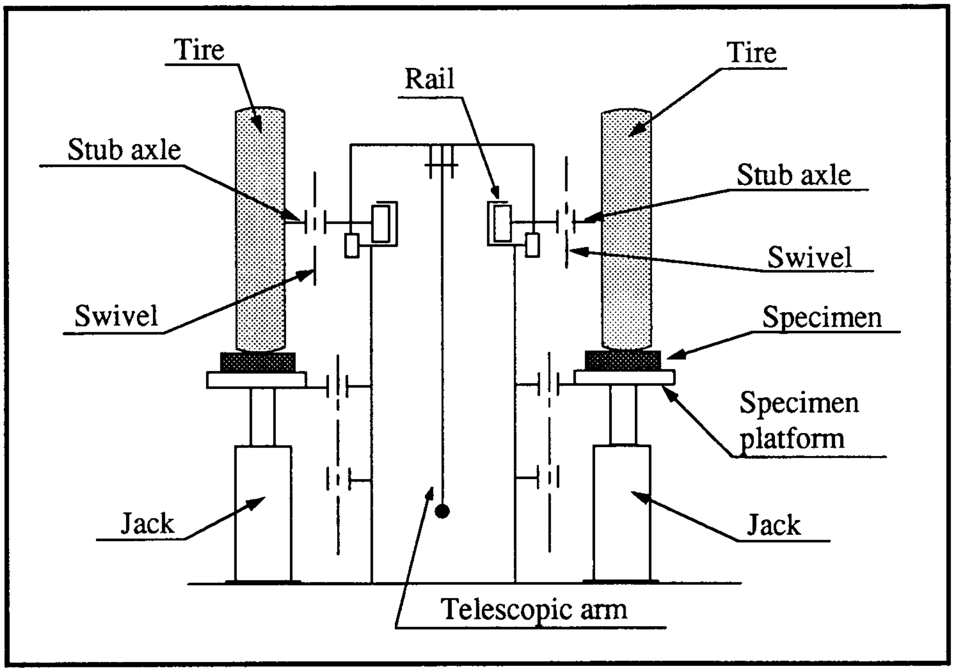
The test procedure for the OSU wheel tracking test involved conditioning beams of asphalt-aggregate mixtures to induce water damage and then testing them under the repeated loading of the OSU wheel tracker. Rut depth was the response mode monitored. Figure 2.6 shows a schematic of the OSU wheel tracker. Table 2.17 briefly outlines the procedure and Appendix E gives the detailed test protocol. The beam specimens tested under this conditioning procedure are identified in Table 2.18.

After volumetric data had been obtained, the beam specimen was subjected to a water conditioning program analogous to that within the ECS. There were, however, some minor differences:

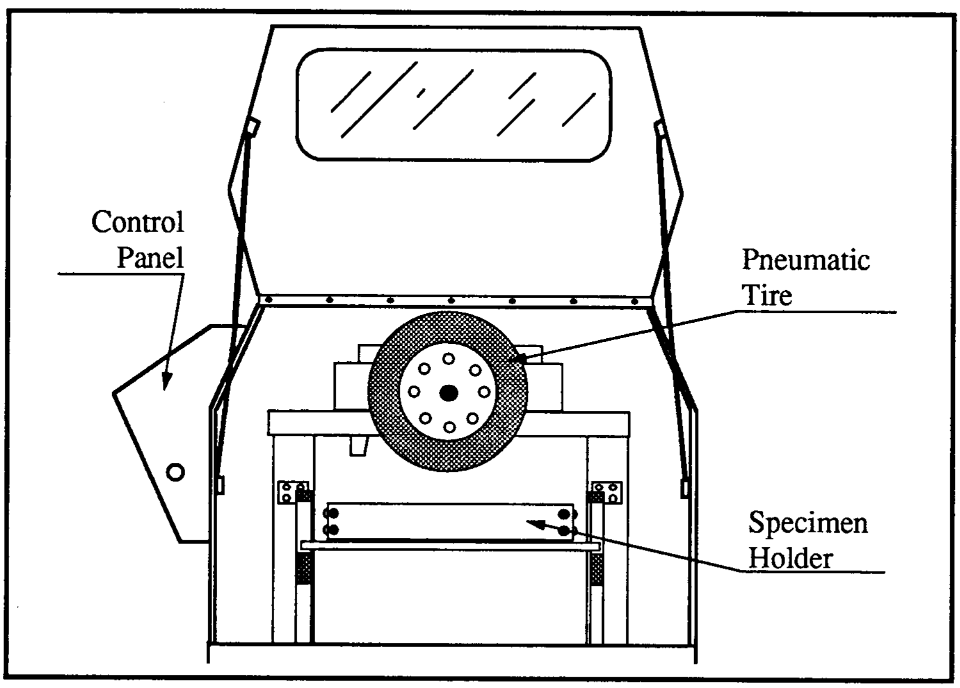
1. The wetting procedure for the beam specimens employed a slightly higher vacuum level and was significantly longer than that employed in the ECS. This was to ensure that the specimens achieved a saturation of between 60 and 80 percent.
2. The duration of some of the conditioning cycles was longer than those in the ECS procedure due to scheduling constraints on the equipment used for thermal conditioning.
3. The order of the conditioning cycles was slightly different for the wheel tracking test program relative to the ECS test program. Again, this was due to scheduling constraints on the equipment used for thermal conditioning.

Once the beam underwent water and thermal conditioning, it was wrapped in plastic wrap to prevent moisture loss and placed within the mold of the OSU wheel tracker. Thin, expanded foam sheets were placed between the beam and the mold wall to prevent movement of the beam under the action of the rolling wheel. A 1/8 in. (3 mm) thick piece of teflon sheeting was placed between the specimen and the OSU wheel tracker platen to provide a frictionless interface. The mold and beam were then placed in the OSU wheel tracker and bolted into place. The system was brought up to the test temperature of 104°F (40°C) for at least two hours.

After the specimen reached the testing temperature, as determined by a thermocouple probe inserted into a hole drilled in the beam, the plastic wrap was removed from the top of the beam to prevent the plastic from being picked up by the pneumatic tire. Testing then began.



a) Schematic



b) Side View

Figure 2.6. Schematic of the OSU wheel tracker

Table 2.17. Summary of OSU wheel tracking test procedure

Step	Description
1	Prepare test specimen as described in Chapter 2 and Appendix C.
2	Determine the gravimetric properties of the beam.
3	Place a latex and silicone sealant seal around the circumference of the beam at mid-height and allow to cure overnight (24 hours).
4	Wet the beam specimen by pulling distilled water through the specimen under a 23 in. (584 mm) Hg vacuum until a degree of saturation of at least 60% is obtained, but for not more than 2 hours.
5	Subject the wet beam specimen to wet thermal conditioning cycles as follows[1]: Heat the specimen to 140°F (60°C) in a distilled water bath for six (6) hours. Cool the specimen to 77°F (25°C) in a distilled water bath for ten (10) hours. Heat the specimen to 140°F (60°C) in a distilled water bath for six (6) hours. Cool the specimen to -4°F (-20°C) in a distilled water bath for eight (8) hours. Heat the specimen to 140°F (60°C) in a distilled water bath for ten (10) hours. Cool the specimen to 77°F (25°C) in a distilled water bath for ten (10) hours.
6	Wrap the specimen in plastic (e.g., Saran Wrap) to retain moisture in the specimen during the testing phase.
7	Place the conditioned beam specimen in the rutting tester and heat the specimen to 104°F (40°C).
8	Perform the OSU wheel tracking (rutting) test on the conditioned beam specimen until 10,000 wheel passes have elapsed. Take rut depth measurements at 0, 200, 500, 1,000, 2,000, 5,000, and 10,000 wheel passes.
9	Plot the rut depth versus wheel passes.
10	Core the rutted beam specimen along the wheel track to obtain cores. Split the cores and perform a visual evaluation of stripping and binder migration.

(after Scholz et al., 1993)

[1] For mixtures from No-Freeze environments, eliminate the -20°C (-4°F) cooling cycle.

Table 2.18. Test plan for the OSU wheel tracker testing

Mixture Number	Mixture Code	Site	Replicate
1	AB5R801	AB5	AB5R802
2	AZ5R801	AZ5	AZ5R802
3	CADR801	CAD	CADR802
4	CAGR801	CAG	CAGR802
5	GAAR801	GAA	GAAR802
6	MN5R801	MN5	MN5R802
7	MS5R801	MS5	MS5R802
8	OR1R801	OR1	OR1R802
9	OR2R801	OR2	OR2R802
10	WA1R801	WA1	WA1R802
11	WIAR801	WIA	WIAR802

A preconditioning wheel load of 50 wheel passes at 92 psi (634 kPa) were applied to the beam specimen to eliminate the high plastic deformations characteristic of asphalt-aggregate mixtures at the onset of loading. After the preconditioning load was completed, measurements were obtained to establish the baseline beam surface profile. These measurements were either obtained electronically (i.e., via computer), using a displacement transducer designed specifically for these measurements, or manually, using the caliper provided by the manufacturer of the wheel tracker. Figure 2.7 shows the 15 positions where the surface profile measurements were obtained. Note that the measurement positions were concentrated near the center of the beam along its longitudinal axis to avoid measuring the high plastic deformations which occur in the region where the rolling wheel slowed down, stopped, and reversed direction at the end of the travel path.

The wheel loading was then increased to 100 psi (689 kPa) and reapplied. Testing proceeded with application of up to 10,000 wheel passes, or until failure occurred (as established by a sudden and significant increase in plastic deformation). After a total of 100, 200, 500, 1,000, 2,000, and 5,000 wheel passes, the load was temporarily halted and the surface profile measured. At the end of 10,000 wheel passes, or after loading had been terminated due to failure, a final surface profile was measured. The beam was then cored to obtain a 4.0-in. (102-mm) diameter core for evaluation of visual stripping and binder migration.

2.4.6 Visual Evaluation of Stripping and Binder Migration

At the completion of each testing procedure, a visual evaluation was performed. Specimens were split in half by applying a diametral static load. The two broken faces were examined to determine the percentage of the surface area that had been stripped of asphalt. The percentage of stripping was reported to be 0, 5, 10, 20, 30, 40 or 50 percent, as shown in Figure 2.8. Fractured faces were neglected in the identification of aggregate faces that had lost their asphalt covering.

In addition to the stripped aggregate, it became evident early in the testing program that some of the field validation mixtures experienced displacement of the

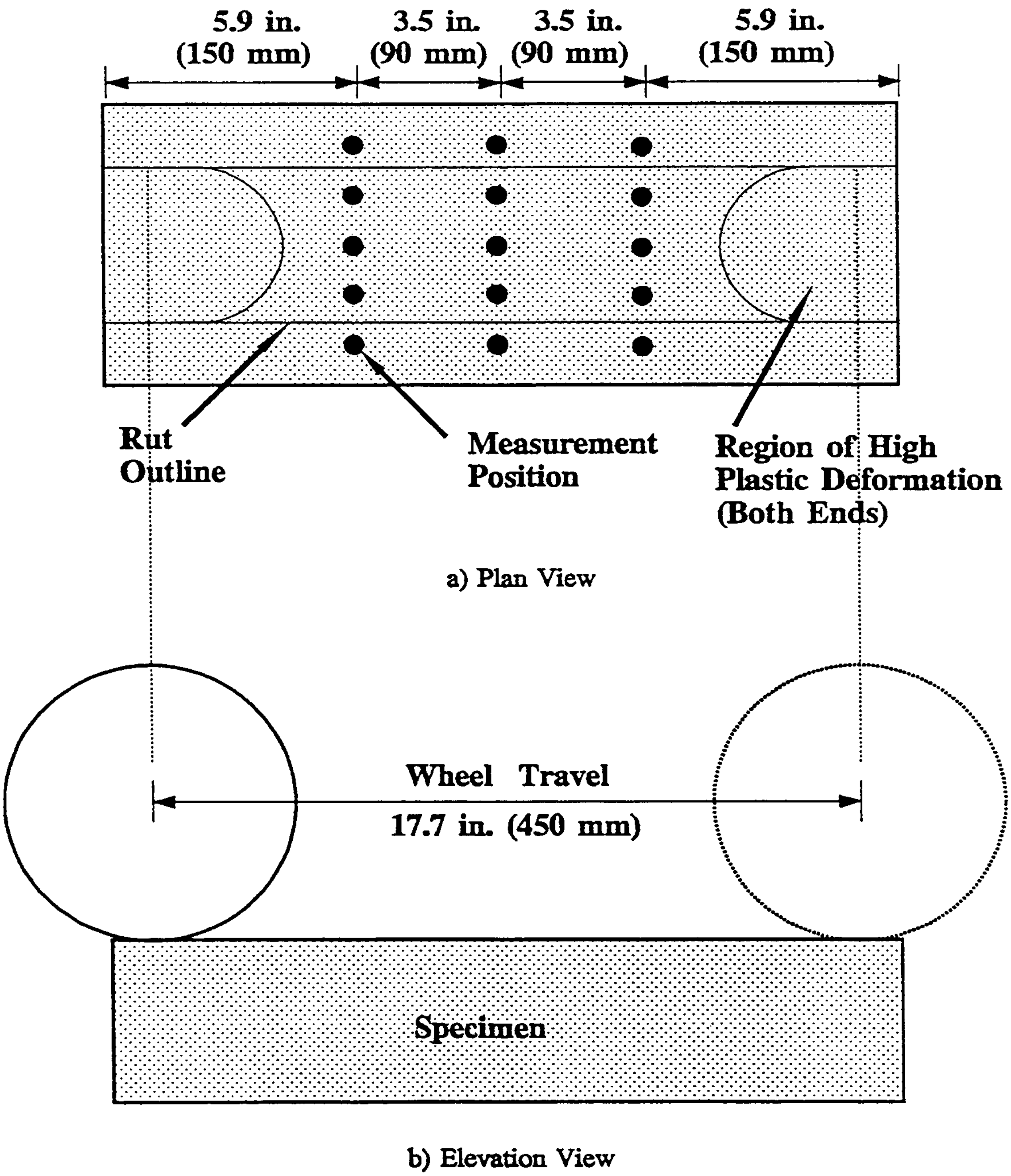


Figure 2.7. Measuring positions for rut depth

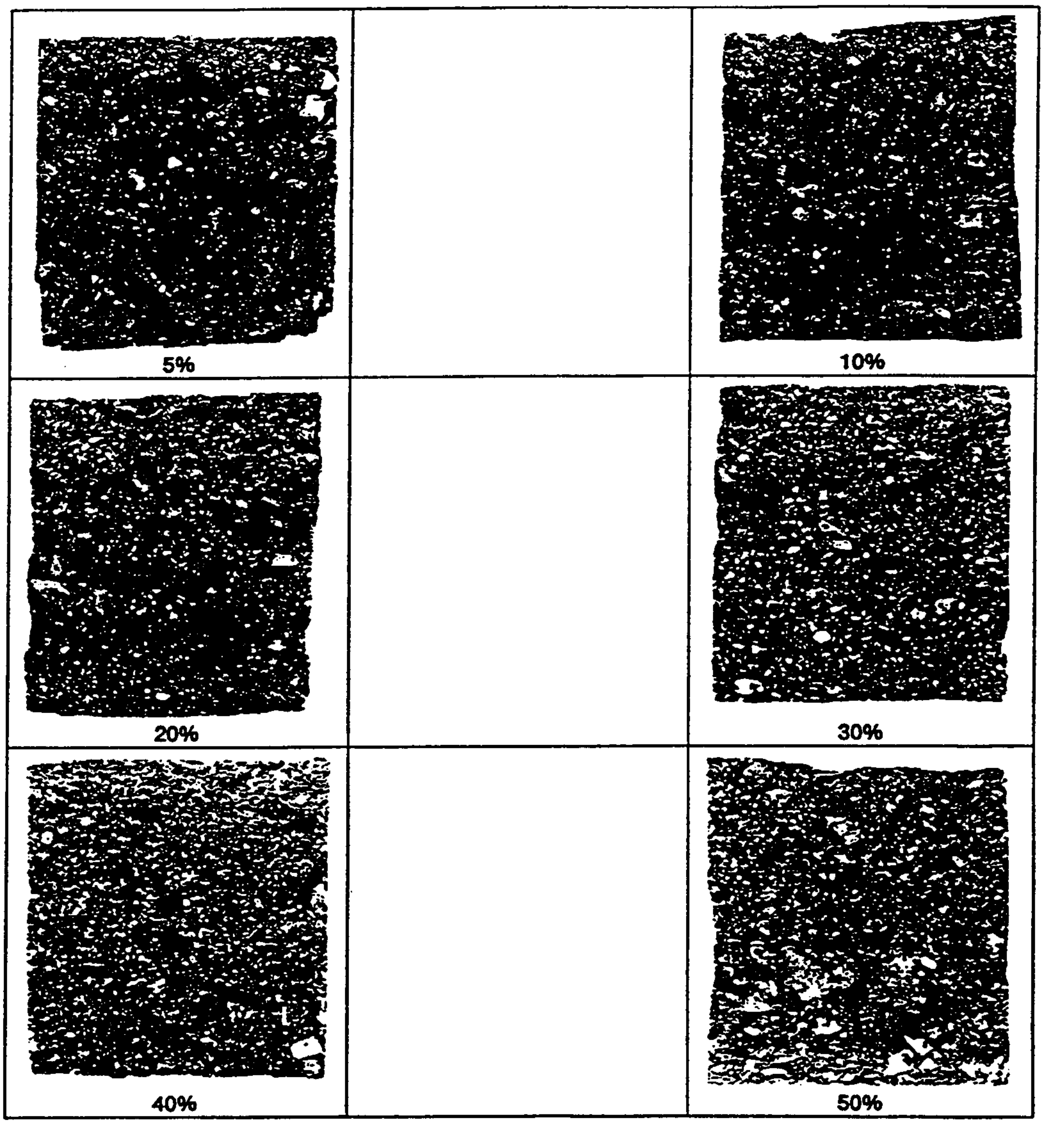


Figure 2.8. Degree of visual stripping rating chart

asphalt binder in the direction of water flow through the specimen during the ECS test procedure. This phenomenon, termed "binder migration," was described by giving the specimen a letter rating, with each letter corresponding to the level of binder movement shown in Figure 2.9.

2.5 Evaluation of Test Apparatus

The ECS was designed and constructed at OSU by Terrel and Al-Swailmi (1993). The results of this test program and evaluation will be used to suggest modifications to the existing system that will be used in future generations of the ECS. For this purpose, the following investigations were undertaken during the testing program.

2.5.1 ECS Loading System

As part of the ECS test procedure for the primary test program, initial values diametral and triaxial modulus values were obtained for each specimen using the MTS hydraulic loading system. This allowed the ECS modulus values, measured at 40 psi, to be compared to modulus values from a standard test system. The accuracy of the ECS for measuring "true" modulus values may be suspect due to the following reasons: (1) specimens are encased in a latex membrane that precludes the triaxial yoke from being cemented directly to the specimens, (2) the gage length of the test is longer than standard (3 in. as opposed to 2 in., used in an attempt to mitigate the effects of the latex membrane), and (3) the system is servo-pneumatic.

2.5.2 ECS Fluid Flow System

The ECS flow system was originally designed to allow flow to the specimen during the ECS conditioning process. Terrel and Al-Swailmi (1993) began to also use the flow system to measure the specimens' coefficient of air and water permeability in

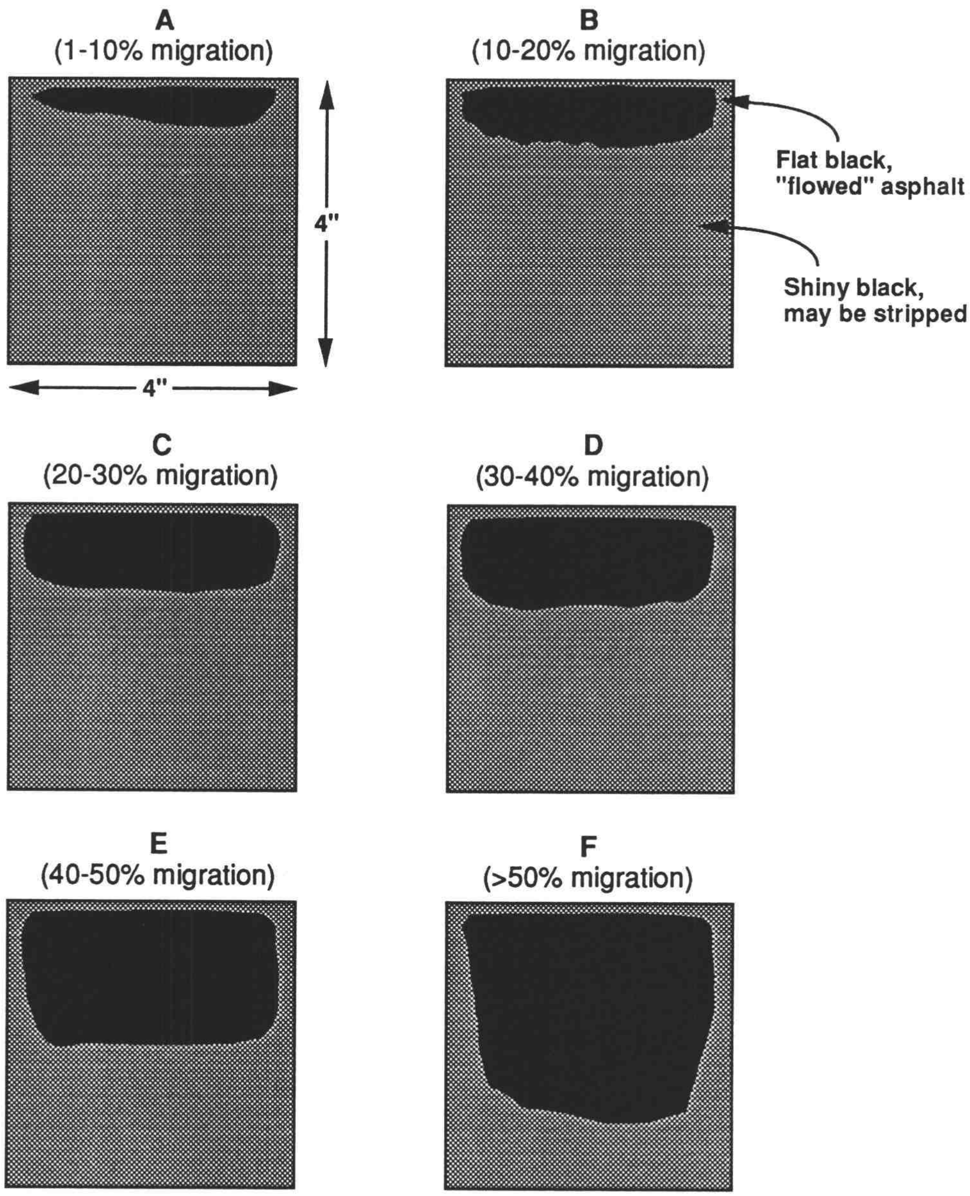


Figure 2.9. Binder migration rating chart

an attempt to better qualify the specimens' void structure. It was hypothesized that permeability readings would give not only an indication of a specimen's void level, the value of permeability increasing with increasing void level, but also the interconnectiveness of the void structure. The coefficient of water permeability could also indicate the change in the void structure as a specimen undergoes cycles of ECS conditioning.

2.5.2.1 Calibration of Pressure Gages and Flow Meters. If the ECS was to function as a permeameter, it was considered prudent to investigate the system more closely to determine if it was functioning correctly. It was important that it gave results that followed fluid flow theory, specifically Darcy's law, which is used to calculate the coefficients of permeability.

Darcy's law may be expressed as:

$$Q = -kiA \tag{2.4}$$

where
- Q = volume flow rate (m^3/s),
- k = the coefficient of permeability (m/s),
- i = hydraulic gradient ($\Delta h/\Delta L$),
- Δh = difference in piezometric head across the specimen (m),
- ΔL = flow path length (m), and
- A = cross sectional area of flow (m^2).

Darcy's law assumes that the flow is saturated, laminar, and non-inertial. The negative sign indicates that the flow is in the direction of the negative gradient; this is neglected for the purposes of the ECS equation.

In the ECS apparatus, the difference in piezometric head is:

$$\Delta h = \frac{\Delta P - \gamma L}{\gamma} \tag{2.5}$$

where
- ΔP = pressure difference across the specimen (N/m^2),
- γ = specific weight of the fluid (N/m^3), and
- L = specimen height (m).

The product of specific weight of the fluid and specimen height is subtracted from the pressure difference across the specimen due to the direction of induced flow, from the bottom to the top of the specimen.

Applying Darcy's law, with the above definition of piezometric head, results in the following equation, which may be used for either air or water flow:

$$k = \frac{Q\,L}{\frac{(\Delta P - \gamma L)}{\gamma} A} \tag{2.6}$$

where
k = the coefficient of permeability (m/sec),
Q = volume flow rate of air or water (m^3/s),
L = average height of the specimen (m),
γ = specific weight of the fluid (N/m^3),
A = cross sectional area of the flow (m^2), and
ΔP = pressure difference across the specimen (N/m^2).

For calculations with air flow, the volume flow rate and air density must be corrected for the average pressure across the specimen, as air is compressible. Water is considered incompressible for the purposes of these calculations. Further discussion of flow data and theory will be presented in Section 4.1.2.

A flow system schematic for the ECS is shown in Figure 2.22. The system can be set to pull only a vacuum across a specimen, against a closed inlet, or allow air or water flow through a specimen. The procedure for running ECS permeability tests is described in Appendix D. The prototype ECS is a dual unit, capable of conducting tests on two specimens simultaneously. Each has a complete, independent flow system. The systems are designated A and B. For the purposes of this test program, a single stand-alone air flow system was used to test all specimens. Two identical systems are incorporated into the prototype ECS system, but the stand alone system was used as a time saving measure.

Three separate calibrations were performed on the dual flow system of the prototype ECS, specifically: (1) gravimetric calibration of the flow meters, (2) calibration of the differential pressure gages using a mercury manometer in parallel, and (3) calibration of the system without a specimen. The gravimetric calibration of the flow meters was performed by placing the outflow reservoir for the system on a digital balance and setting the ECS flow system to a given flow rate, with a stack of porous stones acting as a specimen in the ECS. A series of timed intervals was used and the weight of the water that flowed through the system during the interval was reported. The average for at least three runs was used to determine the gravimetric flow rate. The water was assumed to be at 25°C (77°F), since the room is temperature controlled.

The calibration of the differential pressure gages involved placing a mercury manometer in parallel with the ECS's differential pressure gages. Again, a stack of porous stones took the place of an actual specimen for the purposes of this calibration. The ECS flow system was turned on and a series of differential pressures set using the vacuum regulator gage. The pressures ranged from 2 to 9 psi, which are typical pressure ranges for permeability tests run with asphalt concrete specimens. The ECS differential gage reading and the manometer reading were taken for each pressure. Several runs were performed with both a series of decreasing pressures and a series of increasing pressures, to investigate weather the gages were subject to hysteresis.

The measure of the differential pressures and the flow of the system when the end platens were simply placed on top of each other, with no specimen, and sealed with a latex membrane, was an attempt to quantify the pressure differential that is inherent in the ECS system. This was termed the "system blank" test. It was necessary because the prototype ECS does not measure differential pressure directly across the specimen, but between two points back within the tubing of the flow system, as shown in Figure 2.10. Consequently, it is reasonable to assume that the ECS plumbing may be contributing some amount of head loss to the readings being taken. A series of pressures (i.e., flow rates) was run as was done for the gage calibration.

2.5.2.2 Estimation of Precision for Coefficients of Permeability. Calculation of the coefficients of permeability for air and water using the ECS apparatus involve several sets of gages and flow meters. All of these contribute measurement or reading errors to the calculated values, assuming that each meter reads

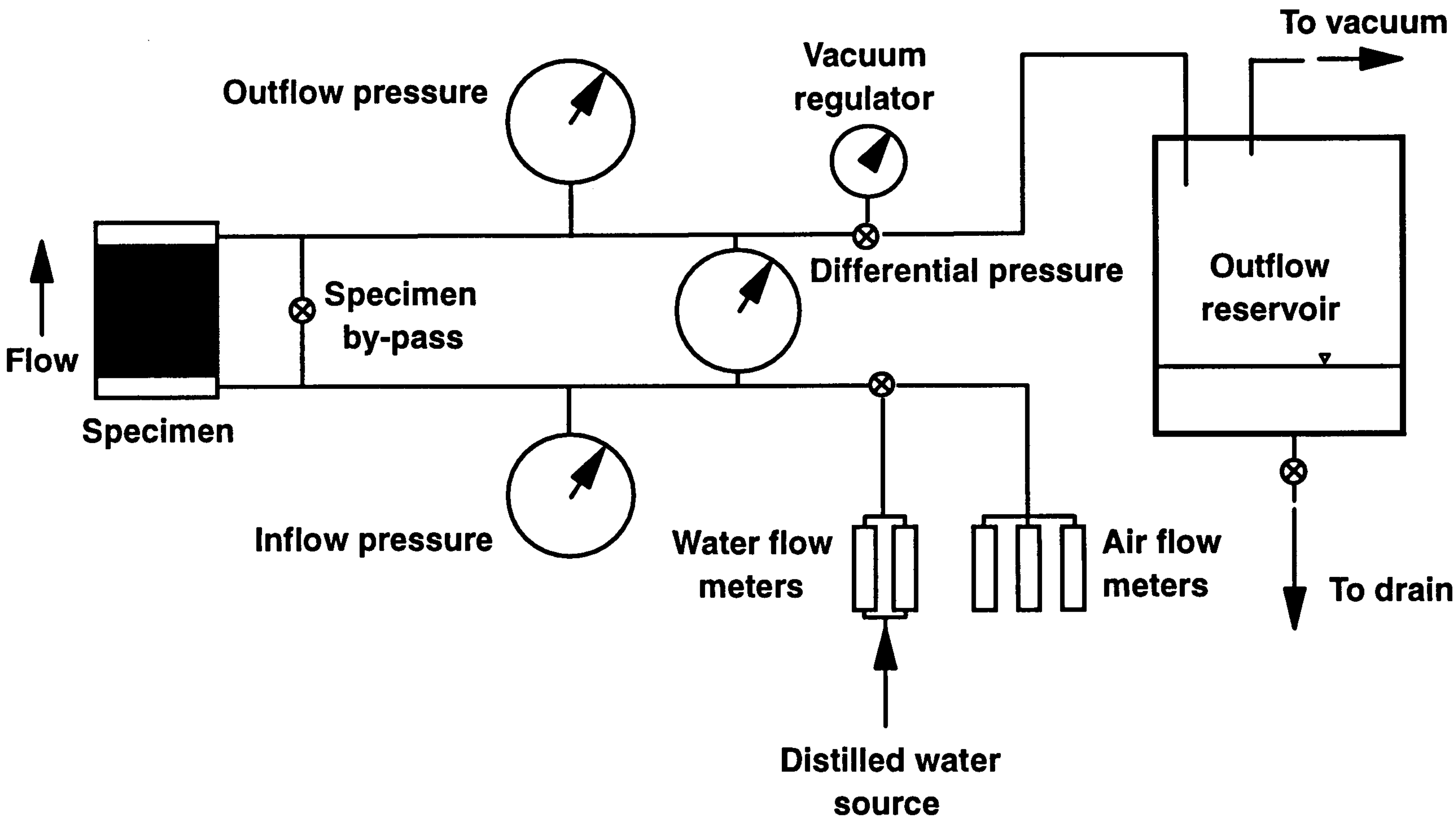


Figure 2.10. Schematic of the ECS flow system

a true value. In Equation 2.6 for the coefficient of permeability, the parameters Q, L, and ΔP all have an associated measurement error. For simplicity, A and γ are assumed to be constant. The measurement error is taken as one half of the smallest division of the gage scale.

It was suggested that one way to determine the error associated with the measurement readings would be to use a random number generator to produce a wide range of values for each variable, within the measurement error of the gage or meter. These values could then be used with Equation 2.6 to determine the range of error in the coefficient of permeability value that would result from the measurement error.

The accuracies with which the gages and flow meters of the ECS read are shown in Table 2.19. A range of values (Table 2.20) was selected for each gage or flow meter reading that was within the range observed during the testing program. A random number generator was then used to vary the measured readings within the measurement error (i.e., for a measure of $\Delta P = 2.0$ psi (14 kPa), with the gage reading to a division of 0.2 psi (1.4 kPa), values generated by the random number generator were 1.9 psi (13 kPa) $\leq \Delta P \leq$ 2.1 psi (14 kPa)).

Table 2.19. Accuracy of instrumentation for the ECS flow system

Meter or Gage	System	Manufacturer	Units	Smallest Division
Differential Pressure Gage, Water Flow	A	Capsulhelic	0-10 psi	0.5
Differential Pressure Gage, Water Flow	B	Capsulhelic	0-10 psi	0.2
Differential Pressure Gage, Air Flow	A, B	Dwyer	0-36 in. Hg	0.1
Water Flow Meter	A, B	Dwyer	2-30 ccm	1
Water Flow Meter	A, B	Dwyer	0.5-12 gph	0.5
Air Flow Meter	A, B	Dwyer	100-1000 ccm	20
Air Flow Meter	A, B	Dwyer	1-10 scfh	0.5
Air Flow Meter	A, B	Dwyer	4-40 scfh	2

1 psi = 6,894.757 N/m^2
1 in. of Hg = 3,376.85 N/m^2
1 U.S. gallon = 3.785 x 10^{-3} m^3
1 ft^3 = 0.02832 m^3

Table 2.20. Parameter values used for estimation of precision for coefficients of permeability

Parameter	**Range of Values, Air Flow**	**Range of Values, Water Flow**
Volume Flow Rate (Q)	1-10 scfh, 4-40 scfh, and 100-1,000 ccm	1-10 gph, 1-30 ccm
Average Height of the Specimen (L)	3.7-4.9 in. (9.4-12.4 cm)	3.7-4.9 in. (9.4-12.4 cm)
Specific Weight of the Fluid at 25°C (77°F), a Constant (γ)	0.0738 lb/ft^3 (11.6 N/m^3)	62.26 lb/ft^3 (9,781 N/m^3)
Cross-sectional Area of the Flow, a Constant (A)	12.6 in.^{2} (81.1 cm^2)	12.6 in.^{2} (81.1 cm^2)
Pressure Difference Across the Specimen (ΔP)	2-14 in. Hg. (6,800-47,000 N/m^2)	2-9 psi (14,000-62,000 N/m^2)

1 U.S. gallon = 3.785 x 10^{-3} m^3
1 ft^3 = 0.02832 m^3

3 RESULTS

This chapter presents the results of the testing program for evaluating the Environmental Conditioning System using field asphalt concrete mixtures. Included are results from the investigation of the ECS loading and flow systems and the results obtained in the ECS and the OSU wheel tracking programs. Diametral and triaxial resilient modulus data from cores taken from in-service field test sections are also presented. Data from both the primary twelve asphalt concrete mixtures, and the nine additional secondary test program mixtures are included.

3.1 Evaluation of Test Apparatus

3.1.1 ECS Loading System

Figure 3.1 shows a comparison between triaxial modulus values for unconditioned, laboratory-compacted specimens from the twelve primary mixtures tested in the MTS and the ECS. The specimens were not encased in a latex membrane at the time of the testing in the MTS. Both tests were run under a constant-stress condition at 40.0 psi (275 kPa).

It was observed during the test program that obtaining repeatable ECS modulus values was very difficult for some field- and laboratory-cored specimens. If specimens were not cored and trimmed very carefully, the ends of the specimens would not be parallel. The ECS modulus is calculated from the average of two readings of axial deformation, provided by LVDTs placed opposite from each other across the diameter of the specimen. When specimens did not have parallel ends, the readings typically did not agree closely with each other, and the calculated modulus values tended to vary between tests.

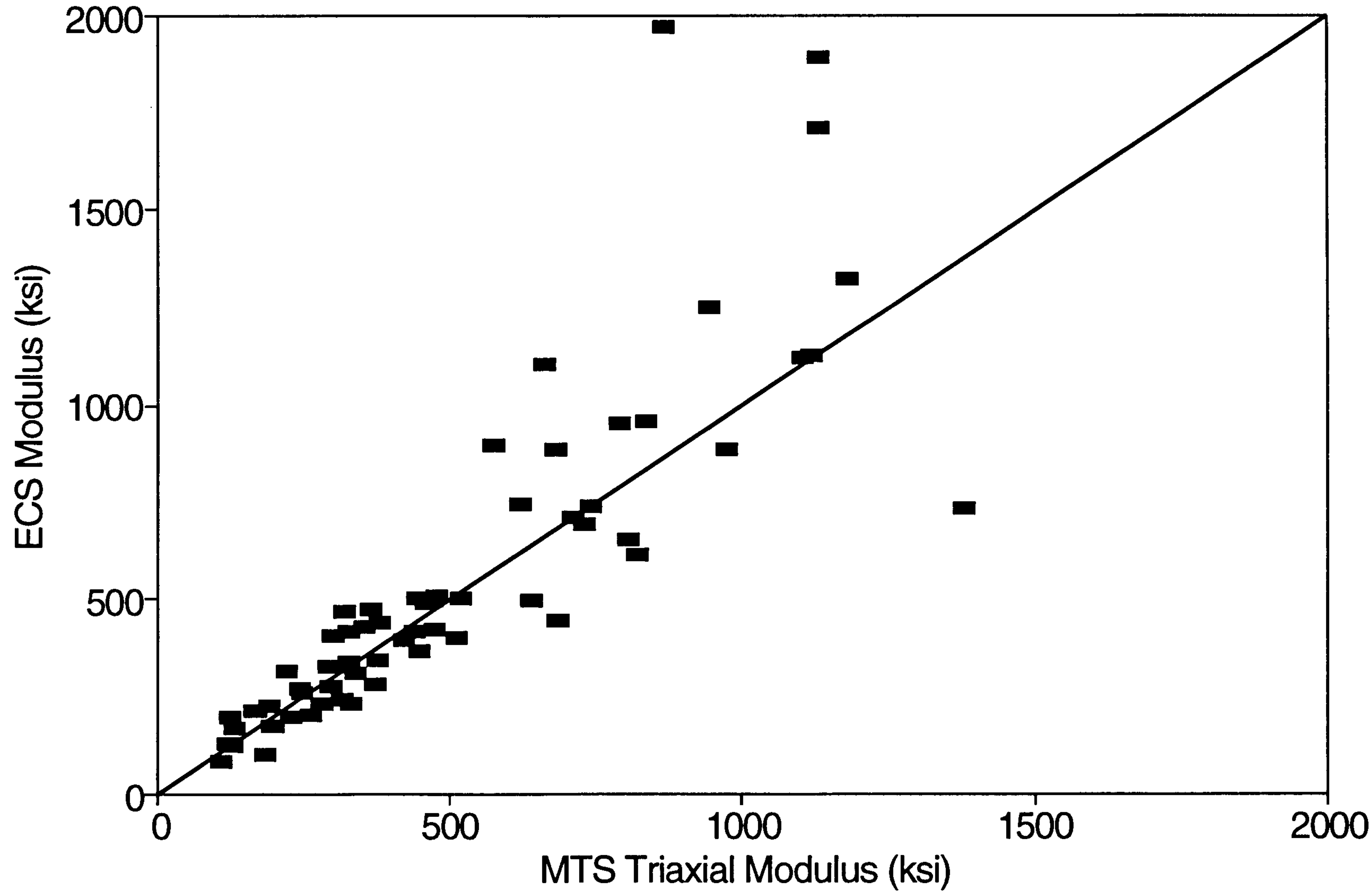


Figure 3.1. Comparison between triaxial resilient modulus as measured by the MTS and ECS

3.1.2 ECS Fluid Flow System

The calibration effort for the ECS fluid flow system was focused principally on the water flow systems. The precision of the calculations for the coefficient of permeability were investigated for both air and water. Additional discussion of the air flow system is provided in Section 4.2.3.

3.1.2.1 Calibration of Pressure Gages and Flow Meters. A total of eight calibration equations resulted from the calibration of the dual prototype ECS water flow system. Each system has two flow meters and one differential pressure gage, which produced one calibration equation each, and each system required a system blank calibration, resulting in a total of four equations per system. For the dual systems, A and B, this resulted in eight calibration equations. The data from the calibrations are given in Appendix F.

Figures 3.2 and 3.3 present the results for the calibration of the differential gages and the system blank. Table 3.1 presents the equations used for the calibrations. Simple linear regression was used to fit the data in each case.

3.1.2.2 Estimation of Precision for Coefficients of Permeability. The variability in the calculated values of the coefficients of air and water permeability was approximated using a random number generator to add variation within the error of the measurement to readings from the pressure gages and flow meters. The air flow system uses one differential pressure measurement and one of three flow meters. Figures 3.4, 3.5, and 3.6 give graphical representations of the ranges in the values of error and percent error that may be obtained from the three flow gages used in the air flow system.

The dual water flow systems, A and B, of the prototype ECS have differential pressure gages that read to different accuracies. Each system also employs two flow meters. Figures 3.7, 3.8, 3.9, and 3.10 give the ranges in the values of error and percent error obtained for the water systems.

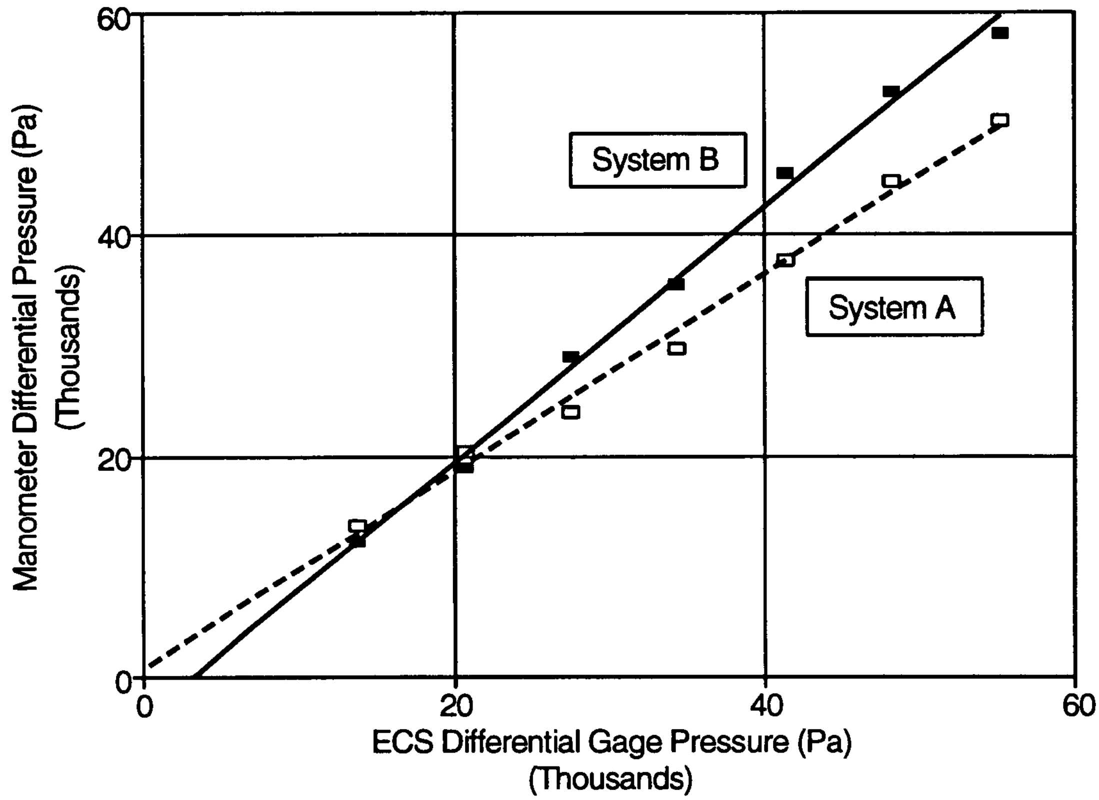


Figure 3.2. Calibration of differential pressure gages

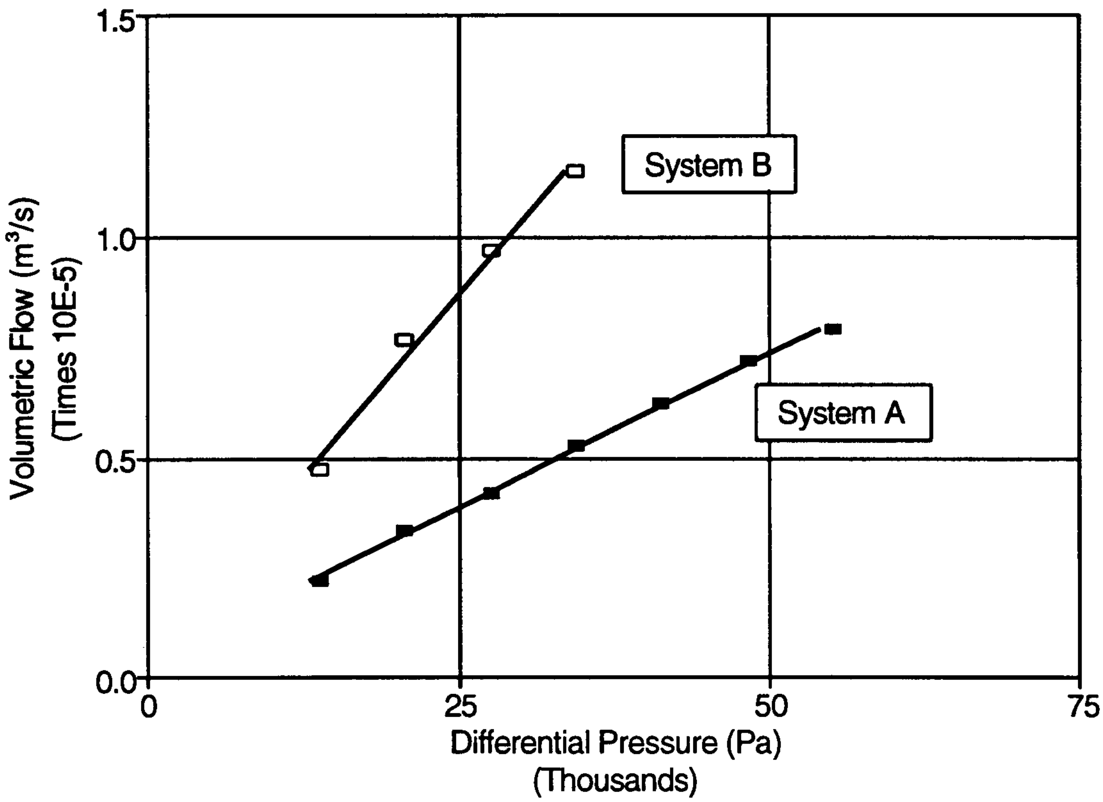
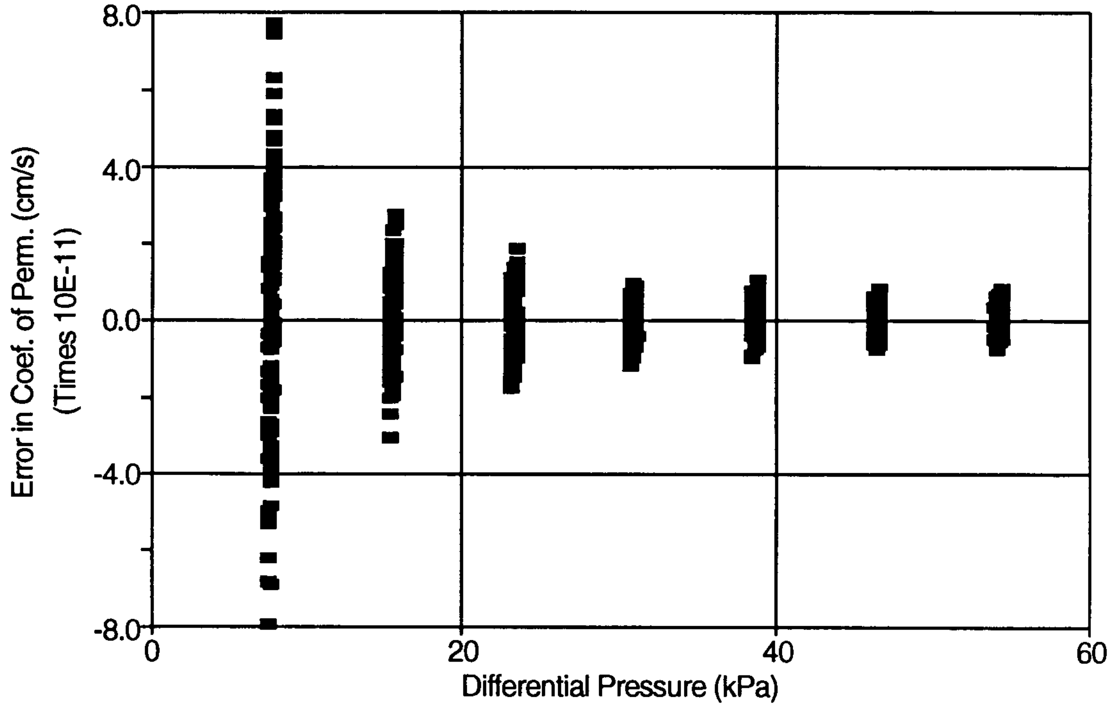


Figure 3.3. Calibration of system blank

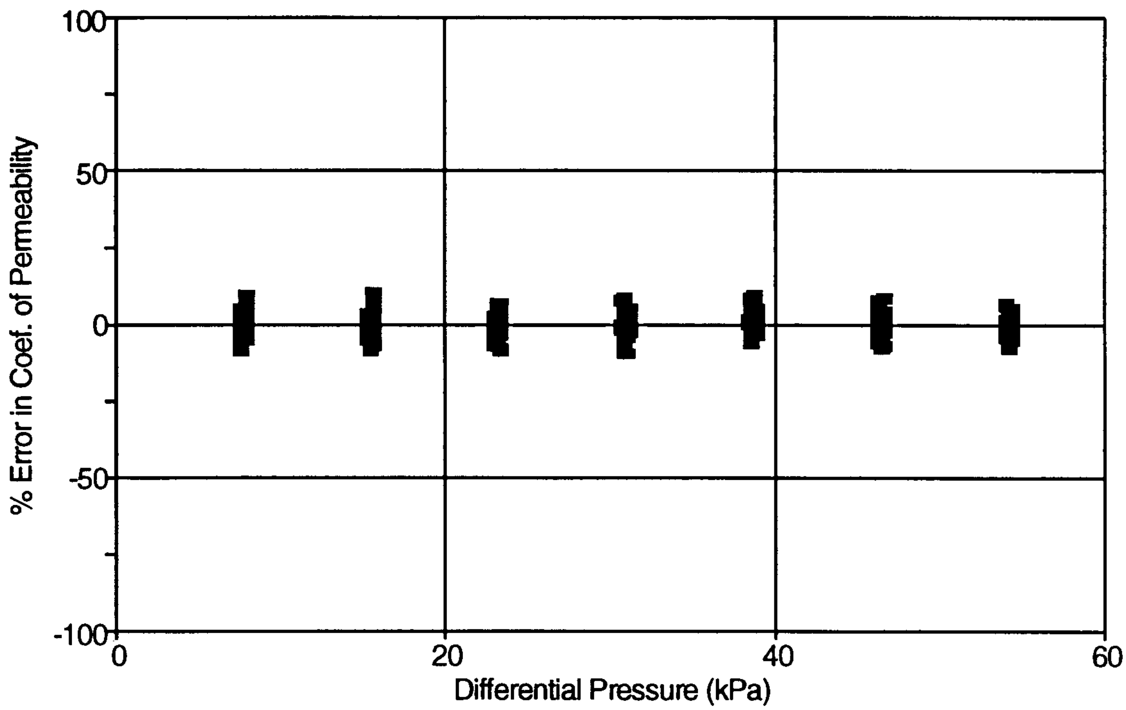
Table 3.1. Calibration equations for ECS water flow systems

System	Calibration	Equation[1,2]
A	System Blank	ΔP (corrected) = ΔP (reading) - (Q * 7.24E+09 - 3046)
B	System Blank	ΔP (corrected) = ΔP (reading) - (Q * 3.06E+09 - 1551)
A	Differential Pressure Gage	ΔP (corrected) = ΔP (system blank) * 0.8879
B	Differential Pressure Gage	ΔP (corrected) = ΔP (system blank) * 1.151
A	Flow Meter (gph)[3]	Q (corrected) = Q (reading) * 0.9982 + 0.4127
A	Flow Meter (ccm)[4]	Q (corrected) = Q (reading) * 0.9069 + 0.9611
B	Flow Meter (gph)	Q (corrected) = Q (reading) * 1.013 - 0.1760
B	Flow Meter (ccm)	Q (corrected) = Q (reading) * 0.7446 + 2.173

[1] ΔP = differential pressure (Pa)
[2] Q = volumetric flow (m^3/s)
[3] Q is in units of the flow meter
[4] Q is in units of the flow meter

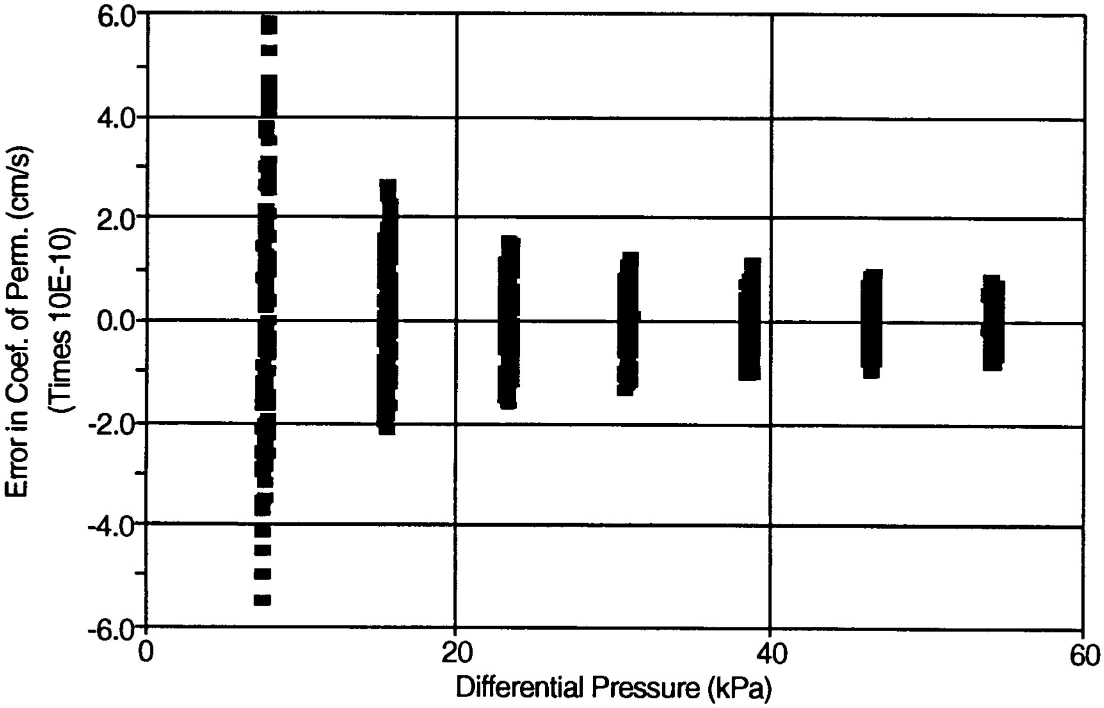


a) Error in the coefficient of air permeability

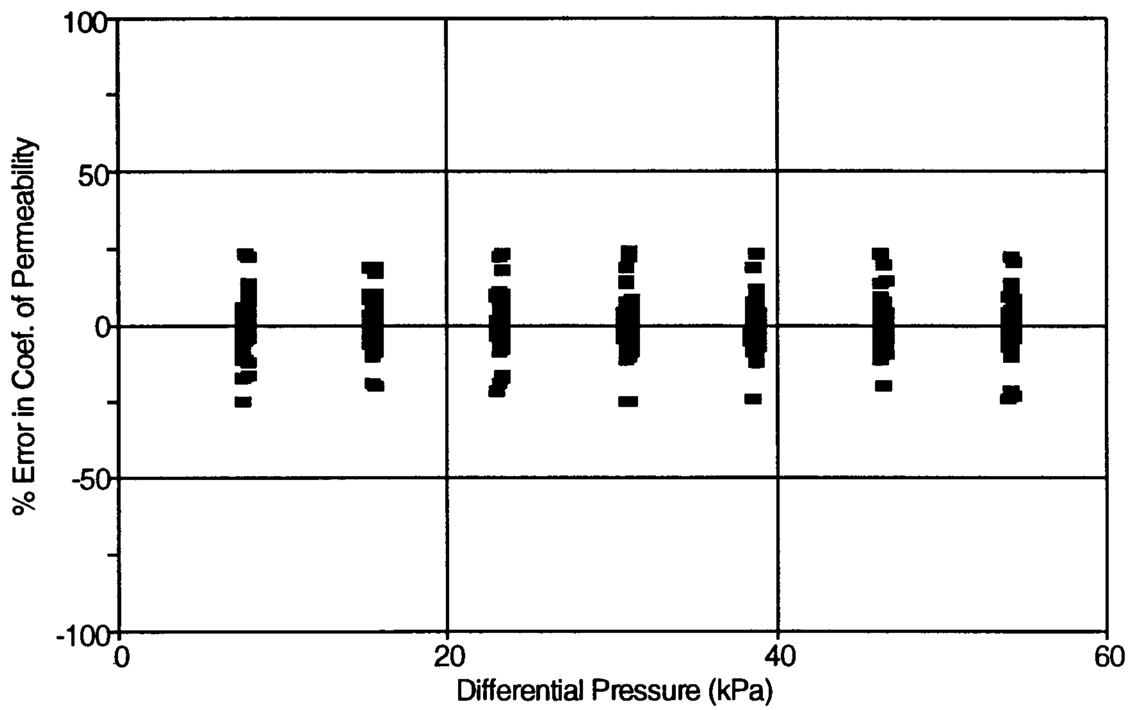


b) Percent error in the coefficient of air permeability

Figure 3.4. Range of error in the coefficient of air permeability, ccm flow meter

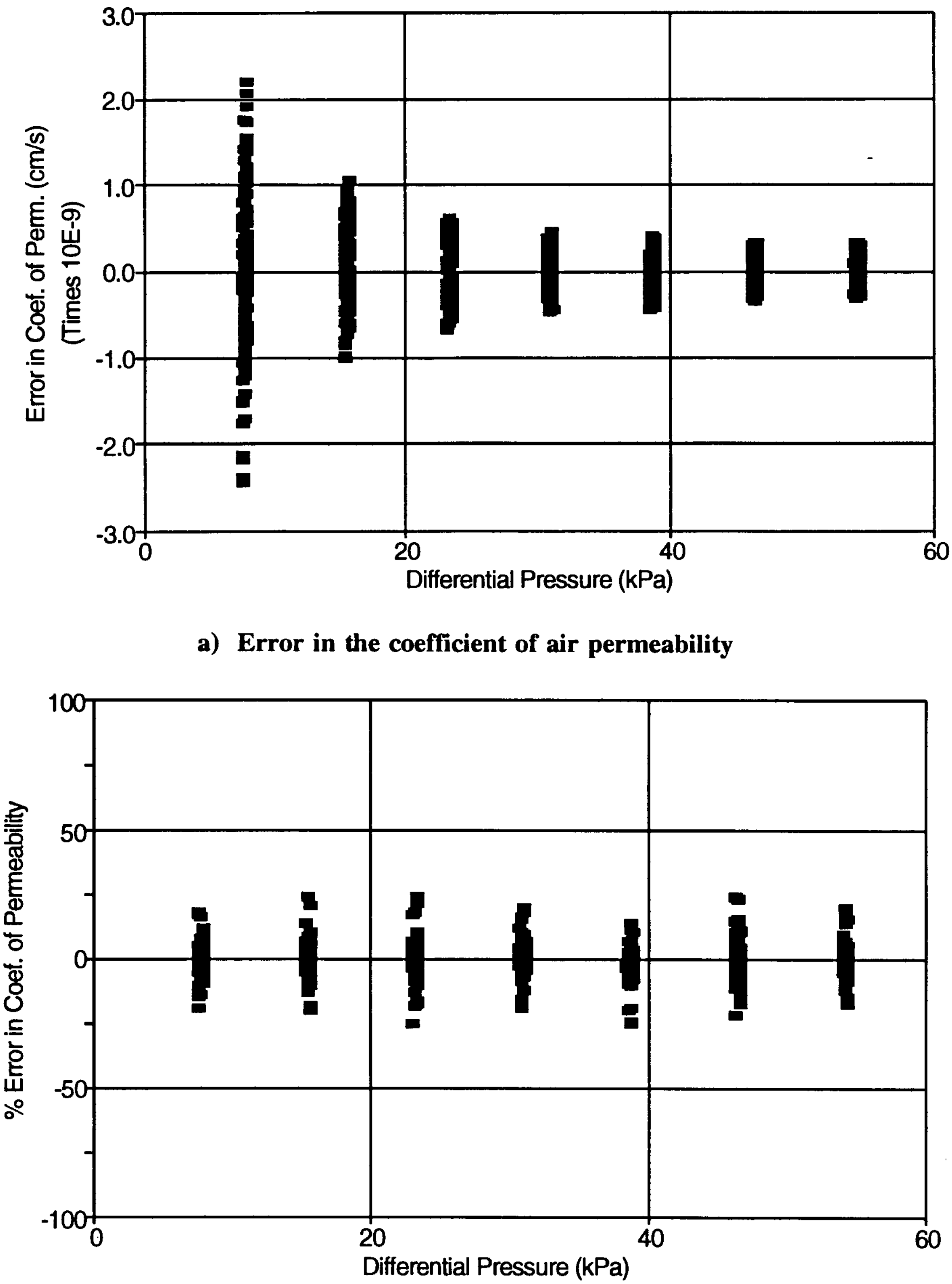


a) Error in the coefficient of air permeability



b) Percent error in the coefficient of air permeability

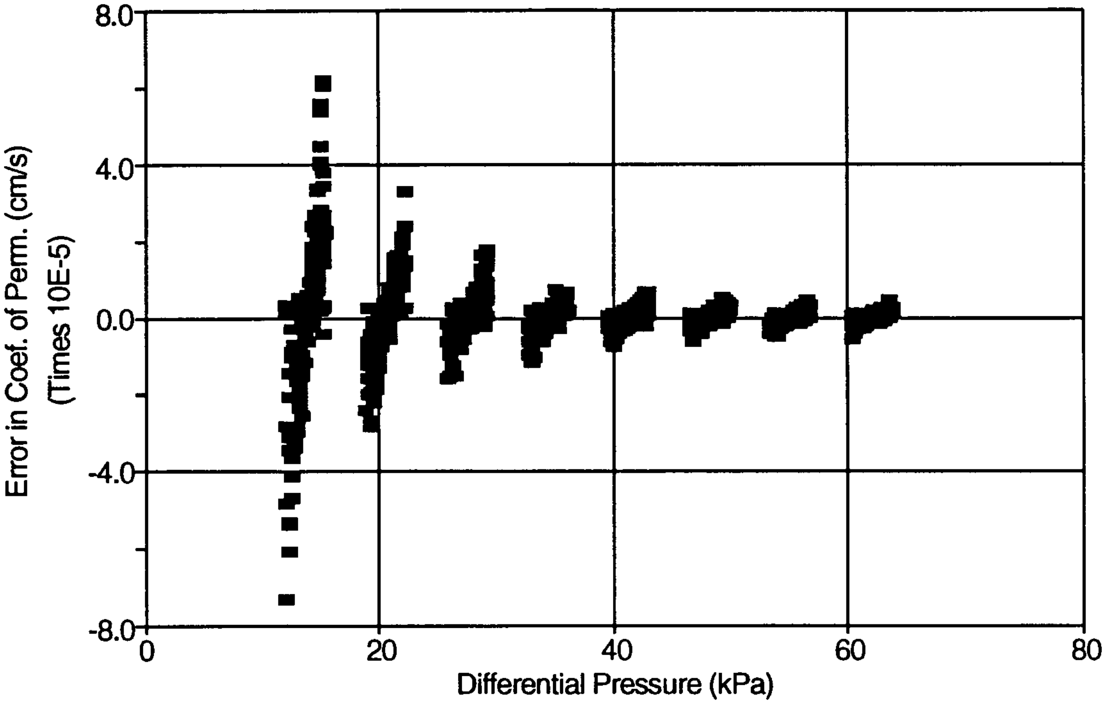
Figure 3.5. Range of error in the coefficient of air permeability, 1-10 scfh flow meter



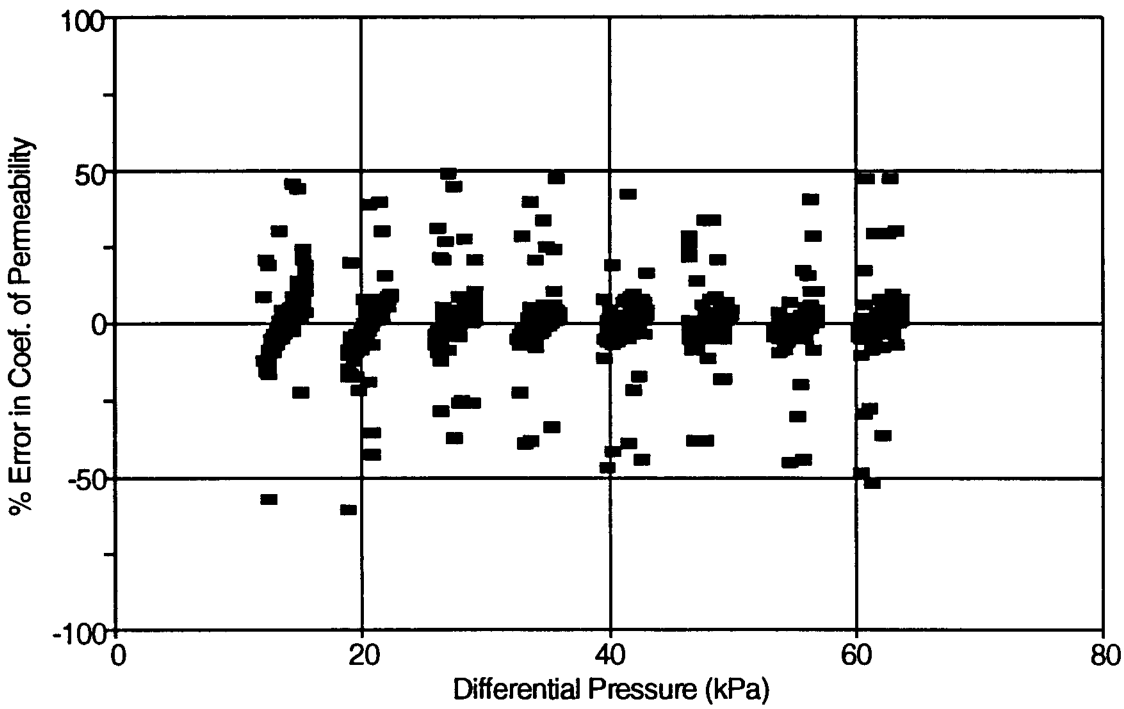
a) Error in the coefficient of air permeability

b) Percent error in the coefficient of air permeability

Figure 3.6. Range of error in the coefficient of air permeability, 4-40 scfh flow meter

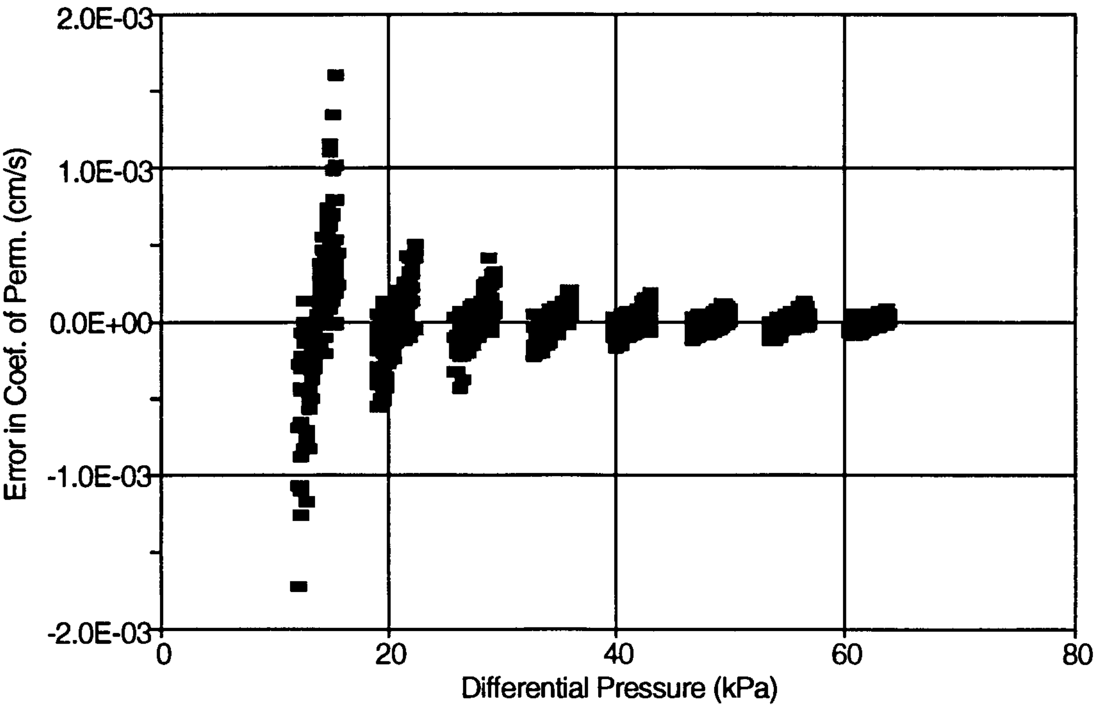


a) Error in the coefficient of air permeability

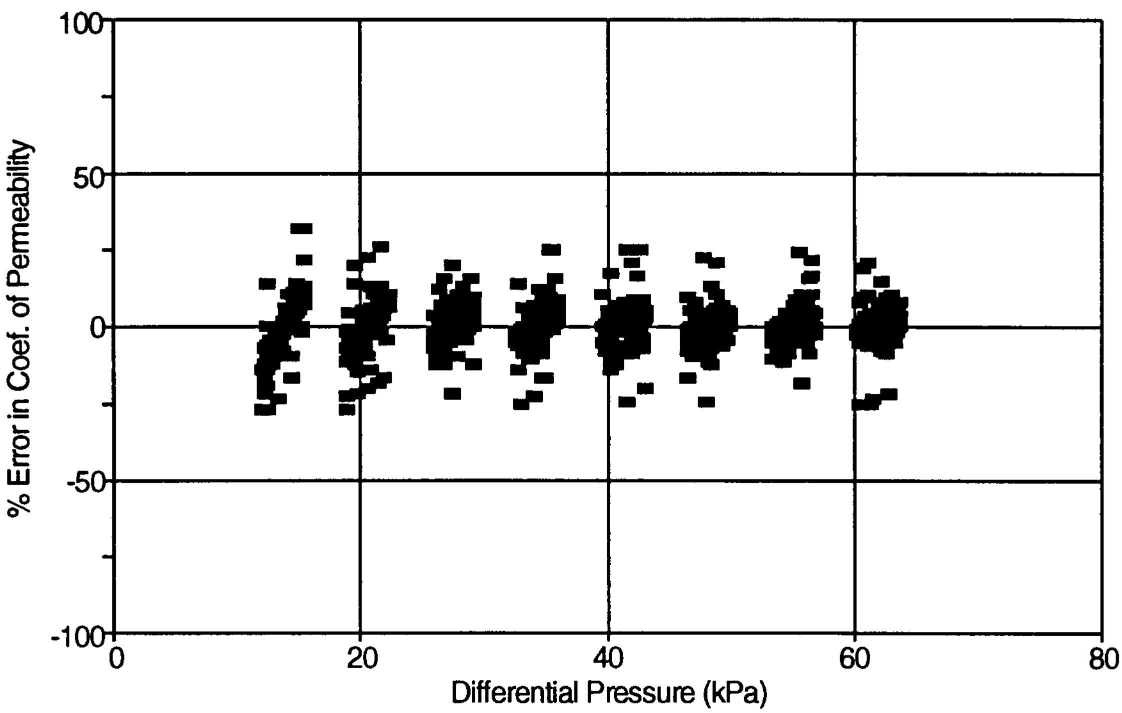


b) Percent error in the coefficient of air permeability

Figure 3.7. Range of error in the coefficient of water permeability, ccm flow meter, system A

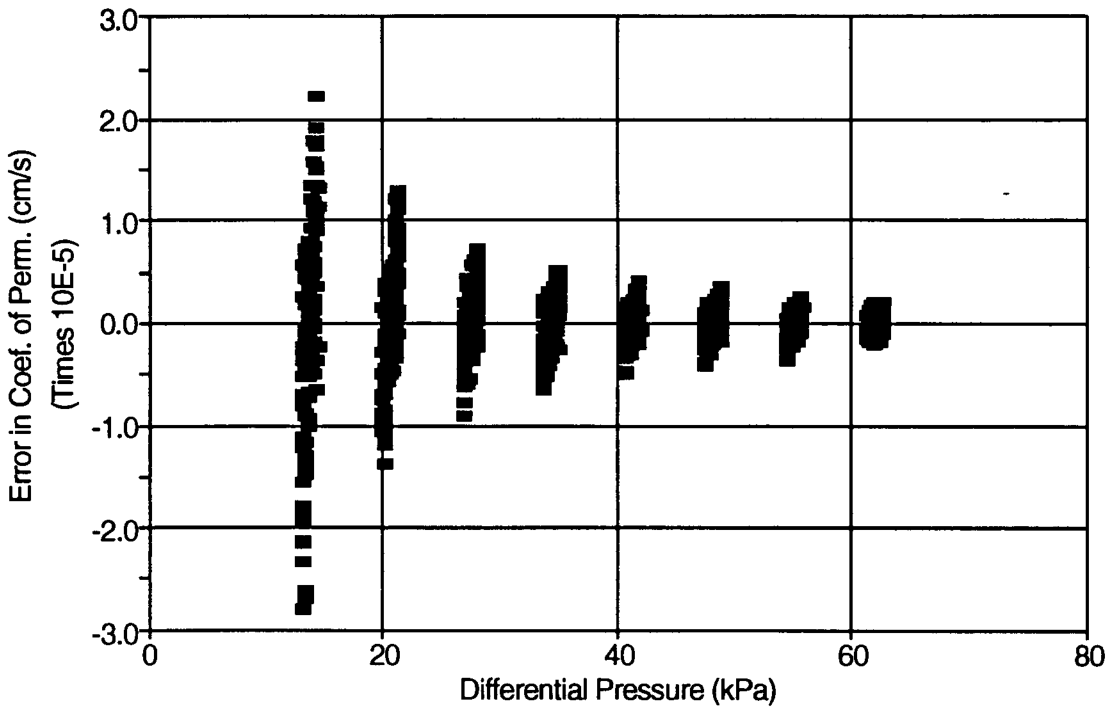


a) Error in the coefficient of air permeability

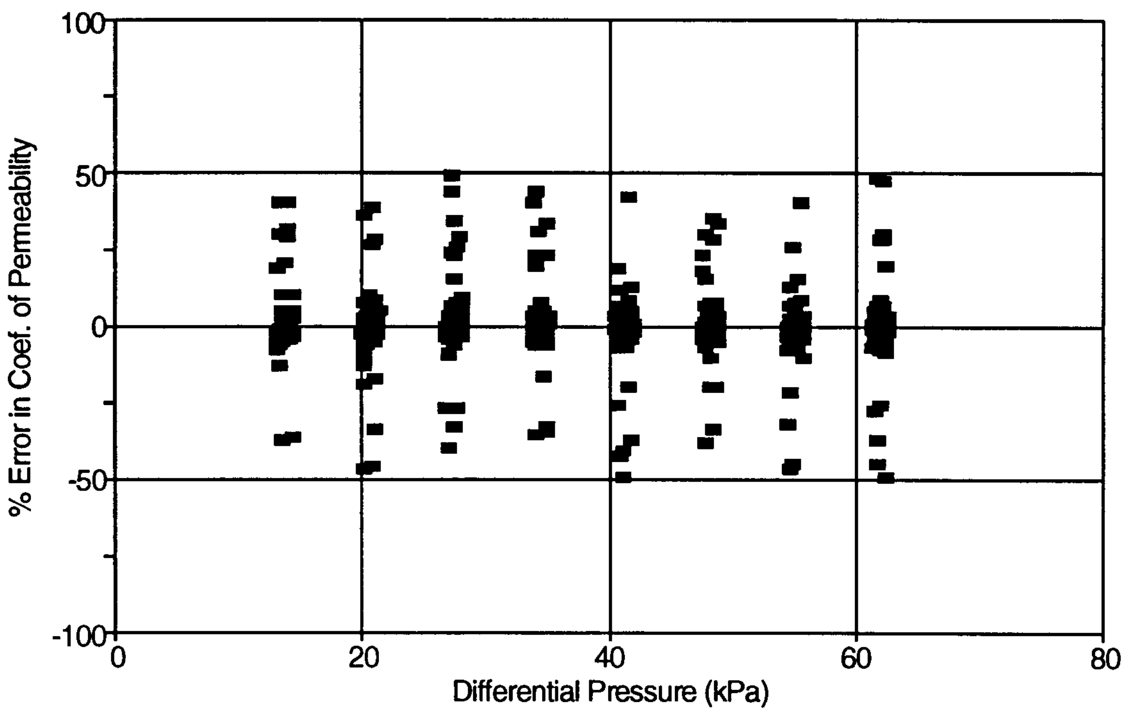


b) Percent error in the coefficient of air permeability

Figure 3.8. Range of error in the coefficient of water permeability, gph flow meter, system A

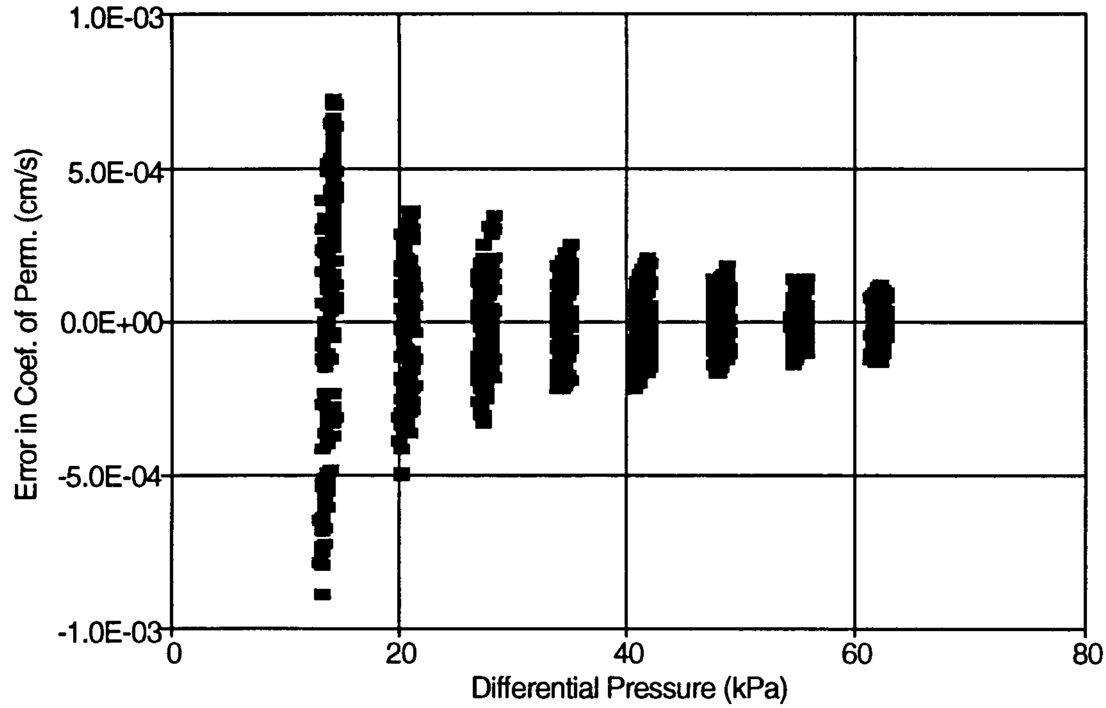


a) Error in the coefficient of air permeability

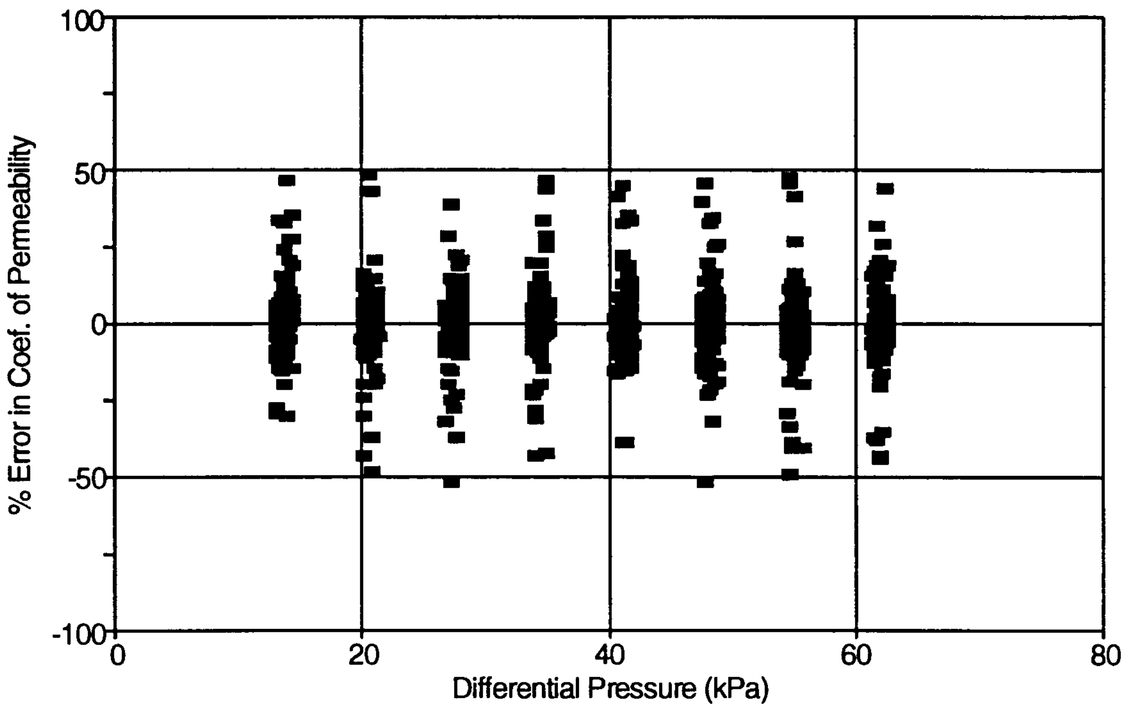


b) Percent error in the coefficient of air permeability

Figure 3.9. Range of error in coefficient of water permeability, ccm flow meter, system B



a) Error in the coefficient of air permeability



b) Percent error in the coefficient of air permeability

Figure 3.10. Range of error in coefficient of water permeability, gph flow meter, system B

3.2 ECS Test Program

The specimens for the original twelve mixtures tested in the ECS program are summarized in Table 3.2. The initial test program included six specimens from each mixture, with the exception of CAB, which only had four specimens. Additional specimens were added to investigate mixtures which had data that varied within the mixture set. The test results for the ECS testing program are shown graphically in Figures 3.11 through 3.22. The complete data set for all ECS testing is presented in Appendix G.

3.2.1 ECS Modulus Data

Each data curve in Figures 3.11 through 3.22 represents a single ECS specimen. The curves define the change in retained resilient modulus (termed ECS-modulus ratio)[1] as a function of the conditioning level (each cycle represents a conditioning cycle within the ECS, with the first three cycles being "hot" cycles and the fourth cycle being the "freeze" cycle). The retained resilient modulus, or ECS modulus ratio, is defined as the ratio of the conditioned resilient modulus to the unconditioned modulus, and is measured at the end of each conditioning cycle. The ECS modulus ratio provides an indication of the amount of stiffness loss in a specimen due to water damage relative to its dry, unconditioned stiffness. Water damage as indicated by a decrease in the ECS modulus ratio may be the result of a loss of adhesion between the asphalt and the aggregate, a loss of cohesion in the asphalt binder, or both. During testing in the ECS, specimens of two mixtures experienced excessive deformation during the test's "hot" cycles: WIA and MS5. This behavior had not occurred during the previous work conducted with the ECS using

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[1] The resilient modulus obtained in the ECS is termed the "ECS modulus" to distinguish it from the traditional diametral and triaxial resilient moduli as well as the dynamic modulus. The ECS modulus is a triaxial resilient modulus with no confining stress (i.e., $\sigma_2 = \sigma_3 = 0$) conducted on a 4.0 in. (102 mm) diameter by 4.0 in (102 mm) high asphalt-aggregate mixture test specimen.

Table 3.2. ECS test specimens, primary test program

Specimen	Air Voids (%)	Visual Degree of Stripping (%)	Binder Migration[1]	Comments
AB5R803	5.5	5	No	
AB5R804	5.3	5	No	
AB5KL01	6.0	5	C	Coarse aggregate stripped
AB5KM03	4.4	5	D	
AB5KH06	2.8	5	E	
AB5KD08	2.6	5	E	Coarse aggregate stripped
AZ5R803	8.3	20	No	General: Fine aggregate stripped, with moderate coarse aggregate stripping
AZ5R805	8.2	20	No	
AZ5KL01	8.4	20	No	
AZ5KM04	8.0	20	No	
AZ5KH05	6.2	20	C	
AZ5KH06	6.3	20	C	
CABKL02	7.4	5	C	
CABKM12	4.9	5	D	
CABKM14	6.0	5	E	
CABKH04	4.1	5	D	
CABKD05	4.0	5	C	
CADR804	9.4	5	No	
CADR806	9.7	5	No	
CADKL02	9.5	5	No	
CADKM04	9.1	5	No	
CADKH05	7.8	5	No	
CADKD07	8.5	5	No	
CADKD08	7.7	5	No	
CAGR803	11.0	20	No	
CAGR805	10.7	20	No	
CAGKL01	9.3	30	No	
CAGKM04	8.8	20	No	
CAGKD06	7.8	30	A	
CAGKD07	7.0	20	B	

Table 3.2. ECS test specimens, primary test program (continued)

Specimen	Air Voids (%)	Visual Degree of Stripping (%)	Binder Migration[1]	Comments
GAAR803	7.6	0	No	
GAAR806	9.1	0	No	
GAAKL12	9.8	5	No	One piece of coarse aggregate stripped
GAAKM11	9.2	0	No	
GAAKH04	7.4	0	No	
GAAKD01	6.4	5	No	One piece of coarse aggregate stripped
MN5R803	11.3	5	No	General: All specimens very similar in
MN5R804	10.6	5	No	appearance except for binder migration
MN5R806	11.7	5	No	
MN5KL03	6.5	5	D	
MN5KM05	5.6	5	D	
MN5KD08	4.4	5	D	
			D	
MN5KD09	3.0	5	D	
MS5R804	7.6	20	No	
MS5R805	8.0	20	No	
MS5KL03	6.9	20	A	
MS5KM04	5.9	20	C	Failed[2] 1st cycle--loading continued
MS5KH07	4.1	20	C	Failed[2] 1st cycle--sample removed
MS5KD08	3.5	20	C	Failed[2] 1st cycle--loading continued
OR1R803	8.3	5	No	General: Orange aggregate stripped
OR1R804	7.4	0	No	
OR1R806	7.3	5	No	
OR1KL02	11.6	5	No	
OR1KM04	9.2	0	B	
OR1KH07	7.0	0	C	
OR1KD08	6.8	0	C	
OR2R803	21.3	10	No	General: Some coarse aggregate shows
OR2R804	20.2	5	No	signs of degradation.
OR2KL02	19.6	20	No	
OR2KH05	17.3	5	No	
OR2KH06	16.2	5	No	
OR2KD08	18.1	10	No	
OR2KD09	16.7	5	No	

Table 3.2. ECS test specimens, primary test program (continued)

Specimen	Air Voids (%)	Visual Degree of Stripping (%)	Binder Migration[1]	Comments
WA1R804	7.0	0	No	
WA1R805	6.6	0	No	
WA1KL20	11.4	5	D	
WA1KL21	10.3	5	E	
WA1KM22	10.3	5	E	
WA1KD07	7.3	5	E	
WA1KD26	8.6	5	F	
WA1KD27	9.1	5	F	
WIAR804	3.4	5	No	
WIAR805	3.5	5	No	
WIAKL01	3.3	5	No	Failed[2] 1st cycle--loading discontinued
WIAKM08	1.8	5	No	
WIAKH15	1.4	5	No	Failed[2] 2nd cycle--loading continued
WIAKD18	0.6	5	No	
WIAKD19	0.7	5	No	

[1] Figure 2.09 illustrates the rating scale for binder migration
[2] Failed due to excessive deformation under repeated axial loading

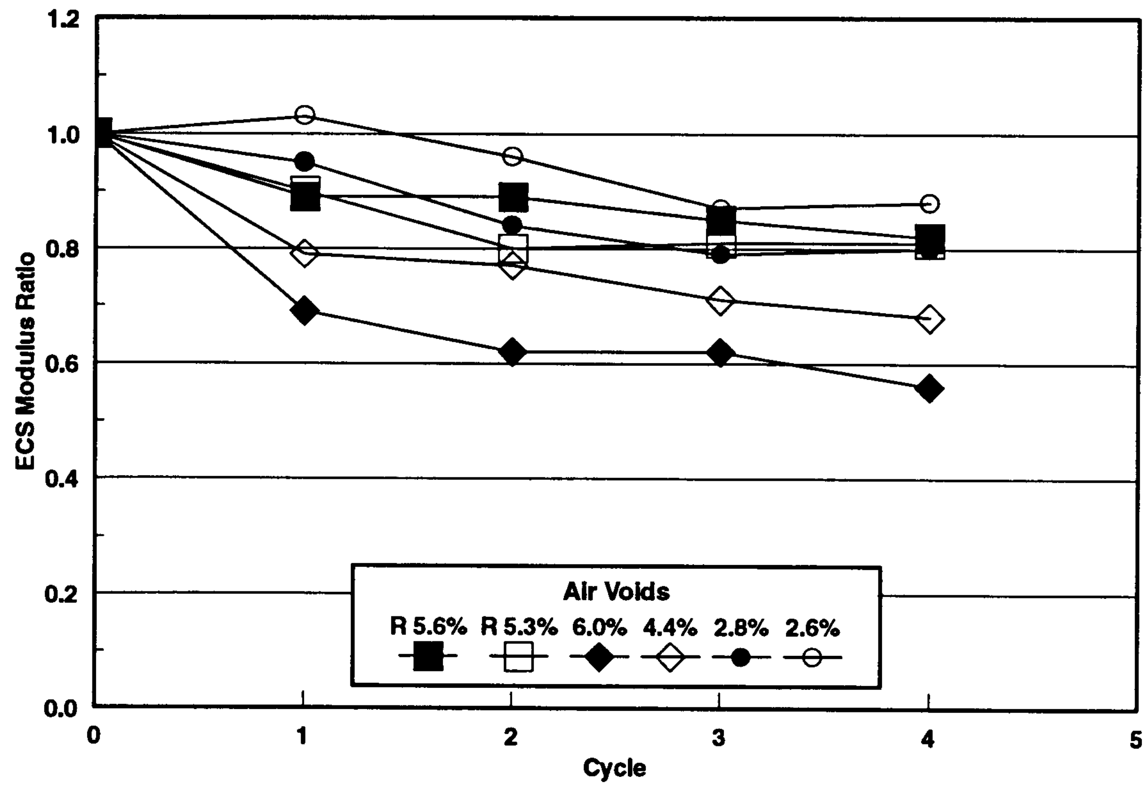


Figure 3.11. Alberta, SPS-5 (AB5) ECS results

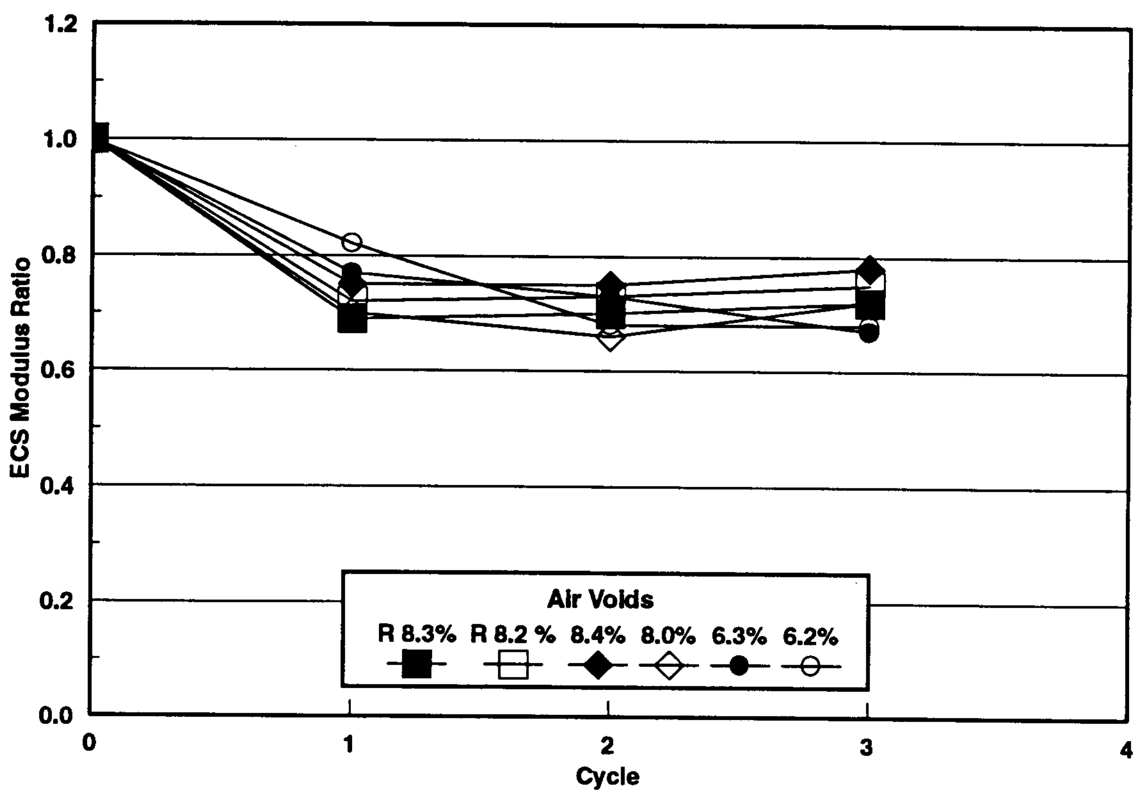


Figure 3.12. Arizona, SPS-5 (AZ5) ECS results

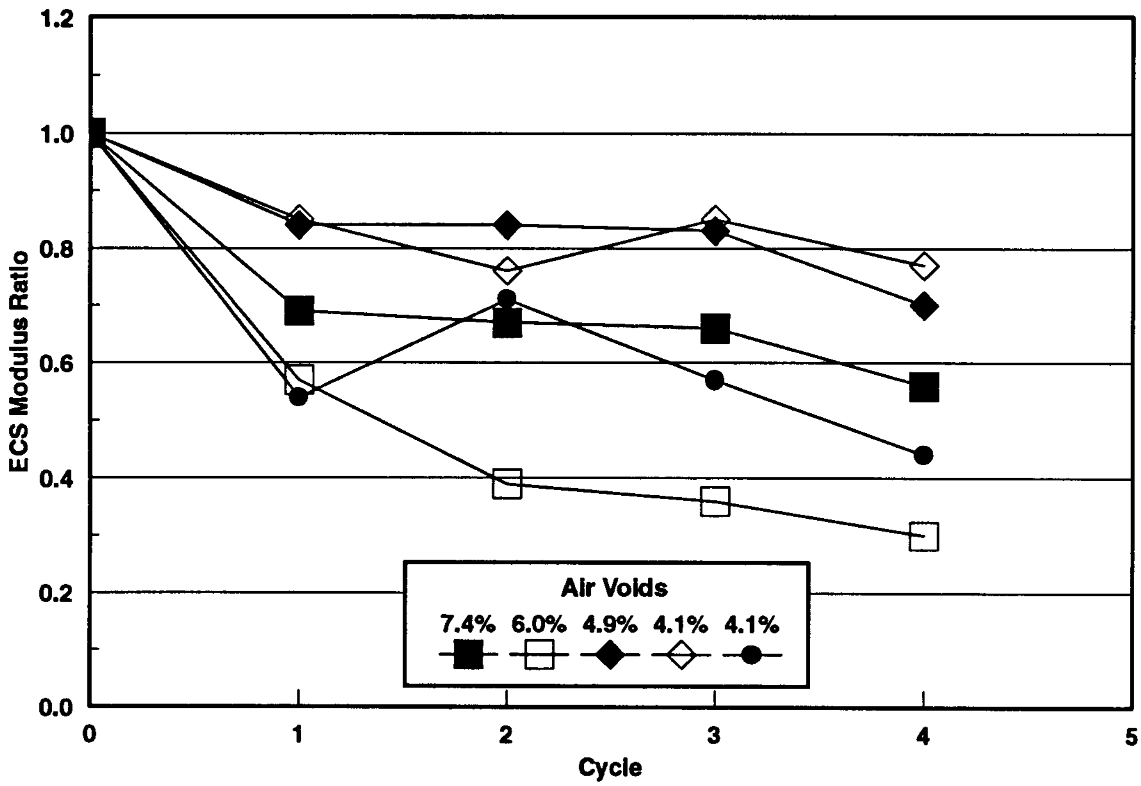


Figure 3.13. California, AAMAS Batch (CAB) ECS results

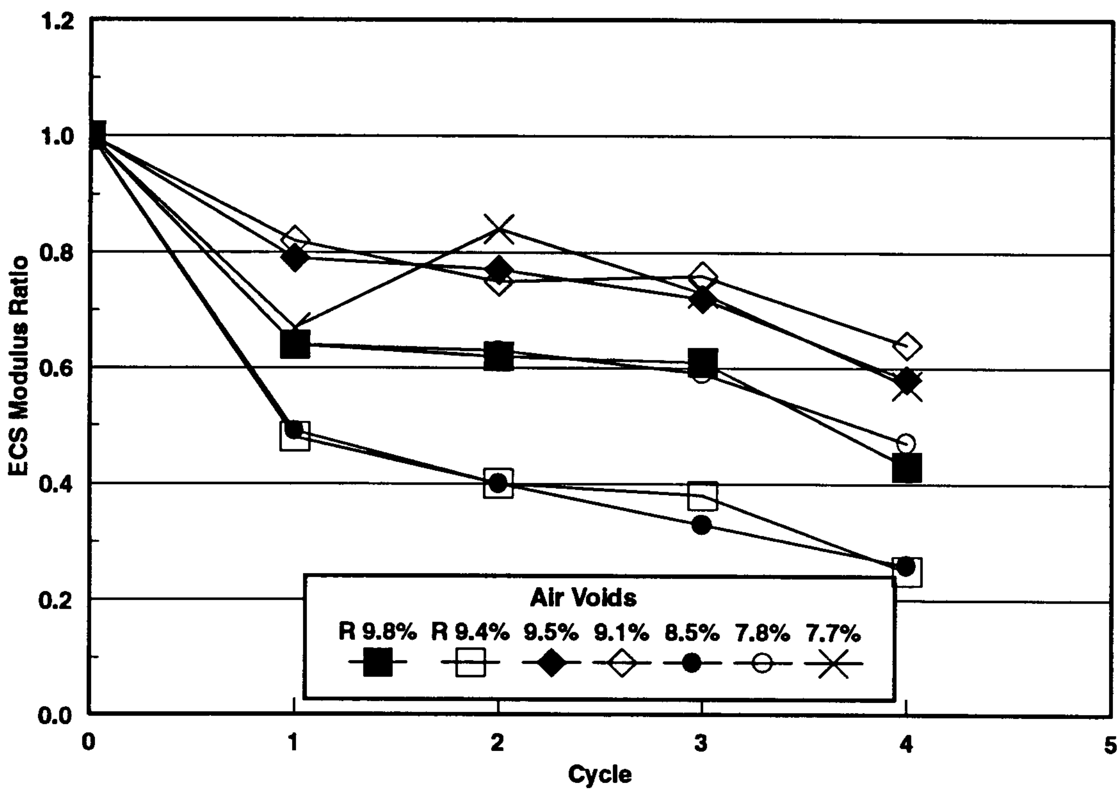


Figure 3.14. California, AAMAS Drum (CAD) ECS results

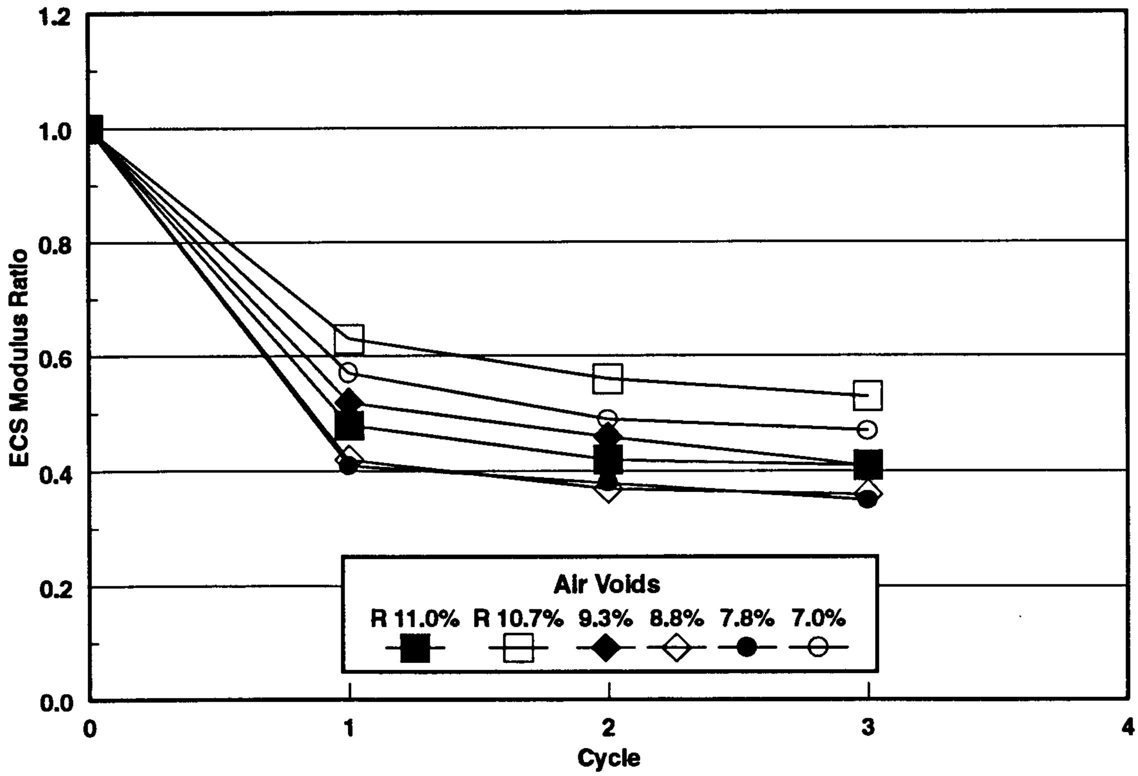


Figure 3.15. California, GPS-6b (CAG) ECS results

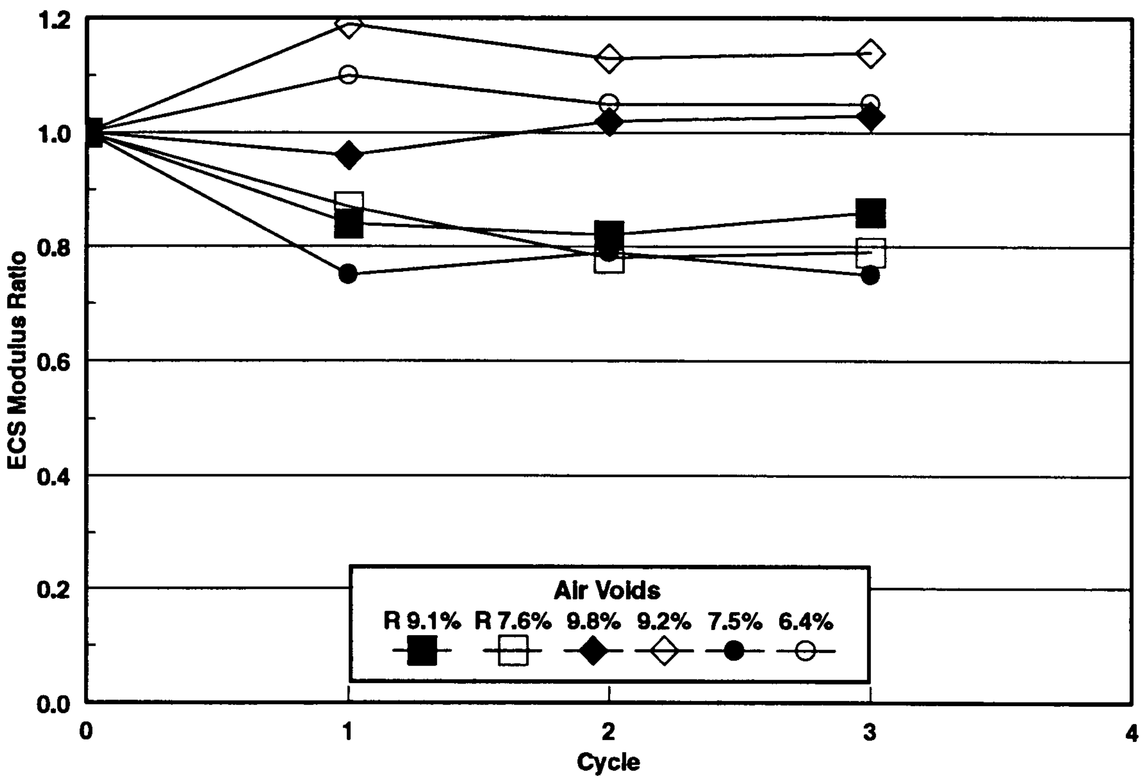


Figure 3.16. Georgia, AAMAS (GAA) ECS results

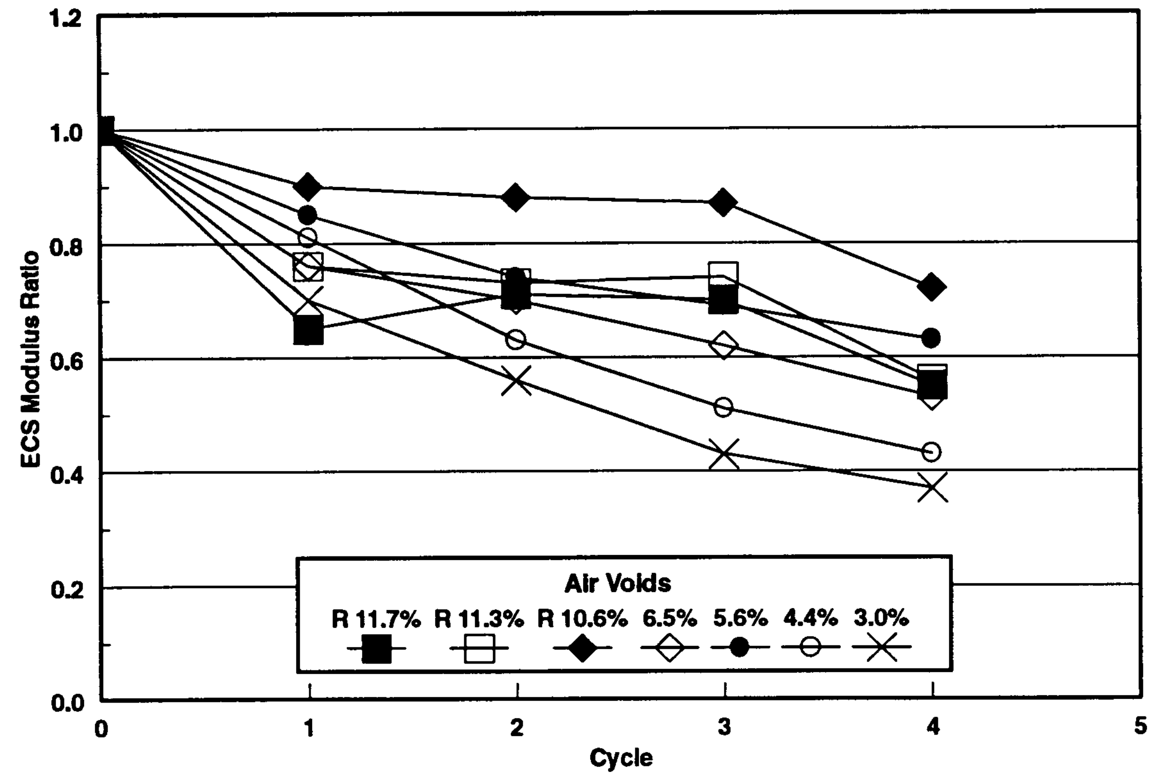


Figure 3.17. Minnesota, SPS-5 (MN5) ECS results

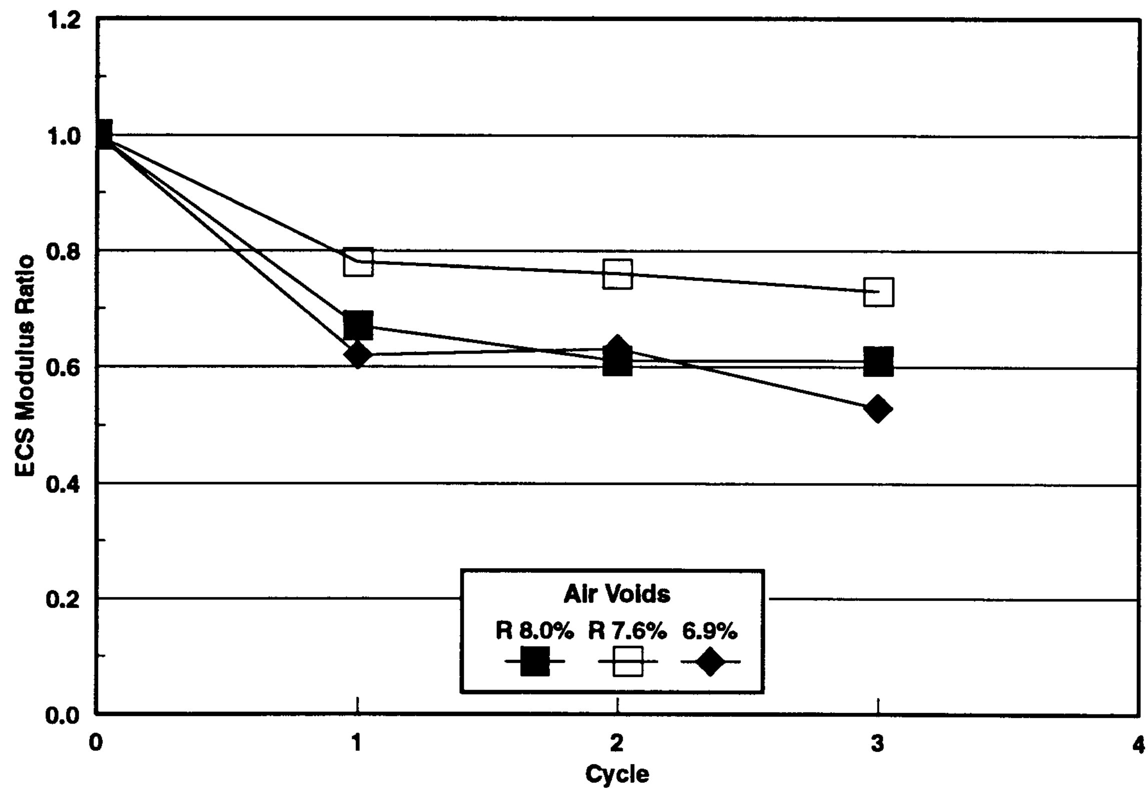


Figure 3.18. Mississippi, SPS-5 (MS5) ECS results

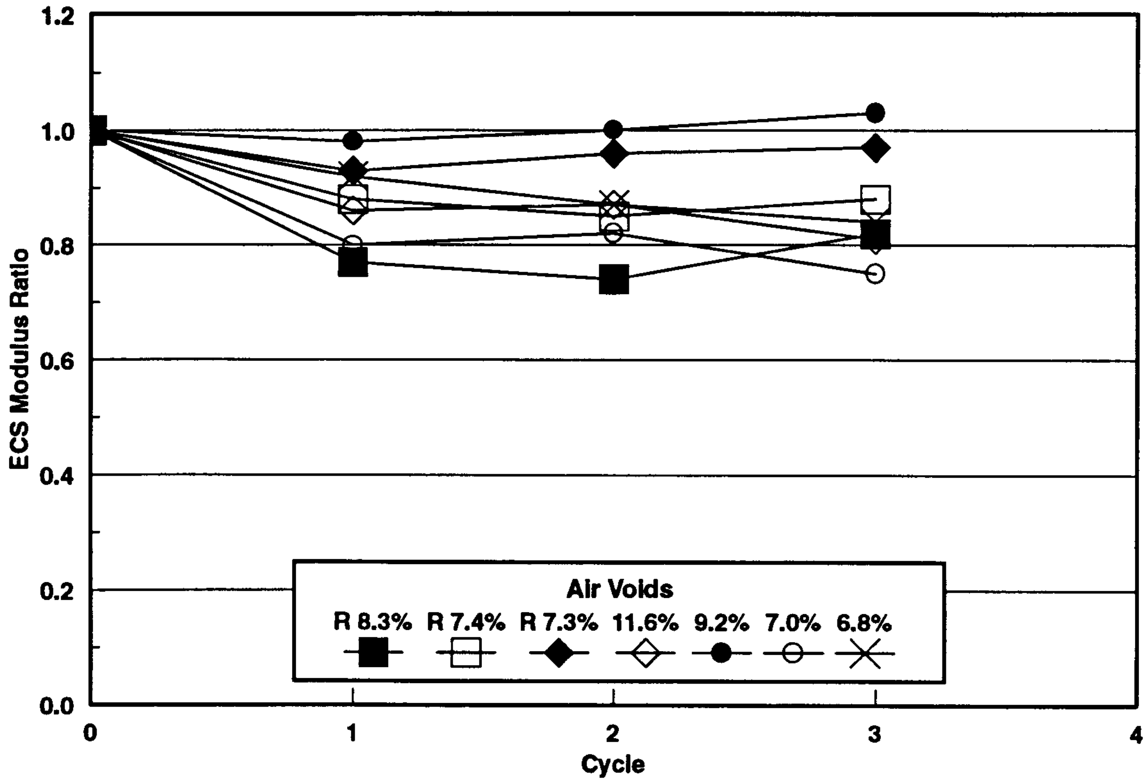


Figure 3.19. Rainier, Oregon (OR1) ECS results

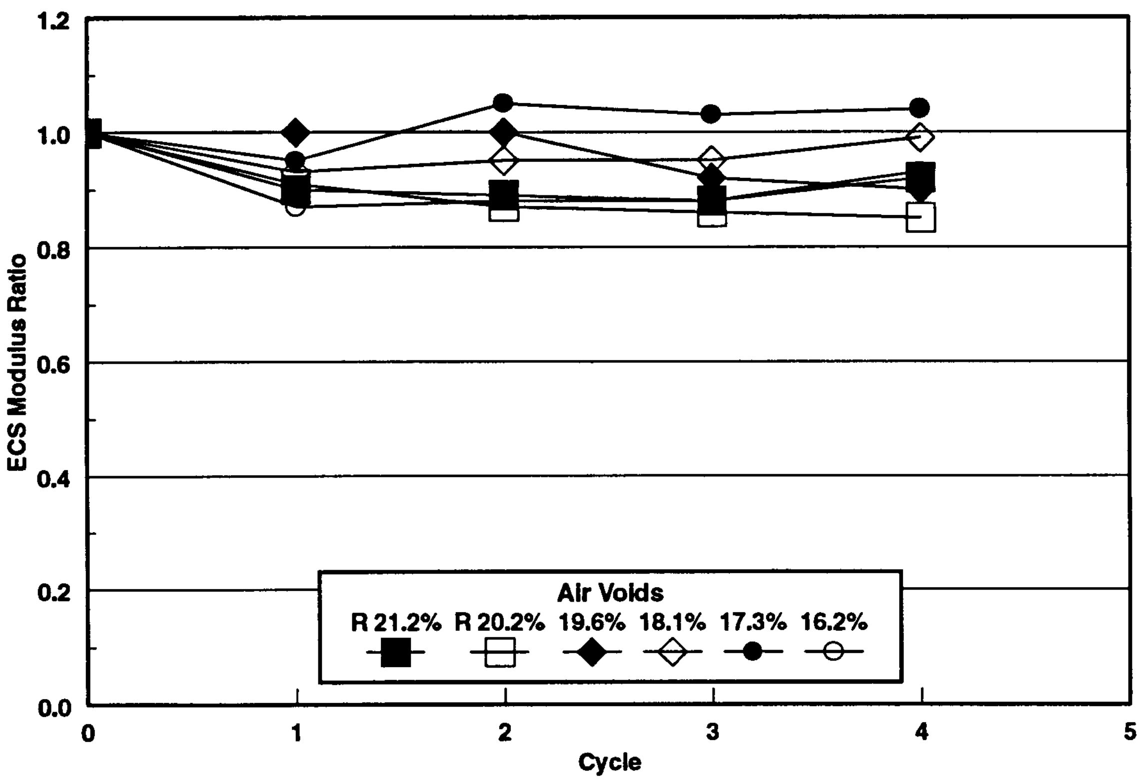


Figure 3.20. Bend-Redmond, Oregon (OR2) ECS results

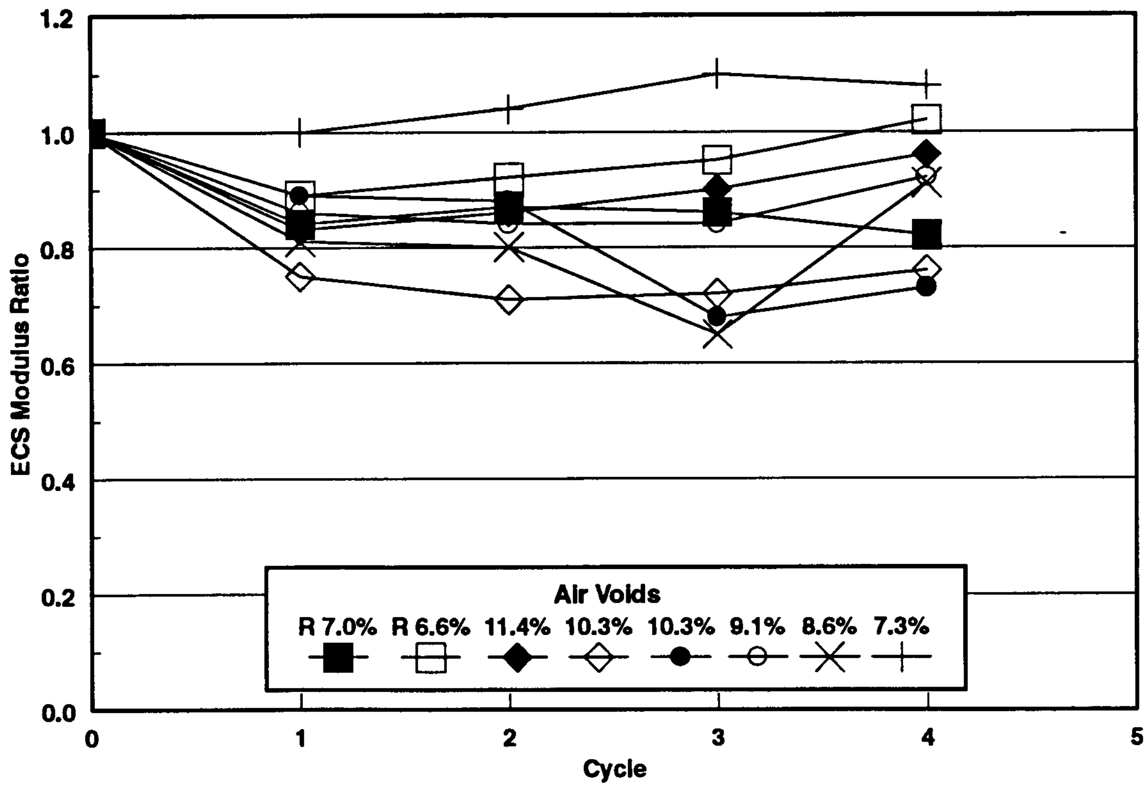


Figure 3.21. Mount Baker, Washington (WA1) ECS results

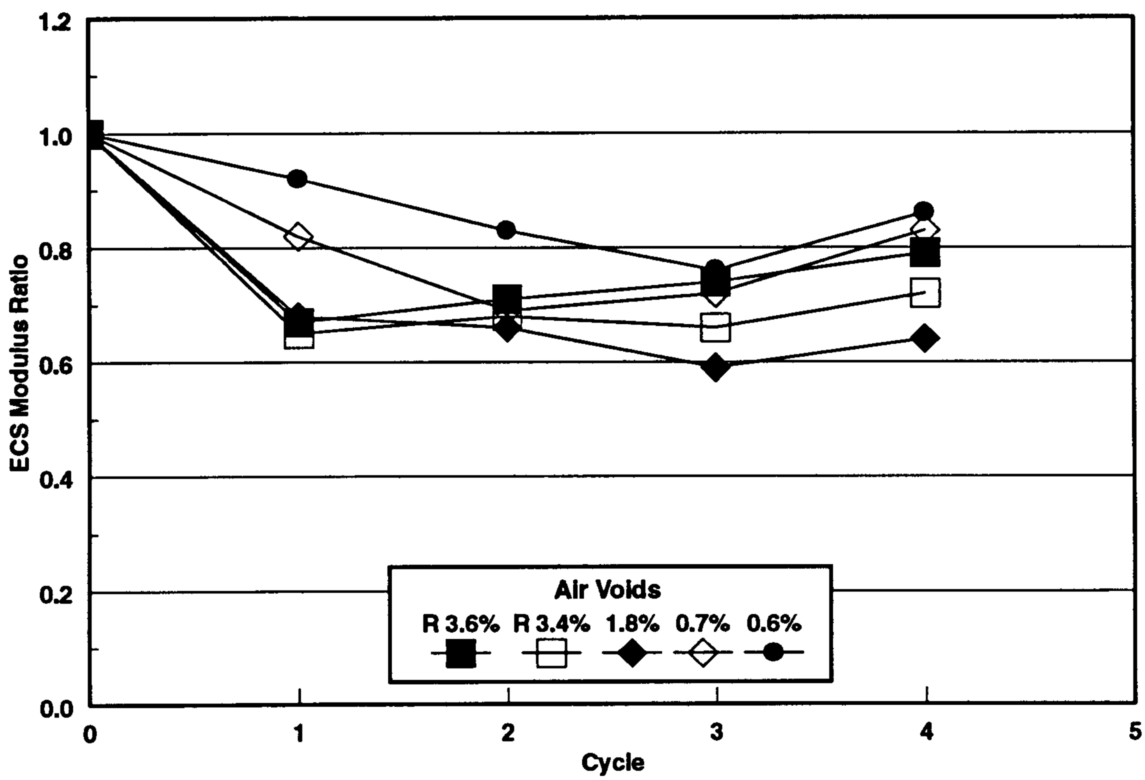


Figure 3.22. Wisconsin, AAMAS (WIA) ECS results

other SHRP asphalts and aggregates. For the purposes of this report, specimens that deformed excessively within the ECS (defined as a loss in sample height of between 5-15 percent, so that the yoke which holds the LVDTs to the specimen could no longer be mounted) were considered "failed," and were not used for the statistical analysis that follows.

In some cases, "failed" specimens were left in the ECS for further conditioning, without the repeated loading, even though it was impossible to take further modulus readings. In other cases, the repeated loading was stopped before the specimen had deformed to the extent that modulus testing was impossible; the specimen was further conditioned without loading, with modulus testing taking place between cycles. The data for these specimens also appear in Appendix G. The specimens which experienced "failure" due to excessive deformation within the ECS test apparatus are identified in Table 3.2.

3.2.2 Degree of Visual Stripping and Binder Migration Data

The visual degree of stripping evaluated after the completion of the ECS procedure indicates the level of adhesion loss between a specimen's asphalt binder and aggregate. Binder migration may be the result of both a loss of adhesion between the asphalt binder and the aggregate, and a loss of cohesion within the asphalt binder. In order for asphalt binder particles to migrate within the specimen, the particles must first debond from all surrounding material. This includes both loss of adhesion between the binder and the aggregate, and loss of cohesion between binder particles. The complete data set from the ECS testing program is included in Appendix G.

3.2.3 Permeability Data

Average values of the coefficients of permeability and the intrinsic permeabilities for all mixtures are reported in Table 3.3. The coefficients of air and

Table 3.3. Average coefficients of permeability, intrinsic permeabilities for primary mixtures[1]

Mixture	Coefficient of Permeability, Air (cm/sec)	Intrinsic Permeability, Air Flow (cm^2)	Coefficient of Permeability, Water (cm/sec)	Intrinsic Permeability, Water Flow (cm^2)
AB5	3.89E-06 (1)[2]	6.15E-10 (1)	2.67E-05 (3)	2.43E-10 (3)
AZ5	2.29E-05 (4)	3.63E-09 (4)	6.78E-05 (4)	6.18E-10 (4)
CAB	7.08E-06 (1)	1.12E-09 (1)	2.61E-05 (1)	2.38E-10 (1)
CAD	6.97E-05 (7)	1.10E-08 (7)	1.11E-04 (7)	1.01E-09 (7)
CAG	4.59E-05 (6)	7.26E-09 (6)	2.80E-04 (6)	2.55E-09 (6)
GAA	5.50E-05 (6)	8.69E-09 (6)	4.50E-04 (6)	4.10E-09 (6)
MN5	5.98E-05 (4)	9.47E-09 (4)	4.20E-04 (4)	3.83E-09 (4)
MS5	9.57E-06 (1)	1.51E-09 (1)	6.56E-05 (2)	5.98E-10 (2)
OR1	4.04E-05 (4)	6.39E-09 (4)	7.24E-04 (5)	6.59E-09 (5)
OR2	8.10E-05 (4)	1.28E-08 (4)	2.93E-02 (5)	2.67E-07 (5)
WA1	1.00-05 (3)	1.59E-09 (3)	1.93E-04 (3)	1.76E-09 (3)
WIA	--[3]	--	--	--

[1] For new, unconditioned, laboratory-fabricated specimens
[2] Indicates number of specimens represented in average
[3] Indicates permeability too low to read with ECS apparatus

water permeability were calculated using Darcy's law, as described in Appendix D. The calibration factors reported have been applied to the water flow data. The coefficient of permeability is dependent on both the media and the fluid. The intrinsic permeability is a property of the media only. The two terms are related as follows:

$$k = K\frac{\gamma}{\mu} \tag{3.1}$$

where k = coefficient of permeability (m/s),
K = intrinsic permeability (m^2),
γ = specific weight of the fluid (N/m^3), and
μ = viscosity of the fluid ($N\text{-}s/m^2$).

It was not uncommon for specimens to have coefficients of air and water permeability too low for the ECS equipment to measure. Of the 78 specimens tested, 37 were impermeable to air in the ECS apparatus and 32 were impermeable to water after the initial 30 minute "wetting" procedure. The lower limits of the ECS permeability apparatus are approximately 1.14E-07 in./s (7.90E-07 cm/s) for air and 2.86E-06 in./s (7.17E-06 cm/s) for water. Also, five of the specimens tested were impermeable to air, and yet permeable to water after the 30-minute wetting procedure.

Figure 3.23 shows the relationship between the coefficient of air permeability and the percent air voids. Similar data for the coefficient of water permeability are shown in Figure 3.24. These data are for new, laboratory fabricated specimens. For both air and water flow, the coefficient of permeability tends to increase with increasing air voids.

Figures 3.25 through 3.36 show the variation of the coefficient of water permeability throughout the ECS test procedure.

3.2.4 Deformation Data

Figures 3.37 through 3.47 present the deformation data from the original mixtures tested in the ECS. Mixture OR2 is not included because it was not subjected to repeated loading during the hot cycle conditioning. Specimens which exhibited excessive deformation may not be shown, as the LVDTs quickly extended beyond

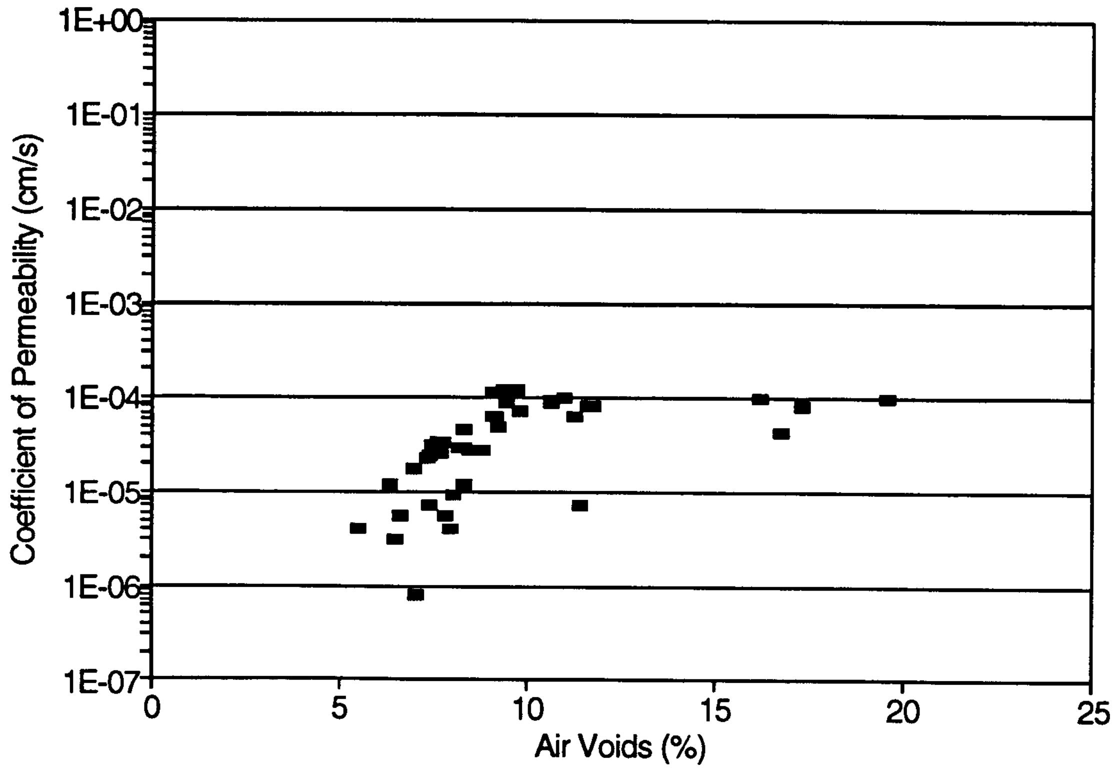


Figure 3.23. Variation in the coefficient of air permeability with air voids

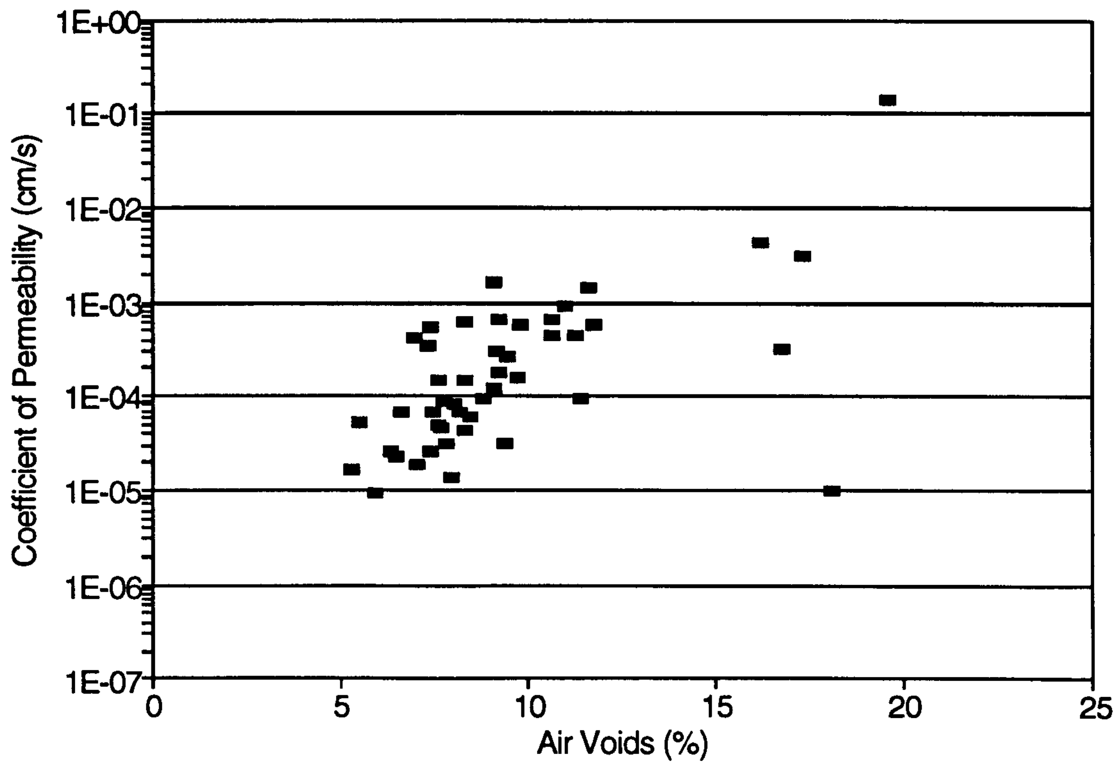


Figure 3.24. Variation in the coefficient of water permeability with air voids

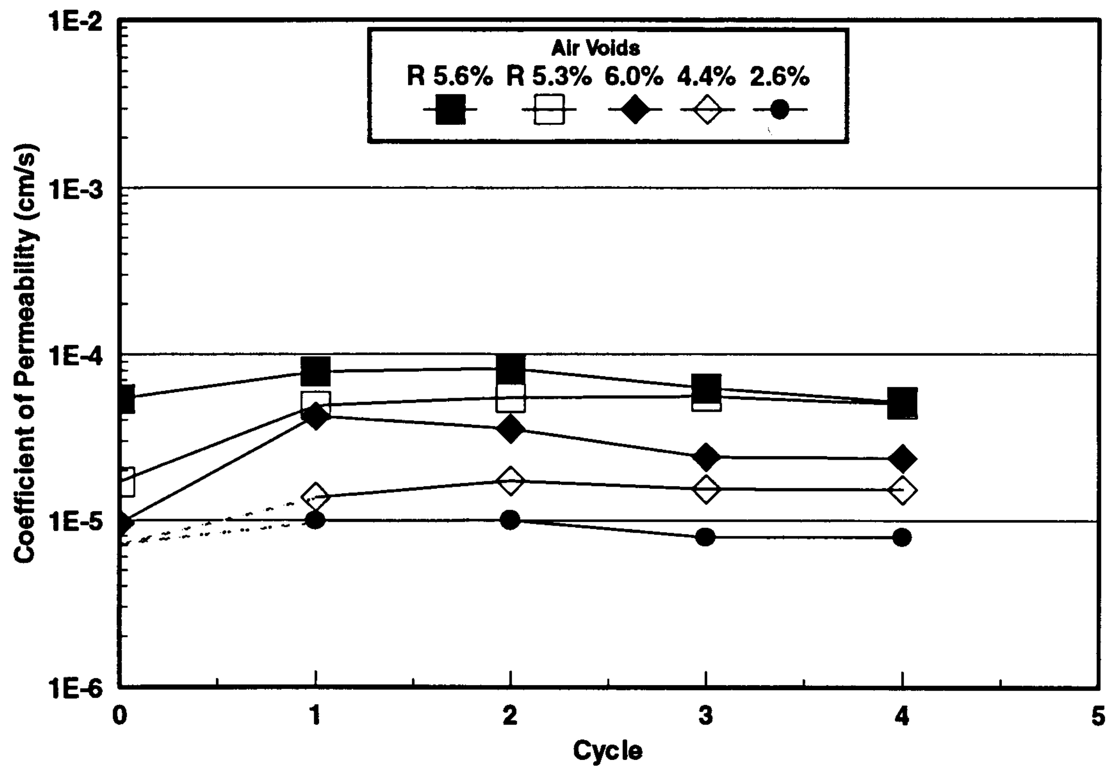


Figure 3.25. Variation in the coefficient of water permeability in the ECS procedure, Alberta, SPS-5 (AB5)

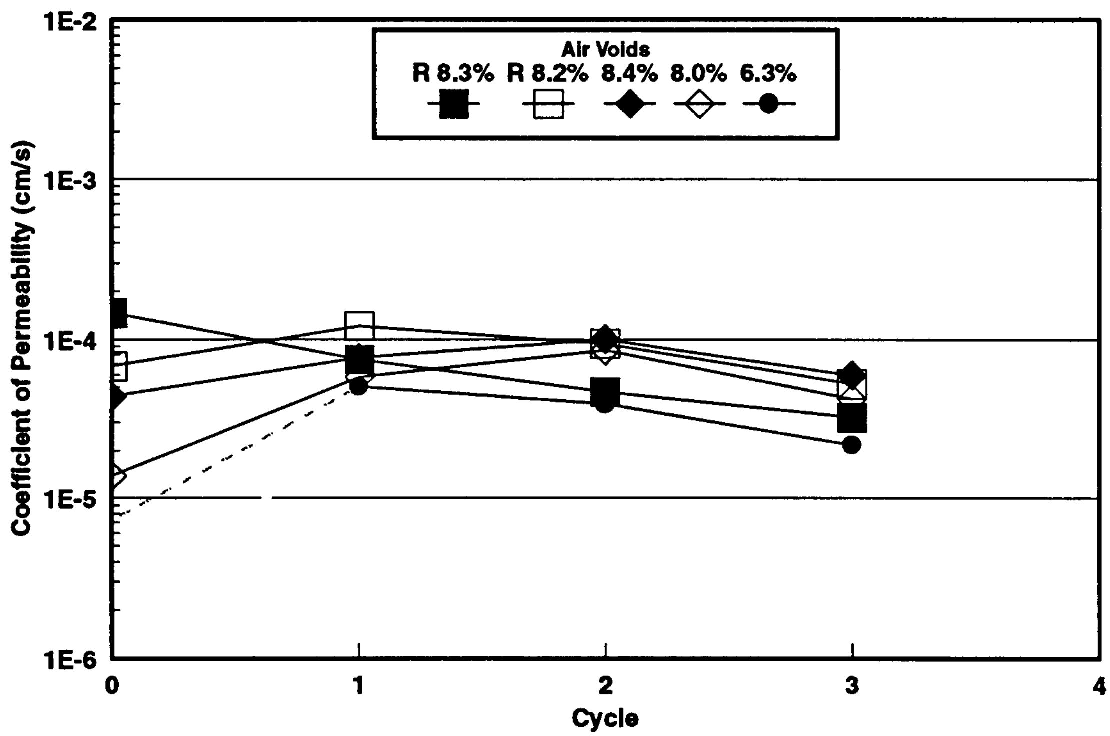


Figure 3.26. Variation in the coefficient of water permeability in the ECS procedure, Arizona, SPS-5 (AZ5)

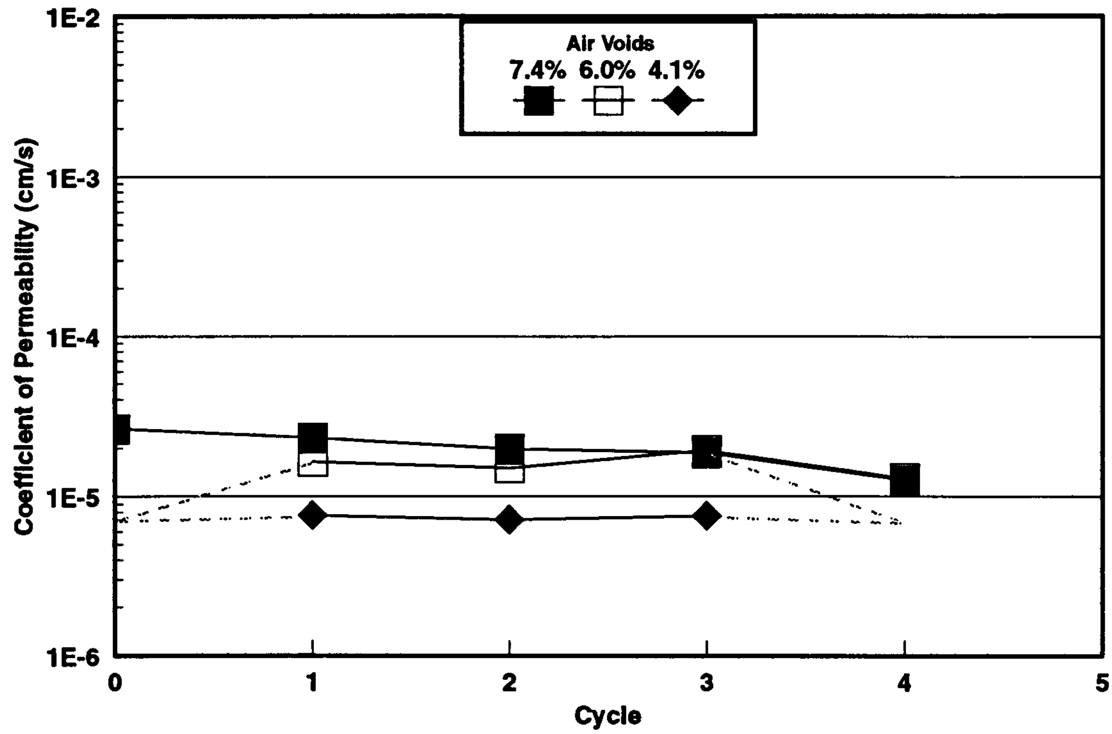


Figure 3.27. **Variation in the coefficient of water permeability in the ECS procedure, California, AAMAS Batch (CAB)**

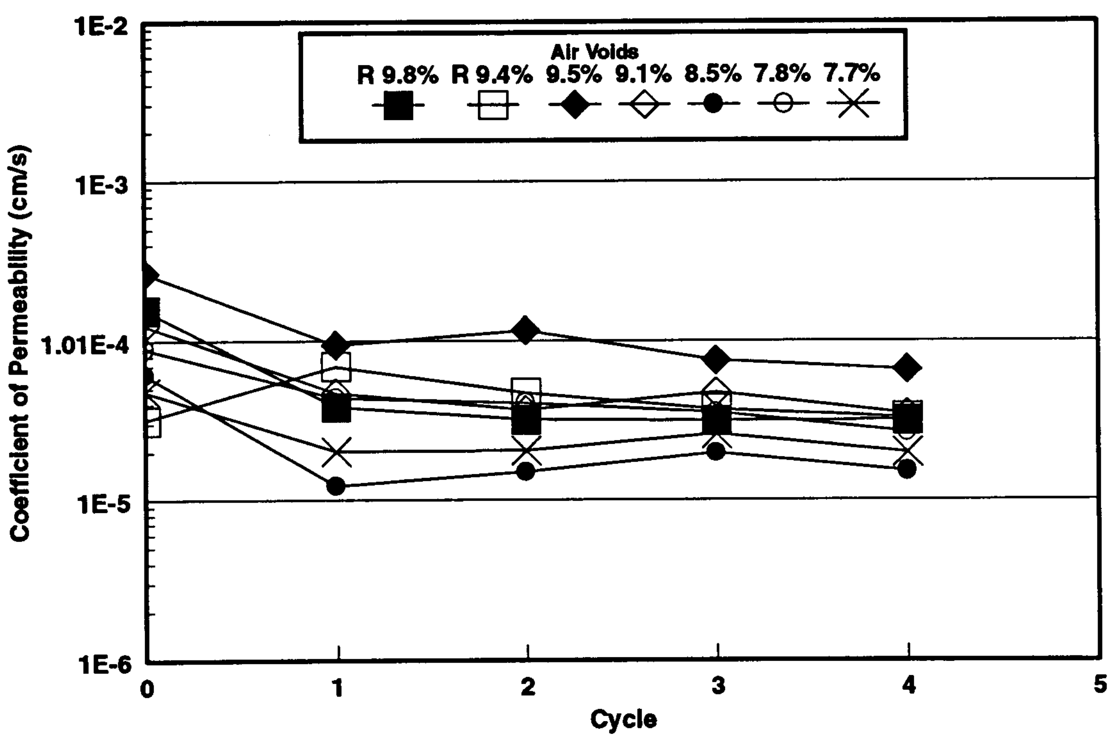


Figure 3.28. **Variation in the coefficient of water permeability in the ECS procedure, California, AAMAS Drum (CAD)**

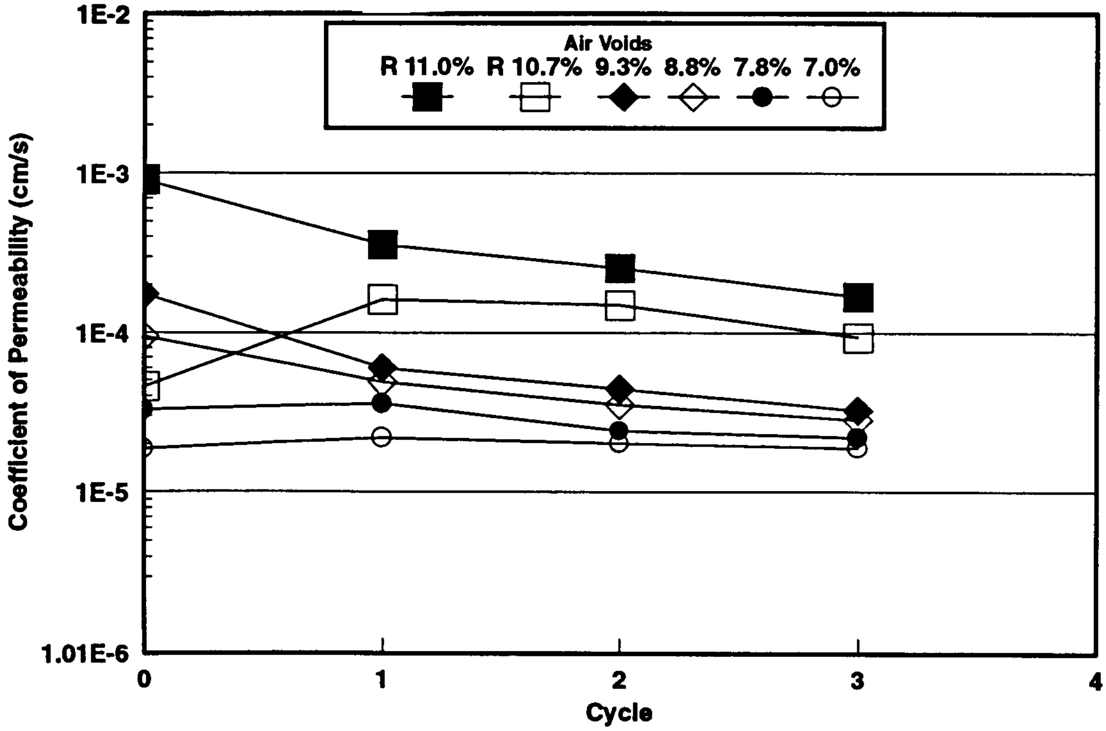


Figure 3.29. Variation in the coefficient of water permeability in the ECS procedure, California, GPS-6b (CAG)

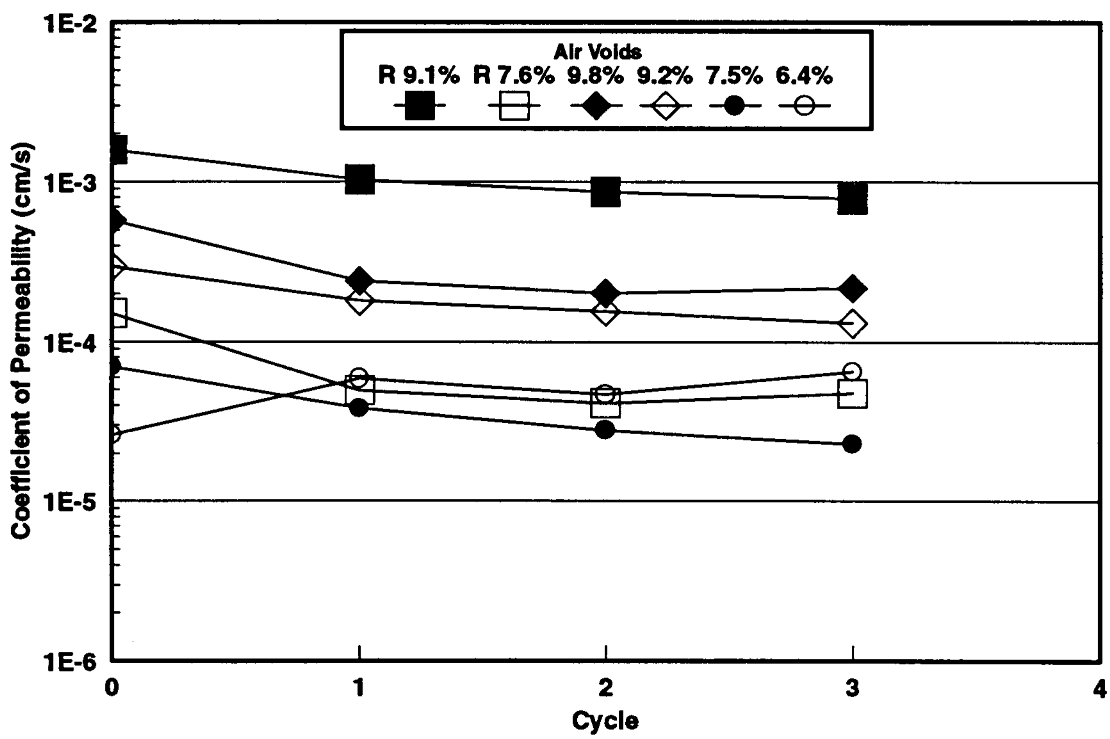


Figure 3.30. Variation in the coefficient of water permeability in the ECS procedure, Georgia, AAMAS (GAA)

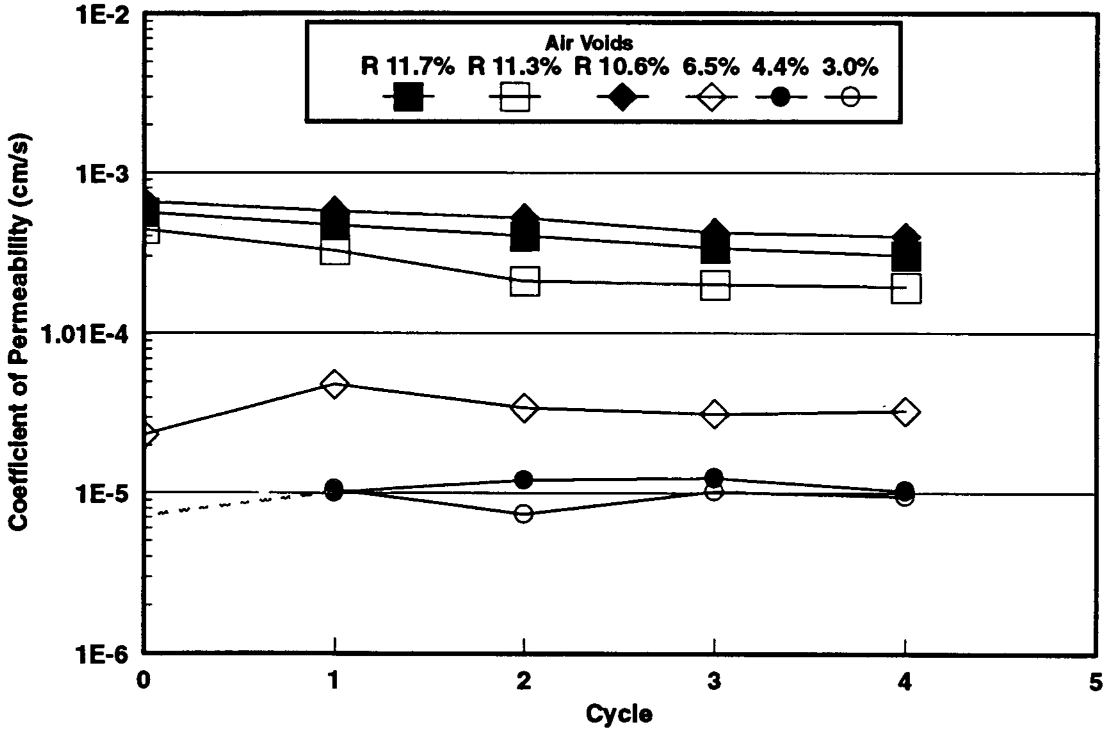


Figure 3.31. Variation in the coefficient of water permeability in the ECS procedure, Minnesota, SPS-5 (MN5)

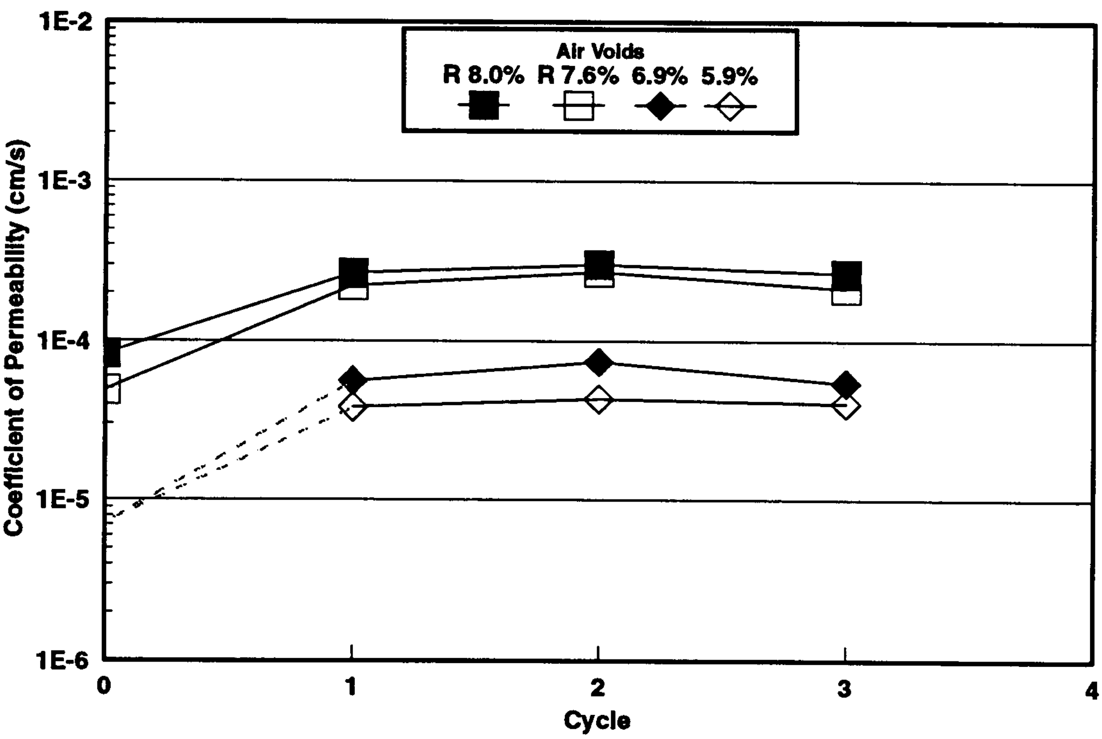


Figure 3.32. Variation in the coefficient of water permeability in the ECS procedure, Mississippi, SPS-5 (MS5)

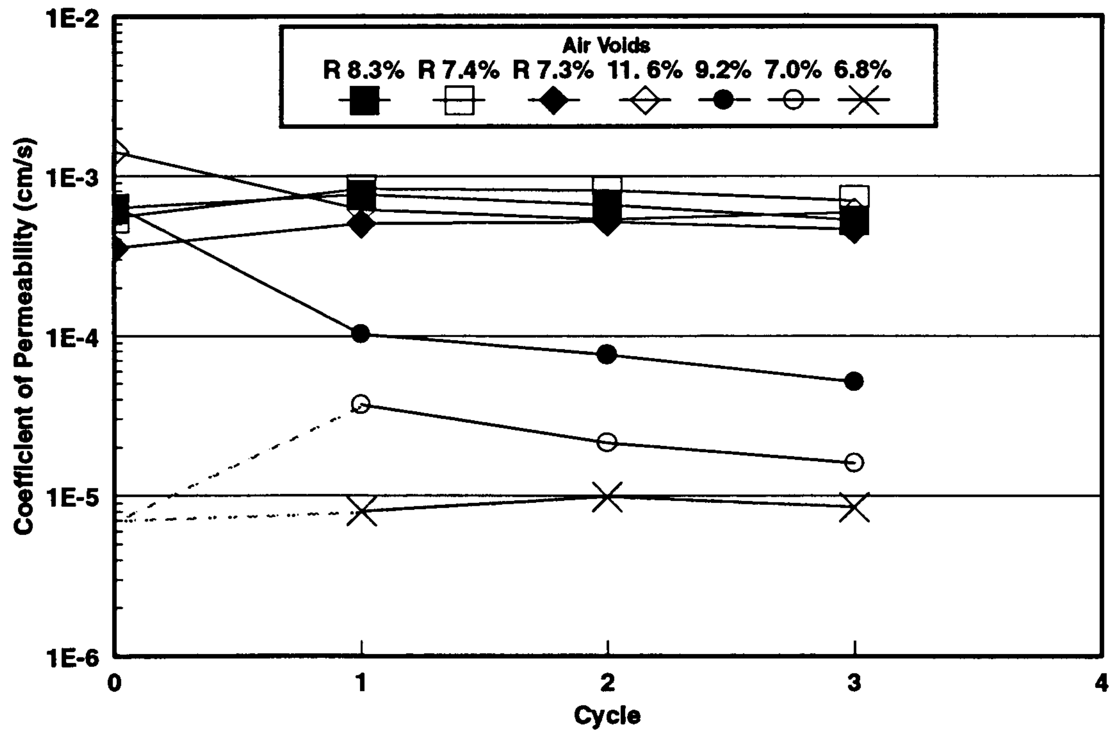


Figure 3.33. Variation in the coefficient of water permeability in the ECS procedure, Rainier, Oregon (OR1)

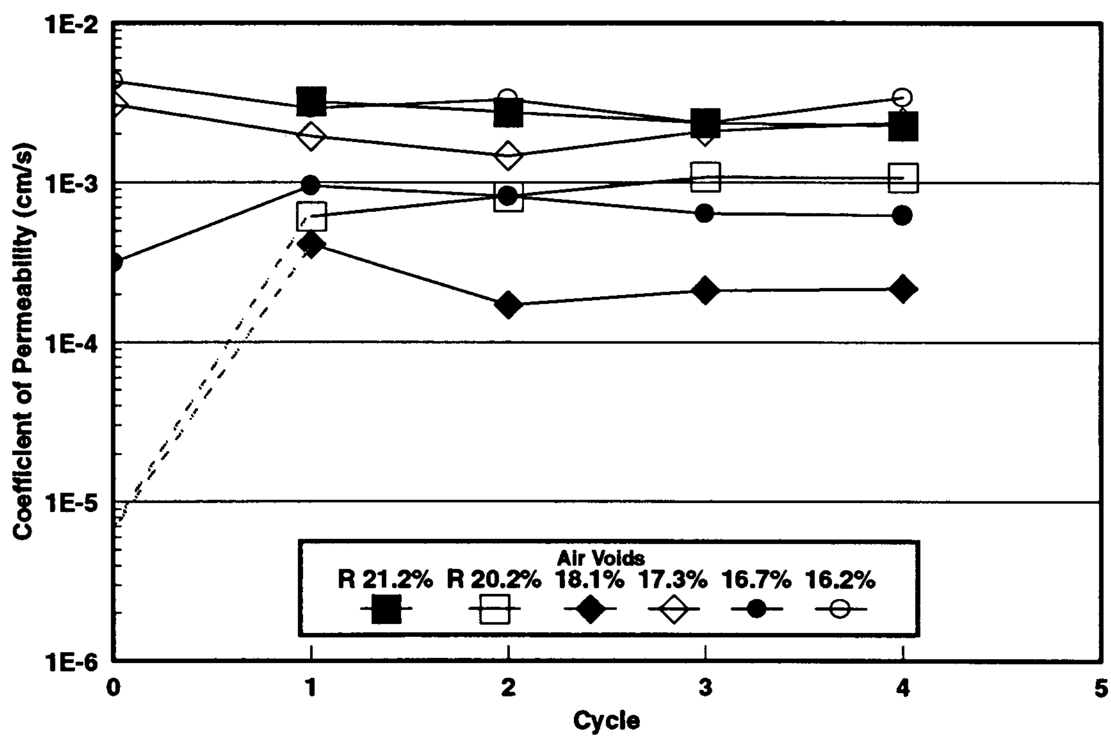


Figure 3.34. Variation in the coefficient of water permeability in the ECS procedure, Bend-Redmond, Oregon (OR2)

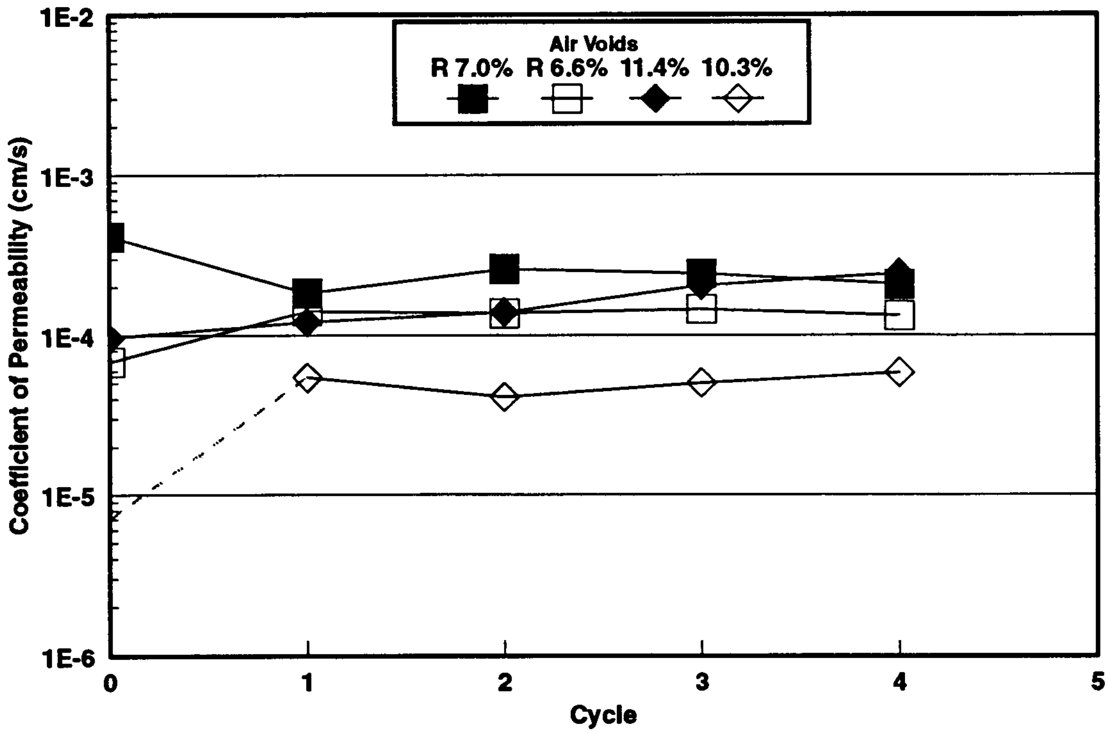


Figure 3.35. Variation in the coefficient of water permeability in the ECS procedure, Mount Baker, Washington (WA1)

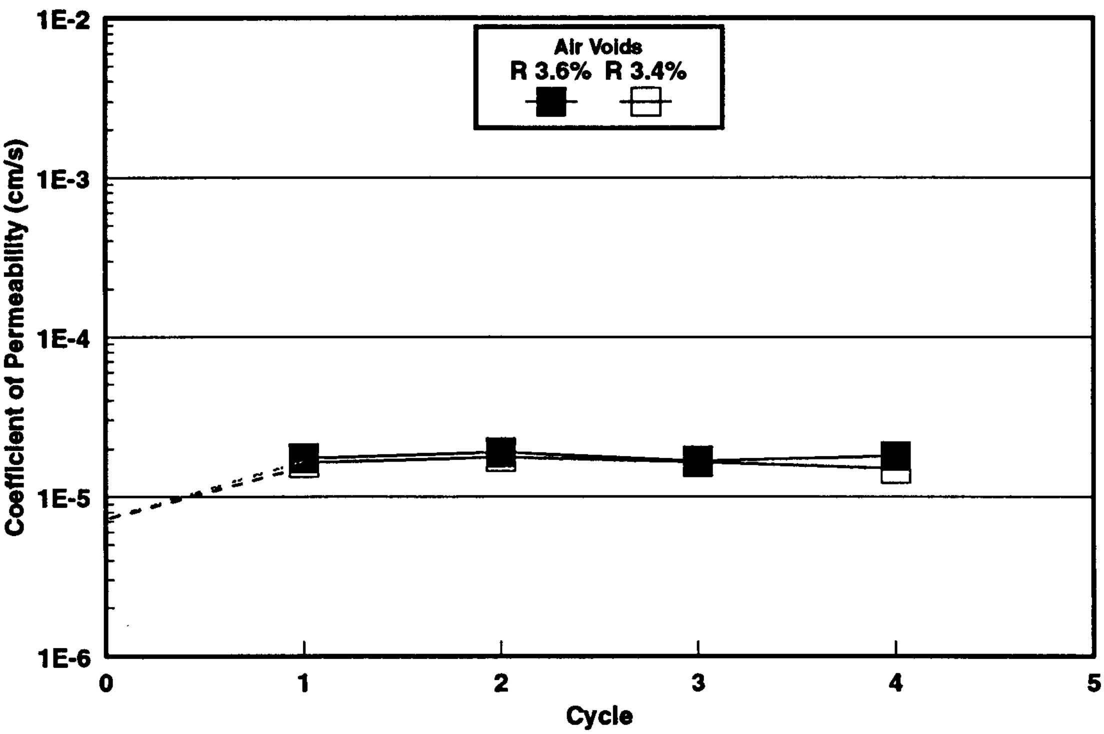


Figure 3.36. Variation in the coefficient of water permeability in the ECS procedure, Wisconsin, AAMAS (WIA)

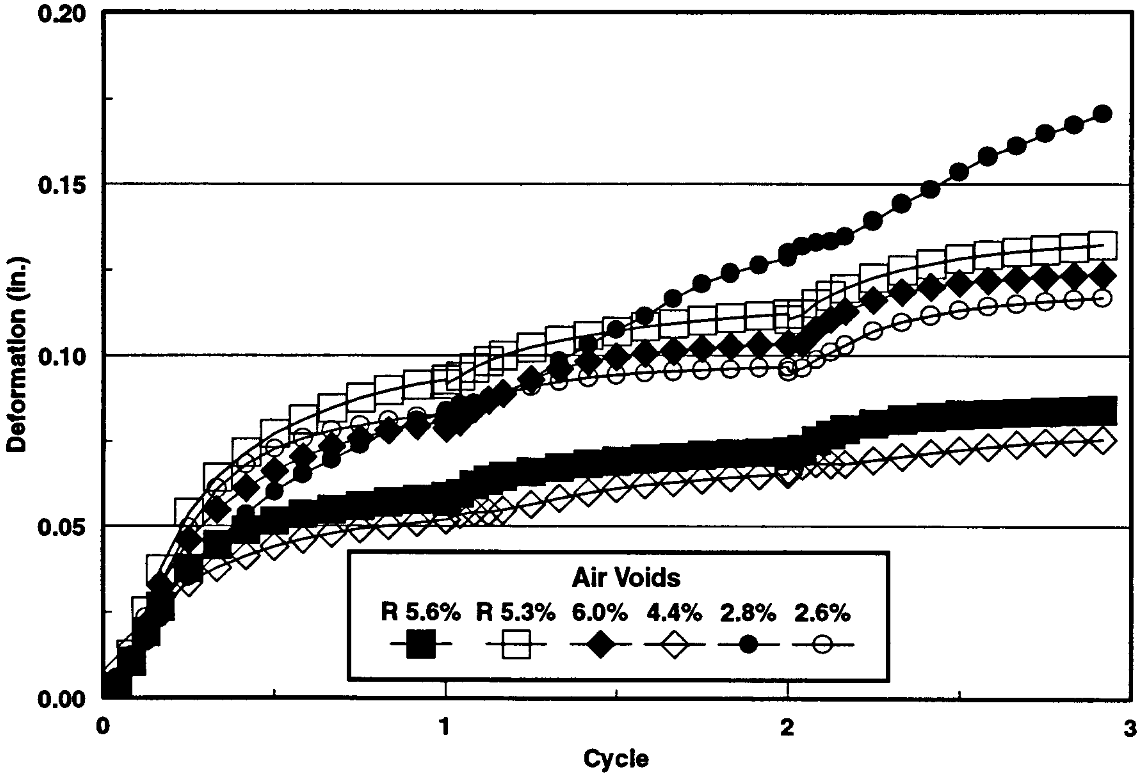


Figure 3.37. Alberta, SPS-5 (AB5) deformation data

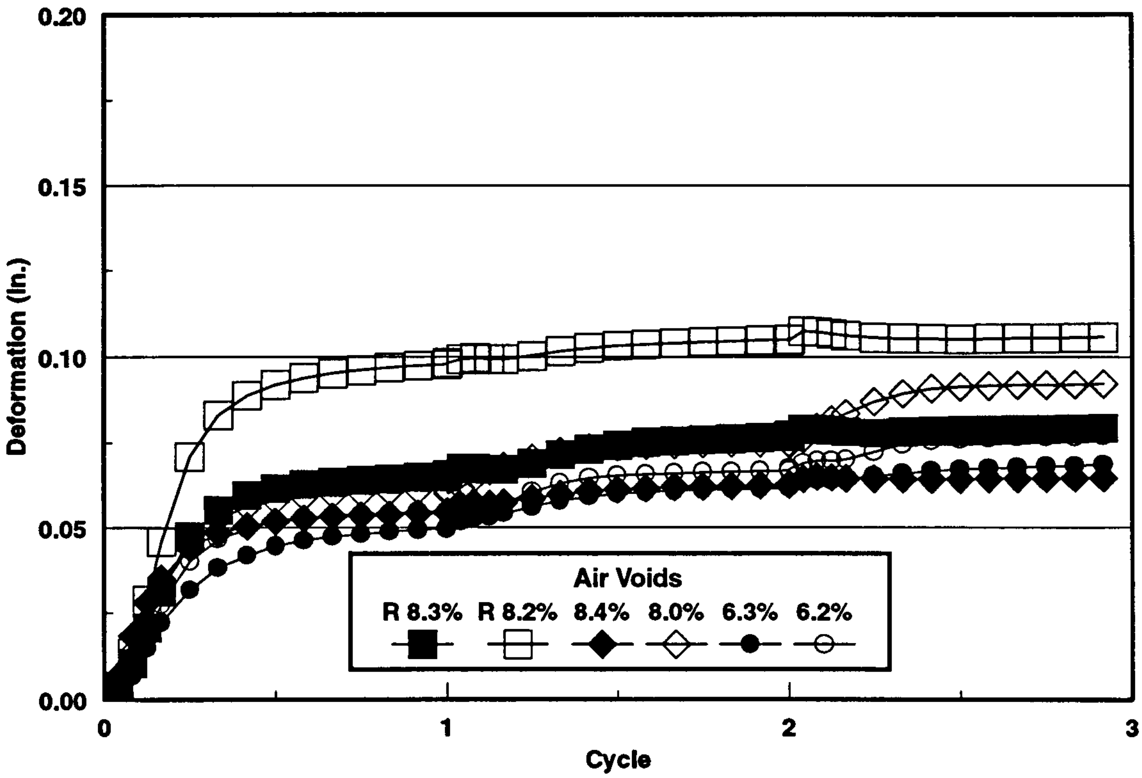


Figure 3.38. Arizona, SPS-5 (AZ5) deformation data

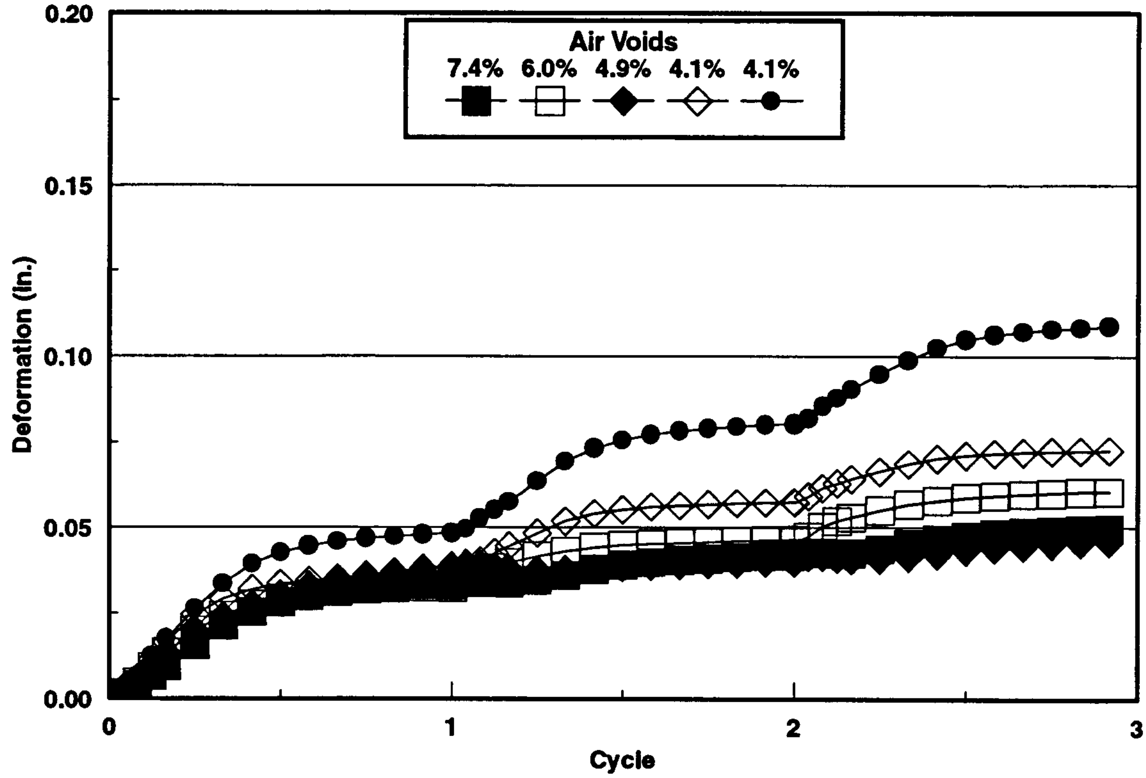


Figure 3.39. California, AAMAS Batch (CAB) deformation data

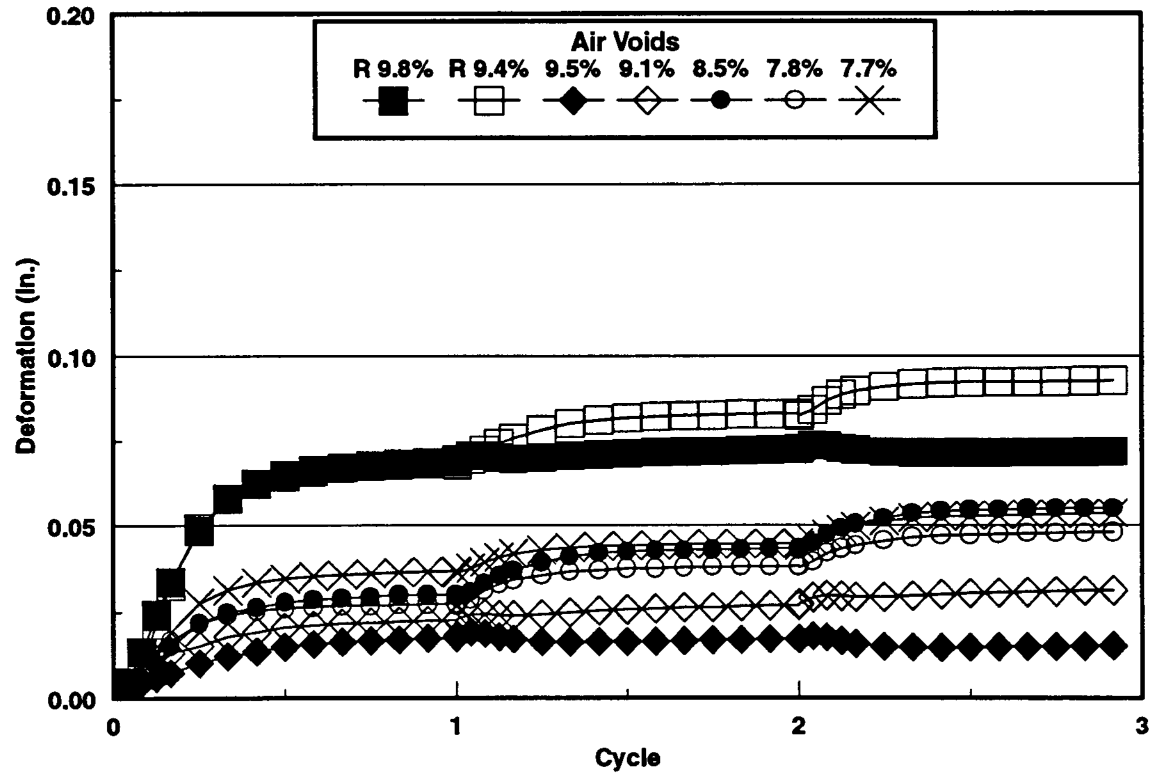


Figure 3.40. California, AAMAS Drum (CAD) deformation data

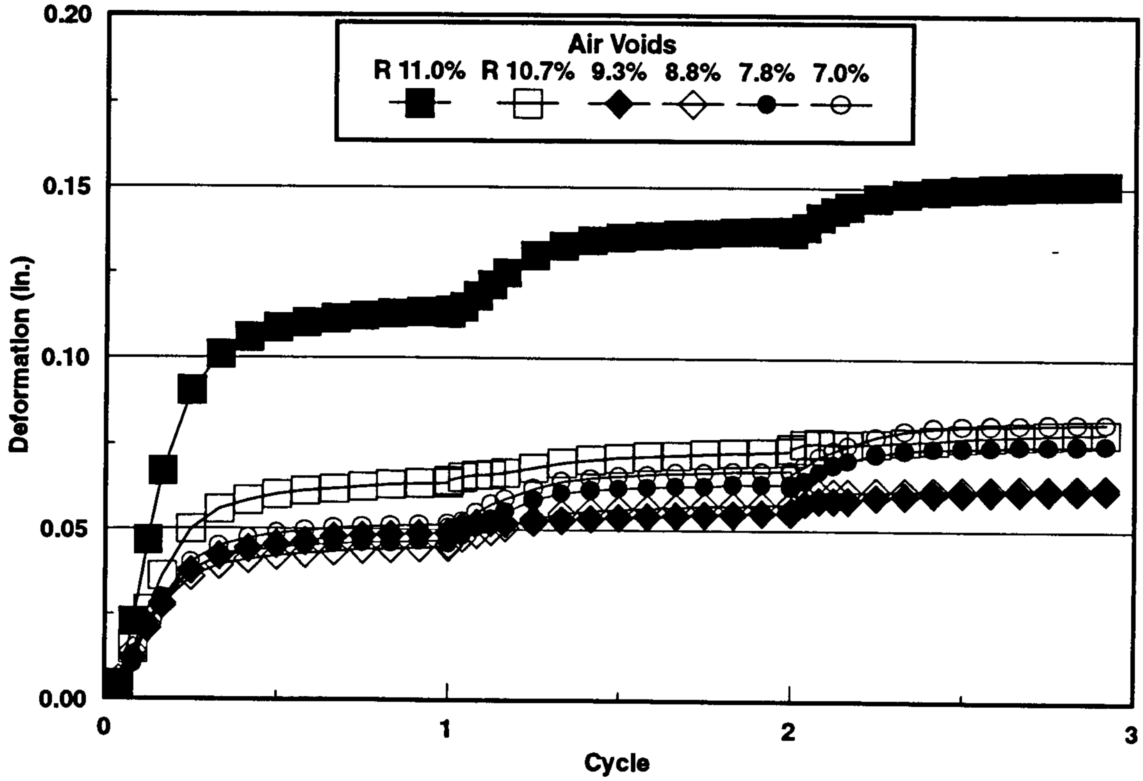


Figure 3.41. California, GPS-6b (CAG) deformation data

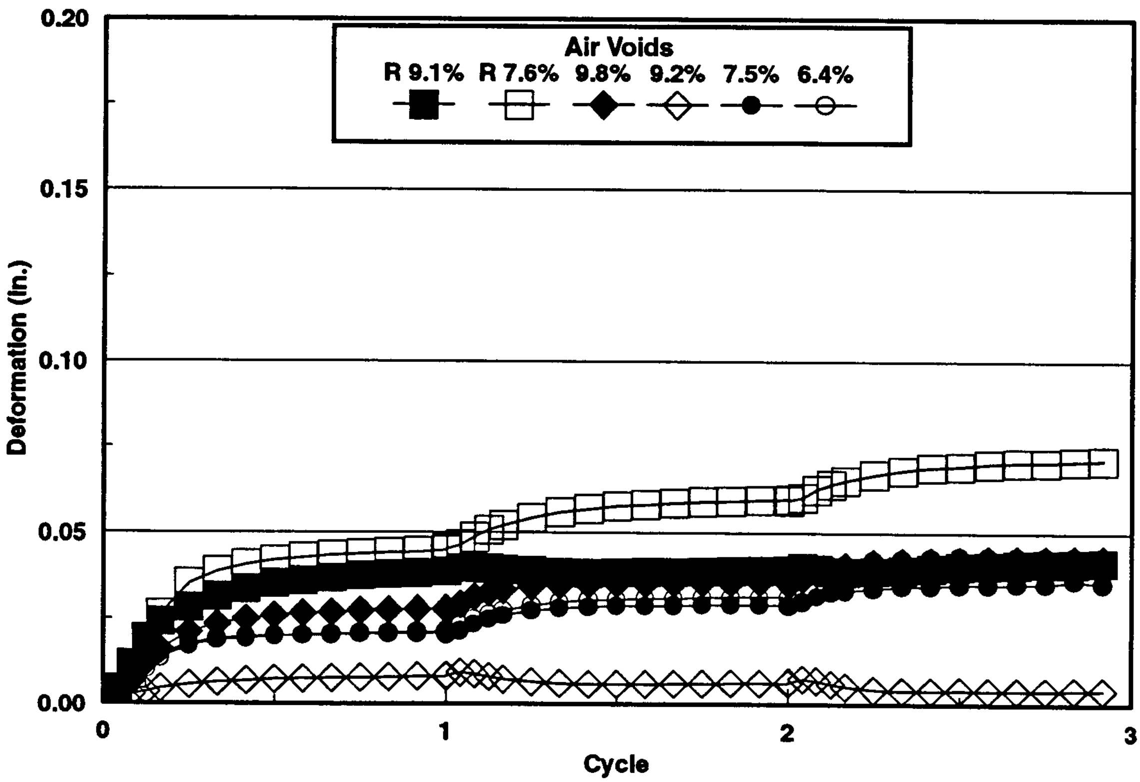


Figure 3.42. Georgia, AAMAS (GAA) deformation data

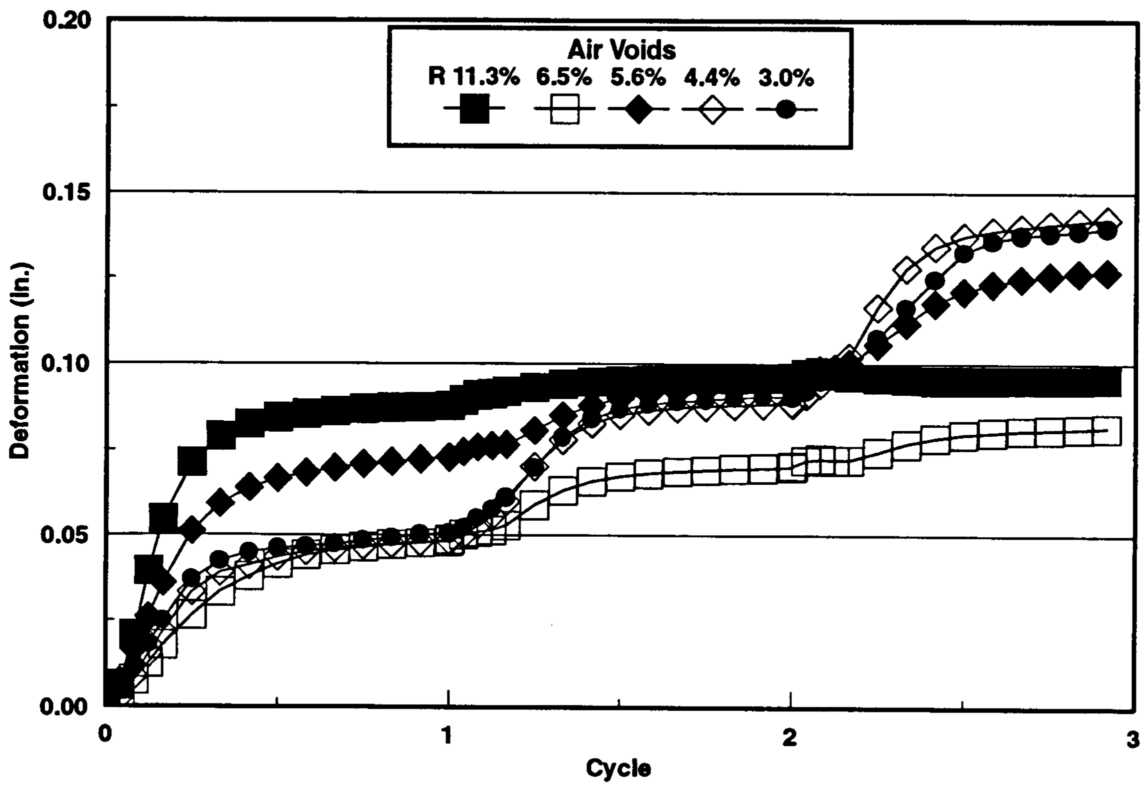


Figure 3.43. Minnesota, SPS-5 (MN5) deformation data

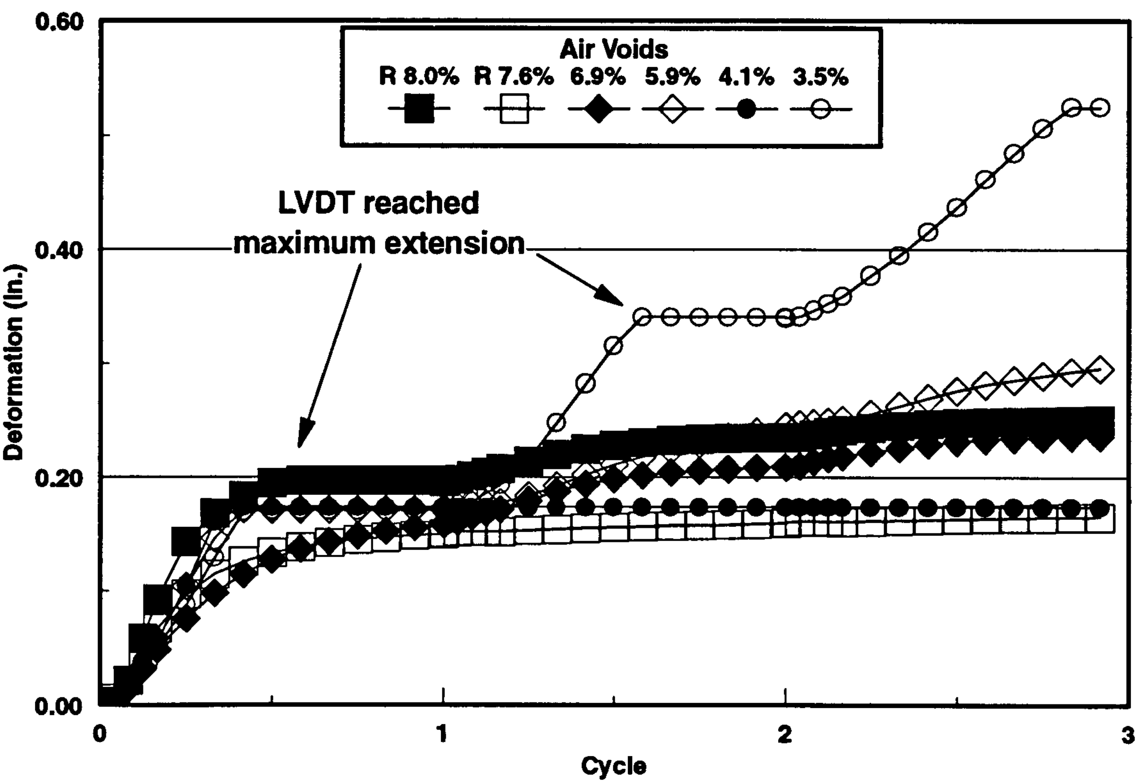


Figure 3.44. Mississippi, SPS-5 (MS5) deformation data

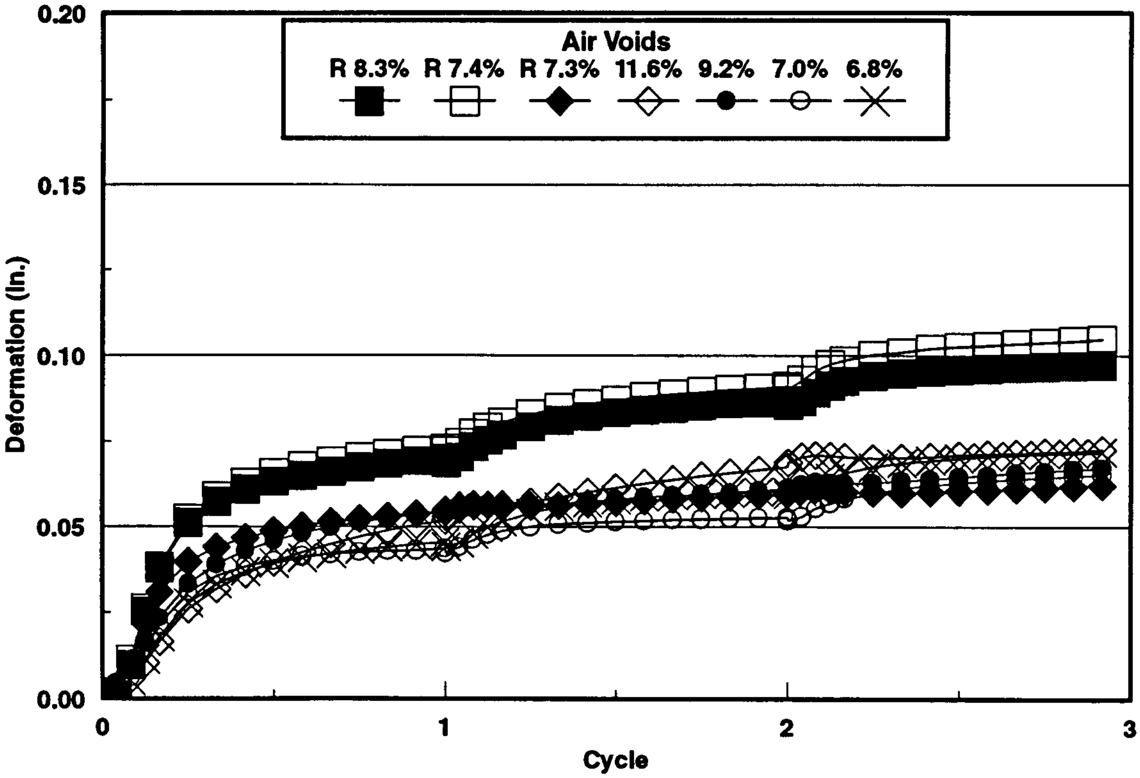


Figure 3.45. Rainier, Oregon (OR1) deformation data

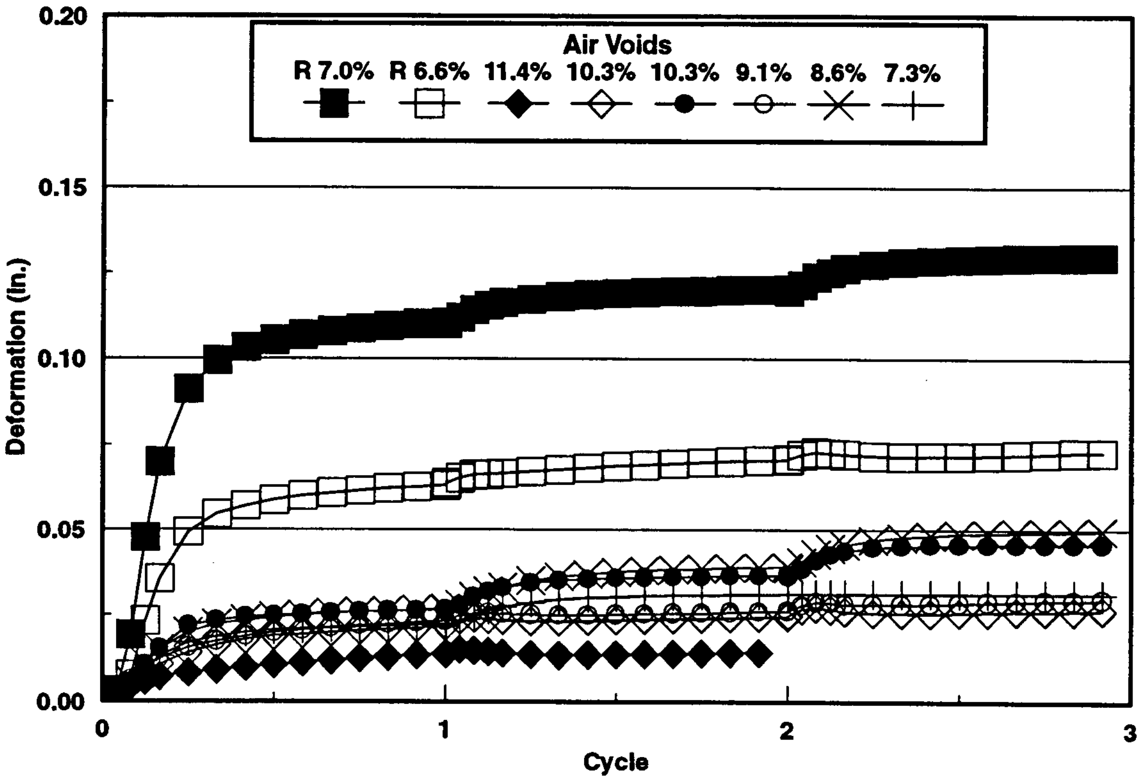


Figure 3.46. Mount Baker, Washington (WA1) deformation data

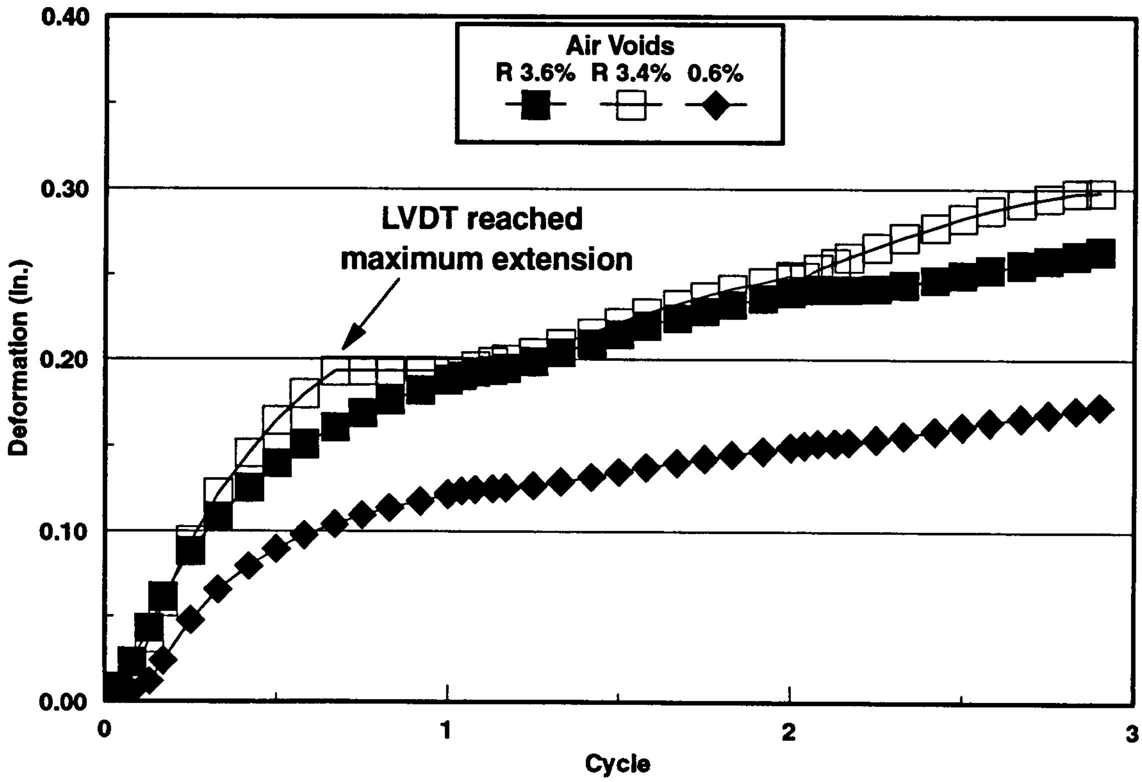


Figure 3.47. Wisconsin, AAMAS (WIA) deformation data

their ranges in these cases. Other specimens are missing due to computer malfunctions at the time of testing (i.e., disk drive full, unable to write to file).

3.2.5 Secondary Mixtures

The specimens tested in the secondary ECS testing program are summarized in Table 3.4. The ECS modulus ratio results are shown graphically in Figures 3.48 through 3.56. The complete data set is provided in Appendix G.

3.3 OSU Wheel Tracking Program

Results from the OSU wheel tracking program are summarized in Table 3.5 and shown graphically in Figure 3.57. It should be noted that the beam designated CADR802 was loaded incorrectly during testing and therefore has been dropped from the analysis of the data. Each beam represents a unique specimen and its rut depth will be used for statistical analysis. The average rut depth of two specimens from the same mixture is used in Figure 3.57 only for illustration.

Two mixtures, CAG and MN5, produced specimens which failed within the OSU wheel tracker. Failure was defined as a rut depth of greater than 20.0 mm (0.79 in.). The beams made of the MN5 mixture failed within 1,000 wheel passes and testing was discontinued. The beams made of the CAG mixture failed within 2,000 wheel passes and testing was discontinued at 5,000 wheel passes.

A visual degree of stripping was not obtainable for the OR2 (Table 3.5) beam specimens because the powder used on the surface of the beam to prevent adhesion between the beam and the pneumatic tire of the OSU wheel tracker migrated down into the specimen. It was impossible to judge the stripping under these conditions.

Table 3.4. ECS test specimens, additional mixtures from secondary test program

Specimen	Air Voids (%)	Visual Degree of Stripping (%)	Binder Migration[1]	Comments
AZF06	3.3	40	B	General: Coarse aggregate stripped.
AZF07	4.1	50	B	
AZF08	3.6	20	C	
COA05	8.3	5	No	
COA22	8.8	5	No	
COA33	8.3	5	No	
COB27	5.4	10	A	
COB31	5.1	10	A	
COB34	4.5	10	A	
COC12	11.1	20	No	
COC16	10.6	20	No	
COE26	8.2	20	No	
COE32	7.5	20	No	
GAF04	11.7	20	No	General: Aggregate in mixture is very fine.
GAF05	9.9	20	No	
LAF01		5	A	Failed due to excessive deformation, orange aggregate stripped.
LAF03		30	B	Orange aggregate stripped.
TAI09	9.0	30	No	
TAI39	8.5	30	No	
WYO02	8.6	40	No	
WYO05	8.0	30	No	

[1] Figure 2.09 illustrates the rating scale for binder migration

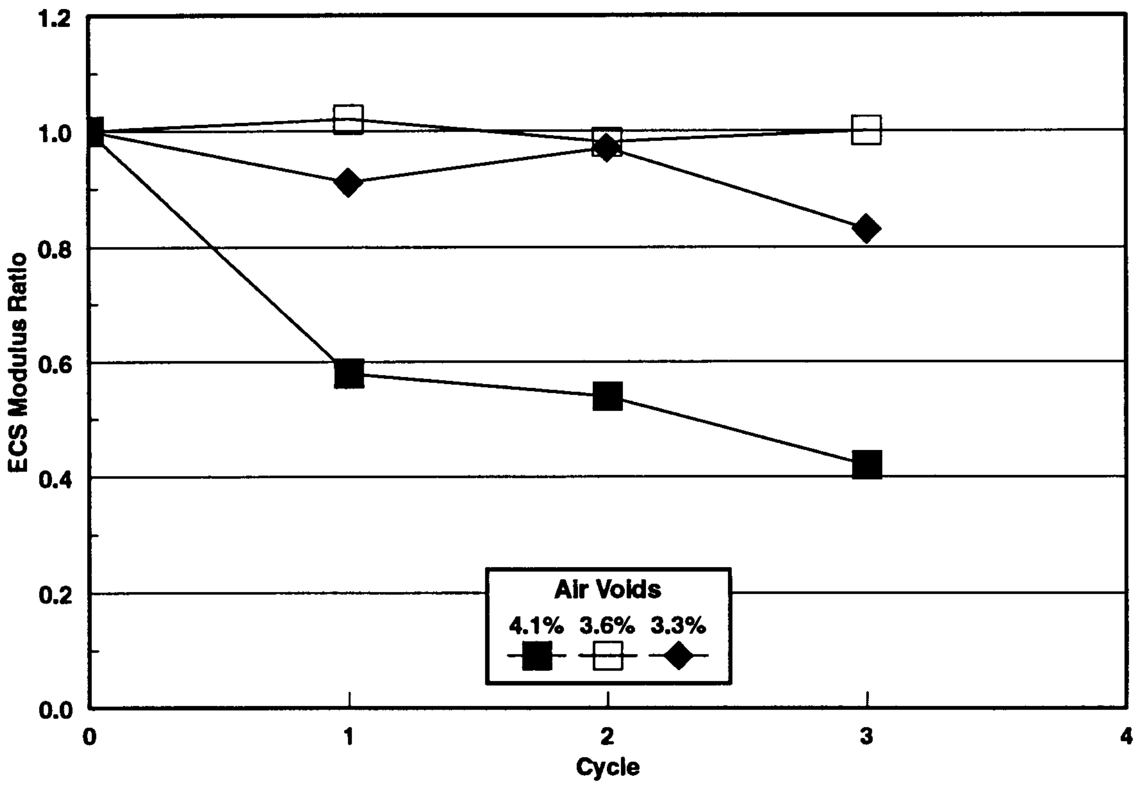


Figure 3.48. Arizona Slurry Seal (AZF) ECS results

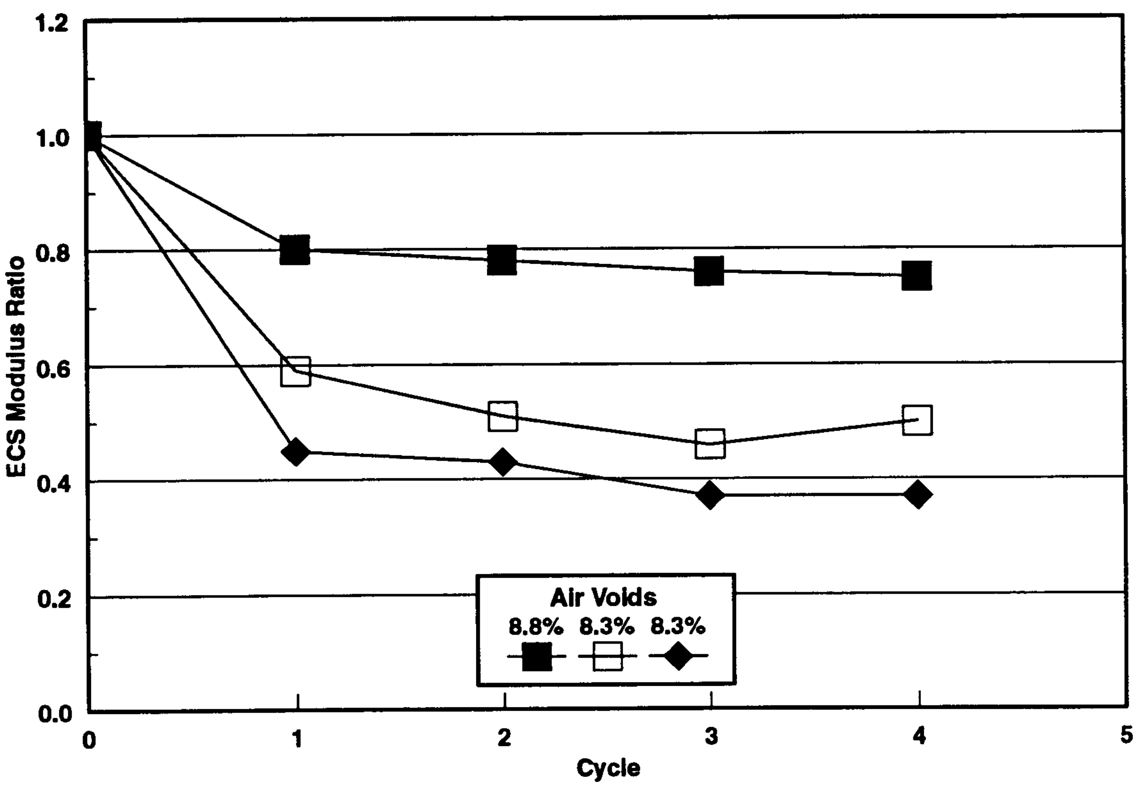


Figure 3.49. Colorado A (COA) ECS results

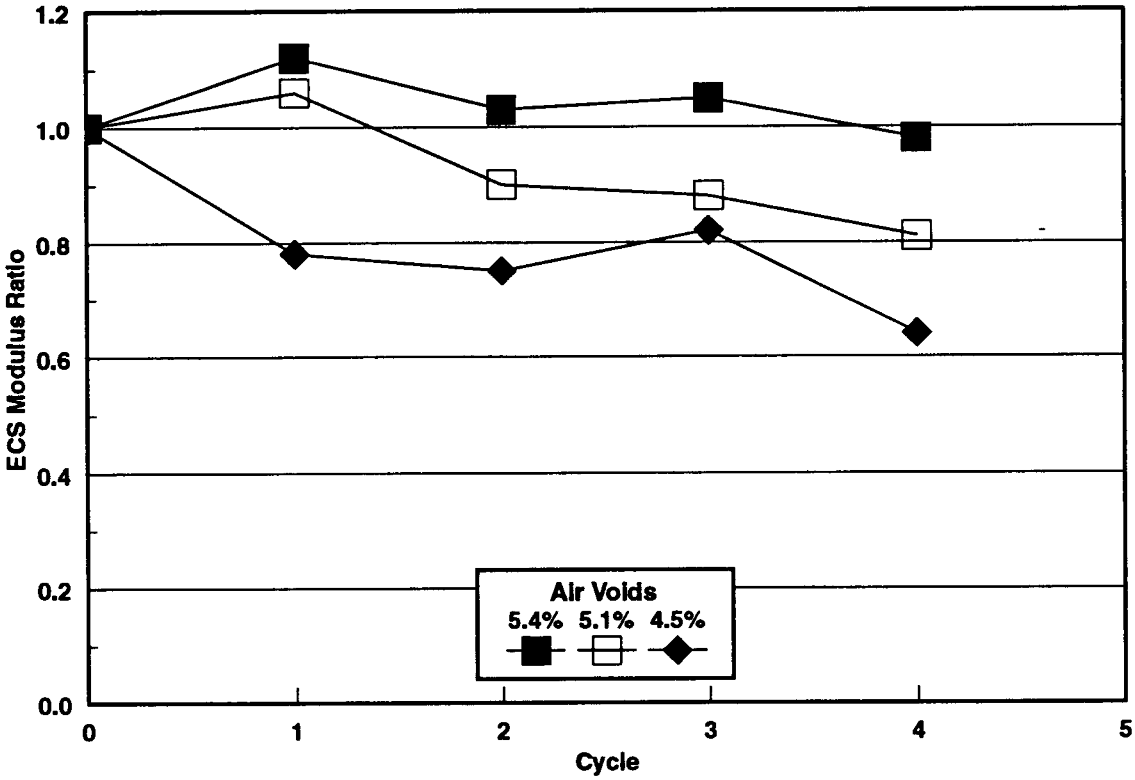


Figure 3.50. Colorado B (COB) ECS results

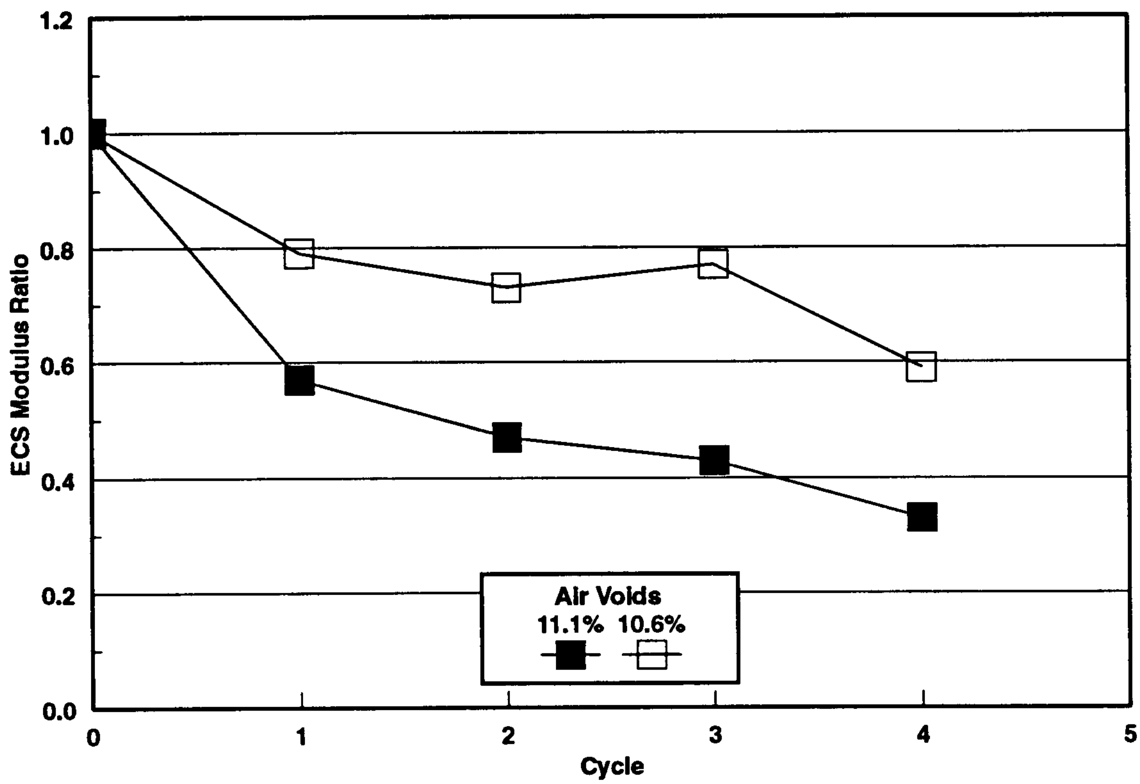


Figure 3.51. Colorado C (COC) ECS results

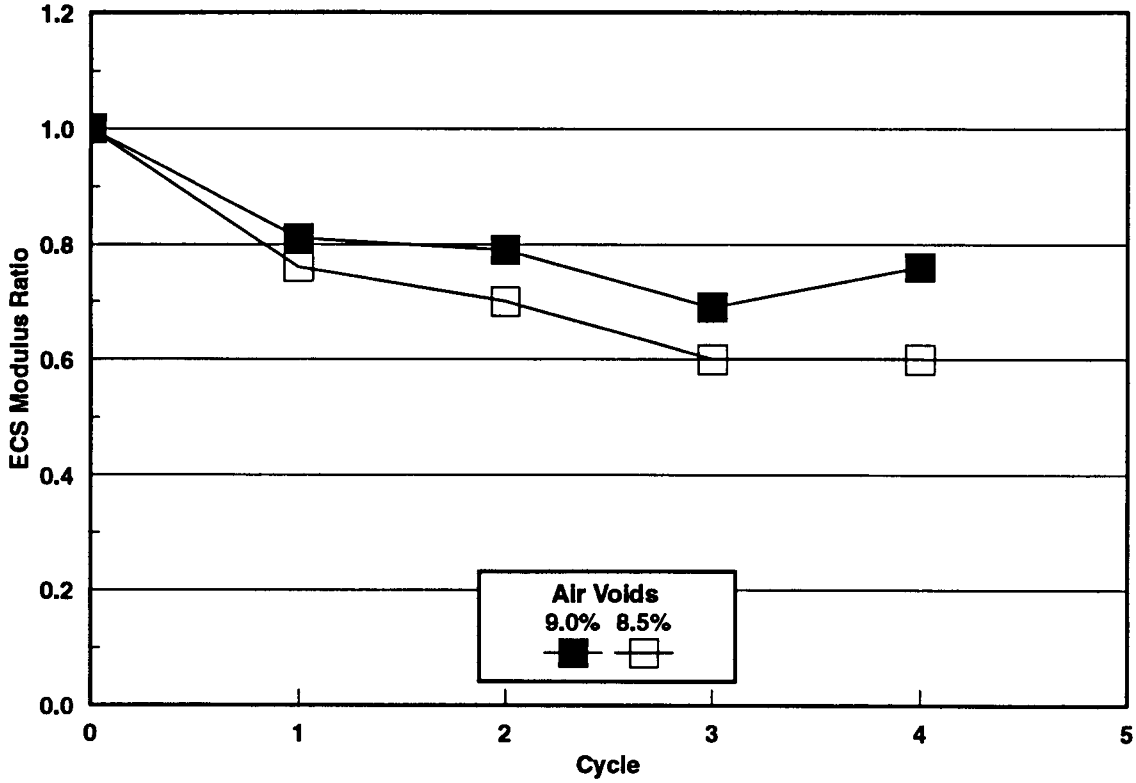


Figure 3.52. Colorado E (COE) ECS results

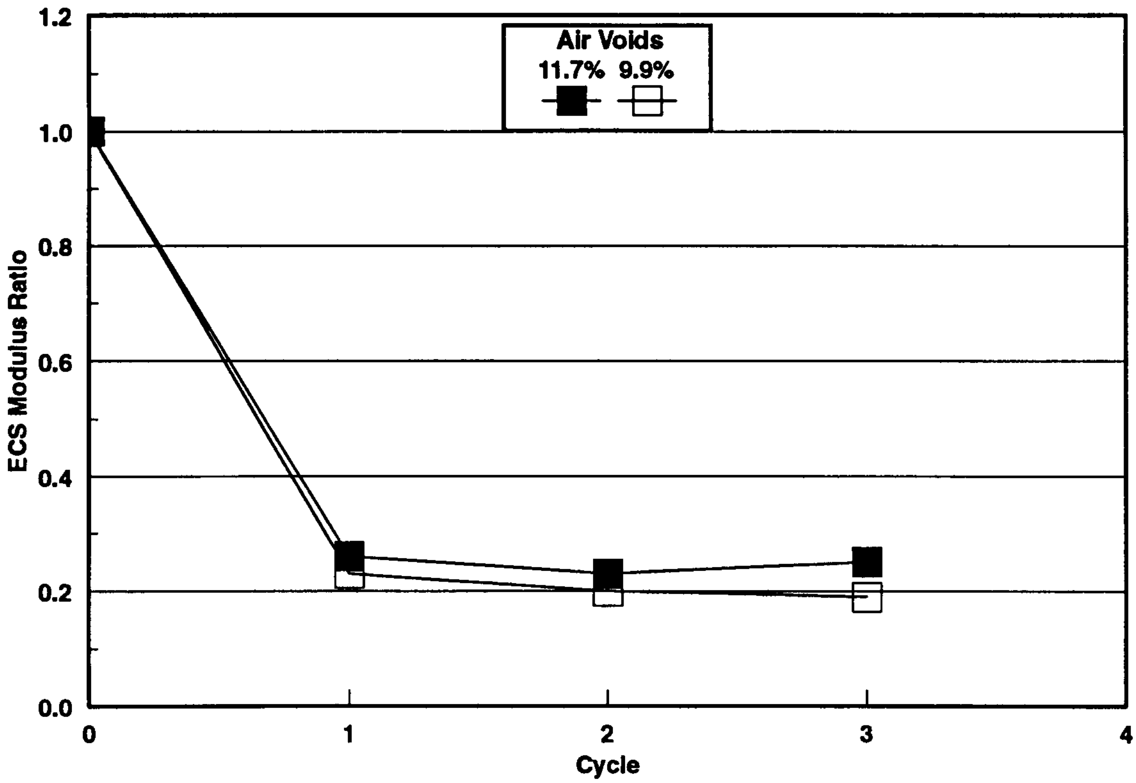


Figure 3.53. Georgia Field (GAF) ECS results

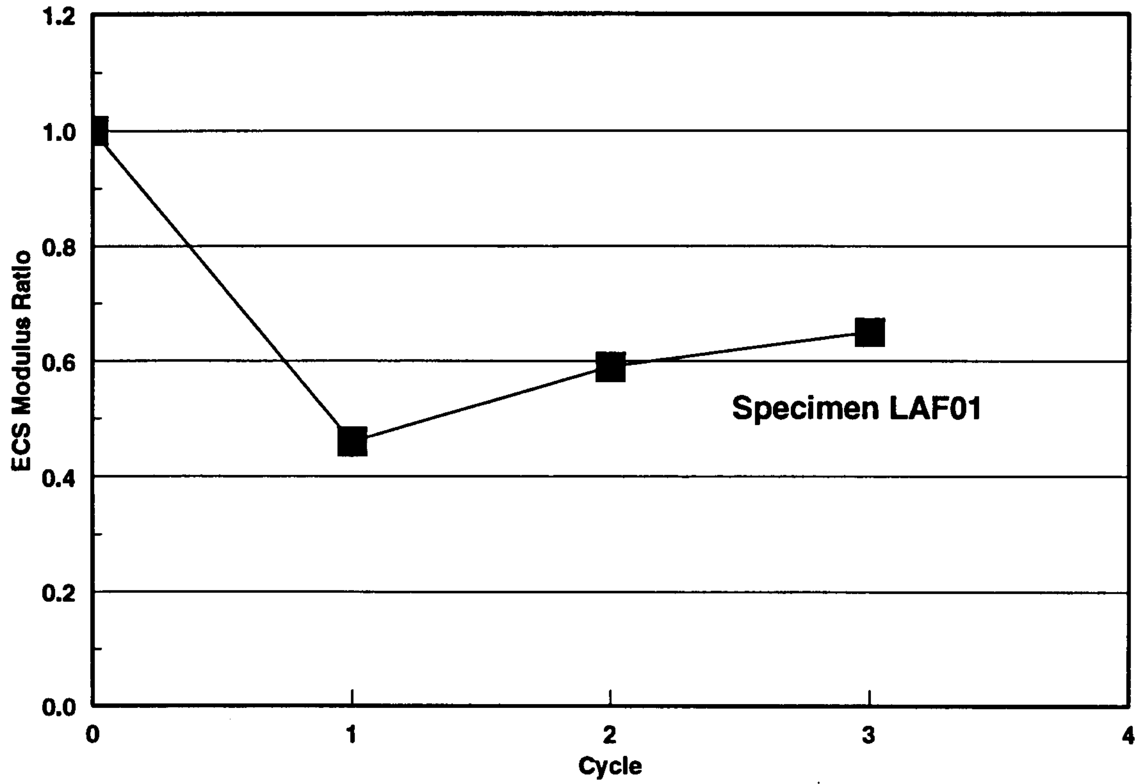


Figure 3.54. Louisiana Field (LAF) ECS results

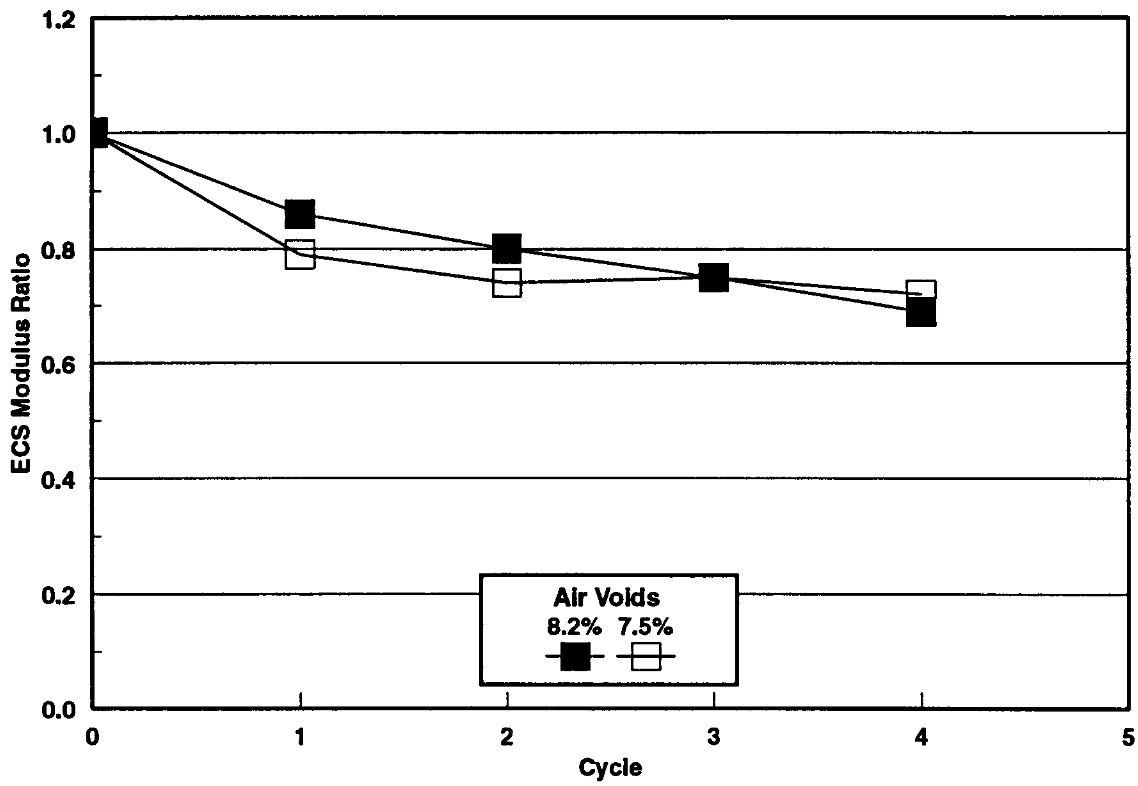


Figure 3.55. The Asphalt Institute Non-Stripping Mixture (TAI) ECS results

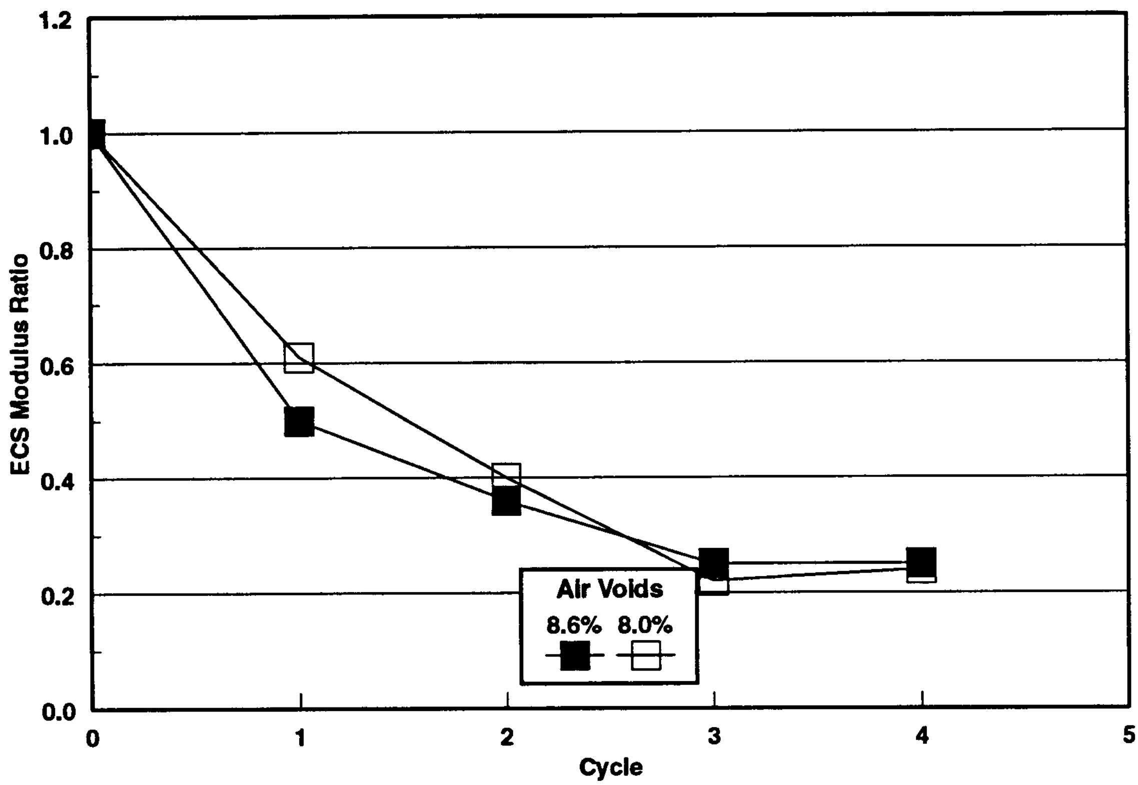


Figure 3.56. Wyoming (WYO) ECS results

Table 3.5. Summary of OSU wheel tracking specimens

Specimen	Air Voids (%)	Percent Saturation (%)	Visual Degree of Stripping (%)
AB5R801	6.6	59	5
AB5R802	6.5	64	5
AZ5R801	8.5	73	10
AZ5R802	8.2	61	10
CADR801	9.7	68	5
CADR802	9.7	71	5
CAGR801	12.0	69	30
CAGR802	12.0	69	30
GAAR801	8.1	59	0
GAAR802	7.4	62	0
MN5R801	12.1	48	5
MN5R802	10.7	52	5
MS5R801	8.4	66	20
MS5R802	8.3	45	10
OR1R801	8.4	61	5
OR1R802	8.4	64	5
OR2R801	21.4	22	--[1]
OR2R802	22.2	23	--
WA1R801	6.6	40	0
WA1R802	6.0	42	0
WIAR801	4.4	43	5
WIAR802	3.8	43	5

[1] Unable to distinguish stripping due to migration of dust into specimen

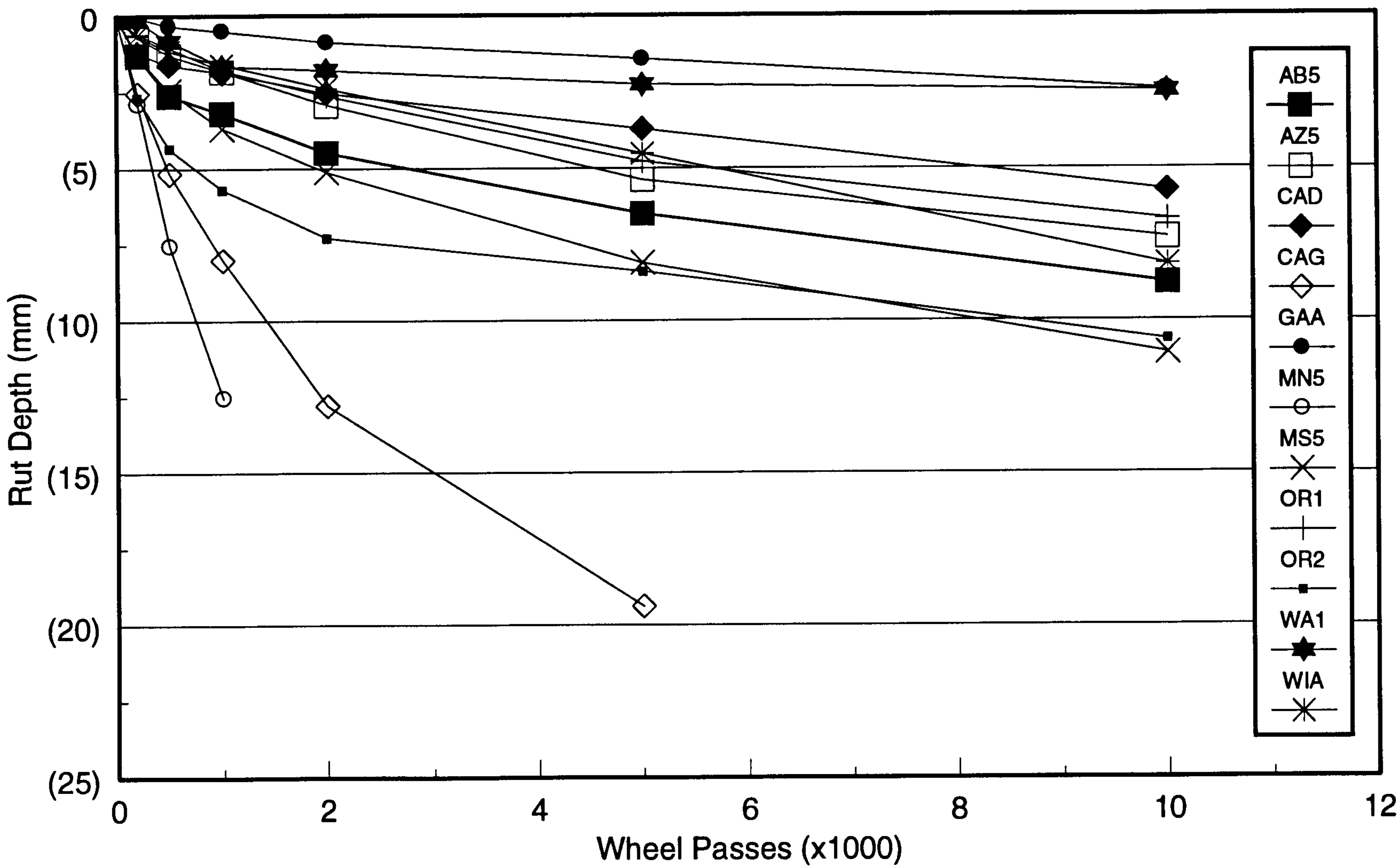


Figure 3.57. Average rut depths for OSU wheel tracking test program

3.4 Field Data

3.4.1 Manual Distress Survey Data

Table 3.6 indicates the date and the condition of each field test section from the most recent distress survey for the site.

3.4.2 Field Core Data

The results of the MTS diametral and triaxial resilient modulus testing of the cores taken from field sites are shown in Figures 3.58 to 3.79. The MTS modulus values of newly-manufactured laboratory kneading compactor cores are shown as a reference. This modulus is termed the "unconditioned modulus value" as the specimens have not undergone any type of conditioning prior to this modulus measurement. The results of the visual stripping evaluation are shown in Table 3.7. The complete data set from the field cores is given in Appendix H.

Table 3.6. Summary of pavement condition surveys

Site	Survey Type	Survey Date	Comments
AB5	Manual	8/92	In good condition, small amount of cracking
AZ5	Manual	8/92	In good condition, some traffic densification
CAB	Manual	8/92	In good condition
CAD	Manual	8/92	In good condition
CAG	Manual	8/92	In good condition
GAA	NA[1]	NA	Covered by wearing course
MN5	Manual	6/92	Some low to moderate severity transverse cracking, 5-8 mm rutting, some low to moderate severity bleeding
MS5	Manual	Spring 1992	In bad condition, reflective cracking, scheduled for overlay
OR1	NA	NA	Covered by wearing course
OR2	Manual	1992	No visual distress with the exception of 1/8 in. to 3/8 in. of rutting
WA1	Manual	9/92	In good condition, no visible rutting
WIA	Manual	1991	In good condition, PDI=0, PSI=4.3, 1/10 in. rutting measured

[1] Information not available

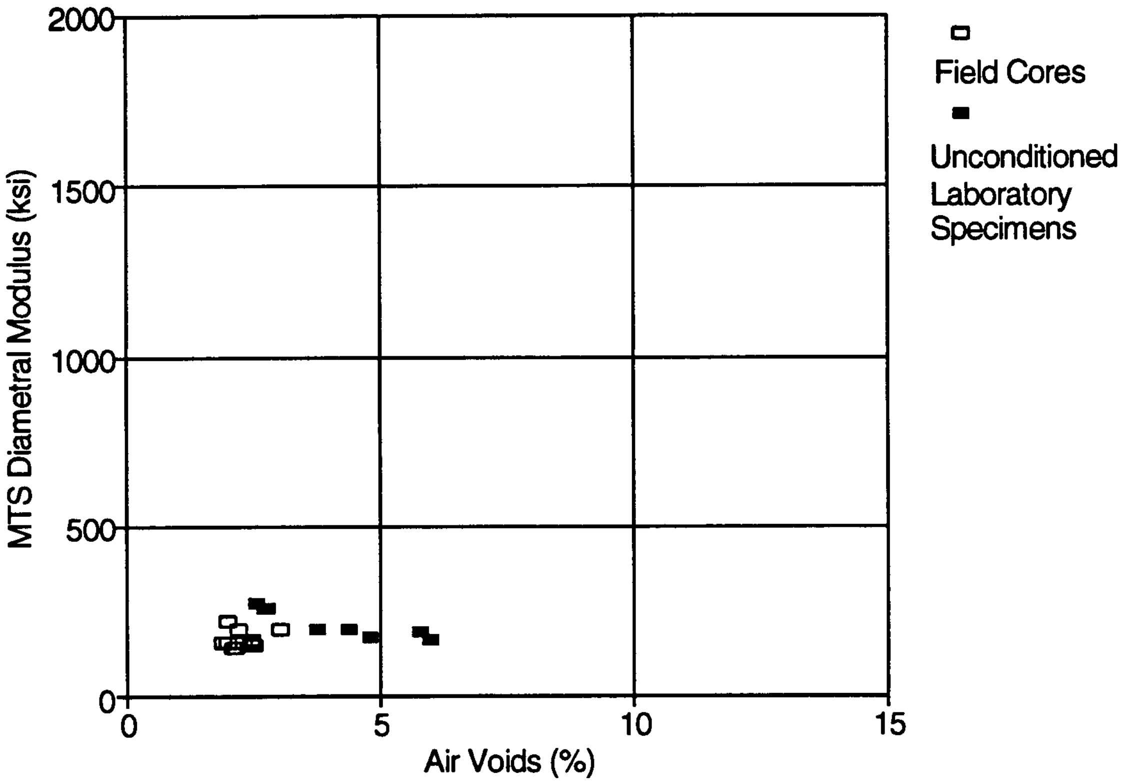


Figure 3.58. AB5 field cores, diametral modulus data

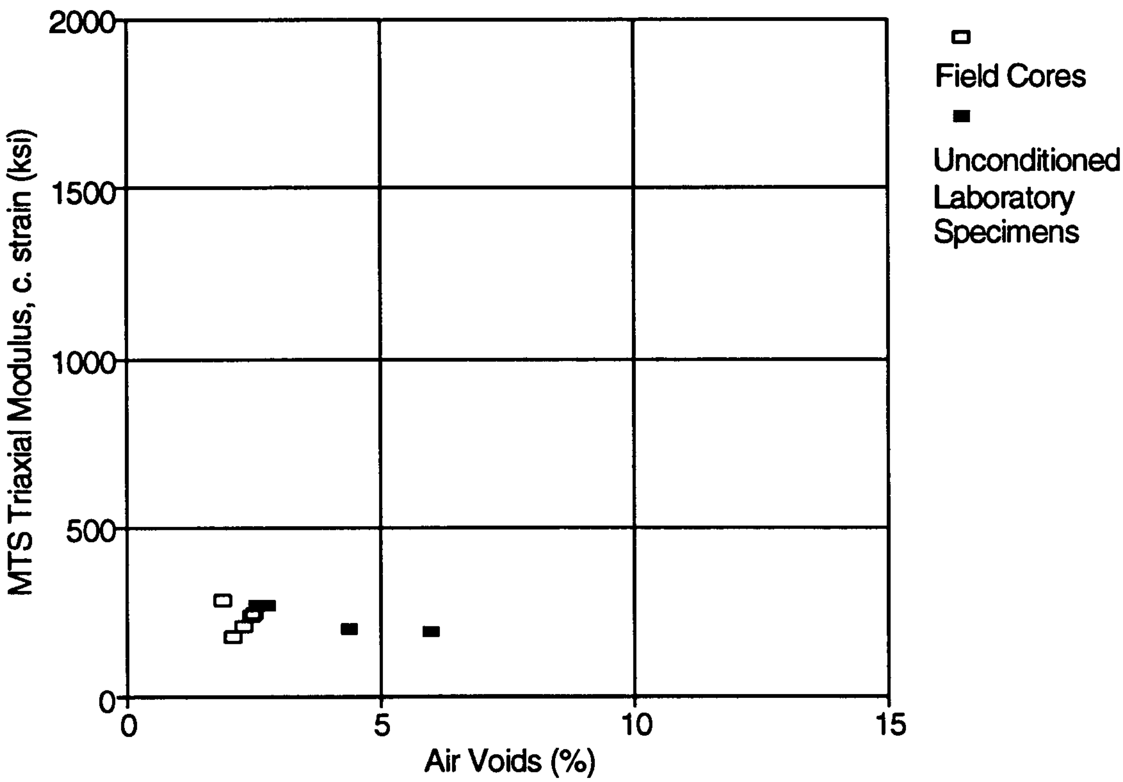


Figure 3.59. AB5 field cores, triaxial modulus data (tested at 100 μ-strain)

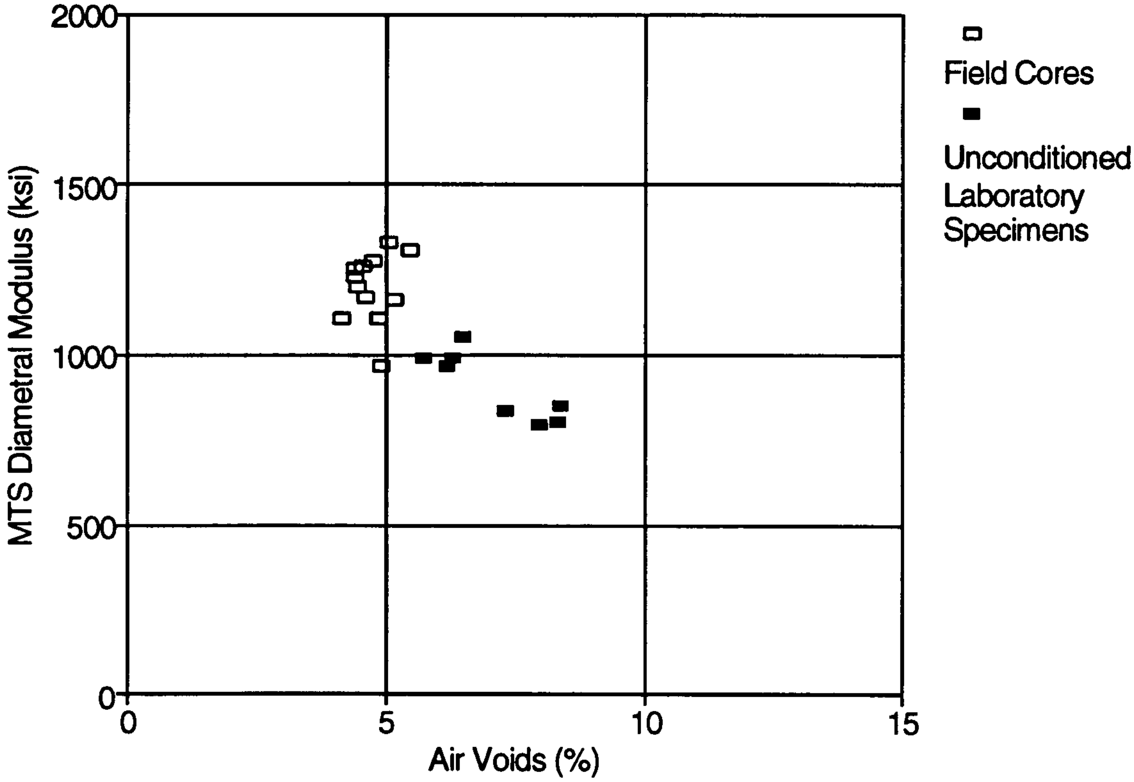


Figure 3.60. AZ5 field cores, diametral modulus data

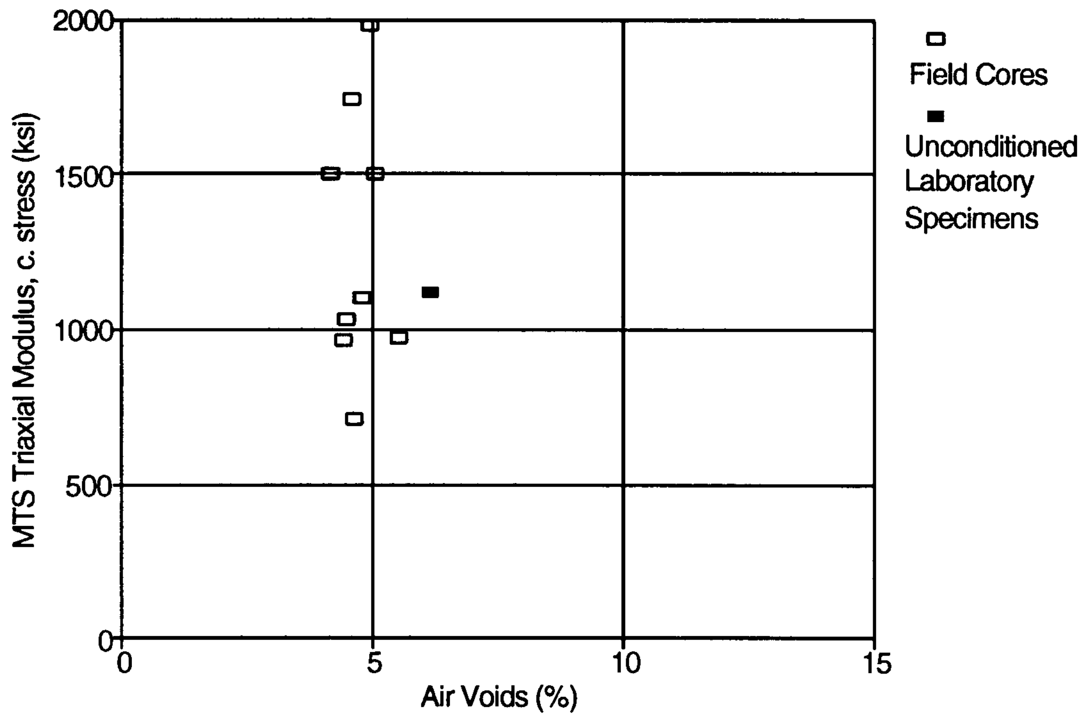


Figure 3.61. AZ5 field cores, triaxial modulus data (tested at 40 psi [275 kPa])

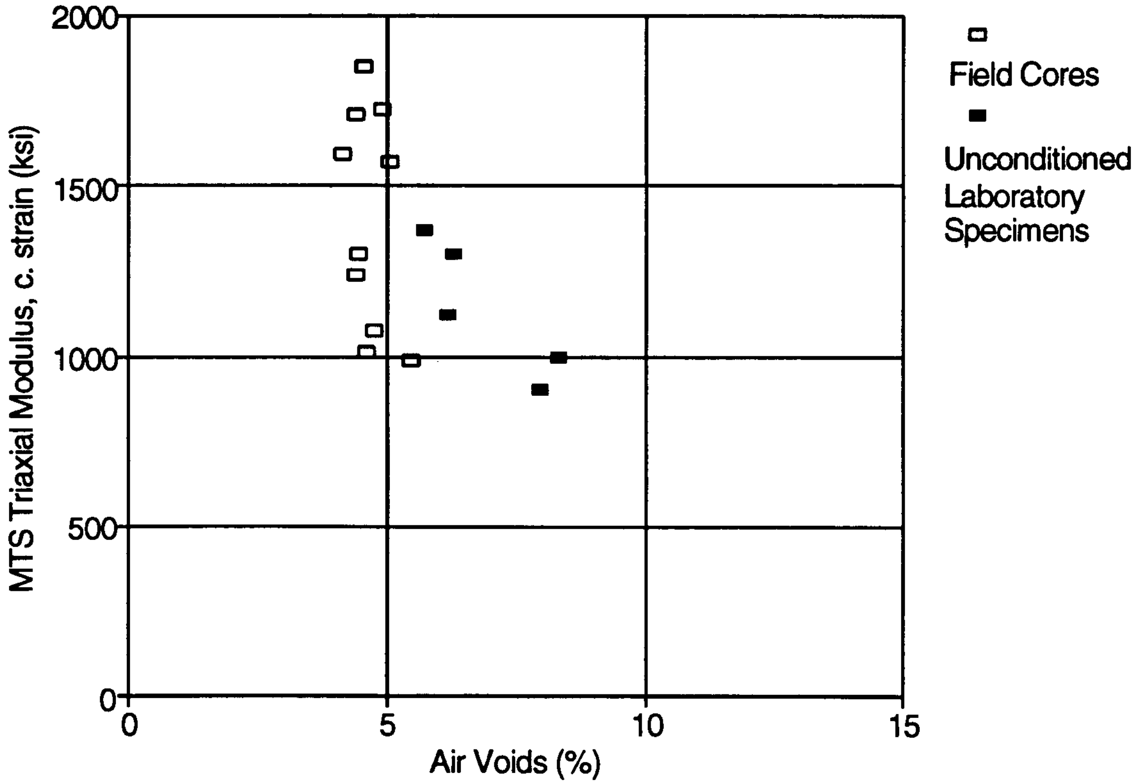


Figure 3.62. AZ5 field cores, triaxial modulus data (tested at 100 μ-strain)

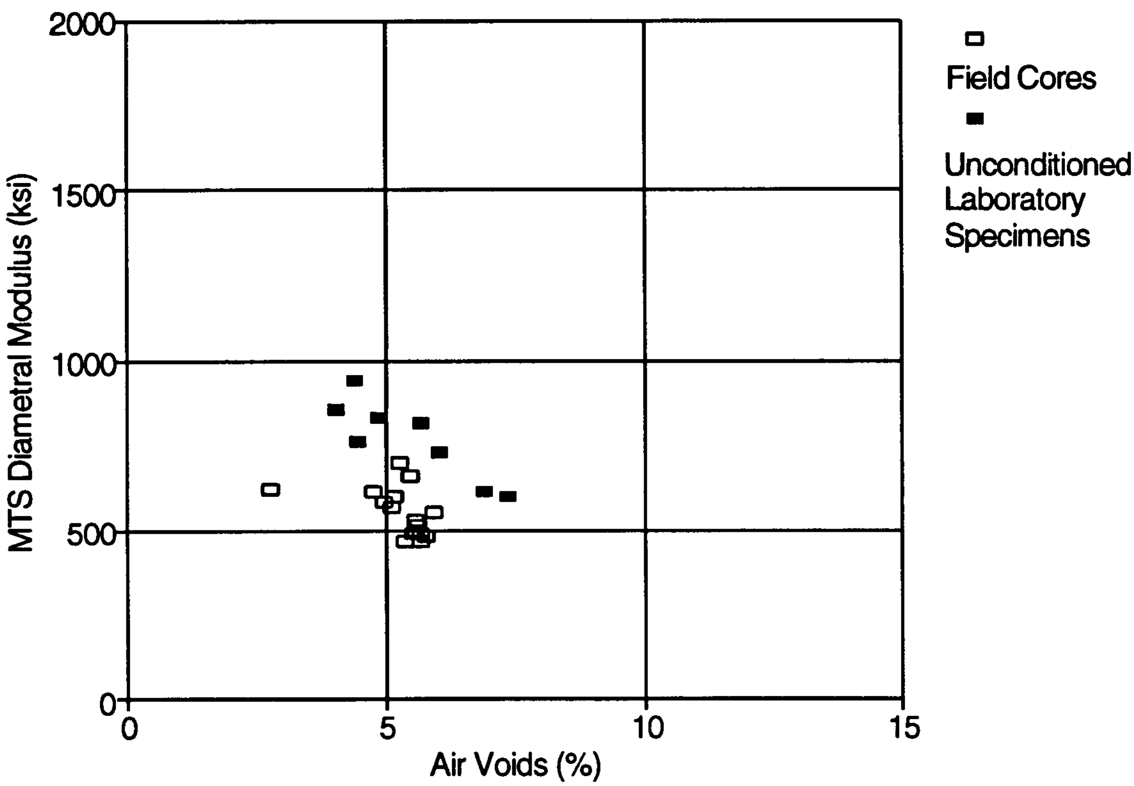


Figure 3.63. CAB field cores, diametral modulus data

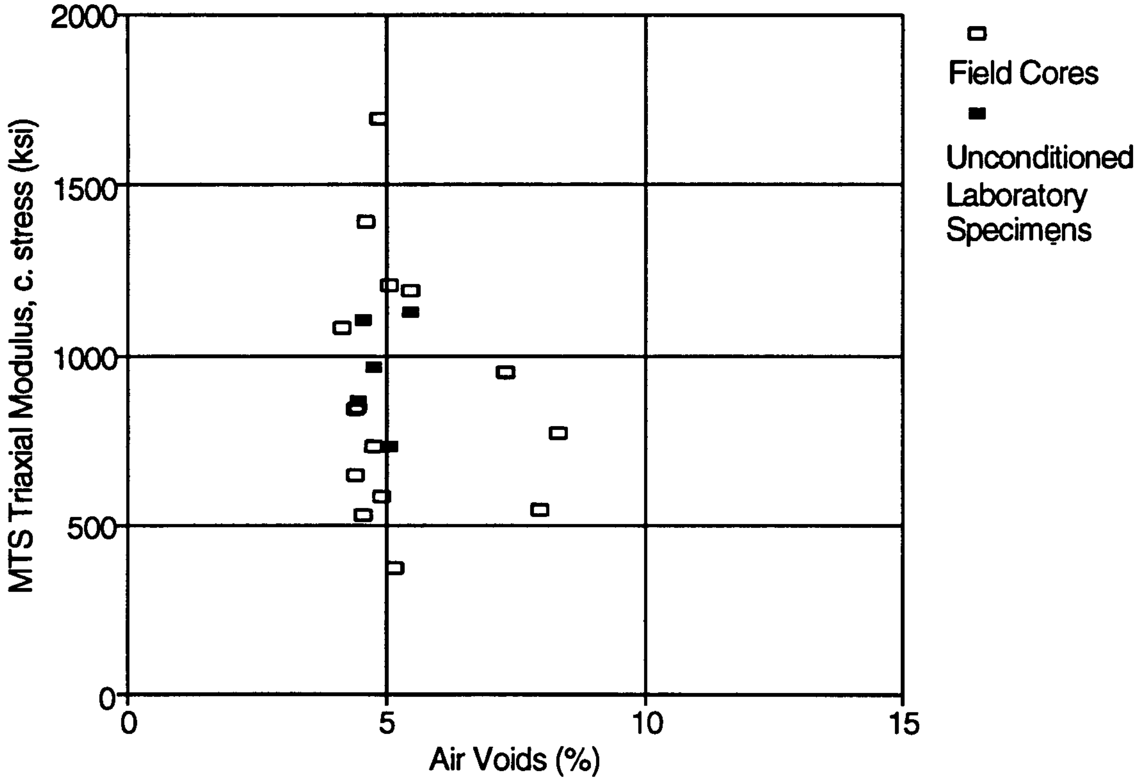


Figure 3.64. CAB field cores, triaxial modulus data (tested at 40 psi [275 kPa])

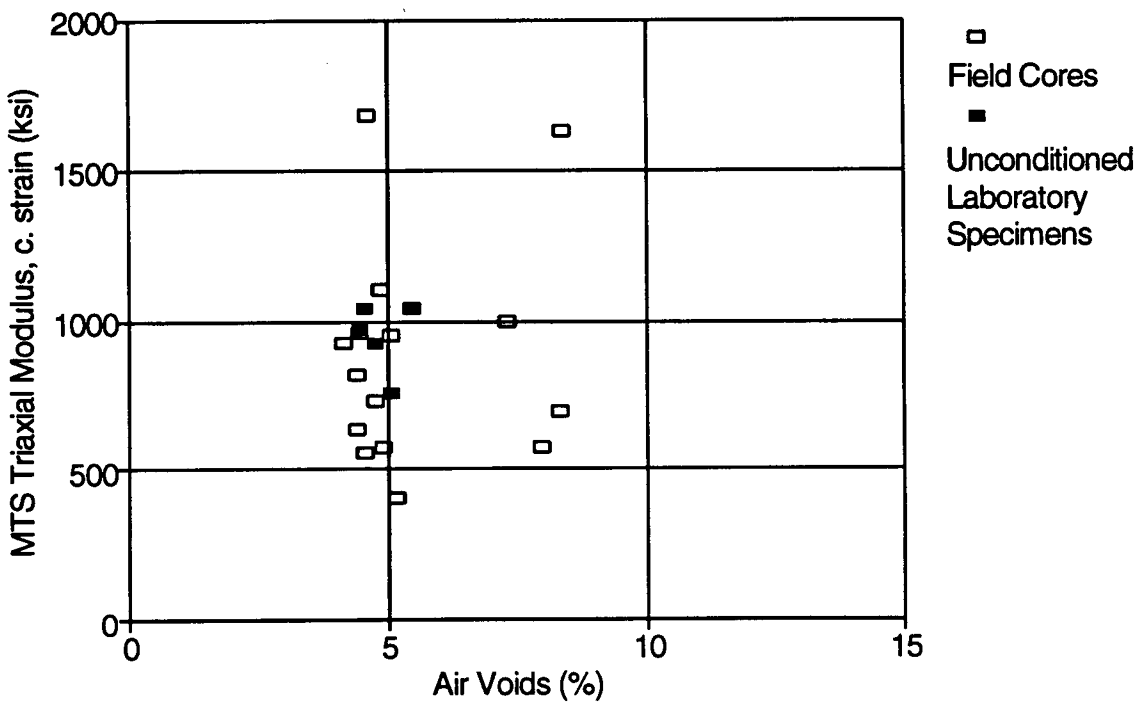


Figure 3.65. CAB field cores, triaxial modulus data (tested at 100 μ-strain)

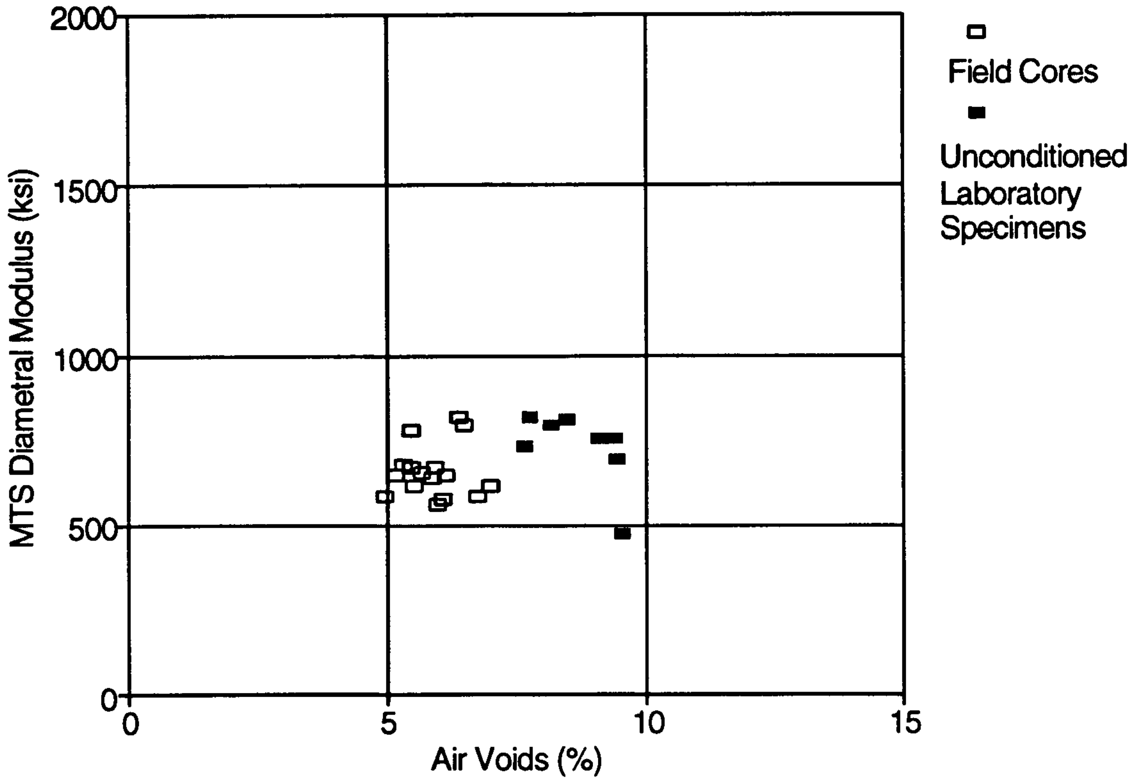


Figure 3.66. CAD field cores, diametral modulus data

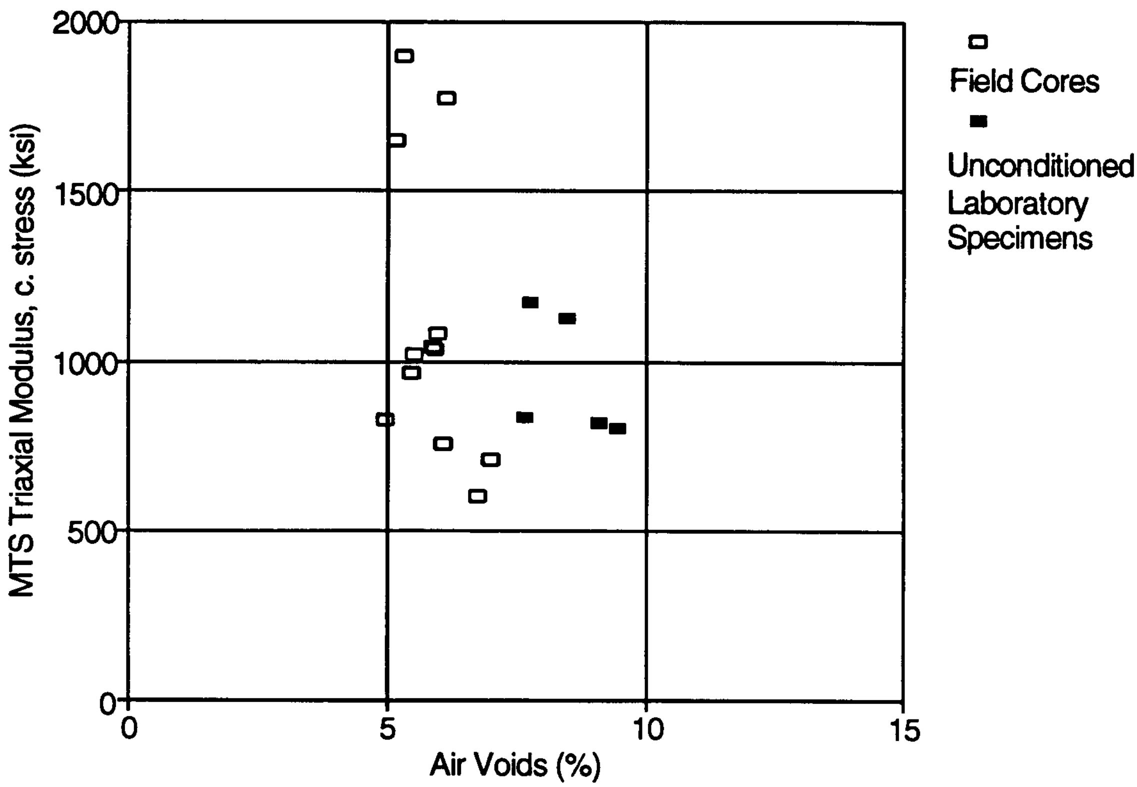


Figure 3.67. CAD field cores, triaxial modulus data (tested at 40 psi [275 kPa])

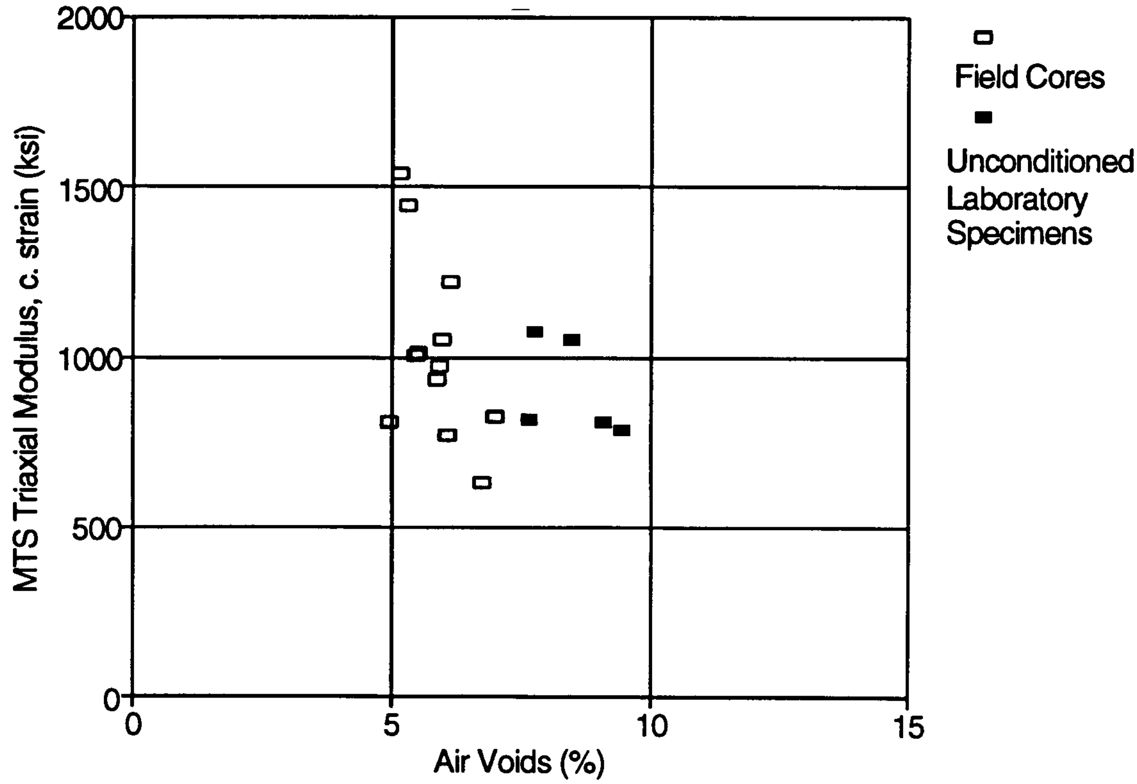


Figure 3.68. CAD field cores, triaxial modulus data (tested at 100 μ-strain)

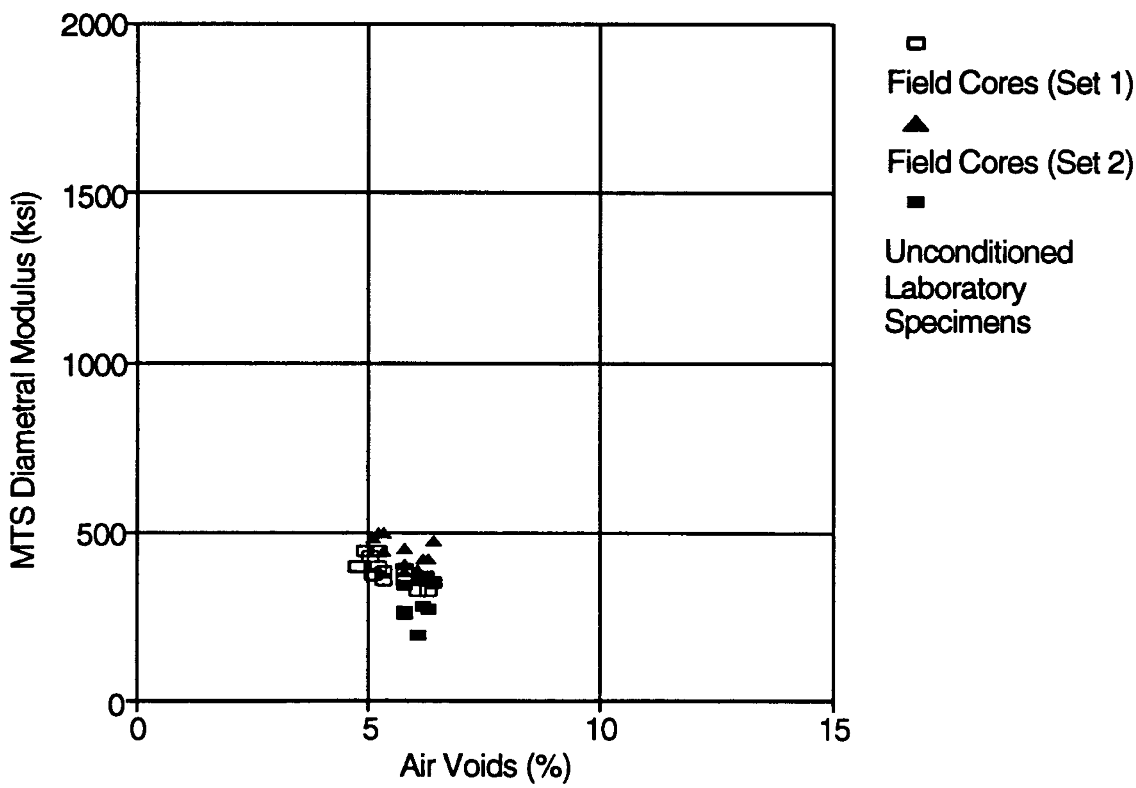


Figure 3.69. CAG field cores, diametral modulus data

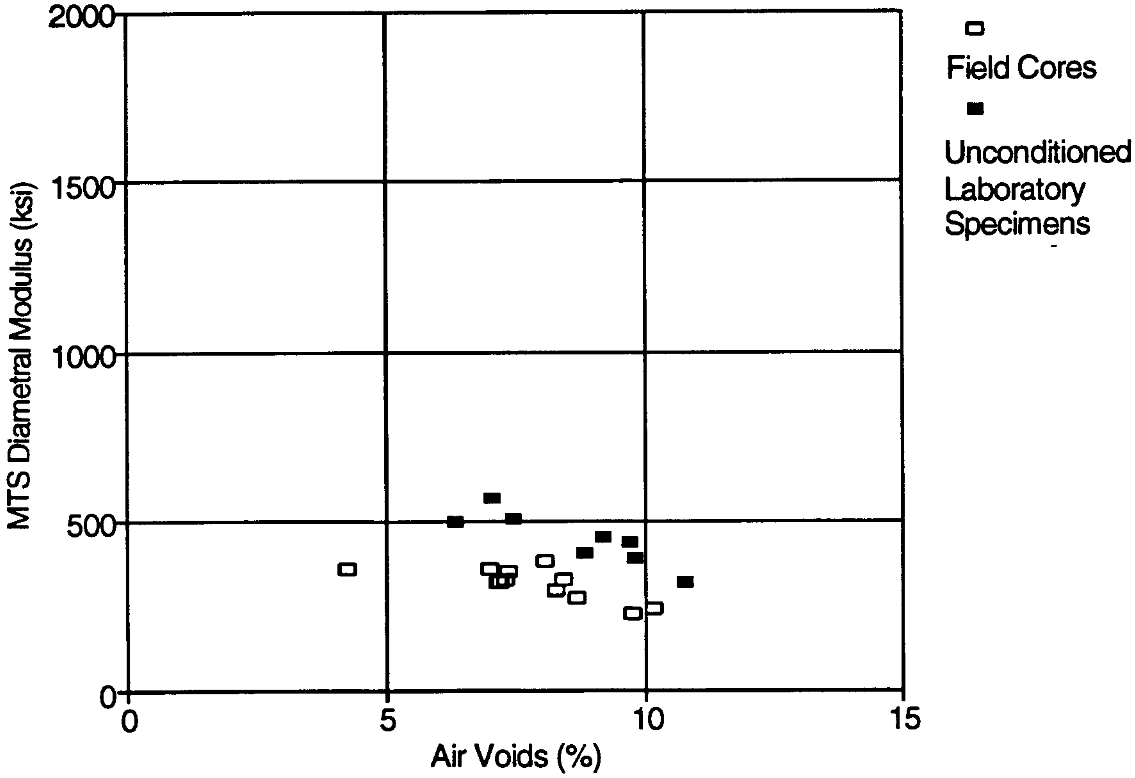


Figure 3.70. GAA field cores, diametral modulus data

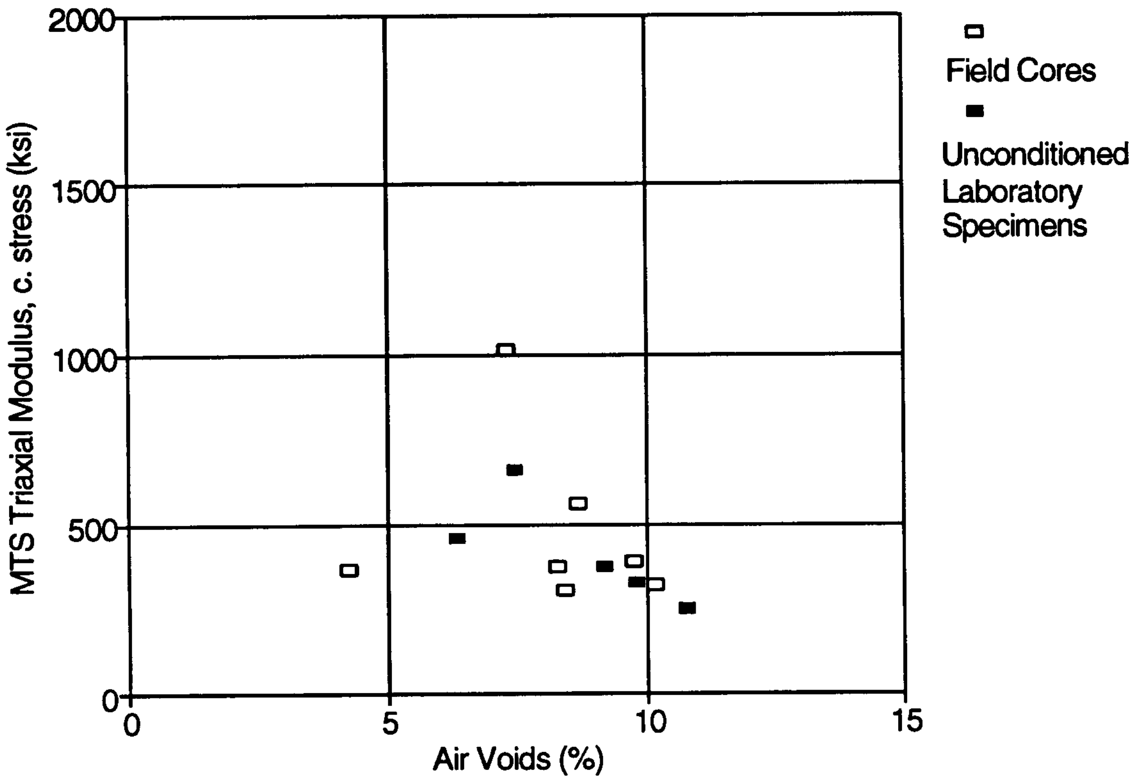


Figure 3.71. GAA field cores, triaxial modulus data (tested at 40 psi [275 kPa])

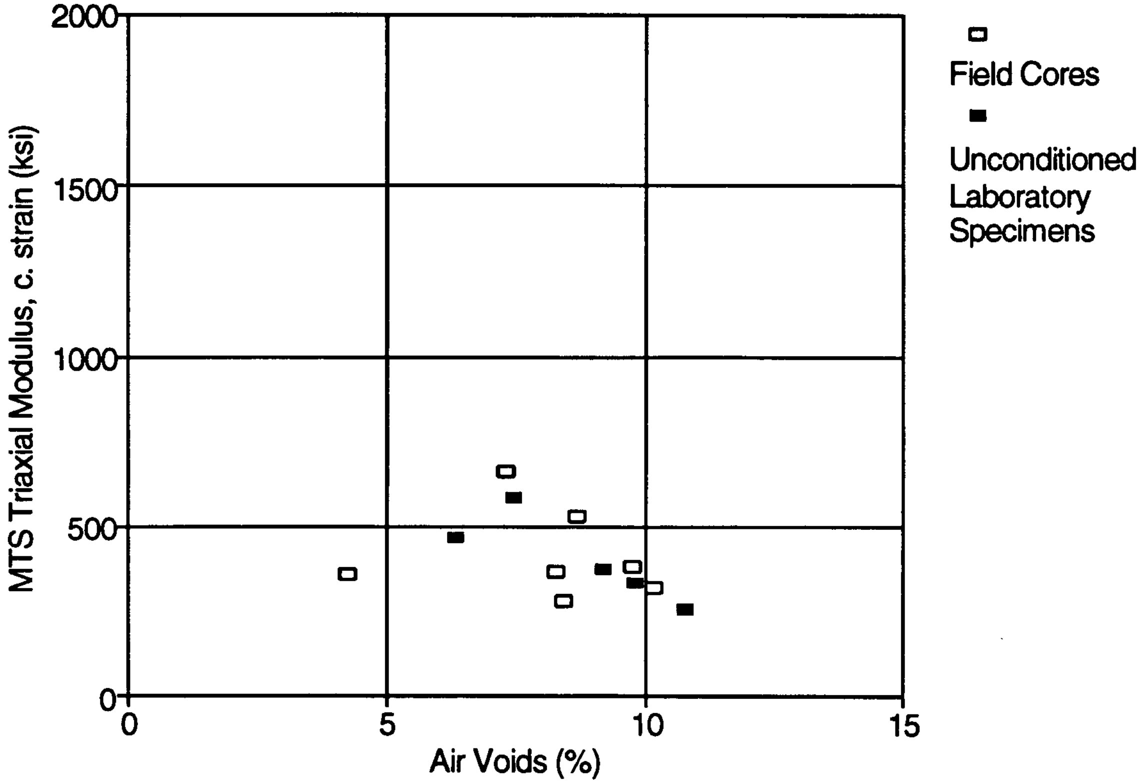


Figure 3.72. GAA field cores, triaxial modulus data (tested at 100 μ-strain)

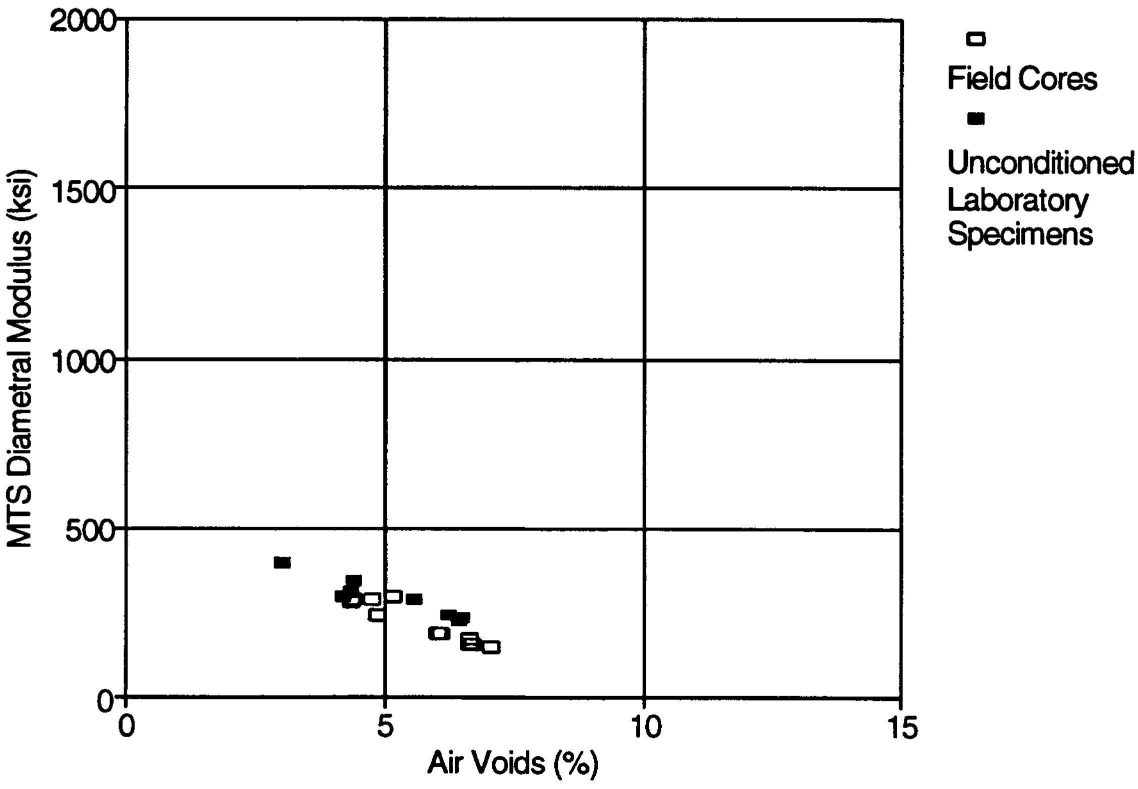


Figure 3.73. MN5 field cores, diametral modulus data

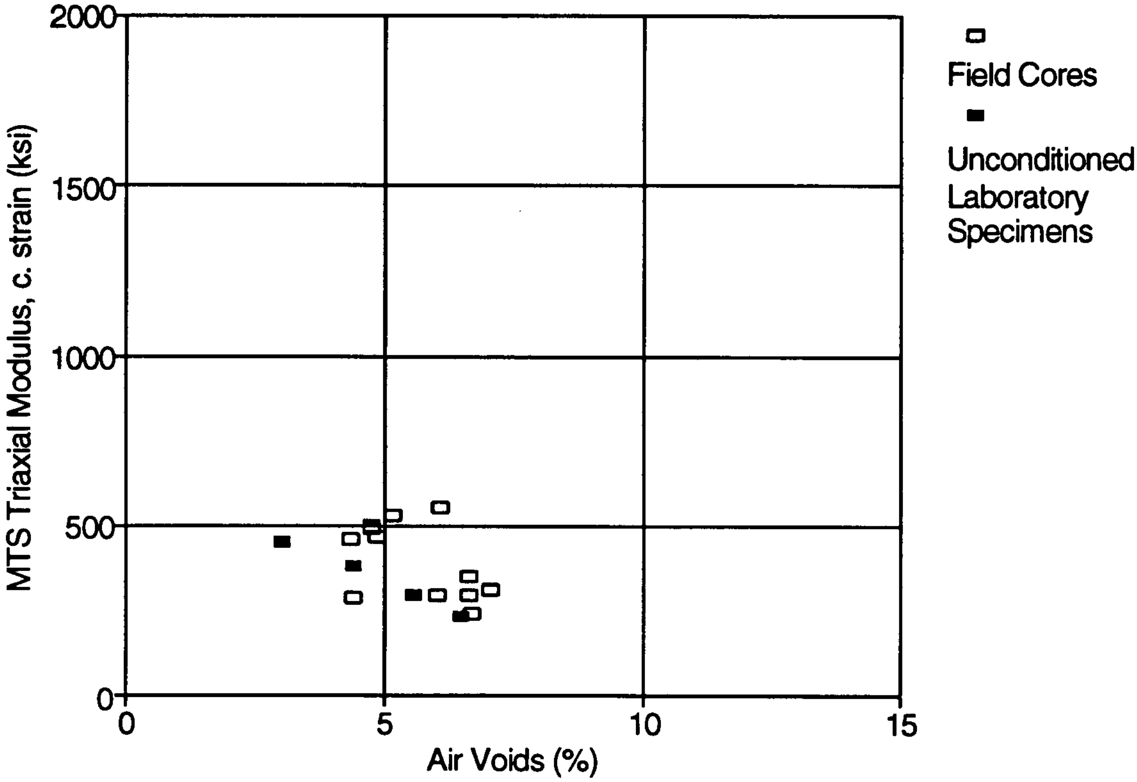


Figure 3.74. MN5 field cores, triaxial modulus data (tested at 100 μ-strain)

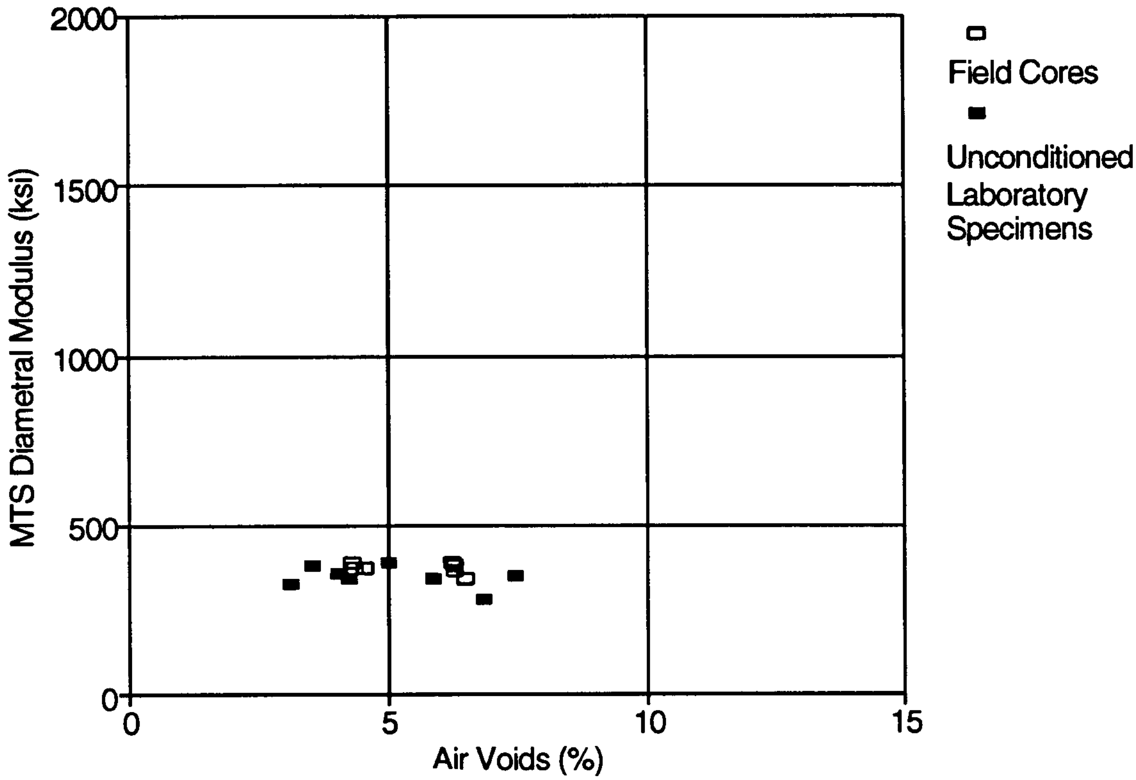


Figure 3.75. MS5 field cores, diametral modulus data

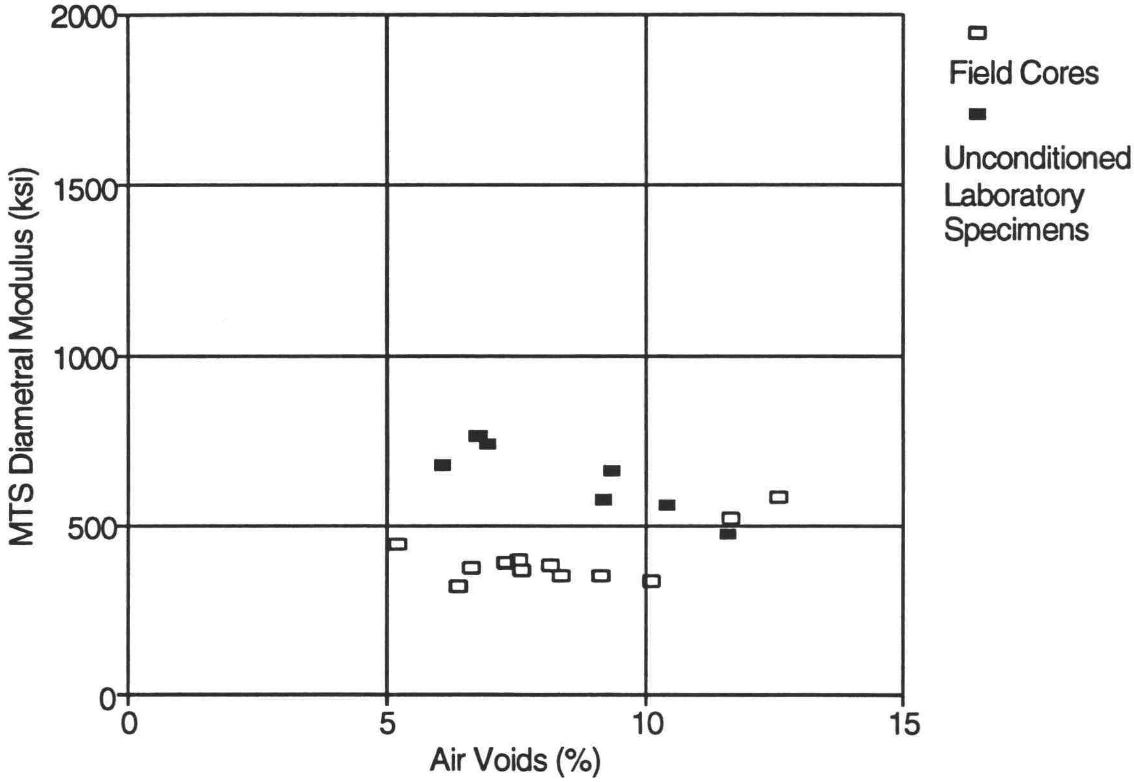


Figure 3.76. OR1 field cores, diametral modulus data

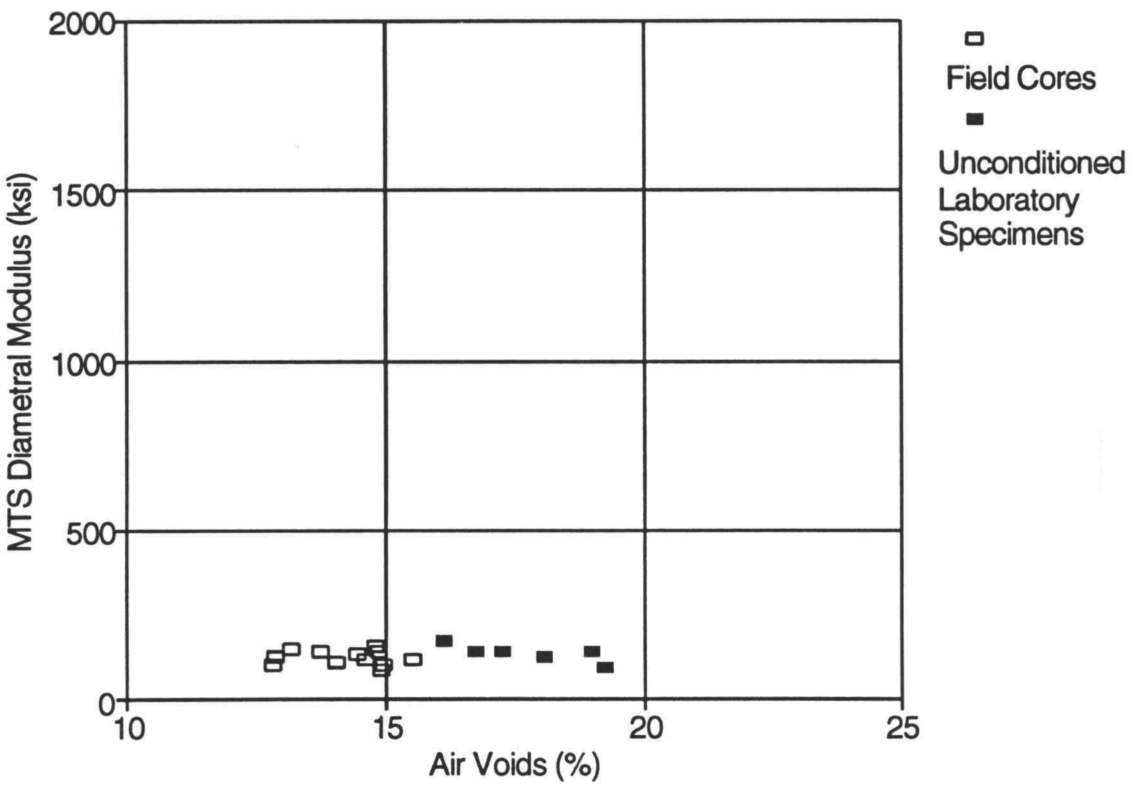


Figure 3.77. OR2 field cores, diametral modulus data

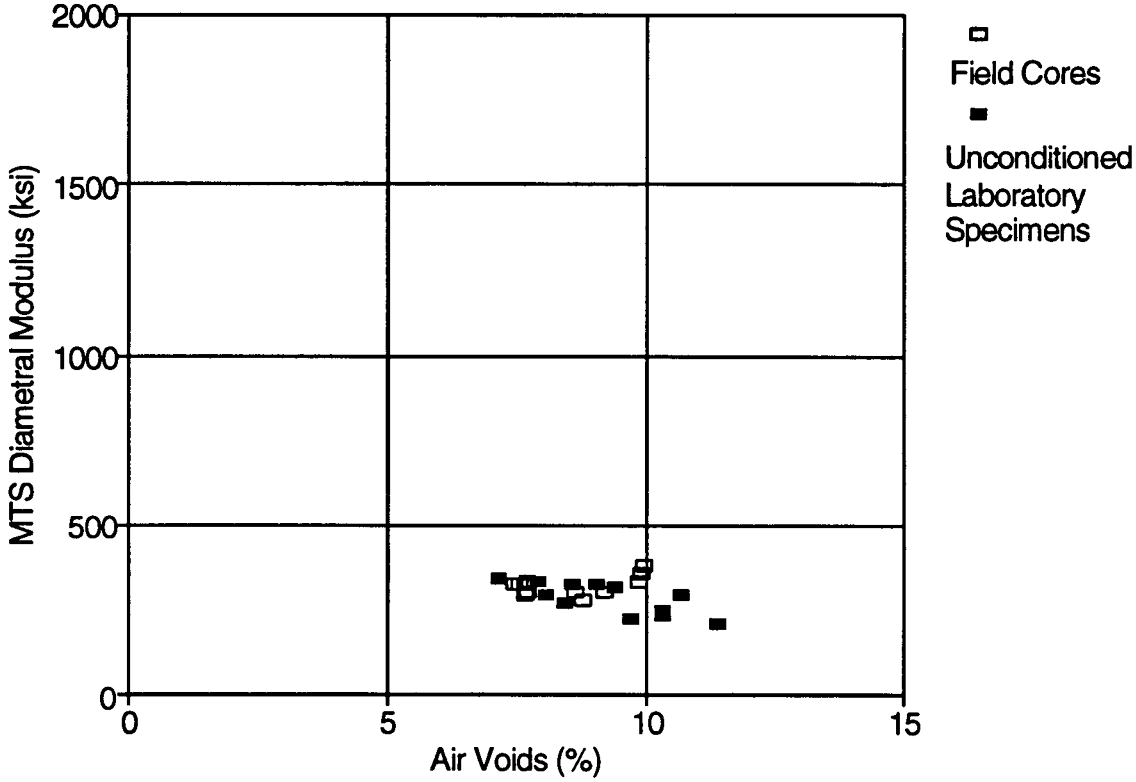


Figure 3.78. WA1 field cores, diametral modulus data

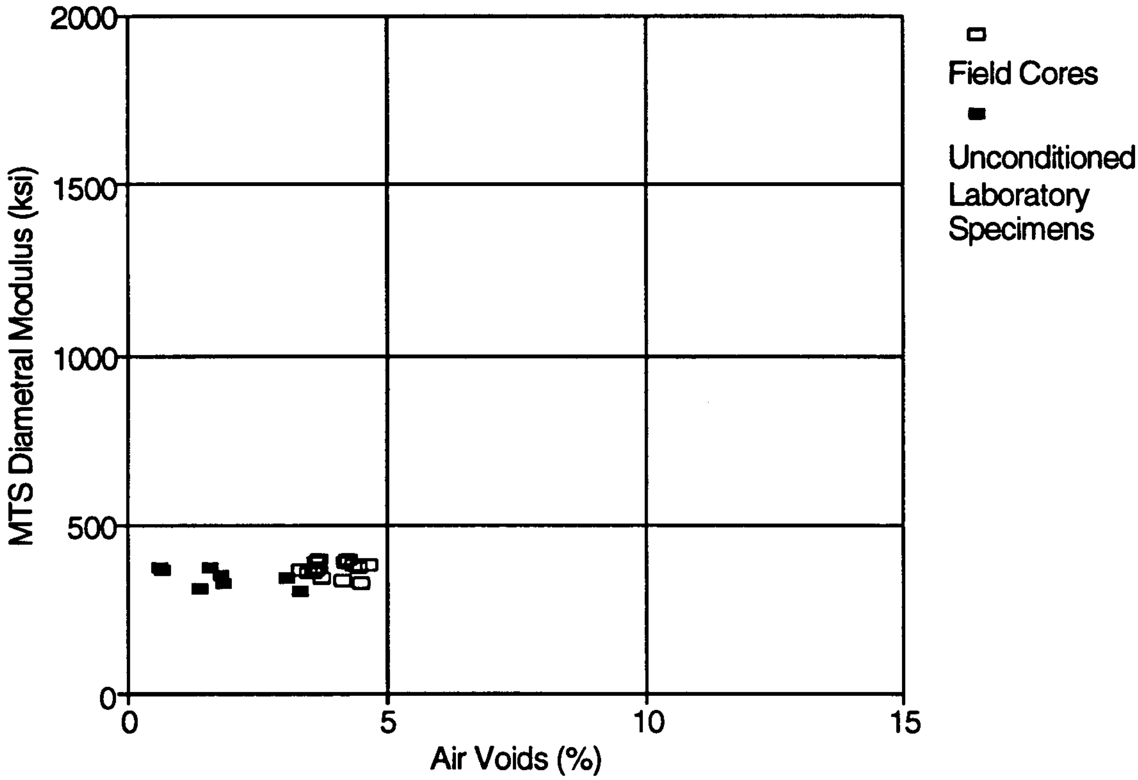


Figure 3.79. WIA field cores, diametral modulus data

Table 3.7. Visual stripping evaluation of field cores[1]

Specimen	Visual Stripping (%)[2]	Comments
AB5F01B AB5F12	10 10	
AZ5F03 AZ5F09	10 10	Fines not stripped as in laboratory specimens
CABF02 CABF10	5 5	
CADF06 CADF07	0 5	
CAGF01 CAGF12	20 20	Very similar to laboratory specimens
GAAF02B GAAF06A	0 5	Very black
MN5F06 MN5F21	5 5	
MS5F02 MS5F03	5 5	Much darker than laboratory specimens
OR1F06 OR1F09	0 5	
OR2F05 OR2F12	10 10	
WA1F01 WA1F07	5 5	
WIAF01 WIAF13	5 5	Asphalt duller than laboratory specimens

[1] No binder migration was observed in field cores
[2] Evaluated according to Figure 2.8, Visual stripping rating chart

4 ANALYSIS AND DISCUSSION OF RESULTS

This chapter presents the analysis and discussion of the results obtained during the evaluation of the Environmental Conditioning System (ECS) using field asphalt concrete mixtures. The performance of the ECS system and the validity of the data from the loading system and the flow system will be discussed, as well as the results of the calibration of the flow systems. This chapter will then present the statistical analysis of the data obtained during the primary test program. The discussion of the testing of the additional secondary mixtures will also be included.

The statistical analysis undertaken on the data from the ECS, the OSU wheel tracker, and the field cores includes evaluating the performance of the mixtures relative to each other in each test format, developing statistical models for predicting mixture performance in each test format, and comparing the performance of the mixtures by test procedure. In addition, the ECS data are investigated to determine if correlations exist among the test's response variables (i.e., ECS modulus ratio, coefficient of water permeability, deformation, degree of visual stripping, and binder migration).

This analysis is designed to determine asphalt concrete mixture properties significant to the performance of a mixture in the ECS and to demonstrate that the ECS test can discriminate between superior and inferior asphalt concrete mixtures as demonstrated by their performance in full-scale field sections and in the OSU wheel tracker. The analysis of results will also form the basis for specifications regarding the use of the ECS in a mix design system. It is not the intention of this analysis to provide exact equations for use in predicting the performance of asphalt concrete mixture with regard to water sensitivity in the ECS, OSU wheel tracker or field, but to provide guidance on the basic relationships that affect performance.

4.1 Evaluation of Test Apparatus

The ECS equipment used in this program is the prototype apparatus developed at OSU by Terrel and Al-Swailmi (1993). As such, the system has not yet been fully investigated for accuracy and precision. The following sections provide some preliminary data on the ECS loading system and flow systems, and some initial calibrations and calculations performed to check the validity of results from these systems.

4.1.1 ECS Loading System

The ECS loading system is a servo-pneumatic system capable of loadings up to approximately 600 lb (270 kg). Ab-Wahab (1993) reports that the accepted error for resilient modulus values using similar systems is 10 percent. Al-Swailmi (1992) reports a coefficient of variation of 0.6 to 0.9 percent from a limited test program using strain-gages to measure deformation, instead of the standard LVDTs. The ECS loading system has not yet undergone the procedures necessary to develop a statistically accurate precision statement. However, a comparison between results from the ECS and MTS system, a standard test procedure, may be of interest.

Figure 3.1 illustrates the relationship between the triaxial resilient modulus values obtained on unconditioned specimens in the ECS versus measurements taken using the MTS hydraulic system. Using a paired t-test, a comparison can be made between the MTS and ECS results. Testing the null hypothesis H_0: $\mu_d = 0$; the mean difference between the MTS modulus and ECS modulus is 0, indicating that the two testing methods produce the same result, a t-statistic of $t_0 = 1.69$ with a corresponding P-value of 0.096 is obtained. Since this is a two-tailed test, this P-value indicates that the values for resilient modulus obtained by the MTS do not differ from those obtained by the ECS at the $\alpha = 0.1$ significance level, which is appropriate if 10 percent is taken as the error for the two systems. If the accuracy of the modulus test performed by the ECS or MTS is actually less than 10 percent, Al-Swailmi (1992), there is some evidence that the values of modulus differ between the two systems. A complete test program to determine the precision of the ECS modulus test is required to determine the accuracy of the system.

The ECS pneumatic loading system has problems achieving the load magnitudes required for testing stiff specimens at 40 psi (275 kPa). Ab-Wahab (1993) has suggested that pneumatic loading systems may have trouble producing loading similar to those from hydraulic systems due to the compressibility of air. For stiffer specimens, the pneumatic cylinder may not be able to compress the air sufficiently to deliver the higher loadings in the time allowed for the loading pulse (0.1 seconds on, 0.9 seconds off), thus, the modulus values may be lower than expected.

Also, specimens tested in the ECS are encapsulated in a latex membrane and the yokes which hold the LVDTs are not cemented to the specimen, as in standard triaxial testing using the MTS. For these reasons, the modulus values taken with the ECS are always reported as "ECS modulus" or "ECS modulus ratio," and are not expected to be equivalent to those determined using conventional hydraulic testing equipment. Finally, care should always be taken to produce specimens with parallel end faces when trimming samples from the field.

4.1.2 ECS Fluid Flow System

4.1.2.1 Calibration of Pressure Gages and Flow Meters. Results from the analysis and calibrations of the ECS flow system were given in Section 3.1.2. Figures 4.1 and 4.2 show a range of data plotted for volumetric flow rate versus differential pressure. The data for water flow have been corrected according to the calibration equations developed in Section 3.1.2. It is obvious from these results that some concern is justified about the validity of the results for the coefficients of air and water permeability. The data cannot be extrapolated through the origin for either air or water flow, suggesting that the flow systems do not comply with Darcy's law.

Data from both systems should allow for the calculation of the intrinsic permeability of each specimen. The intrinsic permeability is a function of the medium only. Therefore, the intrinsic permeability for a given specimen should be unique, whether calculated from air or water data. Figure 4.3 shows the relation between the intrinsic permeability calculated for the air and water flow data. The two flow systems do not give equivalent values for intrinsic permeability.

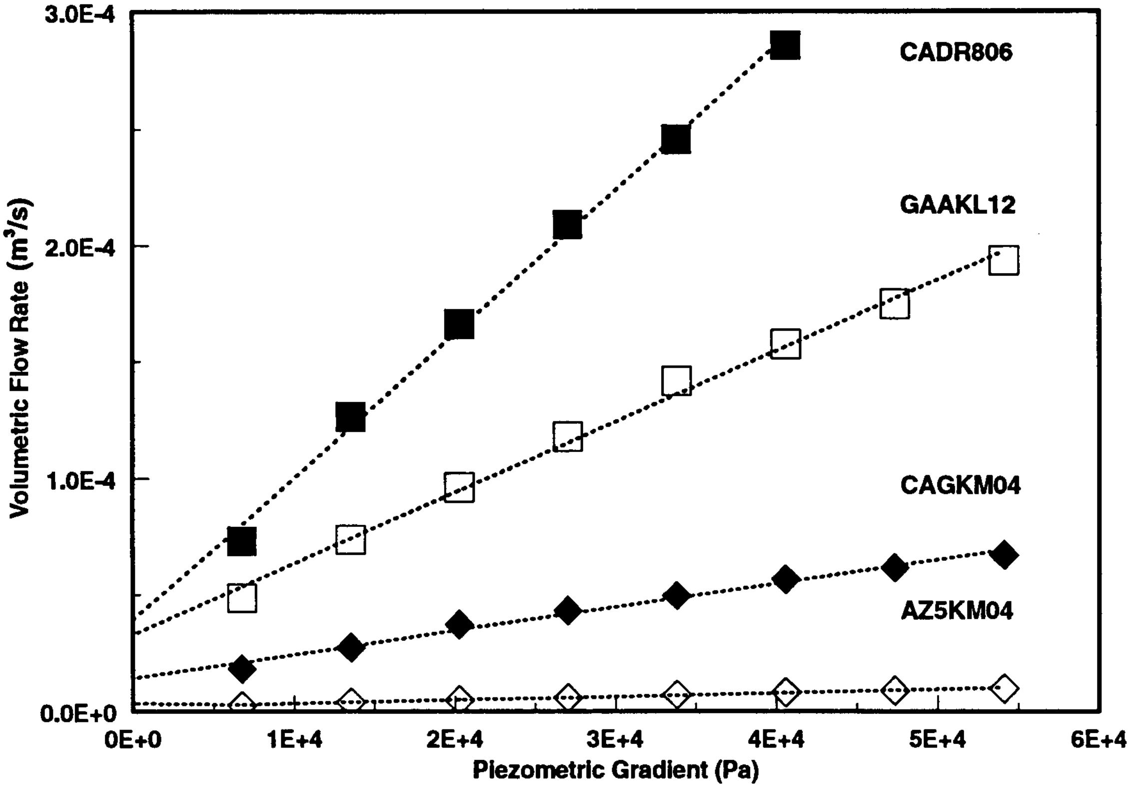


Figure 4.1. Volumetric flow versus piezometric gradient, air flow

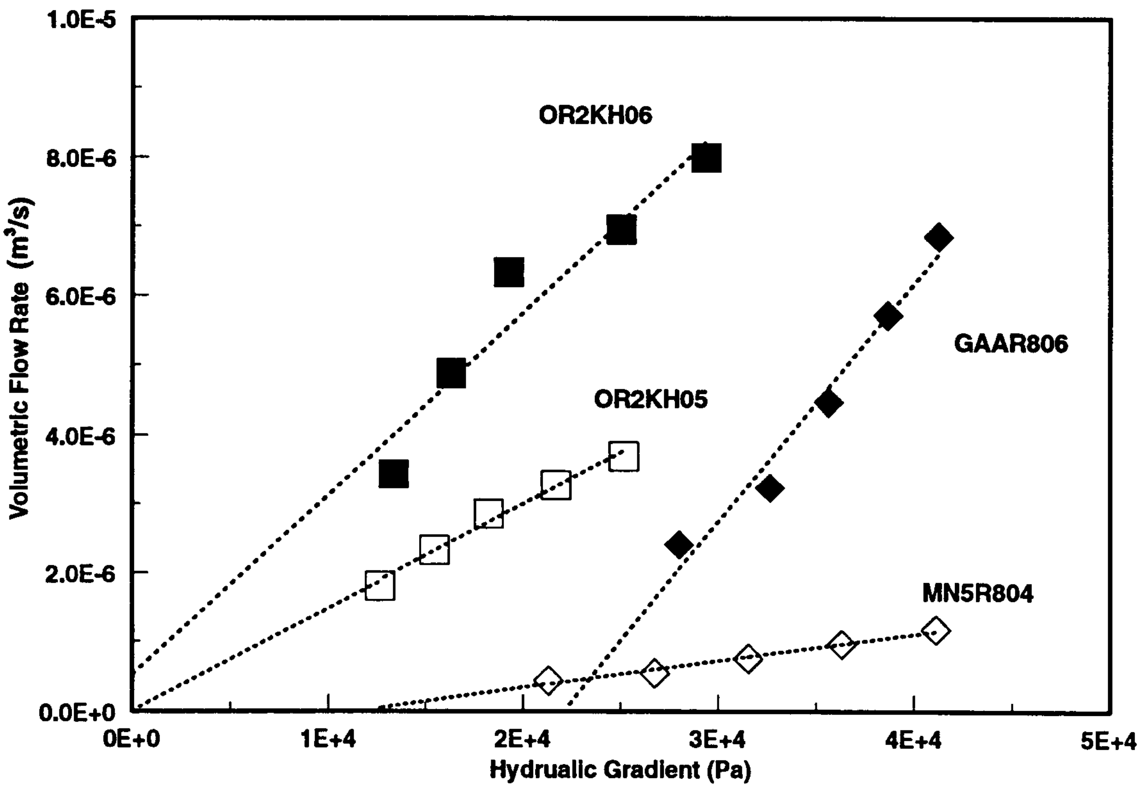


Figure 4.2. Volumetric flow versus hydraulic gradient, water flow

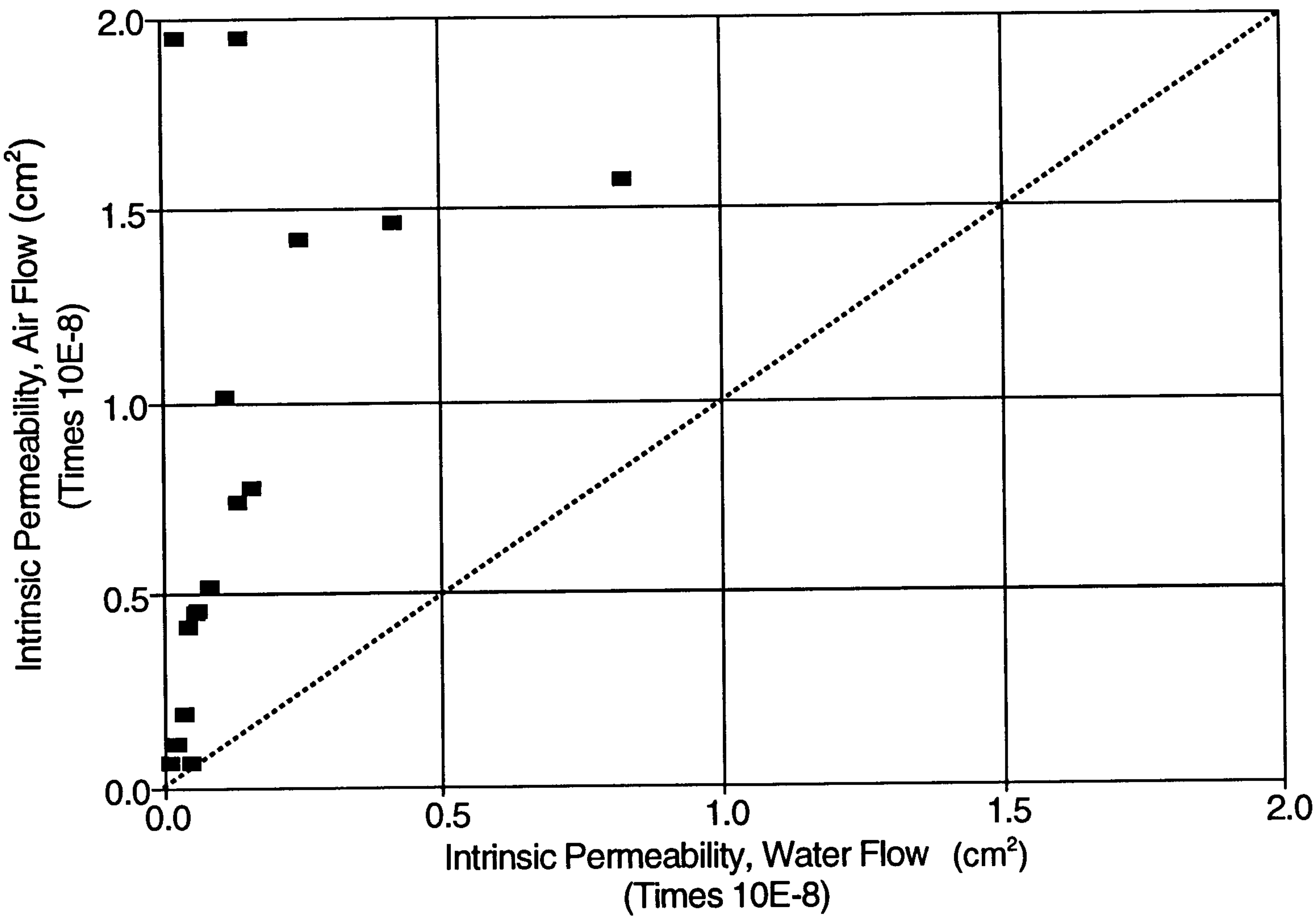


Figure 4.3. Intrinsic permeability calculated from air versus water flow

The first theory that was investigated to correct the data and provide a more accurate determination of the coefficient of air permeability was the Klinkenberg theory for the slip flow of gas. When Darcy's law is used to describe gas flow, an error is introduced due to the slip flow of gases against the surface of the flow area walls (Klinkenberg, 1941). Figure 4.4 indicates the relationship between pressure and the intrinsic permeabilities of a porous medium as determined from gas (K_g) and liquid flows (K_l), proposed by Klinkenberg. The intrinsic permeability from air flow data will be greater than that calculated from water flow data according to this relationship, as was seen in Figure 4.3.

However, Figure 4.5 shows several sets of data from the primary test program plotted according to the Klinkenberg relation. It is obvious that these data do not conform to the relation proposed by Klinkenberg and shown in Figure 4.4. Therefore, it was concluded that some other problem existed with the air flow system.

Dranchuk and Kolada (1968) provided further information on the theory of gas flow. Darcy's law and the Klinkenberg correction are applicable for gases flowing in the range of viscous flow. They do not explain flow in either the visco-inertial or turbulent range. Dranchuk and Kolada propose that for viscous flow, the following equation can be produced from Darcy's law and the Klinkenberg correction:

$$K_a = \frac{2\,\mu\,\bar{Z}\,\bar{T}\,p_o\,L\,Q_o}{A\,T_o\,(\,p_1^2 - p_2^2\,)} \tag{4.1}$$

where

where	K_a	=	apparent permeability,
	μ	=	gas viscosity,
	Z	=	mean gas compressibility factor,
	T	=	mean flowing temperature,
	p_o	=	reference pressure,
	L	=	length of specimen,
	Q_o	=	volumetric flow rate at reference conditions,
	A	=	cross-sectional area of specimen,
	T_o	=	reference temperature,
	p_1	=	upstream pressure, and
	p_2	=	down stream pressure.

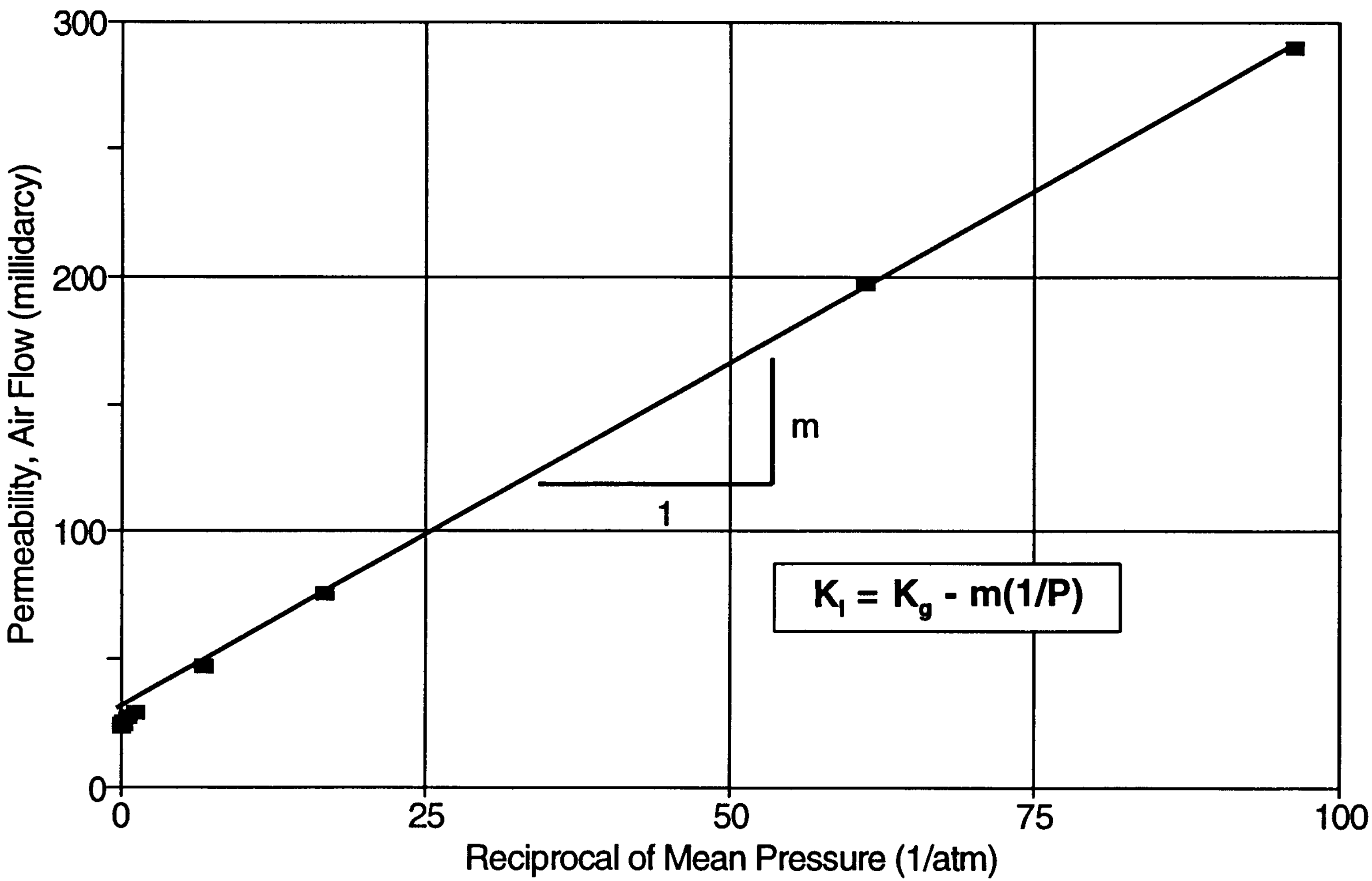


Figure 4.4. Klinkenberg relationship for permeability and reciprocal mean pressure (after Klinkenberg, 1941)

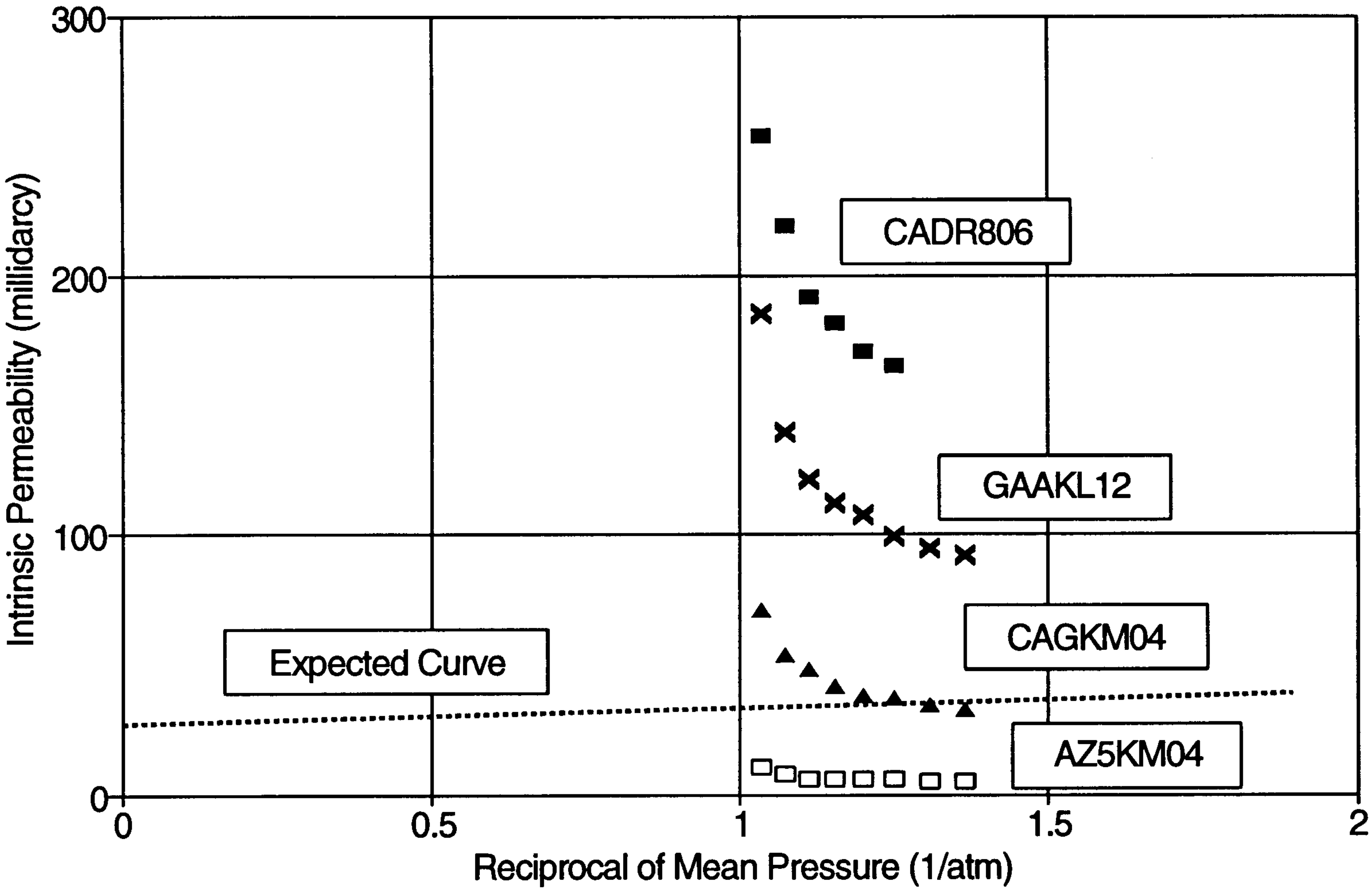


Figure 4.5. Permeability versus reciprocal mean pressure, for ECS air flow

From this equation, Dranchuk and Kolada propose that if

$$\frac{K_a\, A\, T_o}{2\, \mu\, \bar{Z}\, \bar{T}\, p_o\, L} = constant \tag{4.2}$$

a log-log plot of $(p_1^2 - p_2^2)$ versus Q_o should yield a straight line with a slope of 45°, provided that flow is viscous. In the visco-inertial flow range, the data will deviate from the straight line toward the pressure axis. Figure 4.6 shows such a plot for a range of flow values determined with the ECS air flow apparatus. It is assumed that the points taken at the lowest differential pressure and flow are the most likely to be in the viscous flow range. It is obvious that the data do not fall along a straight line at a 45° angle; therefore, it can be concluded that the data is out of the viscous flow range.

If the air flow data are out of the viscous flow range, the coefficient of air permeability calculated by Darcy's law is incorrect, and can only be used as a relative measure of the specimen's tendency to allow air flow. It should not be reported as a true coefficient of permeability for other purposes. A modification to the air flow system would be required to produce flows within the viscous range and to allow a calculation of the coefficient of air permeability with Darcy's law. This could be accomplished by using lower pressure gradients and more sensitive flow meters. The flow meters employed in the current air permeability system are designed for coarse regulation of flow. For the purposes of determining the coefficient of permeability, flow meters designed for such a task would be more appropriate.

It should also be mentioned that the air permeability apparatus used in this test program was prone to blockage by material falling into the outlet in the bottom platen. If material is allowed to accumulate in the tubing of the apparatus, reduced values of the coefficient of air permeability will be measured that are not indicative of the specimen permeability. The system should be cleaned regularly to prevent accumulation of material within the tubing.

The data from the water flow system shown in Figure 4.2 were corrected using the calibration equations reported in Table 3.1. Figure 4.7 shows a typical data transformation provided by the calibration. It is still obvious that the results do not

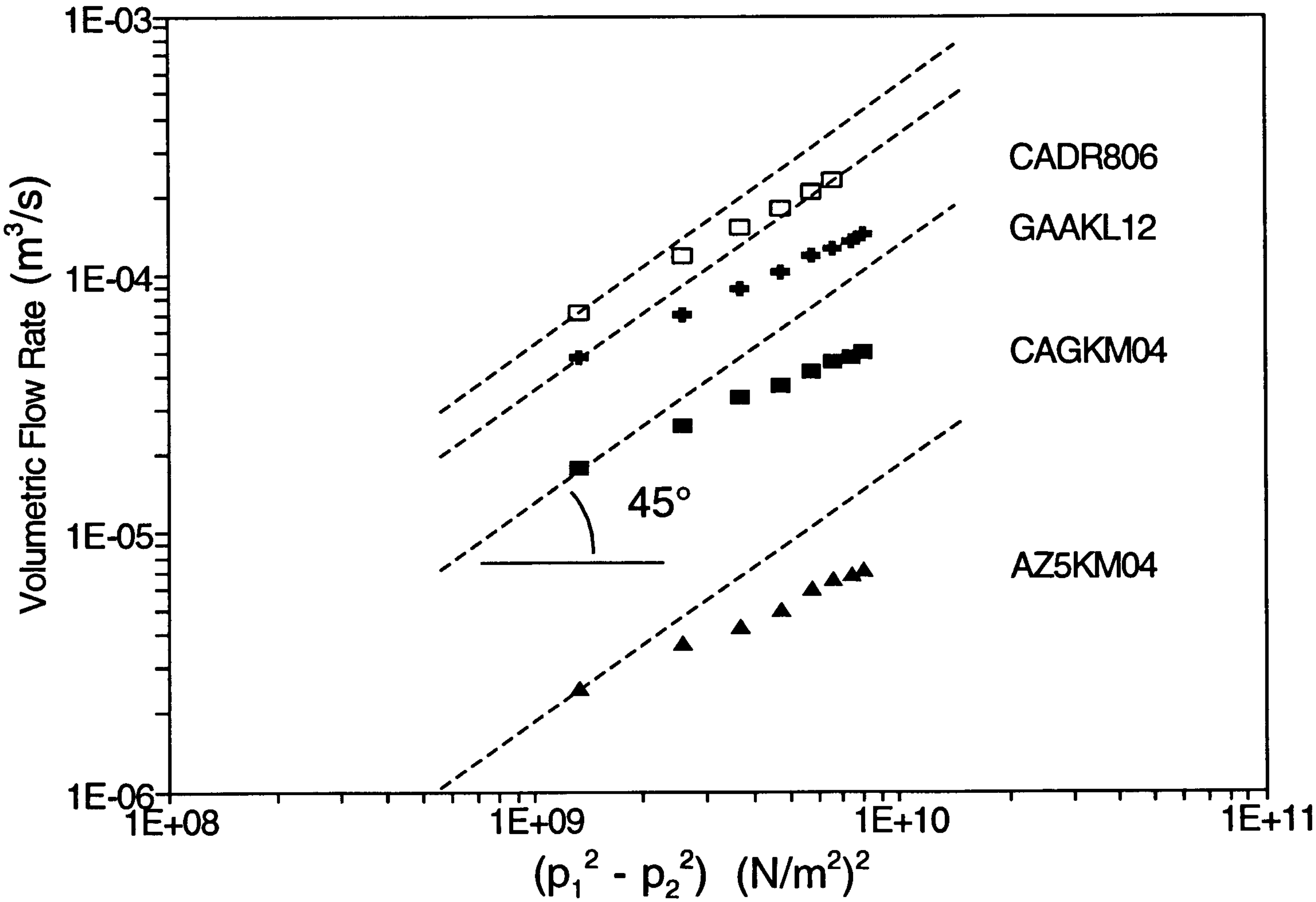


Figure 4.6. ECS air flow plot

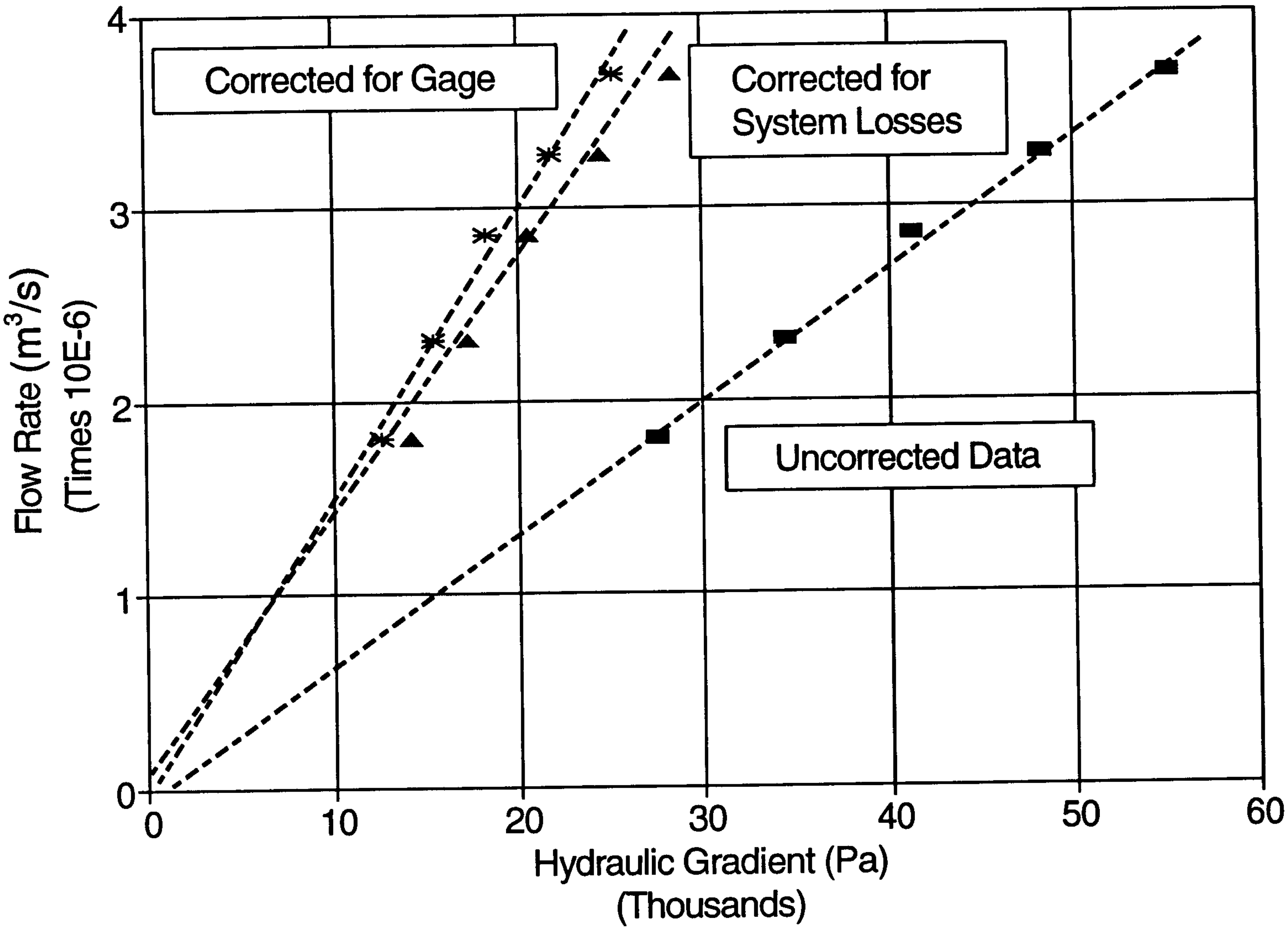


Figure 4.7. Calibration transformation of water flow data

follow Darcy's law for all specimens. The author believes that the deviation of the data results from a leak in the tubing of the ECS flow system. The differential pressure readings do not take place directly across the specimen, but include several feet of tubing and various connections. A leak in this system would cause the pressure gaging to read a differential pressure less than that seen across the specimen, and the difference between the measured and true differential pressure would be a function of the vacuum level. Therefore, the calculated coefficients of water permeability are not true values of the coefficient of permeability and can only be used for relative measures of flow through the specimens. If the integrity of the system varied with time (i.e., new leaks occurred, or tubing and valving was replaced), even relative use of the data might be suspect. The author knows of two instances of replaced tubing during the course of this experimental work.

The problem of leaks in the tubing could be mitigated by placing the differential pressure gage directly across the platens of the ECS specimen frame, instead of back within the tubing. Modification of the water flow system should also include replacing the flow meters. The water flow system uses the same type of flow meters employed in the air system. Meters designed to accurately measure flow quantities would provide better data.

Further use of the values of the coefficients of permeability in this report are relative comparisons only. It is understood that the true values for specimen coefficients of air and water permeability are not represented by the data presented in this report.

4.1.2.2 Estimate of Precision for Coefficients of Permeability. Figures 3.4 through 3.10 indicate that the calculated values of the coefficient of air and water permeability, as measured by the ECS system instrumentation, could have up to a 50 percent error, depending on the system in use. The range of error varies widely and depends on the combination of gaging used for the measurement. The amount of error also changes depending on the magnitude of the reading being taken, as demonstrated by higher errors for lower pressure readings. This is expected as the potential error is a larger percentage of the reading when the magnitude of the reading is smaller.

However, for the set of data generated, the percent error at each pressure level is equivalent in magnitude due to the variation in error resulting from the other parameters in the equation for coefficient of permeability.

The coefficients of permeability are calculated as the average of several readings, each taken at a different pressure. The standard deviation for each set of error values calculated in Section 3.1.2.2 should give an approximation of the standard deviation for a calculated value of the coefficient of permeability for that set of instruments. Table 4.1 presents the standard deviation of the calculated errors. The mean of the errors will approach zero as the number of calculations with the random number generator approaches infinity.

If the errors are normally distributed, 68 percent of the calculated values of the coefficients of permeability will fall within one standard deviation of the error from the true value, if there was no reading error associated with the gages. Ninety-five percent of the values will fall within two standard deviations of the error. For example, 45 percent of the calculations performed with readings taken on system A, from the gph flow meter, will have less than 7.1 percent error associated with the gage reading, and 95 percent will have less than 14.2 percent error. Gaging that reads more precisely, with finer scale divisions, would minimize errors.

4.2 ECS Test Results

4.2.1 ECS Modulus Data

The analysis of the ECS test results employed a General Linear Model (GLM) procedure provided by the SAS software package (SAS Institute Inc., 1988) to compare the mean ECS modulus ratios (the response variable) for each mixture. The GLM approach is appropriate for data from unbalanced test designs, in this case unequal numbers of specimens for each mixture. The general procedure for determining the significance of a variable to the response being investigated used an analysis of covariance approach with the Type III sum of squares. The Type III sum

Table 4.1. Standard deviation of the errors for the coefficients of permeability

System	Standard Deviation of Error (cm/s)	Standard Deviation of Percent Error (%)
Air Permeability, ccm Flow Meter	1.39E-10	2.3
Air Permeability, 1-10 scfh Flow Meter	1.13E-10	5.8
Air Permeability, 4-40 scfh Flow Meter	4.59E-10	6.0
Water Permeability, ccm Flow Meter, System A	9.83E-06	10.0
Water Permeability, gph Flow Meter, System A	2.22E-04	7.1
Water Permeability, ccm Flow Meter, System B	4.41E-06	9.6
Water Permeability, gph Flow Meter, System B	1.87E-04	12.0

of squares reports the significance a variable adds to the model, considering all other variables already in the model, regardless of the order in which the variables are introduced to the model (SAS Institute inc., 1988). The general form of analysis of covariance models is (Montgomery, 1991):

$$y_{ij} = \mu + \tau_i + \beta\,(x_{ij} - \bar{x}) + \epsilon_{ij} \left\{ \begin{array}{l} i = 1, 2, ..., a \\ j = 1, 2, ..., n \end{array} \right. \tag{4.3}$$

where
- y_{ij} = the *j*th observation on the response variable taken under the *i*th treatment,
- μ = the over all mean,
- τ = the effect of the *i*th treatment,
- β = a linear regression coefficient indicating the dependency of y_{ij} on x_{ij},
- x_{ij} = the *j*th observation of the covariate taken under the *i*th treatment, and
- ε_{ij} = the random error component.

For any model being developed, the significance of a covariate, or interactions between covariates, is determined using the F statistic, which is testing the hypothesis that the effect of the covariate, or interaction, is not significant (H_0: $\beta = 0$). Criteria for rejection of H_0 is a significant F-value, as indicated by P-value of less than 0.05. For significant covariates, their inclusion in the model helps explain a significant portion of the variance in the data. In the work conducted here, the treatment effect is mixture type. For any given analysis of covariance, an equivalent regression equation can be determined. It is not the intent of this research to produce exact equations, and therefore these equations are not presented.

The performance comparison of the mixtures used the standard T groups from the least significant difference (LSD) with an $\alpha = 0.05$ to produce a comparison of the mean ECS modulus ratios with a 95 percent confidence interval. The LSD comparison gives the least statistically significant difference between means, with consideration of all variance in the data, including any random error (Montgomery, 1991).

4.2.1.1 Comparison of Mixture Performance. Four comparisons were produced: (1) the ECS modulus ratio for each cycle of the ECS procedure, for the entire data set, (2) the ECS modulus ratio for each cycle of the ECS procedure, for mixtures from Freeze environments, (3) the ECS modulus ratio for each cycle of the ECS procedure, for mixtures from No-Freeze environments, and (4) an overall comparison using the final ECS modulus ratio obtained for each mixture. For mixtures from No-Freeze environments, the final ECS modulus ratio is the ECS modulus ratio after three hot cycles. For mixtures from Freeze environments, the final ECS modulus ratio is taken after three hot cycles and the fourth freeze cycle. The comparison using the final ECS modulus ratio is directly analogous to the performance of the mixture in its particular environmental zone.

The initial comparison among the test procedures used MIX, the asphalt mixture type, as a class variable. This differentiated the performance on the basis of mixture type only. Tables 4.2 through 4.5 show the comparison of mixture performance in the ECS with the ECS modulus ratio. The four cases discussed above are shown. For mixtures MS5 and WIA, only the specimens that survived the ECS procedure without excessive deformation were used in the analysis. The surviving specimens included three MS5 specimens and five WIA specimens.

The mixtures that were tested demonstrated two typical responses. Mixtures seemed to either experience most of their damage during the first ECS conditioning cycle, and then maintained a fairly constant modulus ratio, or continued to decrease in modulus through the later ECS cycles, which demonstrated continuing water damage. Figures 3.11 through 3.22 illustrate that several of the mixtures experienced a high percentage of their reduction in ECS modulus ratio during the first test cycle. Table 4.6 indicates that eight of the mixtures tested experienced over 50 percent of their reduction in modulus during the first cycle. Mixtures which experience a significant reduction in ECS modulus (final ECS modulus ratio of less than 0.7 as discussed in Section 5.2) are very susceptible to water damage and will probably experience water damage early in their lifetimes.

The difference in the slope of the ECS modulus ratio curve between cycles 1 and 3 is also different for each mixture. Table 4.7 indicates the mean values of slope for the ECS modulus curve between cycles 1 3 for the mixtures tested. This data is

Table 4.2. Performance of mixtures by ECS modulus ratio, entire data set

	Cycle 1			Cycle 2		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping[1]	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.95	A	GAA	0.93	A
2	OR2	0.90	A	OR2	0.92	A, B
3	OR1	0.88	A, B	OR1	0.87	A, B
4	AB5	0.87	A, B	WA1	0.87	A, B
5	WA1	0.86	A, B	AB5	0.81	B, C
6	MN5	0.78	B, C	WIA	0.71	C, D
7	WIA	0.75	C, D	AZ5	0.71	C, D
8	AZ5	0.74	C, D	MN5	0.71	C, D
9	CAB	0.70	C, D	CAB	0.67	D
10	MS5	0.69	C, D	MS5	0.67	D
11	CAD	0.65	D	CAD	0.63	D
12	CAG	0.50	E	CAG	0.45	E

	Cycle 3			Cycle 4		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.94	A	OR2	0.92	A
2	OR2	0.90	A	WA1	0.90	A
3	OR1	0.87	A, B	WIA	0.77	A
4	WA1	0.84	A, B, C	AB5	0.76	B
5	AB5	0.78	C, D, E	CAB	0.55	B
6	AZ5	0.72	C, D, E	MN5	0.54	C
7	WIA	0.69	D, E, F	CAD	0.46	C
8	CAB	0.65	D, E, F	[2]		
9	MN5	0.65	D, E, F			
10	MS5	0.62	E, F			
11	CAD	0.59	F			
12	CAG	0.42	G			

[1] Groupings with the same letter designation include means which are not significantly different at $\alpha = 0.05$

[2] The remaining five mixtures were not tested with the freeze cycle

Table 4.3. Performance of mixtures by ECS modulus ratio, freeze data

	Cycle 1			Cycle 2		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping[1]	Mixture	Mean ECS Modulus Ratio	T Grouping
1	OR2	0.90	A	OR2	0.92	A
2	AB5	0.87	A, B	WA1	0.86	A
3	WA1	0.86	A, B	AB5	0.81	A, B
4	MN5	0.78	B, C	WIA	0.71	B, C
5	WIA	0.75	C, D	MN5	0.71	B, C
6	CAB	0.70	C, D	CAB	0.67	C
7	CAD	0.65	D	CAD	0.63	C

	Cycle 3			Cycle 4		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping	Mixture	Mean ECS Modulus Ratio	T Grouping
1	OR2	0.90	A	OR2	0.92	A
2	WA1	0.84	A	WA1	0.90	A
3	AB5	0.78	A, B	WIA	0.77	A
4	WIA	0.65	B, C	AB5	0.76	B
5	CAB	0.65	B, C	CAB	0.55	B
6	MN5	0.65	B, C	MN5	0.54	C
7	CAD	0.59	C	CAD	0.46	C

[1] Groupings with the same letter designation include means which are not significantly different at $\alpha = 0.05$

Table 4.4. Performance of mixtures by ECS modulus ratio, no-freeze data

Rank	Cycle 1			Cycle 2		
	Mixture	Mean ECS Modulus Ratio	T Grouping[1]	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.95	A	GAA	0.93	A
2	OR1	0.88	A	OR1	0.87	A
3	AZ5	0.74	B	AZ5	0.71	B
4	MS5	0.69	B	MS5	0.67	B
5	CAG	0.51	C	CAG	0.45	C

Rank	Cycle 3		
	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.94	A
2	OR1	0.87	A
3	AZ5	0.72	B
4	MS5	0.62	B
5	CAG	0.42	C

[1] Groupings with the same letter designation include means which are not significantly different at $\alpha = 0.05$

Table 4.5. Performance of mixtures by final ECS modulus ratio, regardless of environmental zone

Rank	Mixture	Mean Ratio	T Grouping[1]
1	GAA	0.94	A
2	OR2	0.92	A
3	WA1	0.90	A, B
4	OR1	0.87	A, B, C
5	WIA	0.77	B, C, D
6	AB5	0.76	C, D, E
7	AZ5	0.72	C, D, E
8	MS5	0.62	E, F
9	CAB	0.55	F, G
10	MN5	0.54	F, G
11	CAD	0.46	G
12	CAG	0.42	G

[1] Groupings with the same letter designation include means which are not significantly different at $\alpha = 0.05$

Table 4.6. Percent of ECS modulus ratio reduction that occurs in cycle 1

Mixture	Cycle 1 Mean ECS Modulus Ratio	Mean Final ECS Modulus Ratio	Percentage Final ECS Modulus Ratio Lost in Cycle 1
AB5	0.87	0.76	52
AZ5	0.74	0.72	92
CAB	0.70	0.55	68
CAD	0.65	0.46	65
CAG	0.51	0.42	86
GAA	0.95	0.94	76
MN5	0.78	0.54	49
MS5	0.69	0.62	82
OR1	0.88	0.87	95
OR2	0.90	0.92	115
WA1	0.87	0.90	131
WIA	0.75	0.77	109

Table 4.7. Mean slope of ECS modulus ratio from cycle 1 to cycle 3

Site	Slope
AB5	-0.0498
AZ5	-0.0103
CAB	-0.0224
CAD	-0.0307
CAG	-0.0402
GAA	-0.0093
MN5	-0.0290
MS5	-0.0337
OR1	-0.0029
OR2	0.0014
WA1	-0.0115
WIA	-0.0125

presented graphically in Figure 4.8. The slope is defined as:

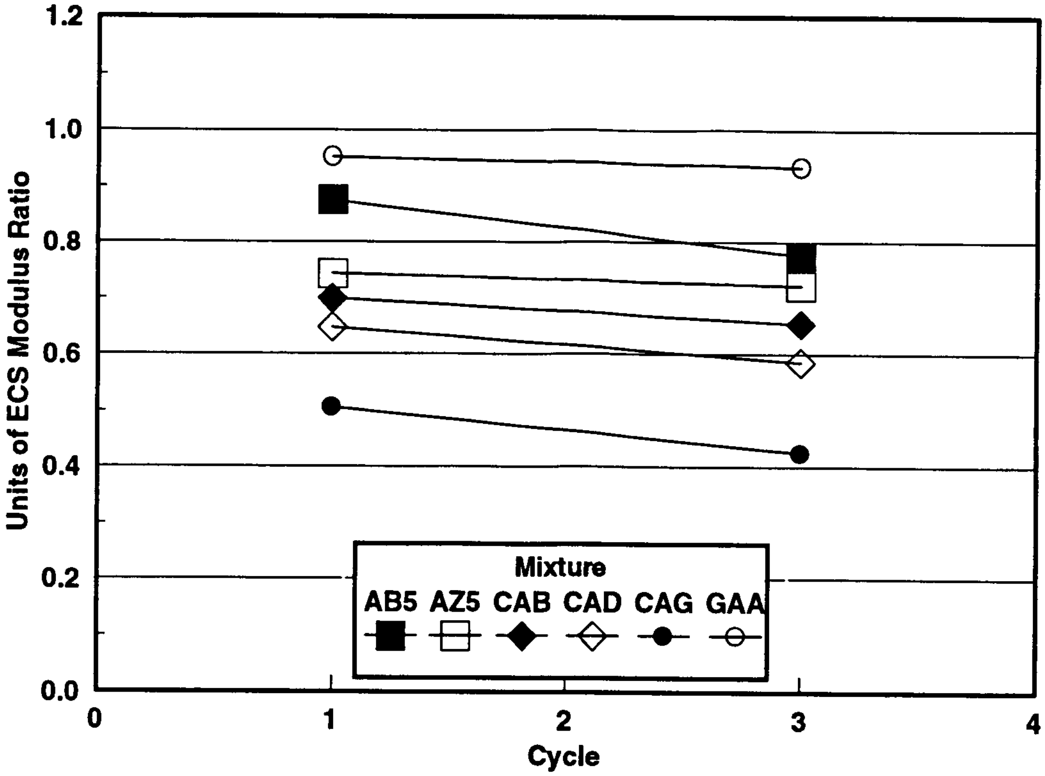
$$Slope = \frac{(Cycle\ 3\ ECS\ Modulus\ Ratio - Cycle\ 1\ ECS\ Modulus\ Ratio)}{(3-1)} \quad (4.3)$$

The slope is an indicator of the rate of damage to the specimen as it undergoes the ECS test procedure. Figure 4.9 shows the change in ECS modulus ratio between cycles 1 and 3 graphically. The slopes of the modulus curves between cycles 1 and 3 indicate that several of the mixtures experience a reduction in modulus ratio between cycles 1 and 3 of 0.100 or greater (AB5, CAG, and MN5). These mixtures continued to experience damage over the course of the test and would probably continue to accumulate damage if subjected to further conditioning. Of the seven mixtures which underwent the fourth freeze cycle, OR2, WA1, and WIA actually had lower ECS modulus ratios after the third cycle than after the final "freeze" cycle. This is illustrated in Figure 4.10.

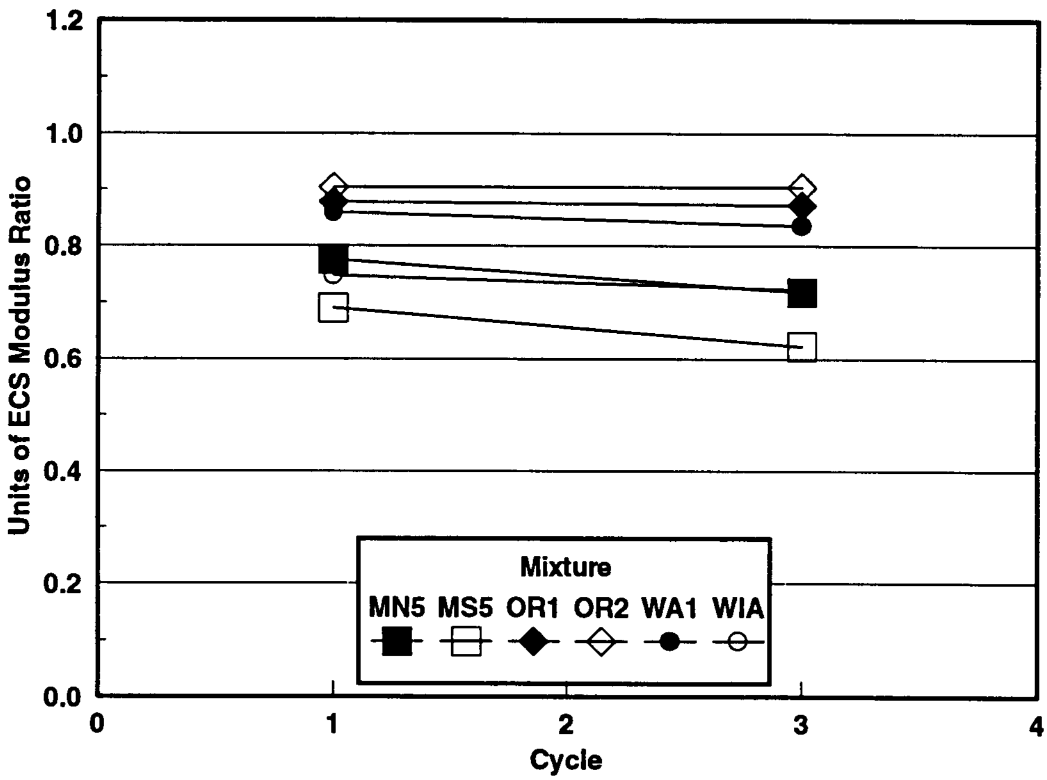
The slope of the ECS modulus ratio curve between cycles 3 and 4 may indicate the effects of aggregate degradation on the ECS modulus. Only one mixture tested (OR2) showed signs of aggregate degradation during visual evaluation. However, OR2 did not experience a significant reduction in modulus during the freeze cycle. It is inconclusive, on the basis of the current data, if the change in ECS modulus during cycle 4 can be attributed to aggregate degradation. A better way of evaluating the split specimen for aggregate degradation would be beneficial.

The model developed using only mixture type as a variable to describe the ECS modulus ratio is reported in Table 4.8. The P-values indicate the significance of mixture type to the prediction of the ECS modulus ratio after each cycle. Also note the similar values of R^2 and the coefficient of variation after each cycle.

4.2.1.2 Prediction Variables for ECS Modulus Ratio. Additional analyses were performed to investigate a more comprehensive set of variables, including ECS test system, compaction method, percent initial air voids, initial coefficient of air permeability, initial coefficient of water permeability, and initial ECS modulus. These variables will be identified as either significant or insignificant to the prediction of



a) Mixtures AB5 through GAA



b) Mixtures MN5 through WIA

Figure 4.8. Slope of mean ECS modulus ratio curves between cycles 1 and 3

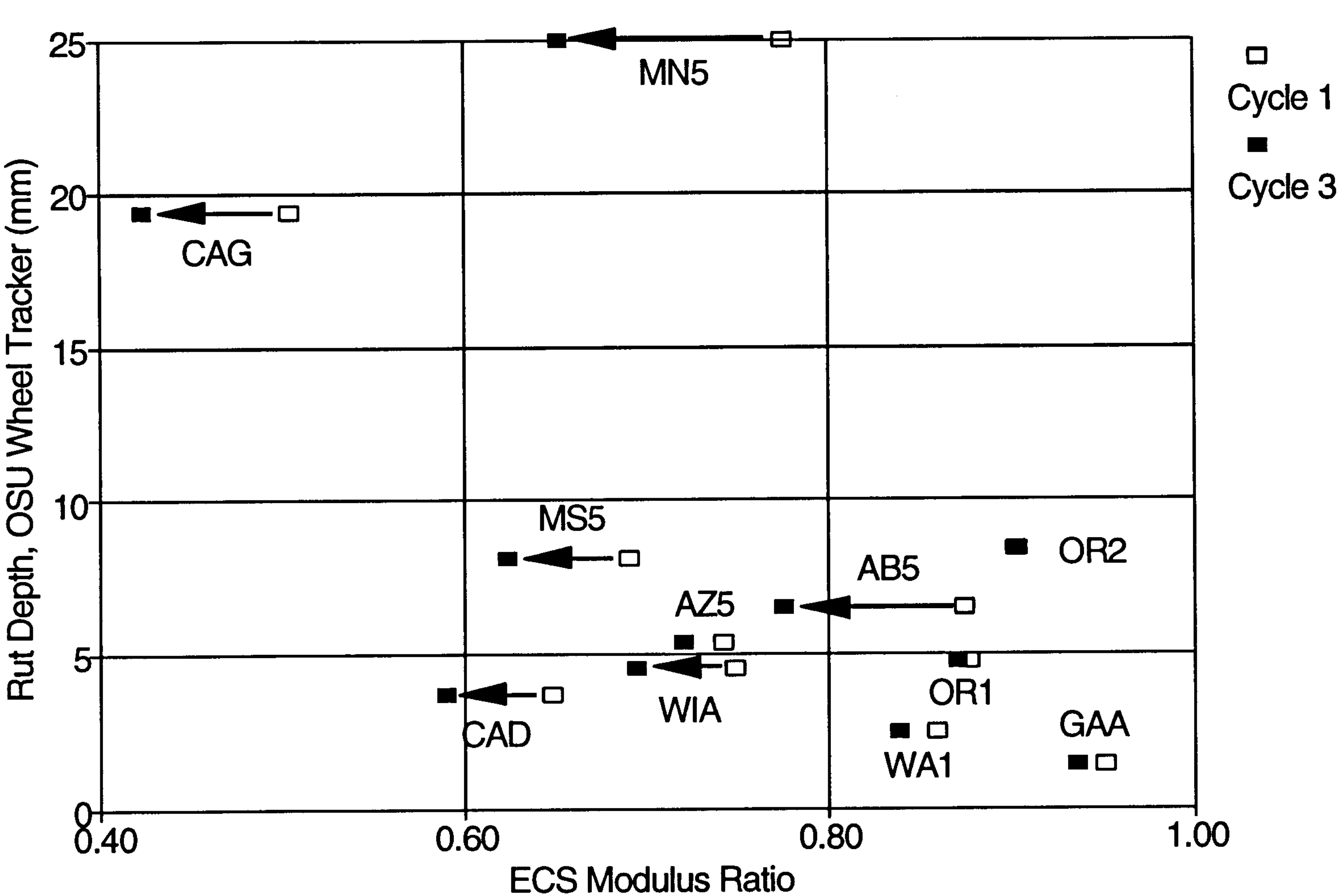


Figure 4.9. Change in ECS modulus ratio between cycles 1 and 3

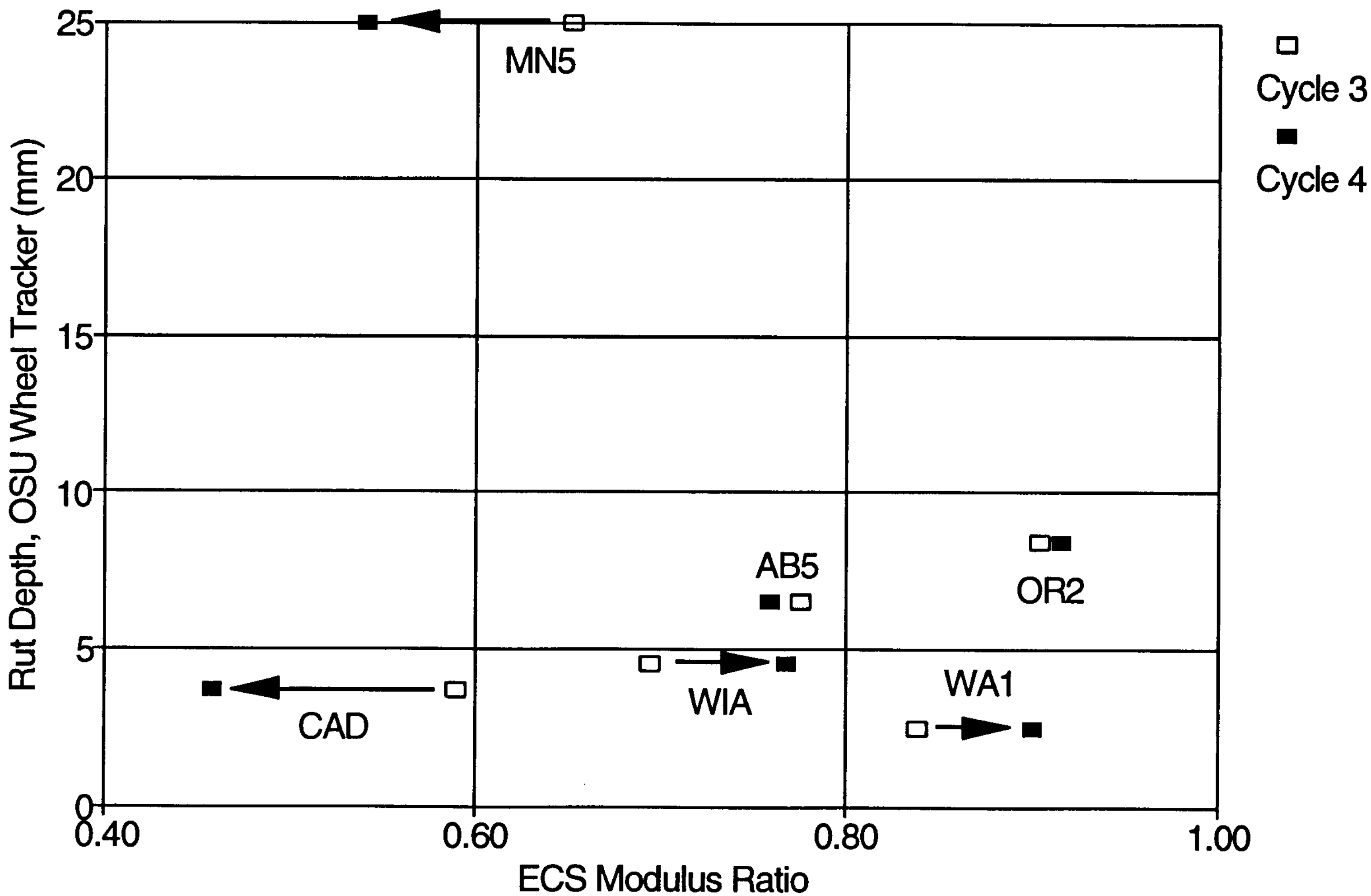


Figure 4.10. Change in ECS modulus ratio between cycles 3 and 4

Table 4.8. Prediction of ECS modulus ratio on the basis of mixture type, entire data set

	Levels	Values
MIX	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA

Cycle = 1
Model: R^2 = 0.62, CV = 13%, and the ECS modulus ratio mean = 0.78

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	11	1.10	9.19	0.0001

Cycle = 2
Model: R^2 = 0.64, CV = 15%, and the ECS modulus ratio mean = 0.75

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	11	1.36	9.81	0.0001

Cycle = 3
Model: R^2 = 0.62, CV = 17%, and the ECS modulus ratio mean = 0.73

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	11	1.54	8.90	0.0001

Cycle = 4
Model: R^2 = 0.69, CV = 18%, and the ECS modulus ratio mean = 0.71

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	6	1.38	14.1	0.0001

performance of a mixture in the ECS with regard to ECS modulus ratio. Mixture type (MIX), ECS system, A or B (SYS), compaction method (COMP), initial ECS coefficient of air permeability (APERM), and initial ECS coefficient of water permeability (WPERM) were presented as class variables in the model. Since both initial ECS coefficient of air permeability and initial ECS coefficient of water permeability measurements resulted in specimens with reported "zero" permeability values, or coefficients of permeability lower than the capabilities of the test equipment,these values were divided into four ranges as shown in Table 4.9. The other variables, air voids (AVOID) and initial modulus (INTM), were analyzed as covariates (or continuous variables) in the model, using their numeric values. The analysis of the full set of variables was performed on the results after each conditioning cycle; however, the statistics for cycle 1 will be used to illustrate the selection of variables significant to the model.

The analysis to investigate the significance of additional variables to the model proceeded by adding variables to the model containing only the variable MIX. If the inclusion of a variable resulted in significant values of the P-value (< 0.05), the variable was considered significant. The variable was then added to the model and possible interactions of that variable were considered. Table 4.10 indicates the results of this study.

Table 4.10 indicates that there are two significant variables after considering MIX: the system used for testing (SYS) and the initial modulus of the mixture (INTM). None of the other variables have significant P-values when combined with MIX alone to constitute a model. The variable INTM, with the most significant P-value, is added to the model first. The interaction of mixture and initial modulus (MIX*INTM) is not significant, indicating that the value of initial modulus has the same effect for each mixture.

The next variables considered are the system used for testing (SYS), the air void level of the mixture (AVOID), and the compaction method (COMP). When added to a model already containing MIX and INTM, AVOID and COMP have significant P-values, but since the P-value for AVOID is more significant than that for COMP, AVOID is added to the model first. The variable SYS loses its significance

Table 4.9. Class variables

Mixture	Levels	Values
MIX	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA
SYS	2	A, B
COMP	2	K, R
APERM	4	Very Low ≤ 1 E-05 cm/sec 1 E-05 < Low ≤ 4 E-05 cm/sec 4 E-05 < Medium ≤ 9 E-05 cm/sec High > 9 E-05 cm/sec
WPERM	4	Very Low ≤ 5 E-05 cm/sec 5 E-05 < Low ≤ 2 E-04 cm/sec 2 E-04 < Medium ≤ 5 E-04 cm/sec High > 5 E-04 cm/sec

Table 4.10. Investigation of significance of variables for prediction of ECS modulus ratio

Variable	Type
Mixture (MIX)	Class
System (SYS)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.100	9.19	0.0001
MIX	11	0.102	9.99	0.0001
SYS	1	0.0512	5.01	0.0289
MIX	11	0.982	9.00	0.0001
AVOID	1	0.0958	0.88	0.352
MIX	11	0.0929	10.9	0.0001
INTM	1	0.154	18.1	0.0001
MIX	11	0.100	9.27	0.0001
COMP	1	0.0140	1.30	0.260
MIX	11	0.0971	8.99	0.0001
APERM	3	0.0125	1.16	0.334
MIX	11	0.0831	7.44	0.0001
WPERM	3	0.0537	0.48	0.698
MIX	11	0.0162	1.83	0.0742
INTM	1	0.00300	0.34	0.564
MIX*INTM	11	0.00690	0.78	0.660
MIX	11	0.0927	10.74	0.0001
INTM	1	0.104	12.06	0.0010
SYS	1	0.00101	0.12	0.734
MIX	11	0.0993	13.4	0.0001
INTM	1	0.0722	29.2	0.0001
AVOID	1	0.217	9.72	0.0028
MIX	11	0.0927	11.8	0.0001
INTM	1	0.186	23.6	0.0001
COMP	1	0.0457	5.81	0.0191
MIX	11	0.0899	10.6	0.0001
INTM	1	0.143	16.9	0.0001
APERM	3	0.00889	1.05	0.378
MIX	11	0.0811	9.40	0.0001
INTM	1	0.157	18.17	0.0001
WPERM	3	0.00619	0.72	0.546

Table 4.10. Investigation of significance of variables for prediction of ECS modulus ratio (continued)

Variable	Type
Mixture (MIX)	Class
System (SYS)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.0127	1.94	0.0571
INTM	1	0.235	35.91	0.0001
AVOID	1	0.0525	8.02	0.0067
MIX*AVOID	11	0.0112	1.72	0.0979
MIX	11	0.0964	13.3	0.0001
INTM	1	0.226	31.1	0.0001
AVOID	1	0.0428	5.89	0.0184
COMP	1	0.0164	2.25	0.139
MIX	11	0.0949	12.8	0.0001
INTM	1	0.185	25.0	0.0001
AVOID	1	0.0678	9.14	0.0038
APERM	3	0.00678	1.00	0.398
MIX	11	0.0831	10.81	0.0001
INTM	1	0.201	28.13	0.0001
AVOID	1	0.0612	7.97	0.0066
WPERM	3	0.00254	0.33	0.8034

after the inclusion of INTM. This is attributed to one system typically being used for stiffer specimens because it was able to obtain higher loading levels.

The interaction between mixture and air voids (MIX*AVOID) is not significant, indicating that air voids has the same effect for each mixture. After AVOID is included in the model, the addition of COMP to the model is no longer significant. This indicates that the difference in compaction method is accounted for by the difference in air voids of the specimens. From the analysis, no other variables or interactions add significance to the model. Therefore, it is concluded that the compaction method, initial ECS coefficient of air permeability, and initial ECS coefficient of water permeability of the unconditioned specimen do not have a statistically significant effect on the final ECS modulus ratio for the mixture when mixture type, initial modulus, and air voids are taken into consideration.

Tables 4.11 and 4.12 show the full statistical analysis for the model mentioned above: MIX and INTM; and MIX, INTM, and AVOID. The variables MIX and INTM are much more significant to the model than AVOID in describing the ECS modulus ratio of a mixture specimen. The P-values indicate that throughout the ECS test procedure, INTM, or the initial modulus of the mixture, continues to be significant in the prediction of the ECS modulus ratio. Table 4.13 gives the statistical analysis for the model MIX, INTM, and AVOID for the final ECS modulus ratio (the combination of cycle 3 results for No-Freeze mixtures and cycle 4 results for Freeze mixtures).

The increasing P-value for AVOID after each ECS cycle indicates that as the ECS procedure continues, the initial value of air voids becomes less significant in predicting the ECS modulus ratio. This is logical, considering that as the specimen undergoes the ECS procedure, the air void level is changed by mechanical changes in the specimen. The specimen deforms under the repeated loading during the hot cycles, and the flow of water within the specimen may cause visual stripping or binder migration, also changing the air void structure. As the test progresses, the initial air void level no longer reflects the true air void structure of the specimen.

Table 4.11. Prediction analysis of the ECS modulus ratio for model I, entire data set

Variable	Type	Levels	Values
Mixtures (MIX) Initial Modulus (INTM)	Class	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA

Cycle = 1

Model: R^2 = 0.71, CV = 12%, and the ECS modulus ratio mean = 0.78

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.0929	10.9	0.0001
INTM	1	0.154	18.1	0.0001

Cycle = 2

Model: R^2 = 0.73, CV = 13%, and the ECS modulus ratio mean = 0.75

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.119	12.6	0.0001
INTM	1	0.199	21.1	0.0001

Cycle = 3

Model: R^2 = 0.76, CV = 14%, and the ECS modulus ratio mean = 0.73

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.146	14.4	0.0001
INTM	1	0.351	34.7	0.0001

Cycle = 4

Model: R^2 = 0.79, CV = 15%, and the ECS modulus ratio mean = 0.71

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.120	10.5	0.0001
INTM	1	0.198	17.3	0.0001

Table 4.12. Prediction analysis of the ECS modulus ratio for model II, entire data set

Variable	Type	Levels	Values
Mixture (MIX) Initial Modulus (INTM) Air Voids (AVOID)	Class Covariate Covariate	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA

Cycle = 1

Model: R^2 = 0.75, CV = 11%, and the ECS modulus ratio mean = 0.78

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.0993	13.4	0.0001
INTM	1	0.217	29.2	0.0001
AVOID	1	0.0722	9.72	0.0028

Cycle = 2

Model: R^2 = 0.75, CV = 13%, and the ECS modulus ratio mean = 0.75

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.118	13.0	0.0001
INTM	1	0.228	25.1	0.0001
AVOID	1	0.0297	3.25	0.0764

Cycle = 3

Model: R^2 = 0.76, CV = 14%, and the ECS modulus ratio mean = 0.73

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.141	14.1	0.0001
INTM	1	0.354	35.4	0.0001
AVOID	1	0.0159	1.59	0.2128

Cycle = 4

Model: R^2 = 0.80, CV = 15%, and the ECS modulus ratio mean = 0.71

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.121	11.1	0.0001
INTM	1	0.228	20.9	0.0001
AVOID	1	0.0305	2.79	0.1033

Table 4.13. Analysis for prediction of final ECS modulus ratio

Final ECS Modulus Ratio
Model: R^2 = 0.82 CV = 14%, and the ECS modulus ratio mean = 0.72

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.194	20.1	0.0001
INTM	1	0.276	28.6	0.0001

Final ECS Modulus Ratio
Model: R^2 = 0.83 CV = 13%, and the ECS modulus ratio mean = 0.72

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	0.194	21.0	0.0001
INTM	1	0.308	33.3	0.0001
AVOID	1	0.0335	3.62	0.0621

Analysis of the data set indicates the relative importance of the initial modulus of a specimen to its performance in the ECS test procedure. This indicates that further discussion of the initial modulus parameter is warranted.

For the twelve mixtures investigated in the ECS, the initial modulus values ranged from 87.4 ksi (602 MPa) for OR2, the open graded mixture, to 1969.3 ksi (13,560 MPa) for CAB. Figure 4.11 shows the relation between final ECS modulus ratio and initial ECS modulus. Figure 4.12 divides the data by mixture type. For several of the mixtures, such as AB5, GAA, and OR2, the initial modulus does not vary substantially. However, for other mixtures, the range of initial resilient modulus is quite large; for example the initial modulus values for CAD range from 616.8 to 1709.5 ksi (4,250 to 11,778 MPa).

A mixtures initial modulus depends on several factors, including gradation, aggregate type, aggregate shape, asphalt content, asphalt type, and air voids. For any particular mixture used in this study, only air voids was varied within a set of specimens for the given mixture. Figure 4.13 indicates the relation between initial modulus and air voids. (The scales of these figures are expanded to accommodate the OR2 open graded mixture.) This indicates that several of the mixtures, including CAG and MN5, experienced significant changes in unconditioned, initial resilient modulus with changes in air void levels. Other mixtures, such as AB5 and OR2, have resilient moduli that are less sensitive to air void levels.

Although the aggregate for each specimen was batched to the required gradation and considered a constant for each mixture, certain asphalt-aggregate mixtures may be very sensitive to relatively minor changes in volumetric properties, such as gradation or asphalt content. This may also contribute to the wide range of resilient modulus values obtained for the CAB and CAD mixtures.

Identifying the initial resilient modulus of a mixture as a variable which influences performance in the ECS, as defined by ECS modulus ratio, requires additional consideration for the purposes of defining the relative performance between mixtures. A mixture that has an initial modulus of 1,000 ksi (6,890 MPa) and a final ECS modulus ratio of 0.6 still has a resilient modulus of 600 ksi (4,130 MPa). However, a mixture that has an initial modulus of 667 ksi (4,500 MPa) has to have a

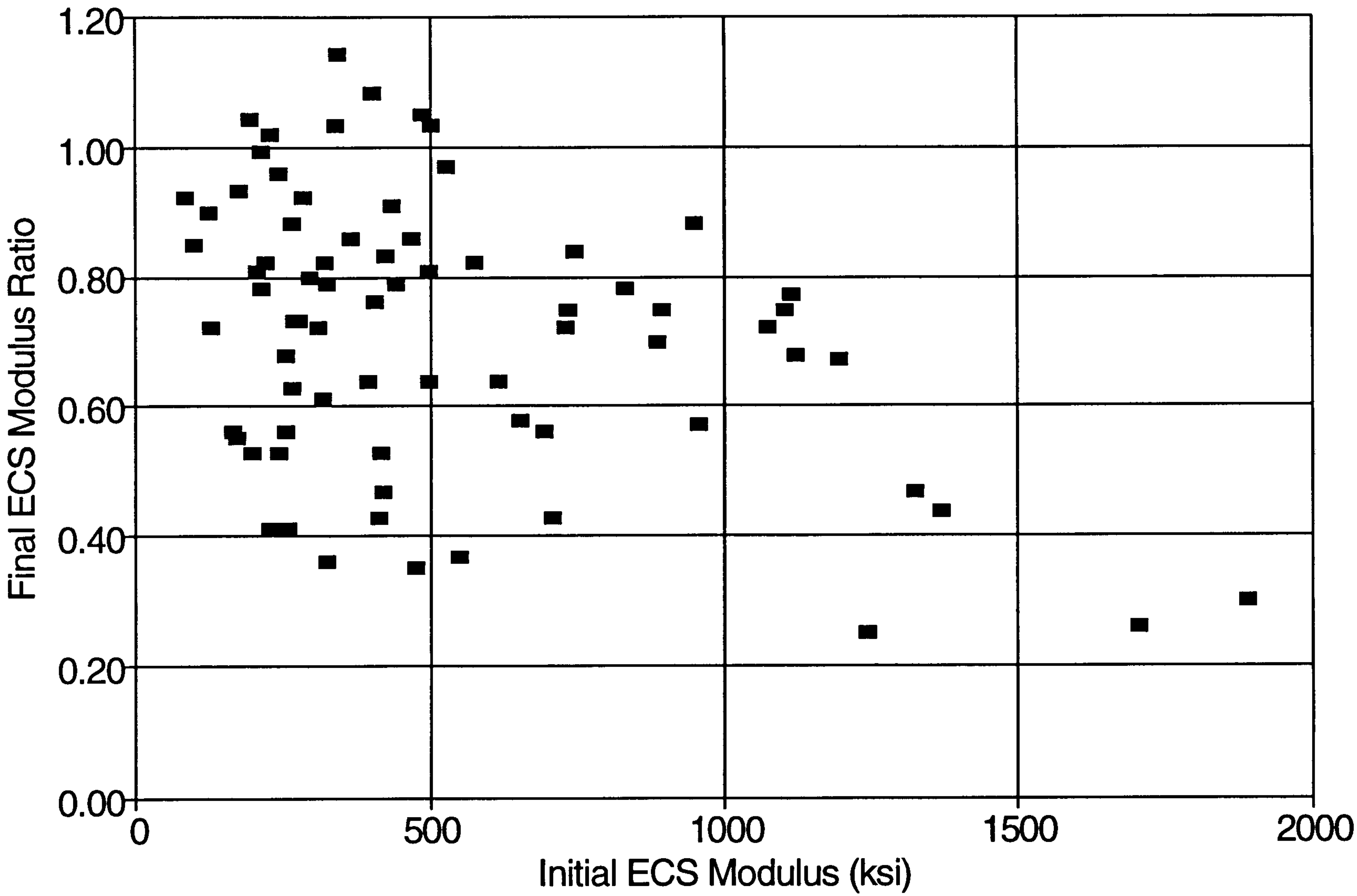
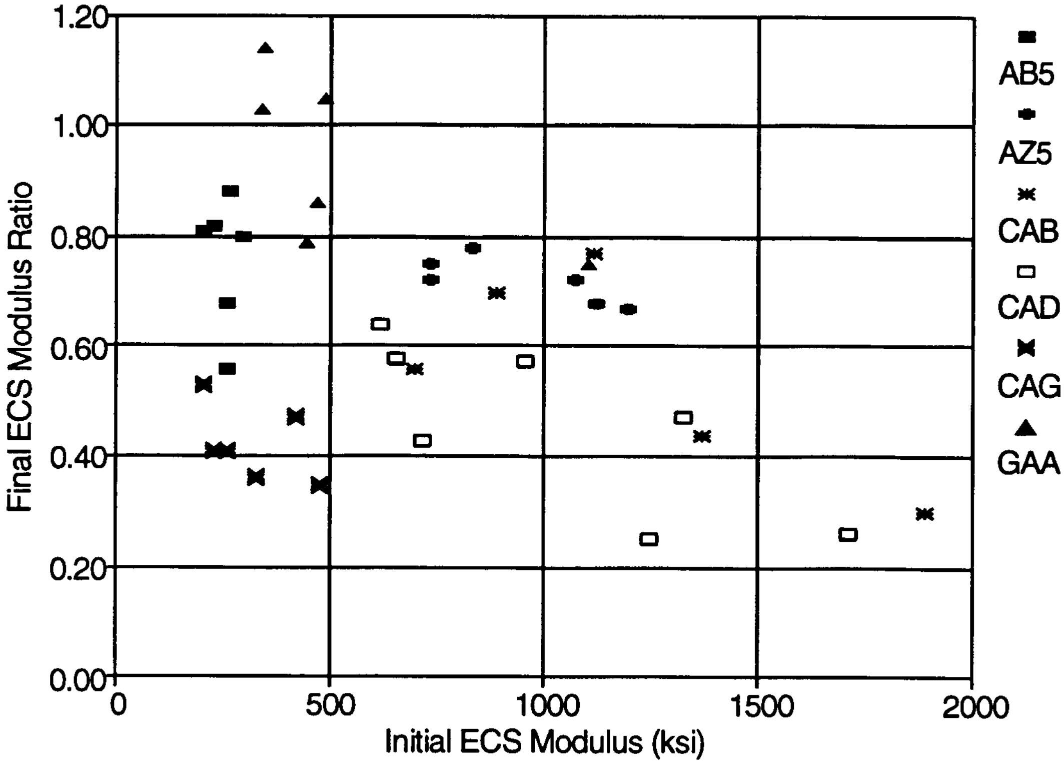
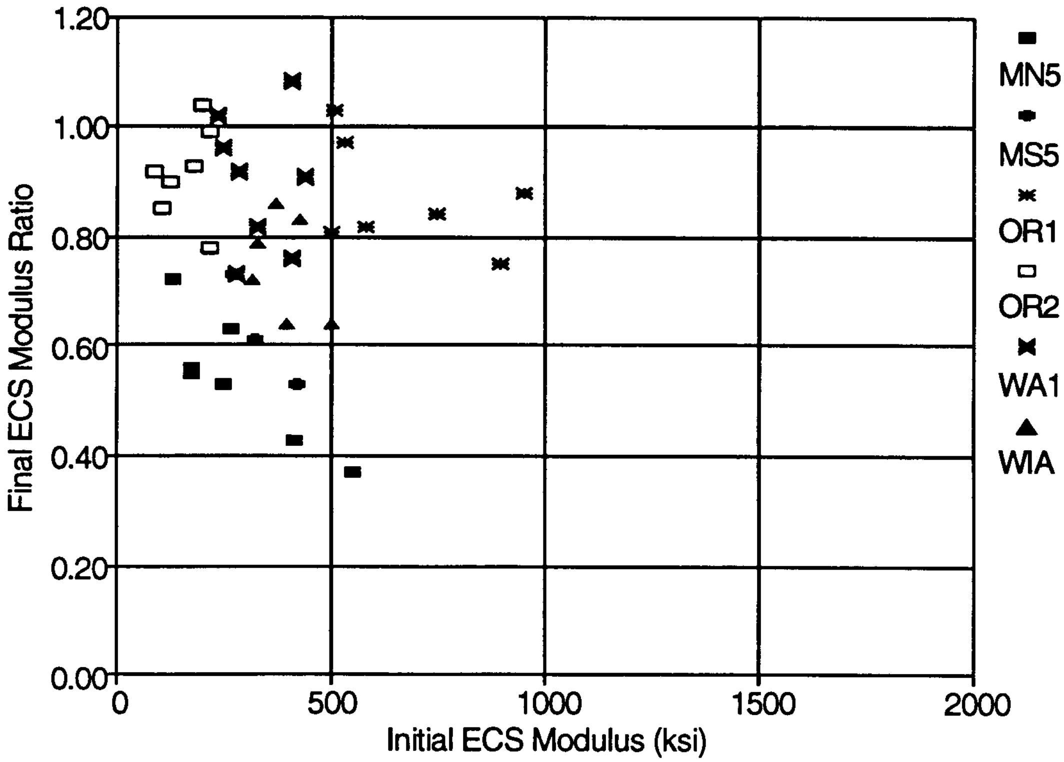


Figure 4.11. Final ECS modulus ratio versus initial ECS modulus

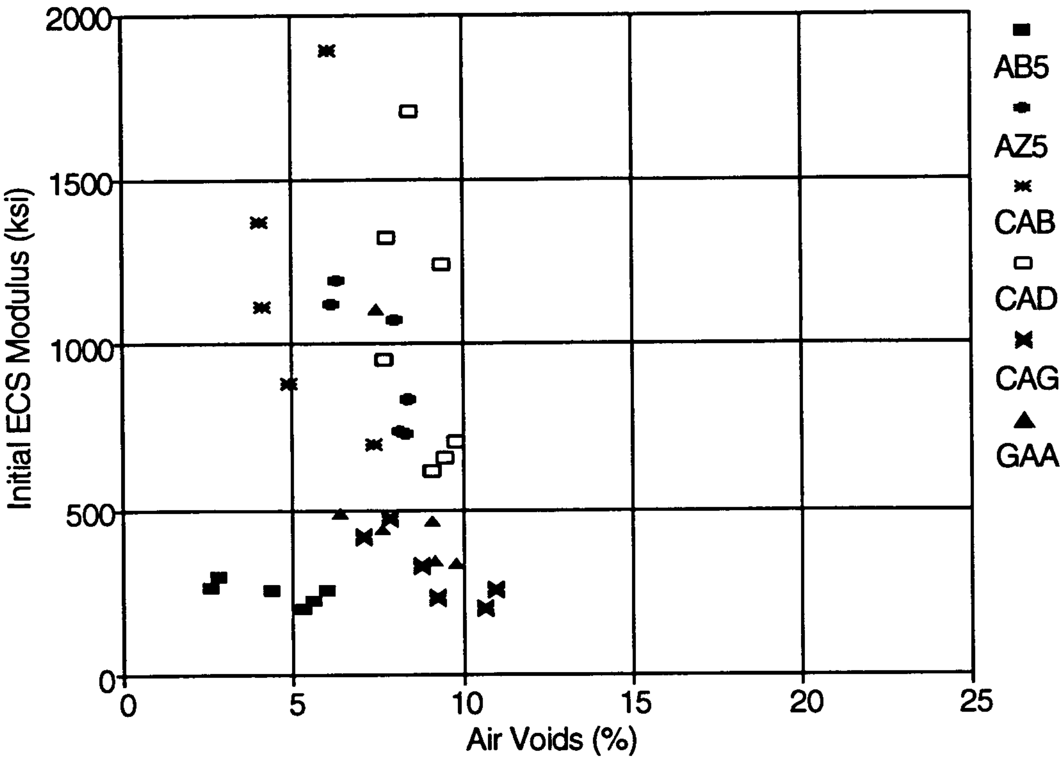


a) Mixtures AB5 through GAA

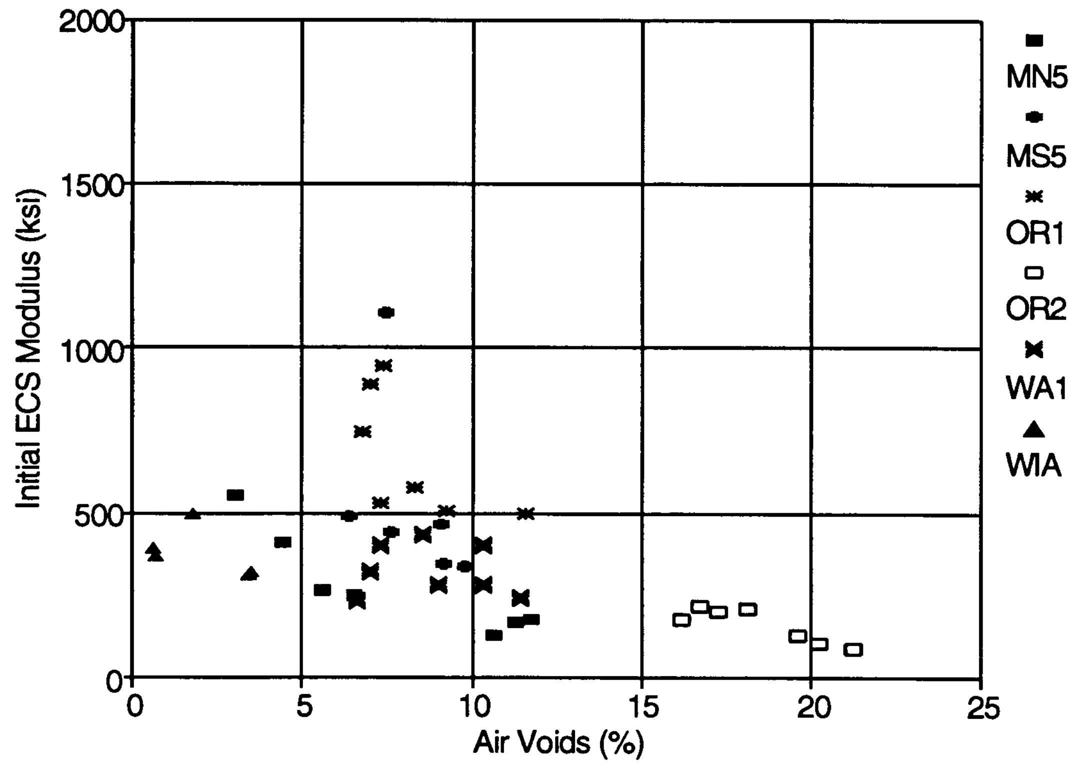


b) Mixtures MN5 through WIA

Figure 4.12. Final ECS modulus ratio versus initial ECS modulus, by mixture



a) Mixtures AB5 through GAA



b) Mixtures MN5 through WIA

Figure 4.13. Initial ECS modulus versus air voids, by mixture

final ECS modulus ratio of only 0.9 to bring it to the same level of resilient modulus, 600 ksi (4,130 MPa).

In considering the performance of two mixtures, their relative levels of stiffness, and not just the reduction in stiffness as quantified by the resilient modulus ratio, must be considered. Determination of the required level of stiffness for a asphalt concrete mixture being considered for placement is beyond the scope of this effort. The ECS will indicate the predicted loss of modulus that a given mixture will experience due to water damage. It is up to the designer to determine if this will lower the modulus value to an unacceptable level.

An additional model was run using a class variable designated ENVR to see if the environment, Freeze or No-Freeze, had a significant effect on the final ECS modulus ratio obtained in the test. Table 4.14 gives the results of this model. The P-values indicate that the environmental zone is not a significant effect in the model. The T grouping of the means for the Freeze and No-Freeze data also indicate this. Therefore, it can be concluded, for the mixtures tested, that neither of the two ECS procedures, three hot cycles or three hot cycles plus a fourth freeze cycle, is statistically more severe. Therefore, subjecting a specimen to the appropriate conditioning for its environmental designation does not influence the performance of the mixture relative to other mixtures tested in conditioning appropriate to their environmental designations.

4.2.1.3 Correlation Between ECS Modulus Ratio and Changes in Specimen Properties. The previous sections have dealt only with the significance of variables in predicting of the performance of an asphalt concrete specimen in the ECS with regard to the ECS modulus ratio. These models used only initial values of the predictor variables. The following analysis will investigate the correlation between the ECS modulus ratio, the coefficient of water permeability, and deformation (all of which have values that change after each cycle), and between the ECS modulus ratio and the degree of visual stripping and binder migration, which are also response variables to ECS conditioning.

Table 4.14. Analysis of final ECS modulus ratios for freeze versus no-freeze environmental zone

Variable	Type	Levels	Values
Environment (ENVR)	Class	2	FRZ, NFRZ

Model: R^2 = 0.0031, CV = 30%, and the ECS modulus ratio mean = 0.72

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
ENVR	1	0.0101	0.22	0.639

Environmental Zone	Mean ECS Modulus Ratio	T Grouping
Freeze	0.71	A[1]
No-Freeze	0.73	A

[1] Means with the same letter T grouping are not significantly different at the α = 0.05 level

Table 4.15 presents the analysis of correlations with ECS modulus ratio. Lottman and Firth (1988) suggest that the proportion of the tensile strength or modulus change due to loss of adhesion may be quantified as equal to the percentage of visual stripping. For example, if a mixture has 40 percent visual stripping, then 40 percent of the modulus loss is due to adhesion loss. The other 60 percent is due to loss of cohesion and aggregate degradation. If the percentage of visual stripping can be used to determine the percentage of stiffness reduction attributed to adhesion loss, in an analogous manner, it might be expected that there would be some correlation between the ECS modulus ratio and the degree of visual stripping, binder migration, or both.

Table 4.15 indicates that there is no significant relation between the ECS modulus ratio and the degree of visual stripping. There is, however, a significant relation between the ECS modulus ratio and binder migration after cycle 3. Therefore, no conclusions can be drawn about a correlation between the ECS modulus ratio and the degree of visual stripping that might allow a determination of the percentage of stiffness loss due to adhesion loss. Since binder migration is believed to be a product of both the loss of adhesion and the loss of cohesion, the only conclusion that can be drawn from the third cycle correlation between the ECS modulus ratio and binder migration is that it appears that binder migration takes place during the first three cycles of ECS testing. Binder migration can not be used to attribute a proportion of the ECS modulus loss to either a loss of adhesion or a loss of cohesion.

The ECS modulus ratio correlates with the coefficient of water permeability after the third hot cycle and inclusion of deformation in the analysis after the first cycle reduces the significance of the mixture to the ECS modulus ratio. These results may indicate that the mechanical changes in the specimen due to deformation and water flow are decreasing the variability due to mixture type in the ECS modulus ratio. As specimens are conditioned during the first three cycles, mixtures begin to act in a similar manner with regard to ECS modulus ratio.

Table 4.15. Correlation between ECS modulus ratio and deformation, coefficient of water permeability, visual stripping, and binder migration

Cycle 1

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
MIX	11	0.0831	8.88	0.0001
WPERM	3	0.00537	1.01	0.697
MIX	10	0.0936	8.40	0.0001
DEF	1	0.0334	3.00	0.0899
MIX	11	0.0983	8.92	0.0001
BM	1	0.00346	0.31	0.577
MIX	11	0.0644	5.84	0.0001
VS	1	0.00302	0.27	0.603

Cycle 2

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
MIX	11	0.0925	7.69	0.0001
WPERM	3	0.0227	1.89	0.141
MIX	10	0.00457	1.10	0.380
DEF	1	0.000284	0.07	0.795
MIX	11	0.124	9.92	0.0001
BM	1	0.0137	1.10	0.299
MIX	11	0.0803	6.31	0.0001
VS	1	0.00369	0.29	0.592

Table 4.15. Correlation between ECS modulus ratio and deformation, coefficient of water permeability, visual stripping, and binder migration (continued)

Cycle 3

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
MIX WPERM	11 3	0.103 0.0707	8.02 5.51	0.0001 0.0021
MIX DEF	10 1	0.00297 0.0101	1.09 3.70	0.3898 0.0603
MIX BM	11 1	0.146 0.0802	9.95 5.48	0.0001 0.0225
MIX VS	11 1	0.0956 0.0000958	5.99 0.01	0.0001 0.939

Cycle 4

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
MIX BM	6 1	0.167 0.00984	9.85 0.58	0.0001 0.631
MIX VS	6 1	0.225 0.00000823	13.39 0.00	0.0001 0.982
MIX WPERM	6 3	0.167 0.007	9.75 0.41	0.0001 0.7480

4.2.2 Degree of Visual Stripping and Binder Migration Data

4.2.2.1 Prediction of Visual Stripping and Binder Migration. An analysis similar to that performed with the ECS modulus ratio data was performed with the visual stripping and binder migration data to determine the mixture variables that may be significant predictors of the degree of visual stripping and binder migration. The exception was that the conditioning cycle was not a factor, as there was only one measure of visual stripping and binder migration performance taken during each test and all of the predictor variables were the initial values for the specimen.

Table 4.16 presents the results of the analysis. The system used for testing (SYS) was not a significant variable for predicting either visual stripping or binder migration and is not included in Table 4.16. For predicting of the performance of a specimen with regard to visual stripping, the only variable of statistical significance is MIX. Therefore, it can be concluded that the degree of visual stripping depends primarily on the mixture type, indicating the importance of the asphalt-aggregate interaction on the adhesion of asphalt concrete.

The results of the analysis for the prediction of binder migration are presented in Table 4.17. Both the compaction method and the mixture type (COMP and MIX) play a very important role in the prediction of binder migration. The role of compaction is not surprising, as none of the roller-compacted specimens that were tested exhibited binder migration. The interaction between MIX and COMP is also significant, indicating that the effect of compaction is not the same for each mixture. The interaction indicates that not all kneading-compacted specimens exhibit similar amounts of binder migration. This may be due to different gradations and asphalt contents in each mixture, which produce different asphalt-aggregate matrices in kneading compaction.

The next significant variable added to the model for predicting binder migration is AVOID. The interaction of MIX and AVOID is also significant, again indicating that AVOID does not have the same effect for each mixture. After the addition of the variable AVOID and its interaction with MIX, no additional variables

Table 4.16. Investigation of significance of variables for prediction of degree of visual stripping

Variable	Type
Mixture (MIX)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	328	46.2	0.0001
MIX	11	323	46.7	0.0001
AVOID	1	12.0	1.71	0.1963
MIX	11	327	45.6	0.0001
INTM	1	2.04	0.28	0.5960
MIX	11	329	47.5	0.0001
COMP	1	17.2	2.49	0.1199
MIX	11	322	43.4	0.0001
APERM	3	0.879	0.12	0.9488
MIX	11	299	41.3	0.0001
WPERM	3	5.95	0.83	0.4817

Table 4.17. Investigation of significance of variables for prediction of binder migration

Variable	Type
Mixture (MIX)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	14.0	6.64	0.0001
COMP	1	68.4	22.6	0.0001
MIX	11	13.2	7.17	0.0001
AVOID	1	17.9	9.67	0.0029
MIX	11	14.4	7.12	0.0001
INTM	1	7.79	3.86	0.0541
MIX	11	12.3	9.38	0.0001
COMP	1	50.0	38.0	0.0001
MIX	11	8.47	6.06	0.0001
APERM	3	16.0	11.4	0.0001
MIX	11	10.7	7.85	0.0001
WPERM	3	16.7	12.4	0.0001
MIX	11	6.48	12.4	0.0001
COMP	1	40.7	77.8	0.0001
MIX*COMP	10	5.28	10.1	0.0001
MIX	11	6.16	17.4	0.0001
COMP	1	15.4	43.6	0.0001
MIX*COMP	10	5.94	16.8	0.0001
AVOID	1	8.82	24.9	0.0001
MIX	11	4.69	11.4	0.0001
COMP	1	19.7	47.9	0.0001
MIX*COMP	10	3.24	7.87	0.0001
APERM	3	2.55	5.47	0.0026
MIX	11	6.03	12.4	0.0001
COMP	1	22.9	47.3	0.0001
MIX*COMP	10	3.46	7.15	0.0001
WPERM	3	1.12	2.31	0.0879

Table 4.17. Investigation of significance of variables for prediction of binder migration (continued)

Variable	Type
Mixture (MIX)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	1.16	8.11	0.0001
COMP	1	6.37	44.5	0.0001
MIX*COMP	10	3.32	23.2	0.0001
AVOID	1	1.04	7.28	0.0103
MIX*AVOID	11	1.08	7.54	0.0001
MIX	11	0.862	5.55	0.0001
COMP	1	5.93	38.1	0.0001
MIX*COMP	10	2.54	16.3	0.0001
AVOID	1	0.989	3.36	0.0164
MIX*AVOID	11	0.748	4.81	0.0002
APERM	3	0.000351	0.00	1.00
MIX	11	1.10	7.28	0.0001
COMP	1	6.15	40.6	0.0001
MIX*COMP	10	2.41	15.9	0.0001
AVOID	1	0.612	4.05	0.0520
MIX*AVOID	11	1.04	6.85	0.0001
WPERM	3	0.0531	0.31	0.820

are significance in the model. The fact that APERM and WPERM were significant before AVOID was added, but were not afterwards indicates that the AVOID term probably accounts for the same variation in binder migration as the initial permeability terms.

Table 4.18 gives the two final models for predicting the degrees of visual stripping and binder migration. It should be remembered that both the degree of visual stripping and binder migration are very subjective evaluations and are graded on coarse scales. The coarse scales used to evaluate degree of visual stripping and binder migration may preclude easy correlations with these variables.

4.2.2.2 Correlation Between Visual Stripping and Binder Migration and Changes in Specimen Properties. Table 4.19 presents the results for analyses of correlation between the degree of visual stripping and the coefficient of water permeability and deformation; and between binder migration and the coefficient of water permeability and deformation, after each cycle. Binder migration is not significantly related to the coefficient of water permeability of the specimen; however, visual stripping shows a significant relationship with coefficient of water permeability throughout the ECS test procedure. The relationship between visual stripping and the coefficient of water permeability is one of the few relationships that holds for all ECS testing cycles and may indicate the importance of flow through the specimen and, potentially, the role of a flow gradient in promoting adhesion loss in asphalt concrete mixtures.

Table 4.19 indicates a correlation between specimen deformation and both visual stripping and binder migration. This correlation is apparent during the first testing cycle, and, for binder migration, the second cycle as well. This correlation may indicate that the deformation of a specimen under the action of the repeated loading mechanically breaks bonds between the asphalt and aggregate and within the asphalt binder matrix. These broken bonds may facilitate visual stripping and binder migration. The mechanical disruption of asphalt films may allow water access to portions of the specimen previously sealed by asphalt binder. The first cycle typically experiences the greatest amount of deformation.

Table 4.18. Final models for prediction of degree of visual stripping and binder migration

Visual Stripping
Model: $R^2 = 0.89$, CV = 33%

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	11	328	46.2	0.0001

Binder Migration
Model: $R^2 = 0.98$, CV = 27%

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	11	1.16	8.11	0.0001
COMP	1	6.37	44.5	0.0001
MIX*COMP	10	3.32	23.2	0.0001
AVOID	1	1.01	7.28	0.0103
MIX*AVOID	11	1.04	7.54	0.0001

Table 4.19. Correlation between visual stripping and binder migration and other ECS variables

Degree of Visual Stripping

Cycle	Source of Error	Degrees of Freedom	Type III Mean Squares	F-values	P-values
1	MIX WPERM	11 1	328 152	70.3 32.6	0.0001 0.0001
2	MIX WPERM	11 1	329 152	70.3 32.5	0.0001 0.0001
3	MIX WPERM	11 1	329 152	70.4 32.6	0.0001 0.0001
4	MIX WPERM	6 3	4.32 151	2.22 77.6	0.0628 0.0001

Binder Migration

Cycle	Source of Error	Degrees of Freedom	Type III Mean Squares	F-values	P-values
1	MIX WPERM	11 1	13.85 0.00	6.44 0.00	0.0001 0.9992
2	MIX WPERM	11 1	13.79 0.00	6.42 0.00	0.0001 0.9571
3	MIX WPERM	11 1	13.77 0.00	6.41 0.01	0.0001 0.9431
4	MIX WPERM	6 3	19.98 0.00	7.48 0.00	0.0001 0.9863

Table 4.19. Correlation between visual stripping and binder migration and other ECS variables (continued)

Degree of Visual Stripping

Cycle	Source of Error	Degrees of Freedom	Type III Mean Squares	F-values	P-values
1	MIX DEF	10 1	334 19.8	71.8 4.25	0.0001 0.0446
2	MIX DEF	10 1	338 15.5	71.4 3.28	0.0001 0.0762
3	MIX DEF	10 1	345 11.3	71.4 2.35	0.0001 0.132

Binder Migration

Cycle	Source of Error	Degrees of Freedom	Type III Mean Squares	F-values	P-values
1	MIX DEF	10 1	13.4 24.9	7.32 13.6	0.0001 0.0006
2	MIX DEF	10 1	13.0 12.3	6.22 5.88	0.0001 0.0192
3	MIX DEF	5 0	12.9 3.67	5.65 1.61	0.0001 0.210

A set of four specimens from mixtures that experienced significant degrees of visual stripping (AZ5, CAG, MS5, and WYO) were each run for a single hot cycle in the ECS in an attempt to attribute the amount of asphalt stripping that takes place in the first cycle. The results were inconclusive, with the visual stripping levels being equal to or lower than those seen for specimens from these mixtures with full ECS conditioning.

Table 4.20 presents the results of the analysis for correlation between degree of visual stripping and binder migration. No significant correlation exists between the degree of visual stripping and binder migration. This indicates that if visual stripping is an indicator of adhesion loss, the amount of adhesion loss does not necessarily indicate the amount of binder migration that will occur. Perhaps binder migration is more a function of cohesion loss and not both adhesion and cohesion loss.

4.2.3 Permeability Data

The analysis of the permeability data is undertaken with the understanding that the coefficients of air and water permeability as measured in this test program are incorrect, and represent only relative values. The ECS flow system must be re-plumbed in order to measure true values of the coefficients of permeability.

After 30 minutes of water conditioning, some specimens initially impermeable to air allowed water to flow. Furthermore, specimens with initial coefficients of water permeability of less than 1.0E-04 cm/s (3.9E-05 in./s) typically show an increase in permeability during the first hot cycle with repeated loading (Figures 3.25 through 3.36). This suggests that the 30 minute "wetting" procedure, and to a greater degree the first hot cycle's heating and loading procedure, tend to open the specimen to flow. Several mechanisms may be at work.

During the wetting procedure, the 30 minute period at 20.0 in. (508 mm) Hg vacuum pressure may allow water to break through thin films of asphalt that may separate voids in the specimen. The 30-minute wetting period may be why break through occurs during water flow and not air flow measurements. In the air

Table 4.20. Correlation between degree of visual stripping and binder migration

Source of Error	Degrees of Freedom	Type III Mean Square	F-values	P-values
MIX	11	328	44.3	0.0001
BM	1	3.62	0.51	0.480

permeability test, the air flow is turned off immediately if the specimen is deemed impermeable, so the pressure differential does not last for more than a few minutes.

During the first cycle repeated loading, specimens with lower coefficients of water permeability may have more thin film breakdown. The repeated loading may cause the asphalt-aggregate matrix to rearrange, breaking the asphalt bonds. Also, repeated loading may increase the pore water pressure within the specimen causing more film damage, especially if water is trapped in pores with only one connecting pathway to other pores or if the pathways between the pores are small. During the first cycle, specimens may also experience a loss of adhesion within the asphalt matrix. This concept is supported by the correlation seen between visual stripping and the coefficient of water permeability in Table 4.19.

Figures 3.24 through 3.36 indicate that within a group of specimens from one mixture, the specimens with lower air voids tend to have lower coefficients of water permeability. This observation is supported by an analysis of the correlation between the initial coefficient of water permeability and air voids. Table 4.21 indicates that air void level is even more significant than mixture type in estimating the coefficient of water permeability for specimens prior to conditioning during the ECS cycles.

During the first cycle of ECS testing, the less porous specimens show increasing coefficients of water permeability. More permeable specimens tend to show a decrease in permeability during the first cycle. The lower permeability specimens have visual stripping similar to the more permeable specimens of the mix; however, they tend to show higher levels of binder migration than the other specimens of the mixture. This trend is true for all of the mixtures which had specimens that displayed binder migration (AB5, AZ5, CAB, CAG, MN5, MS5, OR1, and WA1), but was not indicated by the correlation between binder migration and the coefficient of water permeability found in Section 4.2.2.2. This may be due to the coarse nature of the binder migration scale.

It may be that the lower permeability specimens, which have lower air void levels, present a matrix with thicker asphalt films and less interconnection between pores. Under the action of water flow and repeated loading, higher pore water

Table 4.21. Analysis of the correlation between the coefficient of water permeability and air voids

Model: $R^2 = 0.67$, CV = 92%

Source of Error	Degrees of Freedom	Type III Mean Squares	F-value	P-value
MIX	9	20000000	3.25	0.0084
AVOID	1	155000000	25.21	0.0001

pressures may tend to break these films and move debonded asphalt particles until equilibrium structure of asphalt, aggregate, and voids is reached, where the pores are connected in such a way to provide adequate drainage for the structure under the prevailing conditions. In the more permeable mixtures, which have higher air void levels, the existing pathways between pores may be adequate, and pore water pressures may not be as large under the actions of repeated loading.

During the second, third, and fourth cycles, specimens of all air void levels and permeabilities tend to show either very little variation in permeability or a continual decrease in the coefficient of water permeability. This is probably due to the deformation of the specimen under the repeated loading. This would tend to decrease the air void content of the specimen and create a structure of smaller pores separated by a dense asphalt-aggregate matrix. Typically the fourth freeze cycle does not change this trend.

An analysis was performed to determine whether the change in the coefficient of water permeability over an ECS conditioning cycle was related to the amount of specimen deformation that occurred during the cycle, as proposed. Table 4.22 presents these results. The system in which the specimen was tested was not a significant variable in the prediction of specimen deformation and is not included in Table 4.22. Specimens that had coefficients of water permeability too low for the ECS to measure or that experienced excessive deformation were not included in this analysis. The OR2 specimens were also excluded as they did not receive repeated loading.

There is a significant correlation between the specimen deformation and the change in the coefficient of water permeability during the first cycle. The first cycle of ECS testing is when the specimens undergo the greatest amount of deformation. This deformation, and the mechanical changes it produces in the specimen, seems to be significant for establishing an equilibrium flow within the specimen.

Table 4.22. Analysis of the correlation between change in the coefficient of water permeability and specimen deformation

Cycle	Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
1	MIX	10	8640000	2.72	0.0054
	DEF	1	15500000	4.87	0.0296
2	MIX	10	450000	3.91	0.0002
	DEF	1	371	0.00	0.955
3	MIX	10	172000	1.85	0.0628
	DEF	1	233000	2.46	0.120

4.2.4 Deformation Data

The data for specimen deformation under the repeated loading applied during the three ECS hot cycles was also analyzed to determine mixture properties that were significant in predicting the amount of deformation observed.

Table 4.23 presents the results of the analysis to determine significant variables and Table 4.24 gives the analysis for predicting the final specimen deformation. The mixture OR2 was not included in the analysis as it was not subjected to repeated loading. Other specimens that experienced excessive deformation were also removed from the analysis.

The mixture type (MIX) and compaction method (COMP) are the most significant factors in determining the amount of deformation. The interaction between the two variables (MIX*COMP) is also significant, indicating that compaction does not have the same effect for each mixture. The coefficients of air and water permeability, which were significant to the model with MIX, are no longer significant once COMP and MIX*COMP are added.

The significance of the compaction method on the tendency for the specimen to deform in the ECS implies that rolling wheel compaction and kneading compaction produce specimens that have a different ability to withstand loading. This may indicate something about the integrity of the asphalt-aggregate matrix the two procedures produce. Roller compacted specimens typically did not experience the amount of deformation that kneading compacted specimens did, suggesting that roller compaction may produce specimens that would be less likely to rut under traffic loading. The roller compactor is directly analogous to field compaction methods.

It should also be mentioned that excessive mixture deformation in the ECS may indicate stability problems in the mixture that could lead to rutting in the field. MS5 and WIA, which experienced excessive deformation in the ECS procedure, both appeared to be mixtures with high fines and asphalt contents, typical properties of mixtures prone to rutting problems. Rutting is one of the distress modes associated with water damage. If a mixture experiences rutting in the field, care must be taken to attribute that distress to the appropriate mechanism, stability failure or water damage.

Table 4.23. Investigation of significance of variables for prediction of specimen deformation

Variable	Type
Mixture (MIX)	Class
Air Voids (AVOID)	Covariate
Initial Modulus (INTM)	Covariate
Compaction Method (COMP)	Class
Air Permeability (APERM)	Class
Water Permeability (WPERM)	Class

Source of error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	10	0.00845	18.1	0.0001
COMP	1	0.0299	22.4	0.0001
MIX	10	0.00757	16.3	0.0001
AVOID	1	0.000701	1.51	0.225
MIX	10	0.00664	28.6	0.0001
COMP	1	0.0118	50.9	0.0001
MIX	10	0.00742	15.6	0.0001
INTM	1	0.000156	0.33	0.569
MIX	10	0.00849	27.0	0.0001
APERM	3	0.00383	9.00	0.0001
MIX	10	0.00837	22.1	0.0001
WPERM	3	0.000624	3.76	0.0169
MIX	10	0.00581	33.7	0.0001
COMP	1	0.0116	67.5	0.0001
MIX*COMP	9	0.000489	2.84	0.0114
MIX	10	0.00436	25.7	0.0001
COMP	1	0.00346	20.4	0.0001
MIX*COMP	9	0.000487	2.87	0.0117
APERM	3	0.000204	1.20	0.323
MIX	10	0.00473	29.0	0.0001
COMP	1	0.00763	46.8	0.0001
MIX*COMP	9	0.00502	3.08	0.0077
WPERM	3	0.000284	1.74	0.176

Table 4.24. Prediction analysis for final specimen deformation

Model: R^2 = 0.88, CV = 27%

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	10	0.0119	18.9	0.0001
COMP	1	0.0067	10.7	0.0023
MIX*COMP	9	0.00152	2.42	0.0273

4.2.5 Secondary Mixtures

The secondary mixtures were not included in the previous analyses since only two or three specimens were tested from each mixture. However, the nine secondary mixtures provided the two worst-performing mixtures tested in this program, GAF and WYO. Both of these mixtures have very poor performance in the field with regard to water sensitivity. The mixture LAF, which had experienced failure in the field due to rutting, experienced excessive deformation in the ECS test procedure and had a substantial loss of stiffness and significant visual stripping.

These mixtures also produced the only field cores that exhibited binder migration. The specimens tested for mixtures AZF and LAF were cores taken from surviving areas of pavements that had exhibited very poor performance believed to be the result of water damage. These cores all showed signs of binder migration. This had not been seen in any of the field cores from the primary testing program. This is probably due to the relatively short time the primary mixtures had been in the field.

The specimens prepared by The Asphalt Institute (COA, COB, COC, COE, and TAI) were all very difficult to test. These specimens were compacted in the gyratory compactor with a mold diameter of 3.93 in. (99.8 mm). It was difficult to maintain a good grip on the under-sized specimens with the ECS triaxial yokes. Table 4.25 presents the performance comparison for all 21 mixtures tested, on the basis of mixture type.

4.3 OSU Wheel Tracker Results

A comparison of the mixtures as they performed in the OSU wheel tracker is presented in Table 4.26. This comparison was produced using the LSD procedure and the resulting T groupings. The model included only mixture type (MIX) as a class variable. The dependent variable is rut depth, designated by a negative number. A second model that includes the covariate air voids (AVOID) was also produced. This model is presented in Table 4.27.

Table 4.25. Comparison of performance of all mixtures in the ECS

Rank	Mixture	Mean Final ECS Modulus Ratio	T Grouping[1]
1	GAA	0.94	A
2	OR2	0.92	A, B
3	WA1	0.90	A, B, C
4	OR1	0.87	A, B, C, D
5	COB	0.81	A, B, C, D, E
6	WIA	0.77	A, B, C, D, E
7	AB5	0.76	A, B, C, D, E, F
8	AZF	0.75	A, B, C, D, E, F
9	AZ5	0.72	B, C, D, E, F
10	COE	0.71	C, D, E, F, G
11	TAI	0.68	D, E, F, G
12	LAF	0.65	E, F, G, H
13	MS5	0.62	E, F, G, H, I
14	CAB	0.55	F, G, H, I
15	MN5	0.54	G, H, I
16	COA	0.54	G, H, I
17	COC	0.46	H, I
18	CAD	0.46	H, I
19	CAG	0.42	I, J
20	WYO	0.24	J
21	GAF	0.22	J

[1] Means with the same letter designation are not significantly different at the $\alpha = 0.05$ level, least significant difference = 0.205

Table 4.26. Comparison of mixture performance for the OSU wheel tracking test procedure[1]

Ranking	200 Passes			5,000 Passes			10,000 Passes		
	Mix	T Grouping[2]	Mean Rut Depth (mm)	Mix	T Grouping	Mean Rut Depth (mm)	Mix	T Grouping	Mean Rut Depth (mm)
1	GAA	A	0.050	GAA	A	1.425	GAA	A	2.433
2	WA1	A	0.540	WA1	A, B	2.484	WA1	A	2.713
3	OR1	A	0.592	CAD	A, B, C	3.717	CAD	B	5.733
4	WIA	A	0.642	WIA	A, B, C	4.525	OR1	B, C	6.692
5	AZ5	A	0.708	OR1	B, C	4.775	AZ5	C, D	7.283
6	CAD	A, B	1.217	AZ5	B, C, D	5.383	WIA	D, E	8.158
7	AB5	A, B, C	1.300	AB5	C, D	6.500	AB5	E	8.783
8	MS5	A, B, C	1.333	MS5	D	8.108	OR2	F	10.642
9	CAG	B, C	2.549	OR2	D	8.400	MS5	F	11.092
10	OR2	B, C	2.692	CAG	E	19.397			
11	MN5	C	2.886						

[1] No beams were tested for the mixture CAB

[2] Groupings with the same letter designation include means which are not significantly different at the $\alpha = 0.05$ level

Table 4.27. Prediction variables for rut depth, OSU wheel tracker data

Variable	Type	Levels	Values
Mixture (MIX) Air Voids (AVOID)	Class Covariate	11	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA

Passes = 200
Model: R^2 = 0.87, CV = -45%, and the mean rut depth = -1.324

Source of Error	Degrees of Freedom	Type III Mean Square	F-value	P-value
MIX	10	10.02	2.81	0.0676
AVOID	1	1.83	5.15	0.0494

Passes = 5,000
Model: R^2 = 0.98, CV = -16%, and the mean rut depth = -6.616

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	10	382	37.7	0.0001
AVOID	1	6.44	5.74	0.0436

Passes = 10,000
Model: R^2 = 0.99, CV = -7%, and the mean rut depth = -7.137

Source of Error	Degrees of Freedom	Type III Sum of Squares	F-value	P-value
MIX	10	124	58.2	0.0001
AVOID	1	0.126	0.47	0.514

When interpreting the results of the OSU wheel tracking tests, it is important to compare the air void levels of the beam specimens with both the kneading-compacted specimens tested in the ECS and the cores taken from the field. Due to the limited amount of material available for preparing specimens, only two beams were prepared for each mixture. If problems occurred during the specimen manufacturing process, additional specimens could not be fabricated. For example, the MN5 mixture was very difficult to compact, and a significant portion of the mixture was lost due to adhesion to the roller drums. Therefore, MN5 beams had significantly different air voids than intended. Table 4.28 compares the average air void levels of the different specimens.

4.4 Field Core Data

Figures 3.58 through 3.79 indicate that several mixtures had field core modulus values equal to or greater than the modulus values for new, unconditioned laboratory-fabricated specimens. In both the MTS diametral and triaxial modulus data, all the mixtures tested had one or more field cores that were equal in stiffness to unconditioned laboratory specimens. These data indicate that the typical field core used in this study has not experienced any decrease in mixture stiffness that would be the attributable to water damage.

The general performance indicator for field cores was a ratio of the field core MTS diametral modulus to the MTS diametral modulus of a corresponding unconditioned laboratory manufactured specimen. A direct ratio of conditioned field core modulus to unconditioned field core modulus could not be calculated because no cores were taken immediately after construction to represent the unconditioned case. A linear regression equation with the MTS diametral modulus as a function of air voids was developed for each mixture using the unconditioned kneading compacted specimens. This equation was then used to predict a corresponding initial MTS diametral modulus value for an unconditioned field core using the current air void level of each individual core.

Table 4.28. Average air void levels of test specimens, beams, and field cores

Site	ECS Kneading Compacted Specimen (%)	OSU Wheel Tracker Beam (%)	Field Core, Wheel Path (%)	Field Core, Between Wheel Path (%)
AB5	3.9	6.5	1.4	1.4
AZ5	7.2	8.4	4.4	4.9
CAB	5.3	No Beams	5.4	5.6
CAD	8.3	9.7	6.1	5.6
CAG	8.2	12.0	5.3	6.1
GAA	8.2	7.8	8.1	8.1
MN5	4.9	11.4	4.7	6.5
MS5	6.9	8.3	4.7	6.3
OR1	8.4	8.4	11.8	13.0
OR2	17.8	21.8	13.8	15.0
WA1	9.5	6.3	7.7	9.4
WIA	1.0	4.1	3.9	4.05

For field cores nominally 4.0 in. (101.6 mm) in height, a similar ratio of MTS triaxial modulus ratio was also used to compare field core performance directly to performance of the mixtures in the ECS. Initial unconditioned MTS triaxial modulus value for the unconditioned field cores were calculated in the same manner as for the unconditioned MTS diametral modulus values.

Several of the field mixtures have diametral modulus ratios greater than one (AZ5, MS5, WA1, and WIA) as seen in Figures 3.58 through 3.79. This may indicate that these mixtures have undergone some degree of long-term aging in the field since their placement. Long-term aging tends to increase asphalt mixtures' moduli. Lottman (1982) also reported this behavior in field mixtures. In the Lottman study, pavements that had been in place for less than four years were typically stiffer than new mixtures, producing modulus ratios of greater than 1.00. After five years in the field, the effects of water damage began to be significant and modulus ratios decreased. It should be remembered that in the primary test program, all pavements had been in the field for three years or less at the time they were cored for performance evaluation.

The LSD comparison for the field specimens on the basis of retained MTS diametral modulus ratio is presented in Table 4.29. The model again had only mixture type (MIX) as an independent variable. As of 1992, only one field site has deteriorated significantly. MS5 is currently scheduled to be overlaid. This mixture is suspected to be water sensitive; however, difficulties during construction may also have produced a lower-quality mixture in the field.

4.5 Comparison of Test Results

Table 4.30 indicates the performance comparison for the mixtures tested in the three test procedures. For the ECS, this is the comparison based on the final ECS modulus ratio using all twelve mixtures, regardless of environmental zone. This listing corresponds to the rankings given by the OSU wheel tracker, which uses both Freeze and No-Freeze conditioning, and the field, which may present either a Freeze or No-Freeze environment.

Table 4.29. Comparison of mixtures using field core data, based on MTS diametral modulus ratios

Ranking	Mixture	Mean Modulus Ratio	T Grouping[1]
1	WIA	1.19	A
2	AZ5	1.09	A, B
3	MS5	1.09	B
4	WA1	1.07	B
5	CAG[2]	1.00	B, C
6	OR1	0.93	C, D
7	CAG[3]	0.85	D, E
8	MN5	0.82	E
9	CAB	0.72	F
10	CAD	0.68	F
11	GAA	0.67	F, G
12	OR2	0.64	F, G
13	AB5	0.57	G

[1] Groupings with the same letter designation include means which are not significantly different at the $\alpha = 0.05$ level
[2] Second set of CAG cores
[3] First set of CAG cores

Table 4.30. Comparison of mixture performance by test method

Ranking	ECS		OSU Tracking 5,000 Wheel Passes		Field Cores	
	Mixture	T Grouping[1]	Mixture	T Grouping	Mixture	T Grouping
1	GAA	A	GAA	A	WIA	A
2	OR2	A	WA1	A, B	AZ5	A, B
3	WA1	A, B	CAD	A, B, C	MS5	B
4	OR1	A, B, C	WIA	A, B, C	WA1	B
5	WIA	B, C, D	OR1	B, C	CAG[2]	B ,C
6	AB5	C, D, E	AZ5	B, C, D	OR1	C, D
7	AZ5	D, E	AB5	C, D	MN5	E
8	MS5	E, F	MS5	D	CAB	F
9	CAB	F, G	OR2	D	CAD	F
10	MN5	F, G	CAG	E	GAA	F, G
11	CAD	G	MN5	Failed	OR2	F, G
12	CAG	G			AB5	G

[1] Groupings with the same letter designation include means which are not significantly different at the $\alpha = 0.05$ level
[2] CAG cores from second coring

4.5.1 ECS and Field Results

A comparison of the mixture performances in the ECS test procedure to their field performance was made. Field cores which were tall enough to allow MTS triaxial modulus testing were directly compared to ECS specimens, using the laboratory specimen MTS triaxial data at similar air voids to produce initial MTS triaxial modulus data for the field cores. This allowed a modulus ratio to be developed. Six mixtures were evaluated in this manner. For mixtures which were placed in layers that did not produce 4.0-in. (102-mm) cores, the correlation between the performance of the field mixtures, as measured by a diametral modulus ratio, and the performance in the ECS, as measured by the ECS modulus ratio, was investigated.

A model was run using the General Linear Models (GLM) procedure to compare the final ECS modulus ratios with the field core MTS triaxial modulus ratios. Mixture type (MIX) and test procedure (TEST) were the independent variables. The interaction between the two variables was also included (MIX*TEST).

Table 4.31 shows the results of this comparison. The significant variable according to the P-value is TEST. Table 4.32 indicates the values of the mean modulus ratio and standard deviation for each mixture in each test procedure. For five of the six mixtures, the ECS gives a lower modulus ratio, indicating that the ECS specimens have been more severely damaged than the field cores, and that the field cores may be experiencing aging. For the sixth mixture, the ECS and field mean MTS triaxial modulus ratios are within one standard deviation of each other.

A comparison of mixture performance in the ECS and in the field can also be seen in Figure 4.14. The MTS diametral modulus ratio of the field cores versus the final ECS modulus ratio is shown. Final ECS modulus ratios are lower than the MTS diametral modulus ratios obtained from the field cores for eight of the twelve mixtures tested. This indicates that the ECS is predicting more water damage for these mixtures than has yet been experienced in the field. The effects of aging, variation in precipitation and temperature conditions among sites, and the relatively short period of time the mixtures have been in place are probably responsible. From the most recent field distress surveys, it is known that the MS5 field section is showing signs of

Table 4.31. Analysis of the ECS and field core data by test method

Variable	Type	Levels	Values
Mixture Type (MIX)	Class	6	AB5, AZ5, CAB, CAD, GAA, MN5
Test Procedure (TEST)	Class	2	ECS, FLD

Model: R^2 = 0.31, CV = 50%, and the modulus ratio mean = 0.97

Source of Error	Degree of Freedom	Type III Sum of Squares	F-value	P-value
MIX	5	1.28	1.10	0.365
TEST	1	4.51	19.4	0.0001
MIX*TEST	5	2.19	1.89	0.104

Table 4.32. Comparison of mean modulus ratio values by test method for each mixture

Mixture Type	ECS		Field	
	Mean ECS Modulus Ratio	**Standard Deviation**	**Mean Triaxial Modulus Ratio**	**Standard Deviation**
AB5	0.78	0.14	0.77	0.10
AZ5	0.72	0.04	1.21	0.64
CAB	0.55	0.19	1.04	0.56
CAD	0.46	0.15	1.05	0.71
GAA	0.94	0.16	1.10	0.45
MN5	0.54	0.12	1.53	0.58

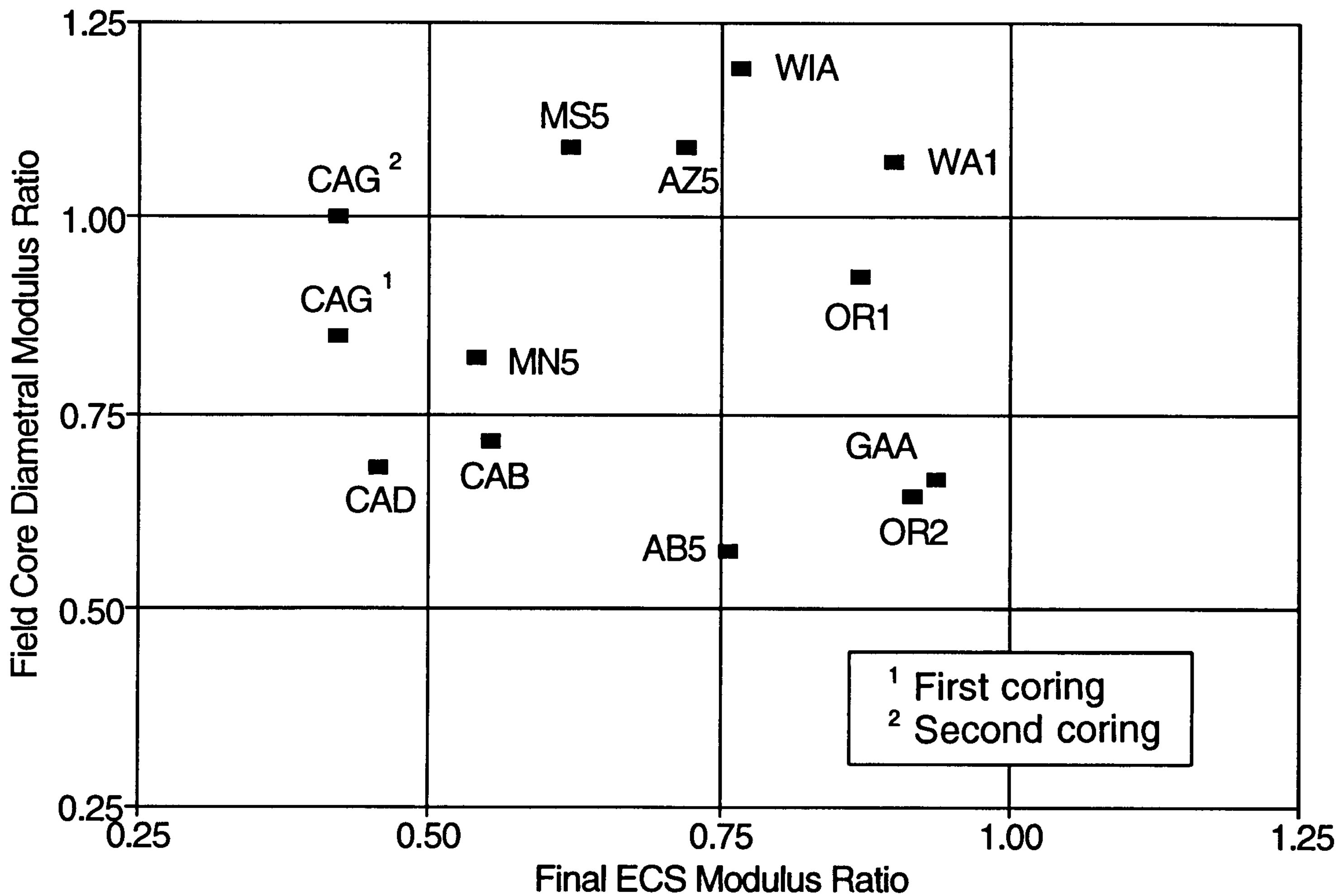


Figure 4.14. Comparison of ECS and field performance

rutting and reflective cracking, and is due to be overlaid. This distress developed over the 1991-92 winter season, after the field cores had been taken in the summer of 1991. At the time of coring the section showed no signs of distress. MS5 is the only field section that at this time shows any substantial distress. For the other four mixtures (AB5, OR1, OR2, and GAA), the ECS indicates that these mixtures will not suffer a high loss of stiffness due to water damage. To date, the field specimens reflect this behavior.

As mentioned above, when comparing the results of the ECS testing with the modulus ratios developed for the field cores, consideration should be given to the potential for the mixtures in the field to be experience long-term aging. The mixtures that are tested in the ECS are subjected to only short-term aging of the loose mixture. In the field, mixtures also experience long-term aging, which tends to increase a mixture's modulus. In the early life of a pavement, before water damage has developed fully, the increase in stiffness due to aging may overwhelm any decrease in stiffness that is beginning to occur due to water damage. The data from CAG illustrate this point. In Figure 4.14, two sets of cores from CAG are represented. CAG^1 represents cores that were taken within one month of paving. CAG^2 represents cores taken approximately one year after paving. This mixture has experienced an increase in MTS diametral modulus during the initial year of pavement life.

Figure 4.15 shows the relationship between the visual stripping shown in field cores and that observed in specimens from the ECS. Typically, field core and ECS specimens from the same mixture appear very similar. However, two differences were noted: (1) asphalt in the field cores appeared to be dull, flat black in color, while the asphalt in the ECS specimens was typically a dark, shiny black, and (2) no migration of asphalt binder was seen in any of the field cores. The differences in the appearance of the asphalt between field and ECS specimens may be due to the aging of the asphalt in the field. The lack of asphalt binder migration in the field specimens may be due to their relatively short life.

Currently, there is no correlation for the amount of field life that the ECS procedure simulates, using either three hot cycles, or three hot cycles and one freeze cycle. The ECS indicates that a mixture will experience a certain decrease in modulus

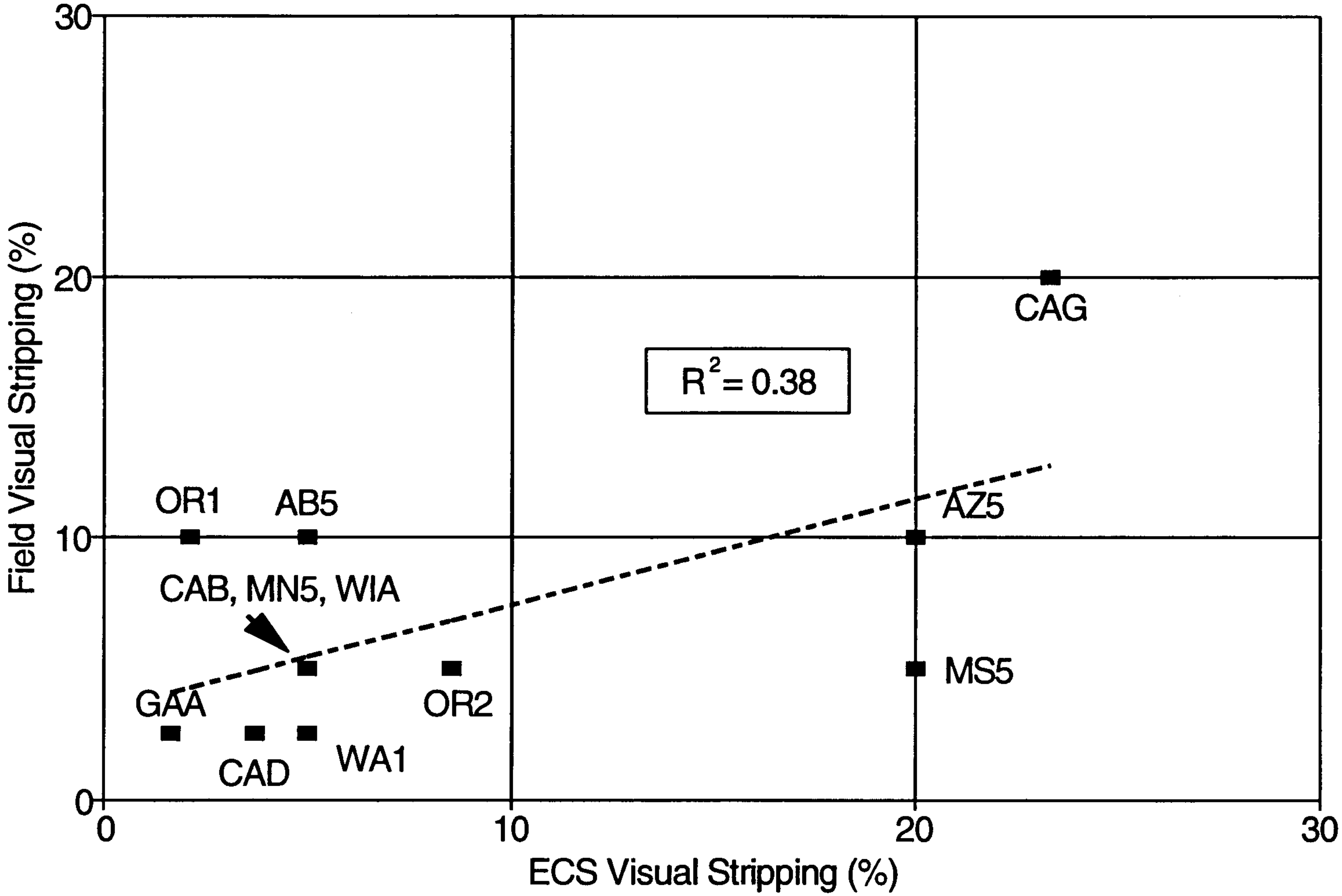


Figure 4.15. Visual stripping, comparison of field and ECS specimens

and a certain level of asphalt stripping and binder migration, but gives no indication of the length of time it will take for this damage to be manifested in the field. Continued monitoring of the mixtures studied in this program will help establish a correlation between performance in the ECS test procedure and expected field life with respect to water sensitivity.

4.5.2 ECS and OSU Wheel Tracker

Figure 4.16 shows the relation between the final ECS modulus ratio and the OSU wheel tracker rut depth. The beams manufactured from the MN5 mixture had air voids over 200 percent of those found in the ECS kneading-compacted specimens, as shown in Table 4.26. If the data points for MN5, on the basis of its high air voids, and OR2, an open-graded mixture, are removed, Figure 4.17 results. There is no valid reason to remove the data point for CAD from the analysis, even though it represents data from only one beam. A best fit line can be placed through these data using simple linear regression, as shown in Figure 4.17. With the exception of the mixtures from California, the data fit this line well.

The correlation of performance is more evident between the ECS data and the OSU wheel tracker data than between the ECS and field core data because ECS and OSU wheel tracker specimens were under laboratory control and received similar preparation and water and temperature conditioning. Specimens from the field do not undergo such well-defined or uniform treatment, as the weather and traffic data presented previously indicate. Construction problems may also affect the quality of the pavement placed in the field. Table 2.5 indicates that two projects, MS5 and OR1, experienced problems during construction.

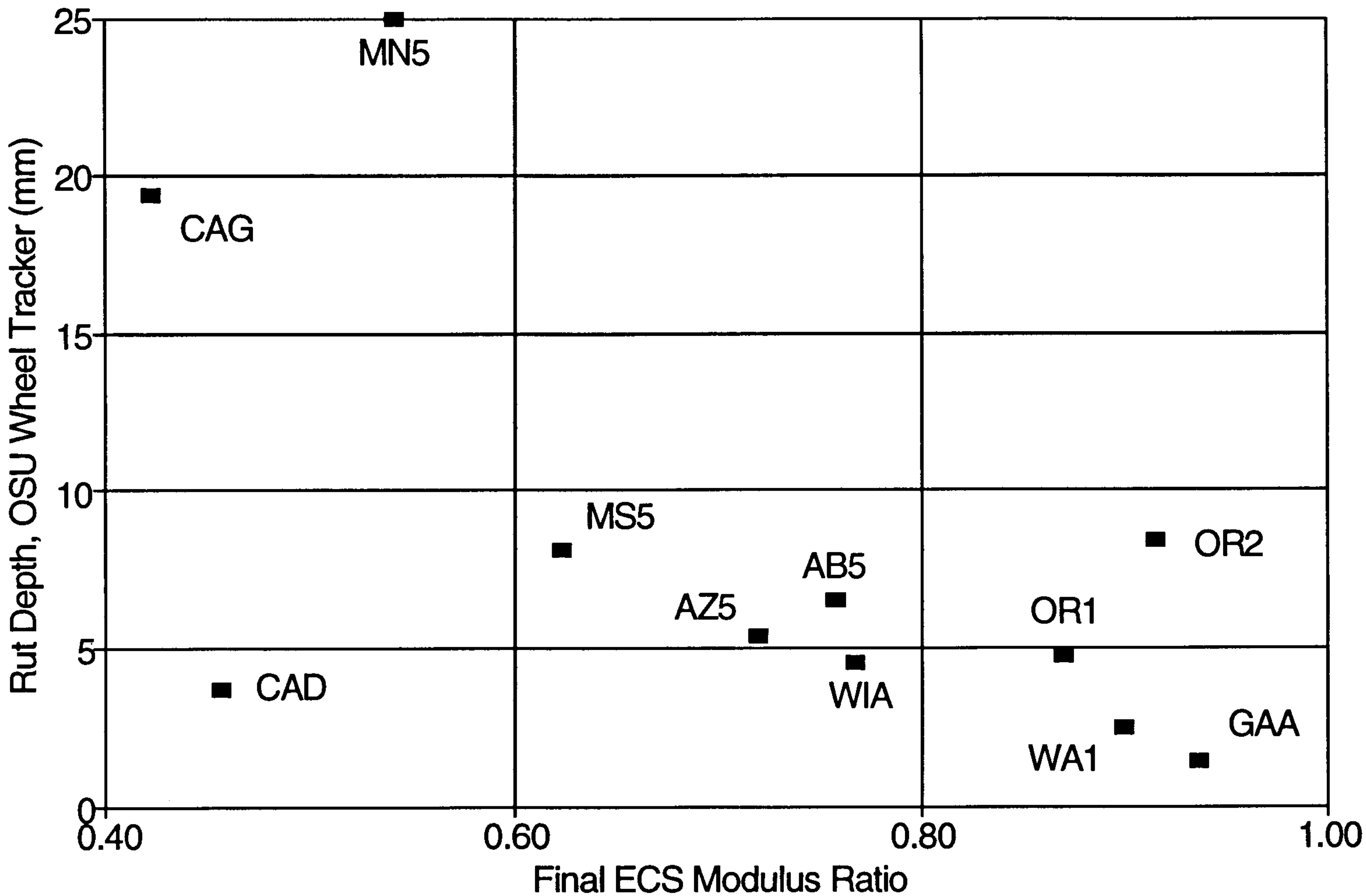


Figure 4.16. Comparison of ECS and OSU wheel tracker performance

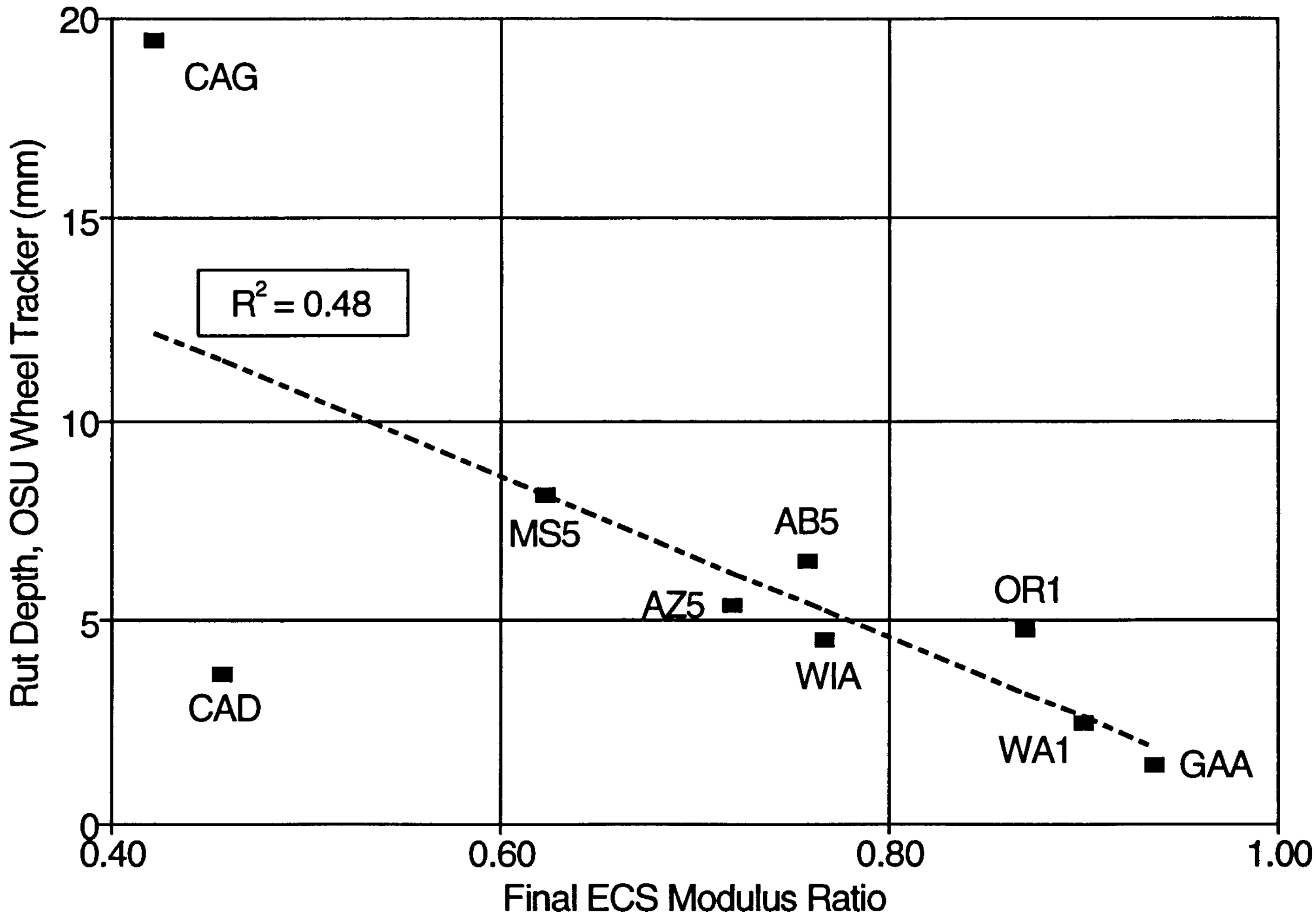


Figure 4.17. Comparison of ECS and OSU wheel tracker performance, MN5 and OR2 removed

4.6 Significance of Findings

From the preceding analysis several significant findings have emerged. These significant findings are summarized as follows:

ECS results:

1. The ECS flow systems, as plumbed in the prototype system, do not comply with Darcy's law. The air system is operating outside of the range of viscous flow. The systems could be modified to allow use as constant-head permeameters.
2. The gage readings for the flow measurements introduce error into the calculated coefficients of permeability, which could be effectively overcome by use of more precise gages.
3. A high percentage of the reduction in ECS modulus ratio occurs in the first cycle of ECS conditioning; however, a significant change may occur between cycle 1 and cycle 3 for some mixtures (MN5, AB5, and CAG).
4. The slope of the ECS modulus ratio curve indicates the rate of water damage to the specimen. At this time, a correlation between cycles of ECS conditioning and the corresponding period of field life has not been established.
5. Of the variables considered (mixture type, air voids, initial modulus, coefficient of air permeability, and coefficient of water permeability), mixture type, initial modulus, and air voids have the strongest influence on a mixture's final ECS modulus ratio.
6. No statement can be made attributing the loss of ECS modulus ratio to adhesion or cohesion based on the amounts of visual stripping and binder migration.
7. There is no statistical difference between the results from mixtures that were subjected to the freezing cycle and those which were subjected to only three hot conditioning cycles. This indicates that neither procedure, three cycles with no freeze, or four cycles with a freeze, is consistently more severe. Therefore, subjecting a specimen to the appropriate

conditioning for its environmental designation will not influence the performance of the mixture relative to other mixtures tested using conditioning appropriate to their environmental designations.

8. Mixture type is the only variable included in this study that is a significant predictor of the degree of visual stripping.
9. Mixture type, compaction method, and air void level are all significant in predicting binder migration.
10. A correlation exists between the coefficient of water permeability after each cycle and visual stripping. This may indicate the importance of distributing water throughout the specimen and maintaining a flow gradient in inducing asphalt stripping.
11. Specimen deformation correlates with the amount of visual stripping and binder migration.
12. Mixture type and compaction method are significant in predicting the deformation in a specimen in the ECS procedure. Roller-compacted specimens typically experience less deformation than laboratory kneading-compactor specimens.
13. Binder migration was observed in ECS specimens for several primary mixtures. The corresponding field cores showed no evidence of binder migration. The cores from AZF and LAF were the only field cores in which binder migration was observed.

OSU wheel tracker results:

1. The air void levels between the beam specimens and the corresponding laboratory kneading-compactor specimens varies for some mixtures (especially MN5), and may result in high rut values that are not indicative of the expected mixture performance.
2. Anomalous results indicate that several of the mixtures should be retested in this apparatus (CAD, CAG, and MN5).

Field data:

1. Long-term aging of mixtures in the field may increase the field cores' modulus, overshadowing the effects of water damage.

Comparison of test procedures:

1. ECS and Field Cores: For mixtures with 4.0 in. (102 mm) high cores, a comparison of triaxial modulus ratios indicates that the ECS tends to induce more water damage than field conditions; however, the difference is not statistically significant.
2. ECS and Field Cores: In a comparison of the final ECS modulus ratio with the field core diametral modulus ratio, the ECS predicts more damage than has been experienced by the field cores for eight of the twelve mixtures tested. It appears that the ECS is predicting damage that has not yet occurred due to the relative youth of the field sections.
3. ECS and Field Cores: The mixtures in the field appear to be experiencing long-term aging, which is not simulated in the ECS test procedure.
4. ECS and Field Cores: The field cores have experienced a range of precipitation, temperature, and traffic conditions which are not seen in the ECS testing. All ECS specimens are tested under the same procedure according to their environmental designation. This will affect the correlation between the performance of a mixture in the ECS and in the field.
5. ECS and OSU wheel tracker: A strong correlation between mixture performance in the ECS and OSU wheel tracker is evident.

4.7 Contributions to the State of Knowledge

The work completed in this program provided several preliminary findings and hypothesis that will be further evaluated as the ECS in incorporated as a standard test. These findings are suggested by the data, but at this time have not been fully evaluated. However, they contribute to the current knowledge of laboratory evaluation of water sensitivity of asphalt concrete mixtures. These findings or hypothesis are summarized as follows:

1. The slope between cycles 3 and 4 may be an indicator of the tendency for aggregate degradation. The data is inconclusive in support of this hypothesis.
2. The ECS modulus ratio correlates with the amount of binder migration after cycle 3. This indicates that binder migration takes place during the first three cycles.
3. The mechanical changes in the asphalt-aggregate matrix under the action of repeated loading may cause breakdown of asphalt-aggregate and asphalt-asphalt bonds, facilitating asphalt stripping and loss of cohesion in the asphalt matrix.
4. Figure 4.18 shows an interpretation of the ECS modulus curve that has been developed during the course of this test program. Further testing with the ECS will help validate the hypothesized interpretation of the ECS modulus curve.
5. The evaluation of degree of visual stripping and binder migration are based on a very coarse scale and are very subjective.

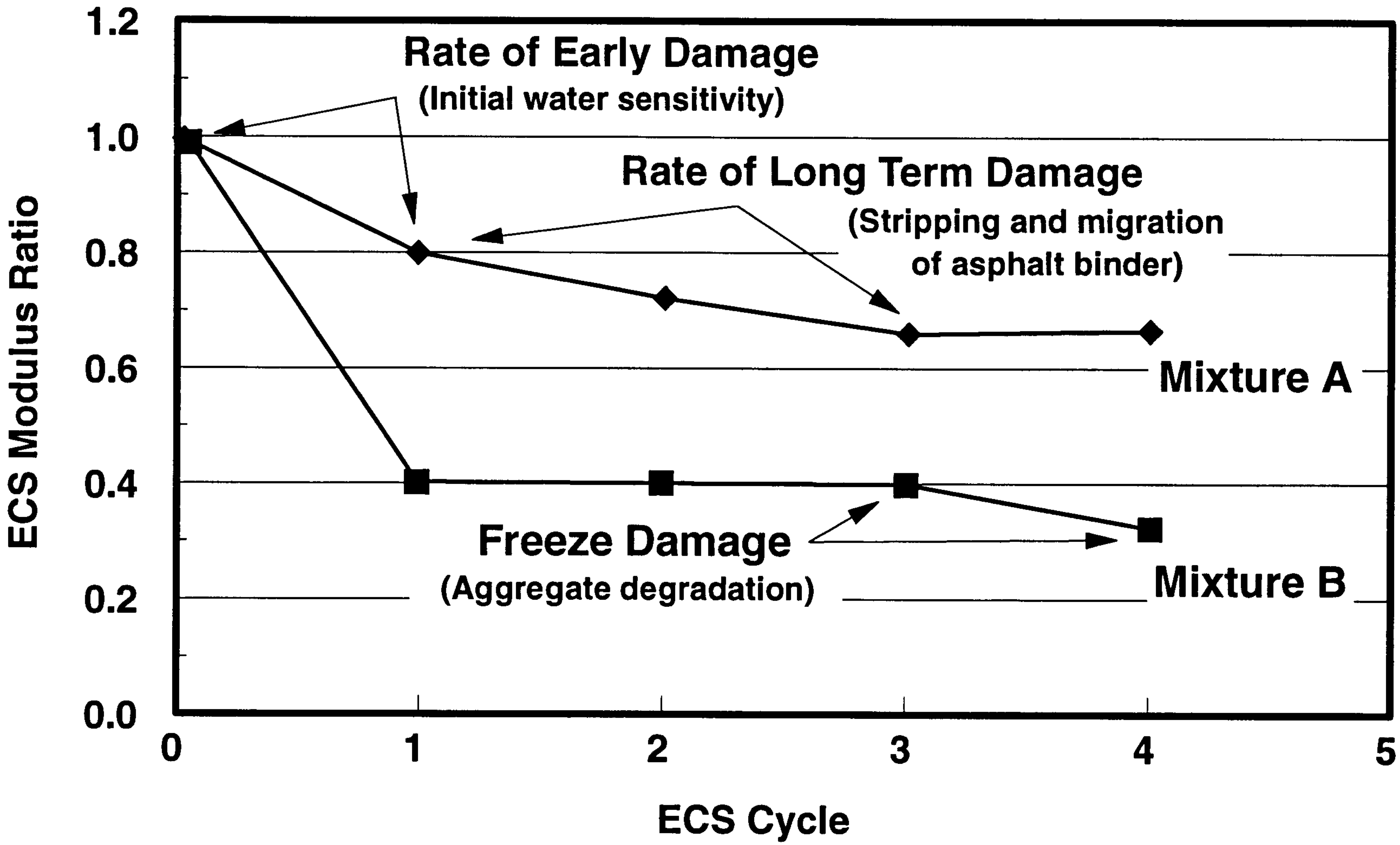


Figure 4.18. Interpretation of the ECS modulus curve

5 GUIDELINES FOR SPECIFICATIONS

The Environmental Conditioning System promises to be a useful tool for evaluating of proposed asphalt concrete mixtures. ECS results may be incorporated into usable specifications for one or more levels of mix design that could be used by state transportation agencies. More specifically, the ECS is being considered for incorporation in the proposed SHRP mix design and analysis program. The ECS procedure will investigate the susceptibility of asphalt mixtures to water damage and will determine whether a mixture can be expected to perform well with regard to water damage, or whether the mixture should be redesigned, aggregate or asphalt changes made, or modifiers added.

Three levels of mix design are being considered in the proposed SHRP mix design program: **Level 1**, low volume roads; **Level 2**, intermediate traffic volume roads and secondary routes; and **Level 3**, primary state routes and high-speed and high-volume roads.

5.1 Mixture Properties

As designed in the laboratory, mixtures selected in the preliminary volumetric mix design will be subjected to short-term oven aging before being compacted into specimens for the ECS. The preliminary mixture design will determine the aggregate and asphalt type to be used and the aggregate gradation and asphalt content.

ECS specimens will then be compacted at two air void levels: 7% ± 1% for Levels 1, 2, and 3, and additional specimens at 10% ± 1% for Levels 2 and 3. Two specimens will be compacted at each level. These air void levels were chosen in accordance with the pessimum voids theory proposed by Terrel and Al-Swailmi (1993). The pessimum voids theory suggests that mixtures with air void levels less than approximately 8 percent will not be prone to water damage due to the low values of permeability. However, mixtures compacted from approximately 8 to 13 percent may be more prone to water damage as water can easily infiltrate into the specimen, but will not flow freely through the specimen.

5.2 ECS Criteria

Two specimens of a given mixture and equal air void level, will be subjected to the ECS procedure using three or four cycles. The fourth, or freeze cycle, is optional for use in environments which experience freeze-thaw conditions. A plot of the ECS modulus ratio versus cycles will be used to rate the specimen performance.

From the data, a final ECS modulus ratio of 0.7 appears to separate mixtures which performed well in the ECS and OSU wheel tracker from those which showed deterioration in the OSU wheel tracker. To date none of the primary field sites have exhibited water damage. Application of a 0.7 final ECS modulus ratio is illustrated in Figures 5.1 and 5.2. Table 5.1 indicates the predicted performance of mixtures evaluated in this test program using the 0.7 criteria. Lottman (1982) recommends minimum cutoff ratios for acceptable mixtures with regard to water sensitivity of between 0.7 and 0.8 (for indirect tensile strength and/or diametral resilient modulus). Maupin (1982) reported differentiation between stripping and non-stripping mixtures when ratios were between 0.70 and 0.75.

When evaluating the performance of mixtures in the ECS, the values of the visual degree of stripping and binder migration should be considered when mixtures have marginally acceptable final ECS modulus ratios (i.e., 0.71-0.80). High values of the degree of visual stripping and binder migration indicate that the specimen has undergone significant loss of adhesion and cohesion, that could lead to raveling or potholing in the field.

In using a final ECS modulus ratio of 0.7 to differentiate between acceptable and unacceptable asphalt concrete mixtures in terms of water sensitivity, it should be noted that the change in ECS modulus ratio that occurs between cycles 1 and 3, as shown in Figure 4.9, moved two of the mixtures tested, MN5 and MS5, from acceptable or questionable, to unacceptable. Furthermore, the change in ECS modulus ratio between cycles 3 and 4, as shown in Figure 4.10, moved the mixture WIA from unacceptable to acceptable. Therefore, when setting criteria for mixture performance in the ECS, the mixtures being evaluated should be subjected to the full ECS

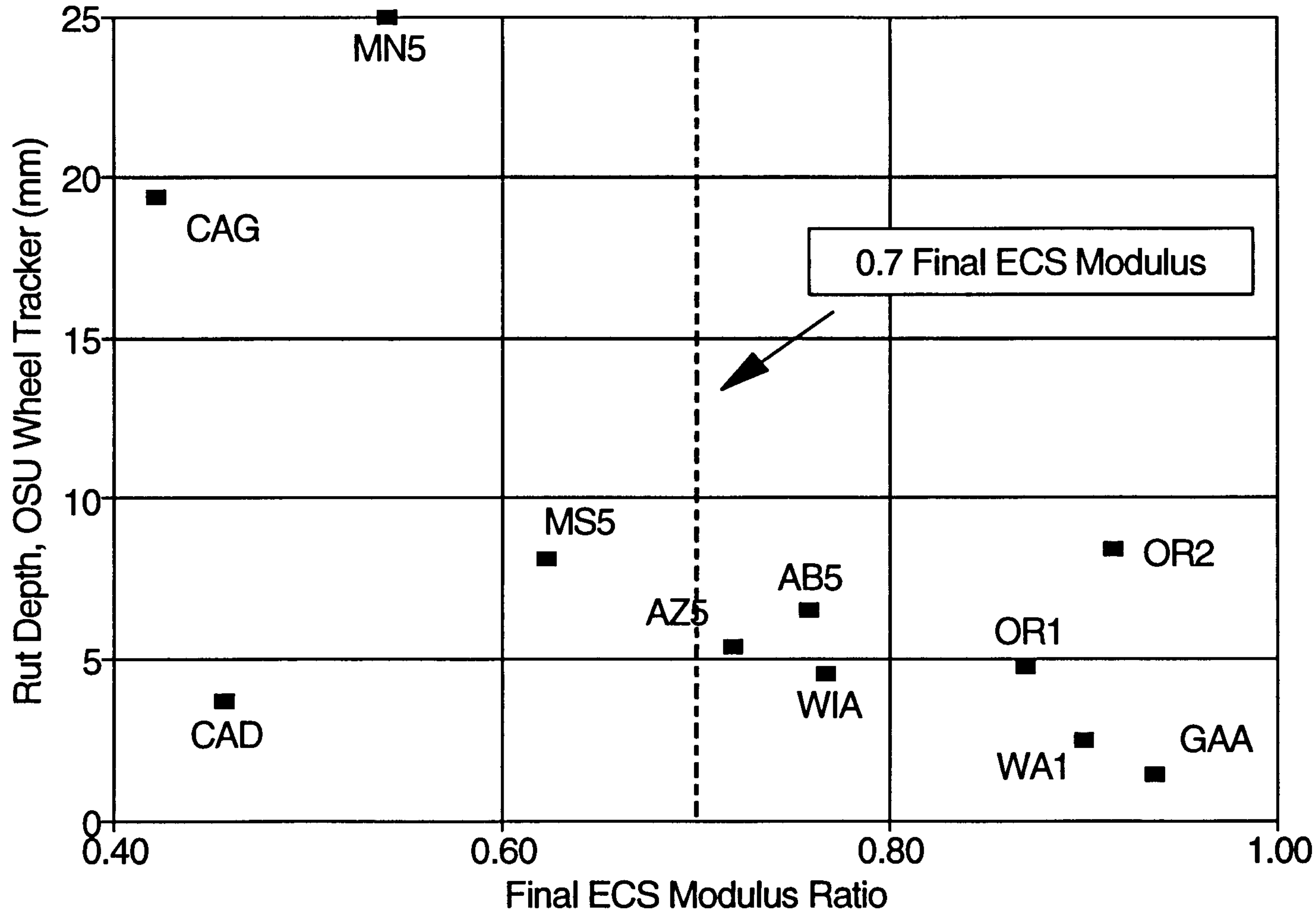


Figure 5.1. Criteria for the performance of mixtures, OSU wheel tracker versus ECS

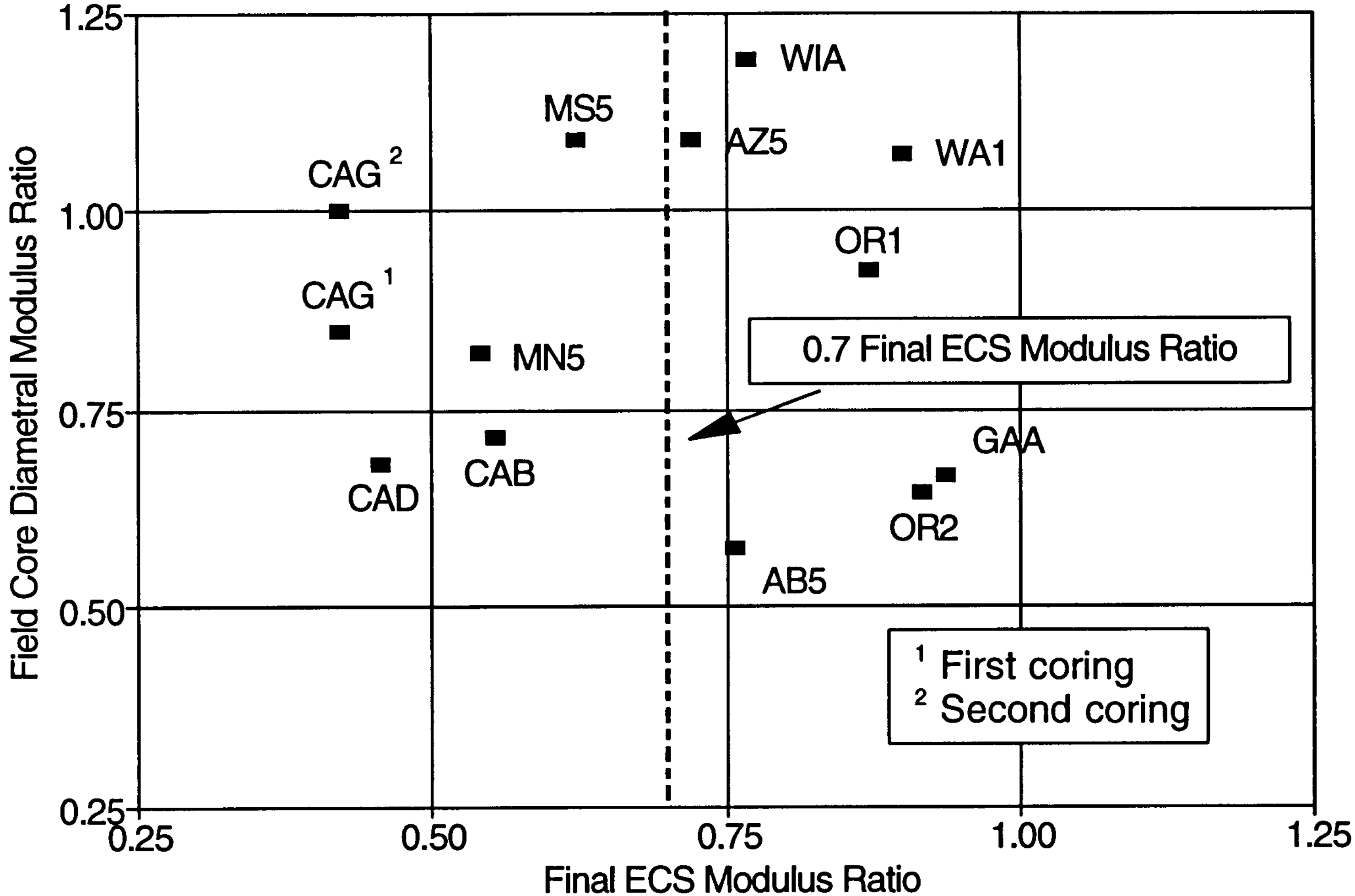


Figure 5.2. Criteria for the performance of mixtures, field versus ECS

Table 5.1. Predicted performance of the mixtures evaluated in the test program

Predicted Performance	Mean Final ECS Modulus Ratio	Mixtures
Good	0.81-1.00	GAA, OR1, WA1, OR1, COB
Fair (check visual stripping, binder migration, and slope of ECS modulus curve)	0.71-0.80	AB5, AZ5, COE, WIA
Poor	less than 0.7	CAB, CAD, CAG, COA, COC, GAF, LAF, MN5, MS5, TAI, WYO

procedure appropriate for their environmental designation. It is recommended that the following procedure be used:

Level 1: If the final ECS modulus ratio is less than 0.7, the mixture should be treated (anti-strip additive) for moisture susceptibility and the treated mixture should be retested in the ECS. If the final ECS modulus ratio is less than 0.8, the slope of the curve between cycles 1 and 3 should be investigated. For mixtures with flat slopes, the mixture is expected to perform well and no treatment is recommended. For mixtures with steeper slopes, where the projected ECS modulus ratio would be reduced to less that 0.7 if one or two more hot cycles were performed, treatment of the mixture for moisture sensitivity should be considered, as these mixtures may experience significant water damage, only at a slower rate than those with final ECS modulus ratios of less than 0.7.

Level 2: For specimens with air void contents of 7% ± 1%, the criteria are the same as in Level 1. For specimens with air void contents of 10% ± 1%, the mixture should be treated for moisture susceptibility if the final ECS modulus ratio is less than 0.6. Again, the slope of the curve between cycles 1 and 3 is an indicator of delayed moisture damage to the mixture.

Level 3: Level 3 varies from Level 2 only in the use of additional tests on the specimens after the ECS test procedure. Specimens from the ECS will be subjected to fatigue and rutting tests to determine whether the mixture can meet these criteria after being subjected to water damage. If the mixture still does not meet fatigue and rutting criteria, it will be redesigned to improve its performance.

5.3 Expected Benefits

Evaluating mixtures with the ECS test procedure should eliminate the placement of mixtures that could experience water damage within the first several years of life. Currently, only one of the mixtures (MS5) tested in the primary effort has failed in the field. This mixture had a final ECS modulus ratio of 0.62 and a slope of -0.0337. The ECS will also identify mixtures that would benefit from the use of admixtures. Asphalt concrete mixtures which show tendencies for water damage over a longer life, as evidenced by steep modulus ratio curves between the first and third cycles, can be treated to extend pavement life. The mixture should be re-evaluated with the ECS after an appropriate admixture has been chosen.

The technology of the ECS apparatus and procedure is at the level of other equipment currently in standard use at the state highway agency level. The test procedure, with four cycles of testing requiring 48 hours, is of comparable or less duration than other standard water sensitivity tests (e.g., AAHSTO T 283 and AASHTO T 165; AASHTO, 1986).

6 CONCLUSIONS AND RECOMMENDATIONS

The work performed to evaluate the ECS test procedure using actual field asphalt concrete mixtures provides an initial database of information correlating the performance of mixtures in the field, in the ECS, and in the OSU wheel tracker. The limited amount of materials available and the length of time that pavements have been in the field indicates that additional time and testing will only better define the role of the ECS in modern mix design.

6.1 Conclusions

The following conclusions can be drawn from the data collected in this testing program:

1. The ECS can discriminate among mixtures that are predicted to perform well and those that are predicted to perform poorly with regard to water sensitivity.
2. The slope of the modulus ratio curve between cycles 1 and 3 is an indicator of the rate of water damage occurring to the specimen.
4. A significant change in the modulus ratio occurs in some mixtures between cycles 1 and 3, moving them from acceptable to unacceptable or questionable in terms of the ECS criteria proposed in Chapter 5 for water sensitivity.
5. Of the variables considered in this study, mixture type, initial modulus, and air voids have the strongest influence on a mixtures final ECS modulus ratio.
6. The twelve primary mixtures evaluated have not been in service long enough to allow a correlation between the cycles of conditioning in the ECS and the corresponding period of field conditioning.
7. The evaluation of visual stripping and asphalt binder migration in a specimen is extremely subjective. Mixture type, and mixture type and compaction method have a significant influence on the amount of visual stripping and binder migration a given specimen exhibits.

8. No conclusions can be drawn about the proportion of the loss of ECS modulus that may be attributed to adhesion loss or cohesion loss, on the basis of the data from this test program. The net absorption test may provide data that would allow a specific proportion of the ECS modulus loss to be attributed to adhesion loss (Al-Joaib, 1993).
9. Aggregate degradation is not discerned well in the visual examination of ECS specimens.
10. In new pavements, the increase in resilient modulus due to the effects of long-term aging in the field may overshadow the reduction in resilient modulus associated with the early stages of water damage to the pavement mixture.
11. There are interactions between variables measured in the ECS test, such as the coefficient of water permeability, ECS modulus ratio, degree of visual stripping, binder migration, and deformation, that may allow the mechanisms of water damage to be further characterized. Testing with additional mixtures and evaluation of specimens after one, two, and three testing cycles would help formalize these correlations.
12. As currently plumbed, the prototype ECS can not be used as a valid permeameter.

6.2 Recommendations

The following recommendations can be made to further validate the use of the ECS procedure for determining the water sensitivity of asphalt mixtures:

1. A strong correlation between ECS performance and the number of years of expected field performance has not yet been made due to the relative youth of the field sections. A continued program of coring to further validate and refine the role of the ECS test procedure in a mix design program is suggested.
2. A controlled program of materials collection, construction of field sections, and continued coring to provide a larger database for the ECS criteria should be developed. Enough asphalt and aggregate should be sampled at the time of

construction to allow both ECS specimens and OSU wheel tracker beams (at least four) to be manufactured. Several of the primary mixtures tested should have been replicated due to anomalous results from the OSU wheel tracker (CAD, CAG, and MN5). However, there was no opportunity to complete this work due to lack of original aggregates.

3. The procedure evaluating visual stripping and binder migration in mixtures should be improved to remove as much of the subjectivity as possible. The use of optical scanners to determine the amount of stripping in a mixture is worthy of investigation. Evaluation of aggregate degradation should also be addressed.
4. The ECS should be used to provide a systematic look at the effects in variations in volumetric mixture proportions, such as gradation, asphalt content, and air voids, on mixture performance. The pessimum voids concept proposed by Terrel and Al-Swailmi (1993) suggest that mixtures with a certain range of air voids level may be prone to water damage due to the structure of the void system. Gradation and asphalt content also will affect the air void structure of a mixture.
5. The ECS equipment and procedure should be included as a standard mix design component. The criteria presented in Chapter 5 is recommended for any mix design system proposed.
6. The ECS air and water flow systems should be redesigned for use as permeameters. Differential pressure readings should be taken directly across the length of the specimen and appropriate flow metering should be used. For the air flow system, it is critical to keep flow within the viscous flow range. All gages should be selected to minimize measurement error.
7. A full, statistically-designed experimental program should implemented to determine the precision of the ECS modulus and modulus ratio.
8. Investigation of the phenomena of binder migration, through the use of asphalt extraction on specimen sections exhibiting binder migration, would serve to determine if movement of the binder is actually occurring.

9. A program to quantitatively evaluate the benefit of additives such as lime, proprietary chemicals, and polymers on water sensitive asphalt and aggregate combinations using the ECS should be initiated.

6.3 Recommendations for Pooled Fund Study

A pooled fund study (Terrel, 1993) has been proposed to further evaluate the ECS in real-world situations and by user agencies that are currently experiencing water damage. Testing will include field validation of older projects where distress is further developed than in the twelve primary sections used in this study, and round-robin testing with several state highway agencies, including side-by-side comparison of the ECS and AASHTO T 283 (or whatever water sensitivity test the state highway authority is currently using). This study has been jointly proposed to the Federal Highway Administration (FHWA) by Oregon State University and the Strategic Highway Research Program (SHRP).

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APPENDICES

Appendix A

Aggregate Gradations for the Primary Mixtures

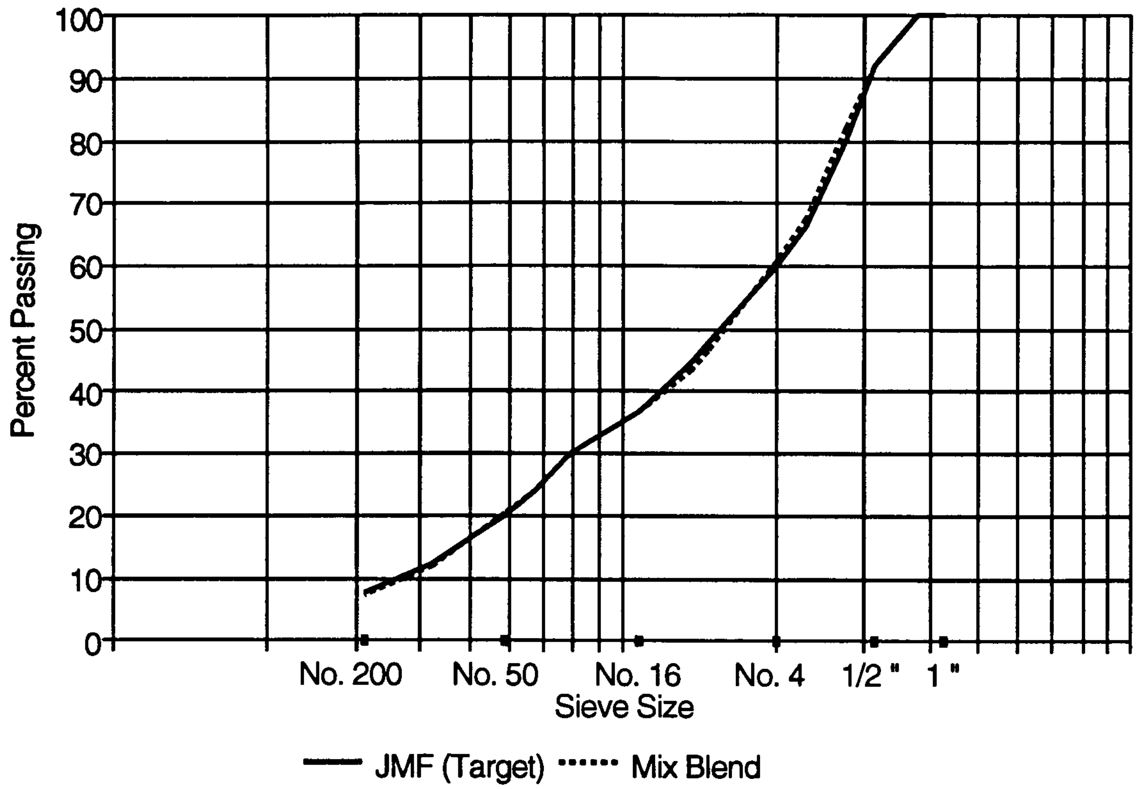

Figure A.1. Aggregate gradation for Alberta, SPS-5 (AB5)

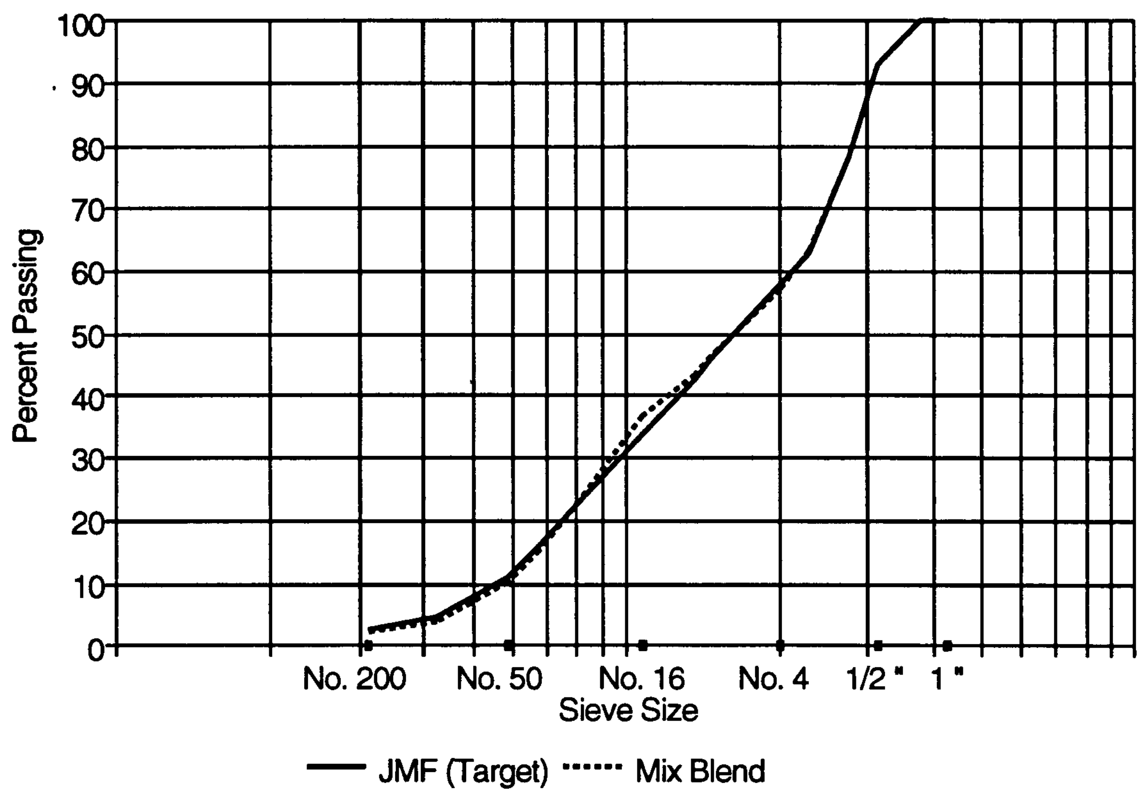

Figure A.2. Aggregate gradation for Arizona, SPS-5 (AZ5)

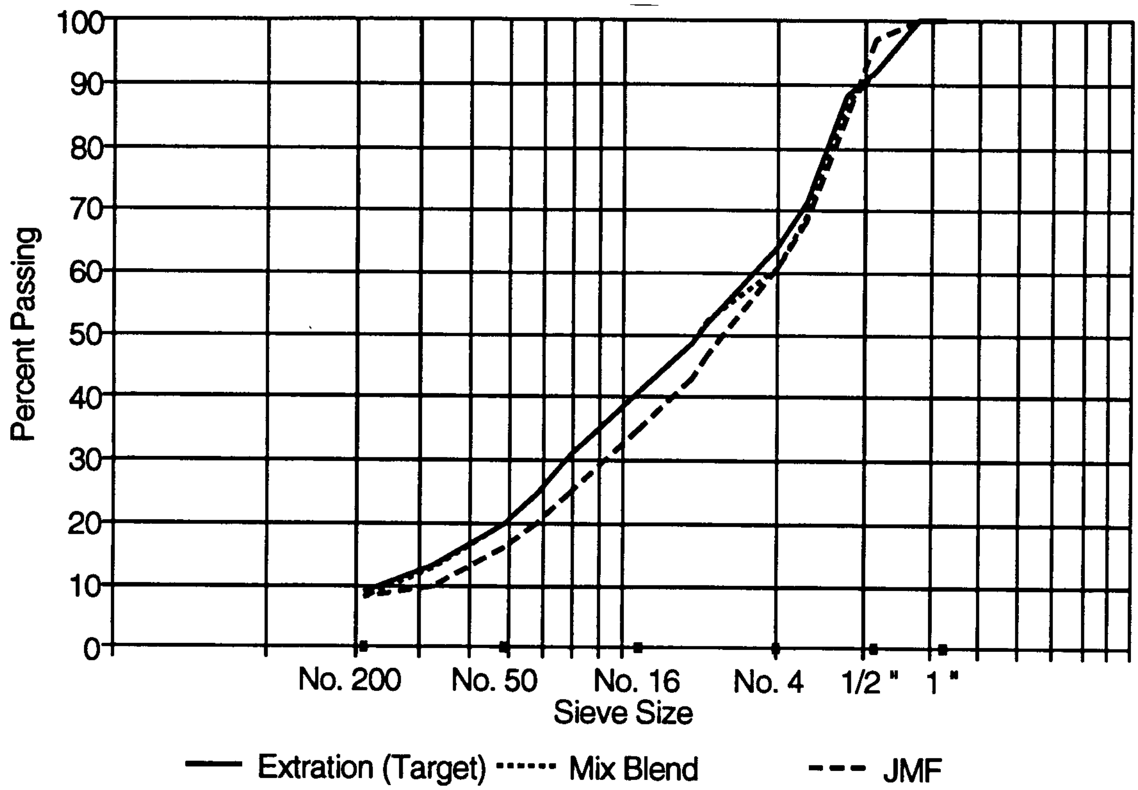

Figure A.3. Aggregate gradation for California, AAMAS Batch (CAB)

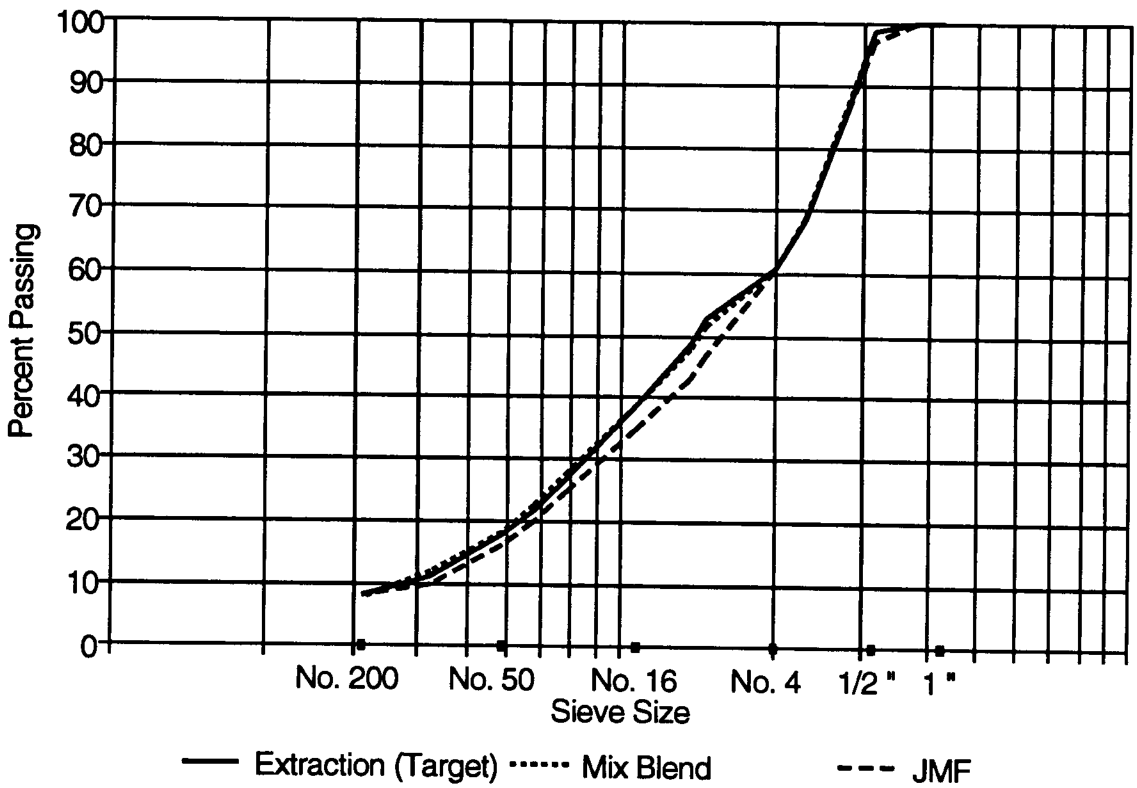

Figure A.4. Aggregate gradation for California, AAMAS Drum (CAD)

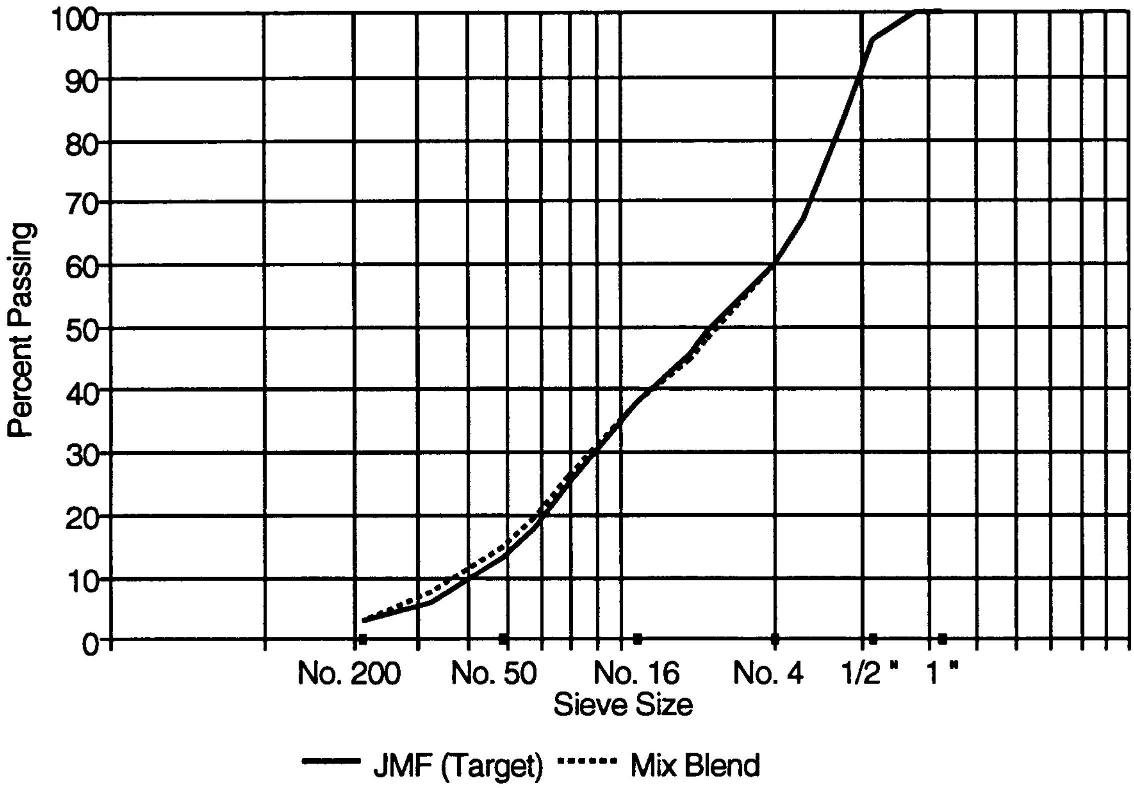

Figure A.5. Aggregate gradation for California, GPS-6b (CAG)

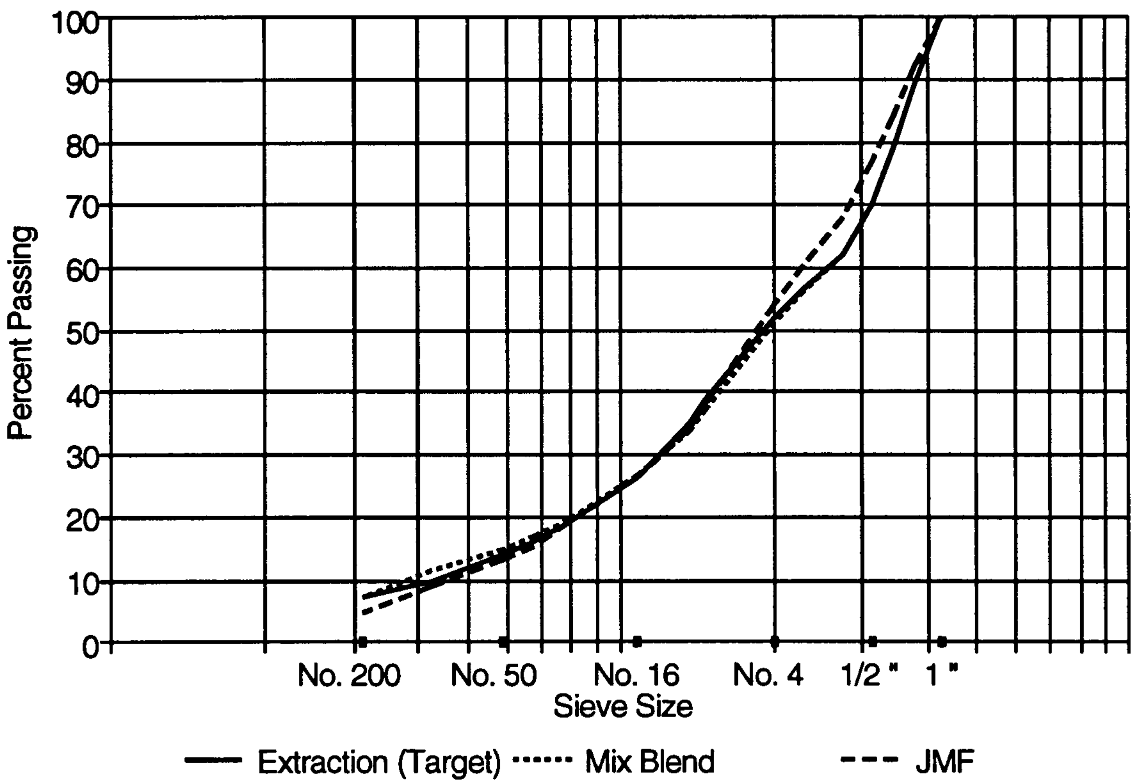

Figure A.6. Aggregate gradation for Georgia, AAMAS (GAA)

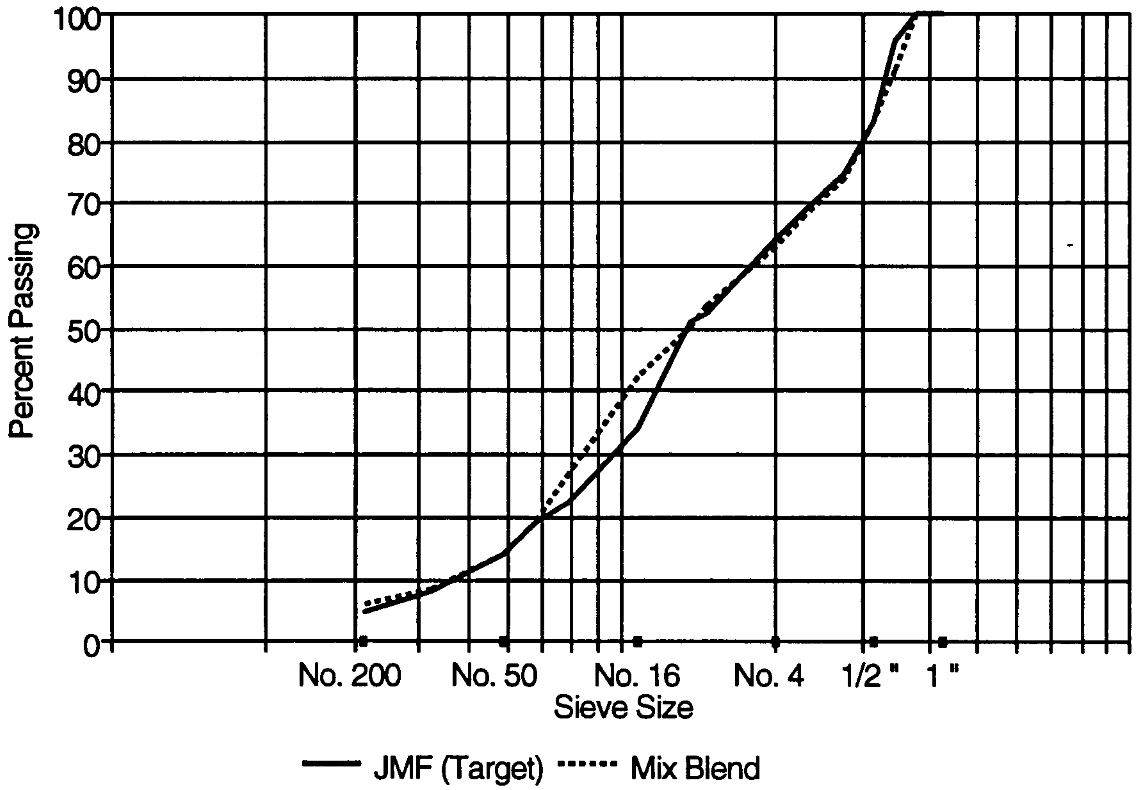

Figure A.7. Aggregate gradation for Minnesota, SPS-5 (MN5)

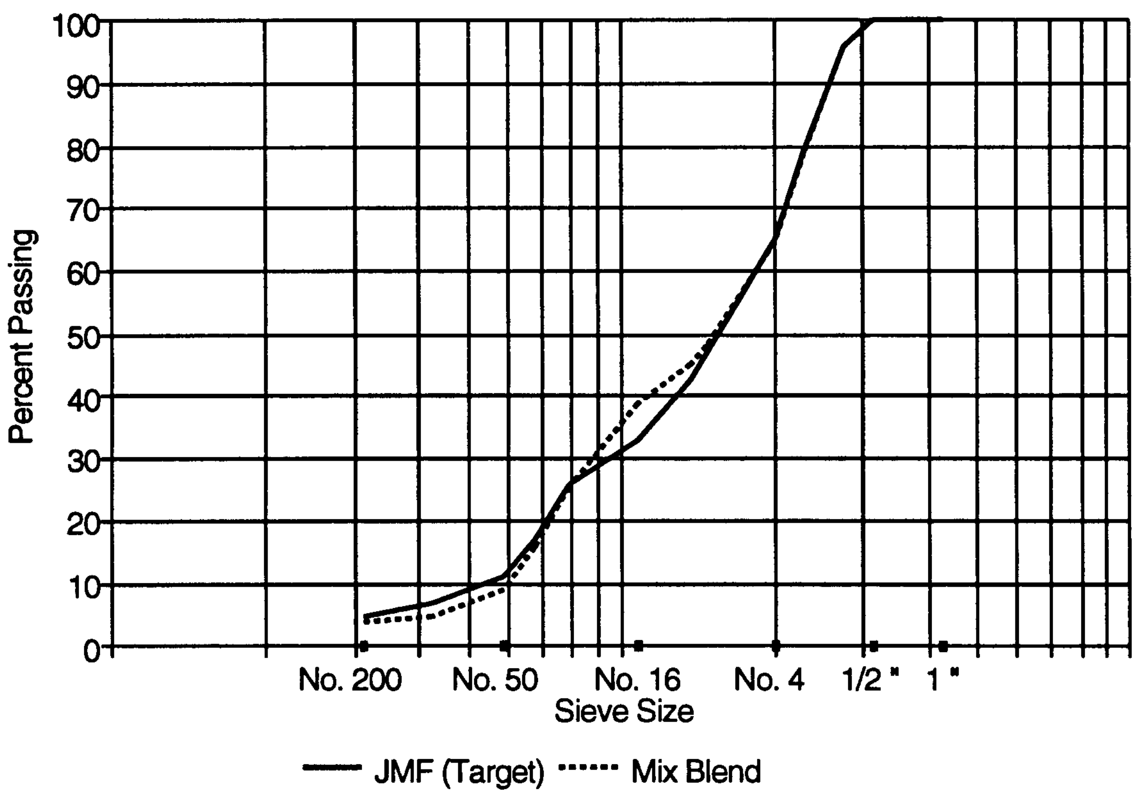

Figure A.8. Aggregate gradation for Mississippi, SPS-5 (MS5)

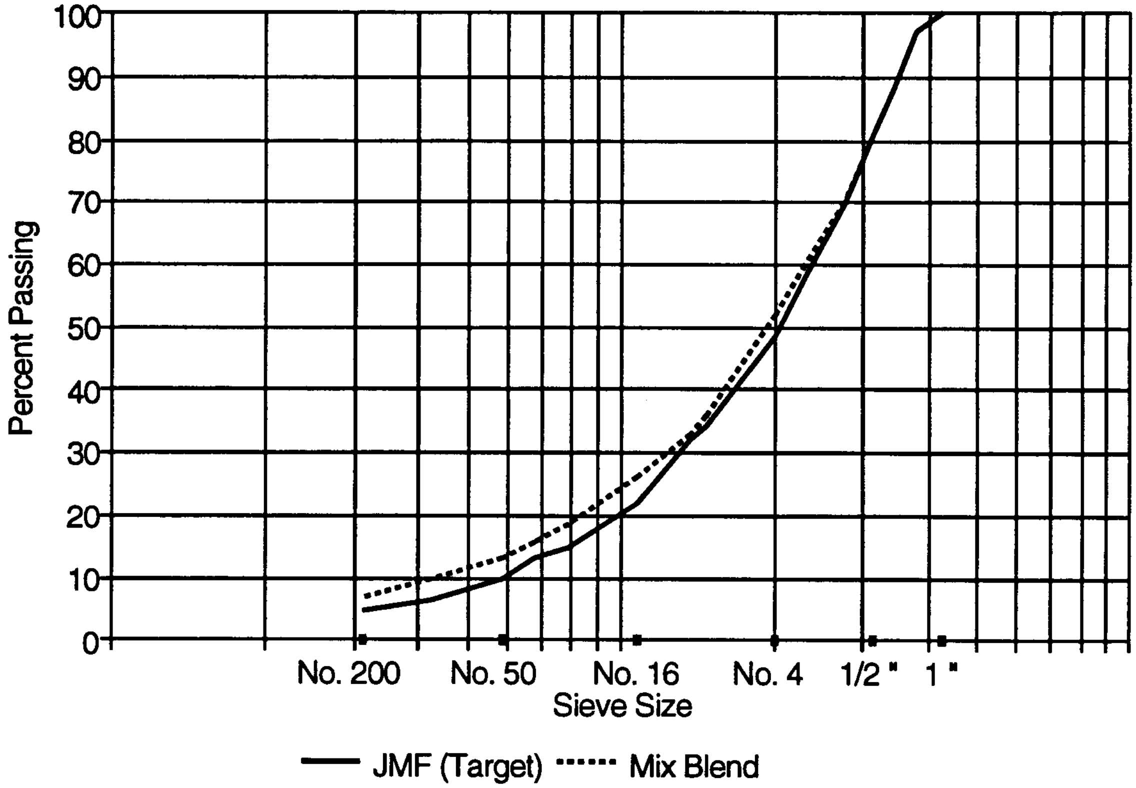

Figure A.9. Aggregate gradation for Rainier, Oregon (OR1)

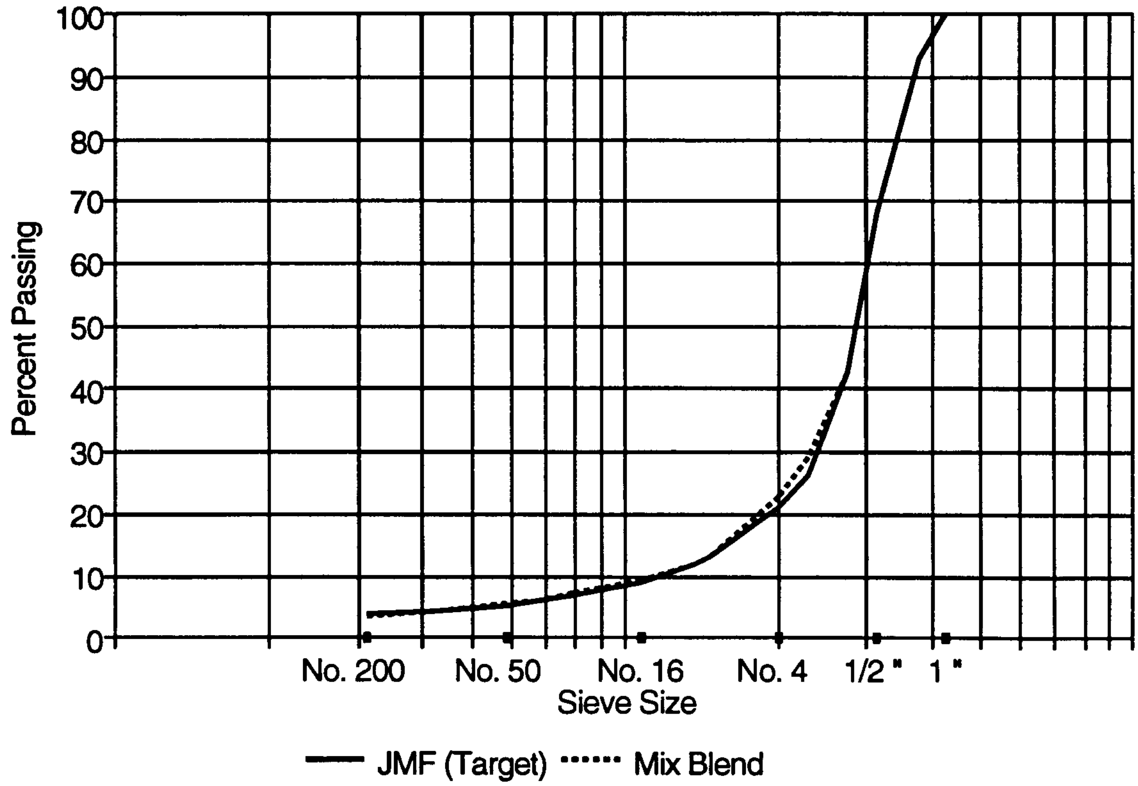

Figure A.10. Aggregate gradation for Bend-Redmond, Oregon (OR2)

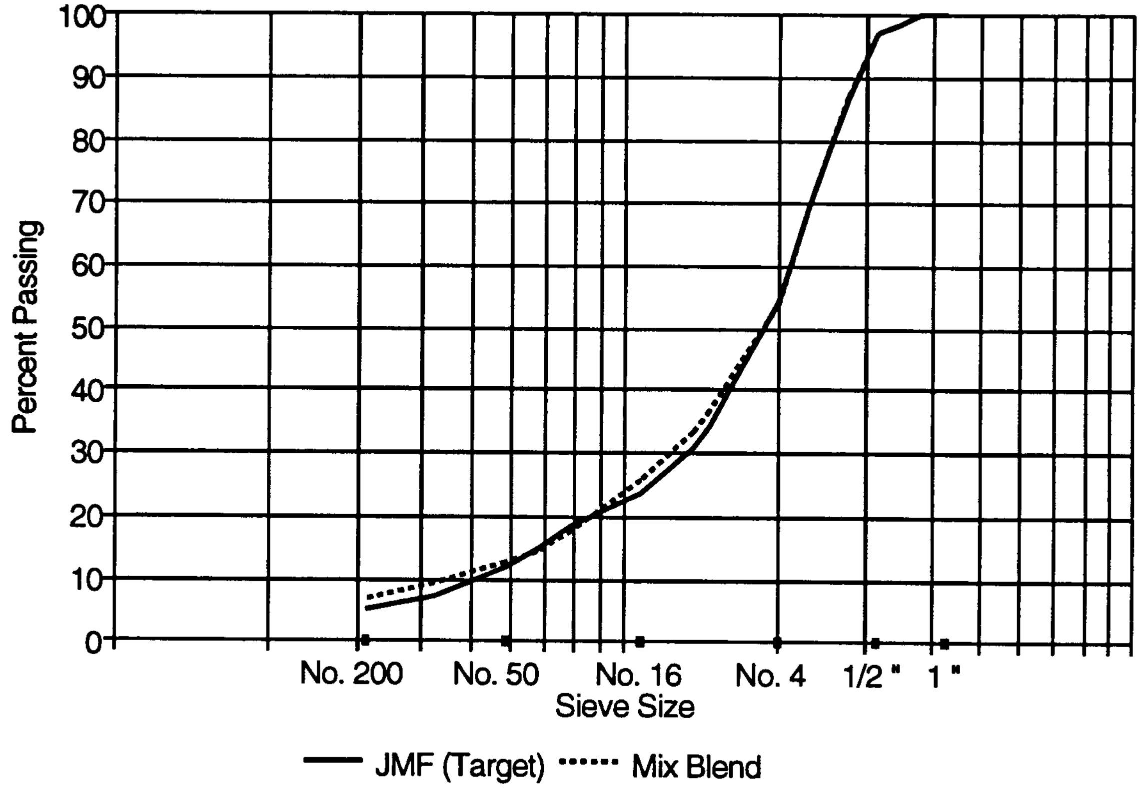

Figure A.11. Aggregate gradation for Mount Baker, Washington (WA1)

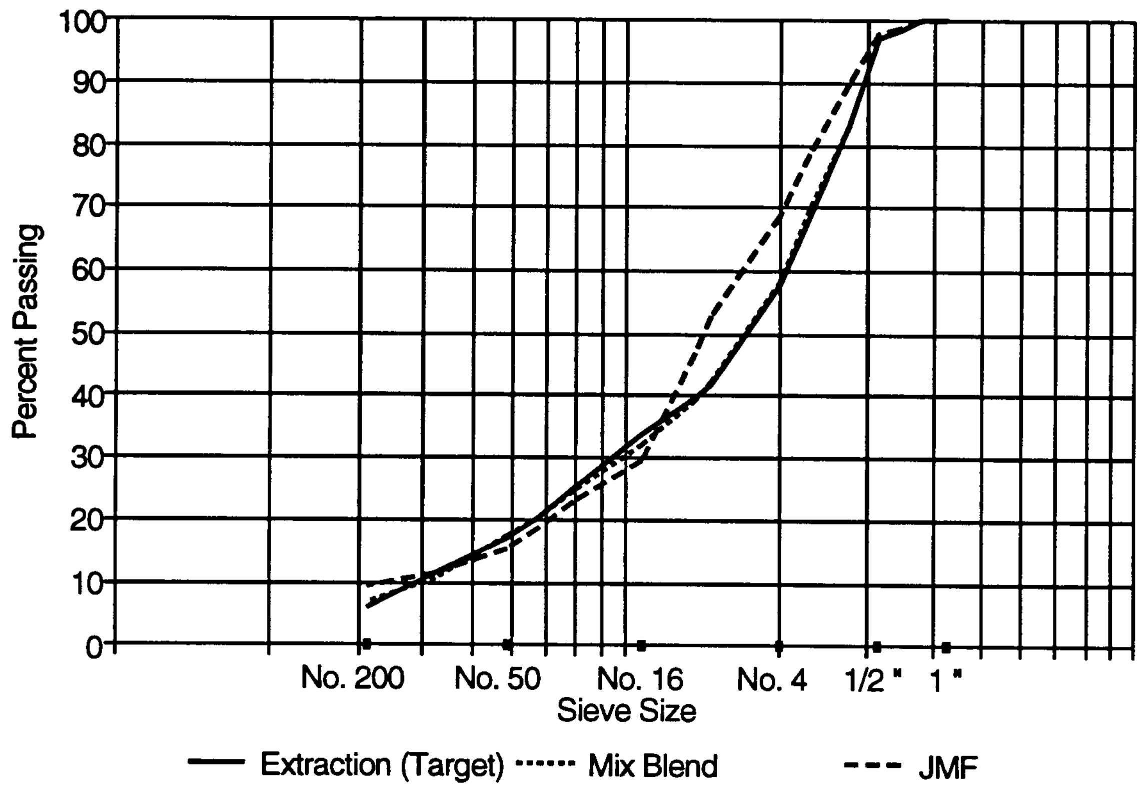

Figure A.12. Aggregate gradation for Wisconsin, AAMAS (WIA)

Appendix B

Standard Practice for

Preparation of Test Specimens of Bituminous Mixtures by Means of Laboratory Kneading Compaction

AASHTO DESIGNATION: T ###-YY
(ASTM DESIGNATION: D ####-YY)

This document is the draft of a test method being developed by researchers at Oregon State University for the Strategic Highway Research Program (SHRP). The information contained herein is considered interim in nature and future revisions are expected. It is also recognized that this document may lack details with respect to the test equipment (schematics, dimensions, etc.); more details will be provided after the test procedure is finalized. This version represents the state of the test procedure as of March 1, 1993.

The test method is in a format similar to the test methods contained in the American Association of State Highway and Transportation Officials' (AASHTO) standard specifications. At the conclusion of SHRP, selected test methods will be submitted to AASHTO for adoption into its standard specifications.

1. SCOPE

1.1 This method describes the mixing and compaction procedures to produce cylindrical specimens (approximately 101.6 mm in height x 101.6 mm in diameter) of bituminous concrete in the laboratory by means of a mechanical kneading compactor as it varies from ASTM D 1561-81a, Preparation of Bituminous Mix Test Specimens by Means of California Kneading Compactor. It also describes the procedure for determining the air void content of the specimens obtained.

2. APPLICABLE DOCUMENTS

2.1 *AASHTO Test Methods:*

T 11-85 Amount of Material Finer than 75-µm Sieve in Aggregate

T 27-84 Sieve Analysis of Fine and Coarse Aggregates

T 246-81 Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus

2.2 *ASTM Test Methods:*

C 117-90	Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
C 136-84a	Sieve Analysis of Fine and Coarse Aggregates
D 1561-81a	Preparation of Bituminous Mix Test Specimens by Means of California Kneading Compactor
D 2041-78	Test Method for Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures
D 2493-91	Standard Viscosity Temperature Chart for Asphalts

3. APPARATUS

3.1 *Miscellaneous Apparatus* - In addition the apparatus required by ASTM D 1561-81a, the following are required:

3.1.1 Digital thermometers with thermocouple probe
3.1.2 Parafilm (manufactured by American National Can Co., Greenwich, CT)

4. MATERIAL PREPARATION

4.1 *Aggregate* - Aggregate to be used for specimen preparation should be prepared in accordance with AASHTO T-11 and T-27. After the aggregate has dried to a constant weight, remove the aggregate from the oven, and cool to room temperature. Then sieve into the separate size fractions necessary for accurately recombining into test mixtures conforming with specified grading requirements.

4.2 *Material quantities* - The appropriate amount of aggregate and asphalt to give a 4 in. in height x 4 in. in diameter specimen at the appropriate air void level. Recombine aggregate according to mix design information for the particular mix being prepared. Aggregate for a single specimen will be stored in a paper bag until time for mixing.

4.3 *Breaking down asphalt cement* - For asphalts supplied in 5 gal. (19 l) epoxy coated containers, it must first be heated to 135°C (275°F) in a forced draft oven. The container should be loosely covered with a metal lid. This first heating is to subdivide the 5 gal. (19 l) sample into smaller containers for subsequent use. After approximately 1.5 h, remove the sample from the oven, and stir with a large spatula or metal rod. The sample should be stirred every half hour to ensure uniform heating.

Typically, a 5 gal. (19 l) sample will require approximately 5 h for the entire heating cycle.

Note 1: Watch for signs of blue smoke from the asphalt. This would indicate overheating. If a noticeable quantity of smoke is observed, then the oven temperature should be reduced by 10° to 15°F.

Place protective paper or newsprint on the floor in a well-ventilated area. Place empty and clean 1 liter containers on the paper in a sequence convenient for pouring the hot asphalt. Different sized containers may also be used. It is important that the containers be properly labelled with self-adhesive labels or a diamond-tipped pencil prior to pouring.

Remove the 5 gal. (19 l) container from the oven and stir the asphalt for approximately 1 minute. Fill all the containers on the floor, taking care that the labels on the containers are not obliterated. After filling, close all containers tightly, and allow to cool to room temperature, then store at a temperature of 10°C (50°F). Closing the containers prior to cooling will produce a vacuum seal.

4.4 *Determination of mixing temperature* - The mixing temperatures can be estimated from a Bitumen Test Data Chart (Figure B.1). The temperature selected should correspond to a viscosity of 170 ± 20 cS (based on the original asphalt properties).

4.5 *Determination of compaction temperature* - The compaction temperatures can be estimated from a Bitumen Test Data Chart (Figure B.1). The temperature selected should correspond to a viscosity of 665 ± 80 cS (based on the original asphalt properties).

5. MIXING

5.1 *Preparation for Mixing* - At least 6 hours prior to mixing, set oven to the mixing temperature as determined in Section 4.4.

5.1.1 Place all mixing equipment and tools in the ovens at least 4 hours prior to mixing. These include:

- Mixing bowls with lids and scrapers
- At least two spatulas and the scraper spoon
- Metal pans

5.1.2 Place the aggregate in the oven at least four hours prior to mixing.

5.1.3 Place a sufficient number of 1 liter cans of asphalt in the oven at least 2 hours prior to mixing. The lid to the can should remain loosely in place. The asphalt must be periodically stirred throughout the heating process to ensure uniform heating as well as to prevent burning. Also, asphalt that has been at its equiviscous temperature for 3.5 hours or more or asphalt that is burning should not be used and should be discarded.

Note 2: This constitutes the second heating of the asphalt. Any asphalts that have been heated more than twice must be discarded.

5.1.4 Set a forced draft oven to 135° C. This is an oven other than the one set at the mixing temperature.

5.2 *Mixing* - Mixing will proceed as specified in ASTM D 1561 with the following amendments.

5.2.1 After one (1) minute of mixing, stop the mixer, remove the bowl, remove its lid, and scrape any unmixed asphalt off the scraper and spade it into the mix using a spatula.

5.2.2 Scrape any material off the spatula (into the bowl), rotate the scraper by hand to ensure that it is in the bottom of the bowl, and replace its lid.

5.2.3 Place the bowl in the mixer and resume mixing for three (3) more minutes.

5.2.4 Remove the bowl from the mixer and transfer it to the workbench. Measure and record the temperature of the mix.

5.2.5 Remove a metal pan from the oven and place it next to the bowl.

5.2.6 Remove the lid of the bowl and scrape all material from the tines of the lid into the metal pan using a spatula. Repeat this for the scraper.

5.2.7 Dump the remaining mix from the bowl into the cake pan and scrape out all remaining material from the bowl using the scraper spoon.

5.2.8 Shake the cake pan back and forth to ensure uniform depth of the mix, label it accordingly. The mixture shall cover an area of the pan such that the mix is distributed over an area of 80 in.^{2} per kg of mixture. The mixture shall be evenly distributed over the entire area.

5.2.9 Repeat the above steps until all mixes have been prepared.

5.3 *Short Term Aging* - Place the pans of loose mixture in an oven set at a temperature of 135° ± 1°C (275°F) for 4 h ± 1 min. Stir the mixture once an hour. The mixture shall remain distributed over an area of approximately 80 in.^{2} per kg of mixture after each stirring.

6. COMPACTION

6.1 *Preparation for Compaction*

6.1.1 At least 4 hours prior to compacting, set the ovens to the compaction temperature as determined in Section 4.5.

6.1.2 Place all compaction equipment into oven set at the compaction temperature at least 4 hours prior to compaction.

6.1.3 Place loose mixtures into ovens set to compaction temperature 2 hours prior to compaction.

6.2 *Compaction* - Compaction will proceed in accordance with ASTM D 1561-81a.

7. EXTRUSION

7.1 After the specimens have cooled to room temperature place the mold with specimen on a plunger such that the specimen is oriented with the minimum distance that the sample must be pushed through the mold facing upward.

7.2 Place the extrusion collar on top of the mold and center the arrangement in the extrusion device.

7.3. Load the arrangement until the specimen is pushed out of the mold and into the extrusion collar.

7.4 Unload the apparatus until there is enough room for the next mold-plunger arrangement.

7.5 Disassemble the arrangement, remove and label the specimen, and repeat steps 1 through 5 until all specimens have been extruded.

8. CALCULATE THE AIR VOID CONTENT

8.1 Weigh the dry, unwrapped, 25° C (77° F) temperature stabilized specimen and record this as *Mass in Air*, A.

8.2 Wrap the specimen in parafilm so that it is completely watertight with no air bubbles between the parafilm and the specimen. Use the minimum amount of parafilm necessary. Weigh the specimen in air and record this as *Mass in Air with Parafilm*, B.

8.3 Weigh the wrapped specimen suspended in water at 25°C (77°F), taking the reading as soon as the balance stabilizes. Record this as the ***Mass in Water with Parafilm***, C.

8.4 Determine the specific gravity of parafilm at 25°C (77°F) or assume a value of 0.9. Record this as D.

8.5 Calculate the bulk specific gravity of the specimen as follows:

$$G_{mb} = \left[\frac{A}{B - C - \left(\frac{B-A}{D}\right)}\right] \qquad (1)$$

where:

A	=	Mass of dry uncoated specimen in air, g
B	=	Mass of parafilm coated specimen in air, g
C	=	Mass of parafilm coated specimen in water, g
D	=	Specific gravity of parafilm at 25°C (77°F)

8.6 Determine the theoretical maximum specific gravity, G_{mm}, in accordance with ASTM D 2041.

8.7 Calculate the air void content as follows:

$$Air\ Voids = \left[1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right] * 100\% \qquad (2)$$

9. REPORT

9.1 The report shall include the following information:

9.1.1 *Bituminous Mixture Description* - bitumen type, bitumen content, aggregate type, aggregate gradation, and air void percentage.
9.1.2 Mix and compaction temperatures, °C.
9.1.3 Mass of specimen in air, g (A)
9.1.4 Mass of specimen in air with parafilm, g (B)
9.1.5 Mass of specimen in water with parafilm, g (C)
9.1.6 Specific gravity of parafilm (D)
9.1.7 Bulk specific gravity, G_{mb}
9.1.8 Maximum Specific gravity, G_{mm}
9.1.9 Air void content of specimen, %
9.1.10 Height of Specimen, in.
9.1.11 Time of mixing, min

9.1.12 Time of compaction, min

9. PRECISION

9.1 A precision statement has not yet been developed for this test method.

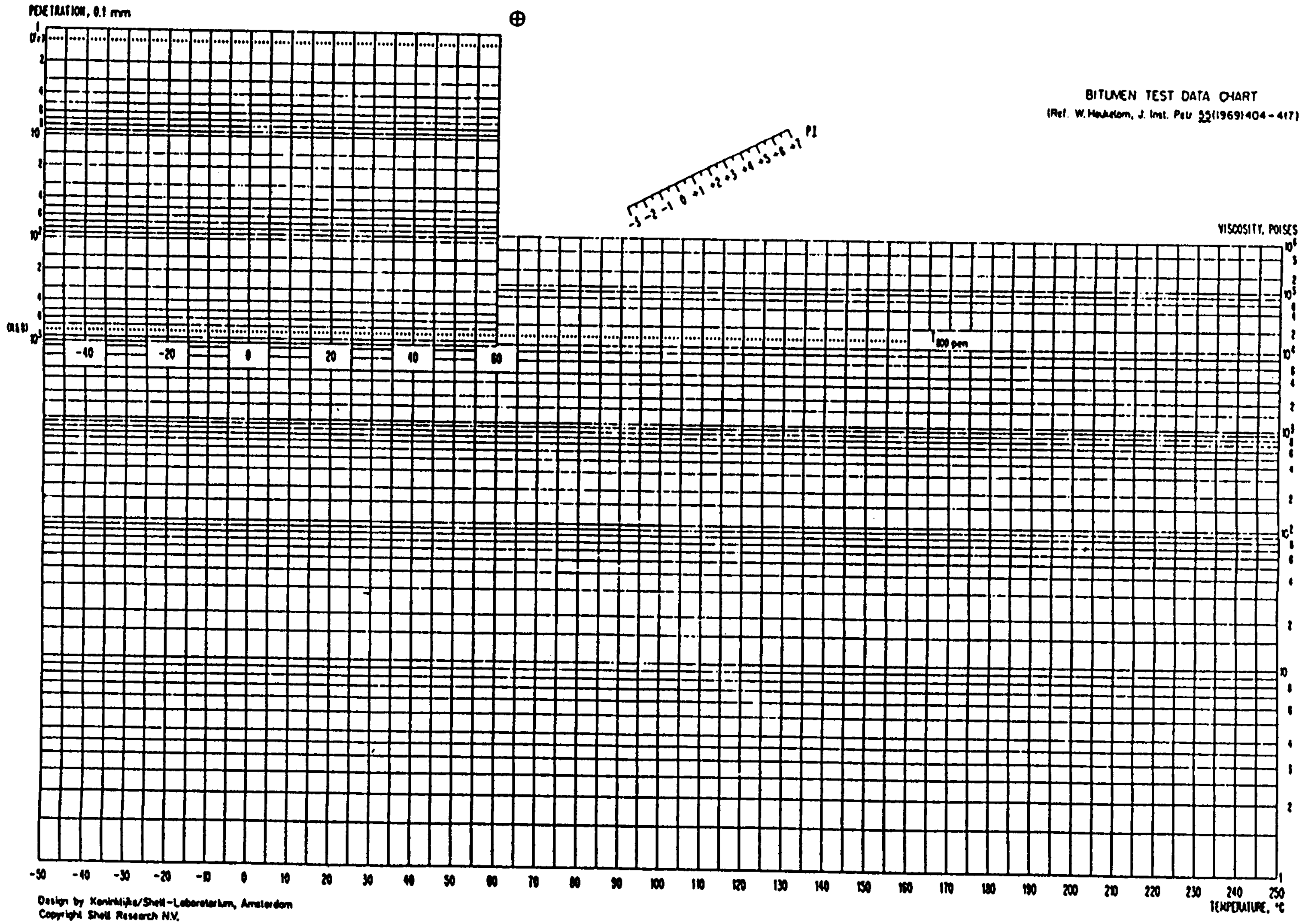

Figure B.1. Bitumen test data chart

Appendix C

Standard Practice for

Preparation of Test Specimens of Bituminous Mixtures by Means of Rolling Wheel Compaction

AASHTO DESIGNATION: T ###-YY
(ASTM DESIGNATION: D ####-YY)

This document is the draft of a test method being developed by researchers at Oregon State University for the Strategic Highway Research Program (SHRP). The information contained herein is considered interim in nature and future revisions are expected. It is also recognized that this document may lack details with respect to the test equipment (schematics, dimensions, etc.); more details will be provided after the test procedure is finalized. This version represents the state of the test procedure as of March 1, 1993.

The test method is in a format similar to the test methods contained in the American Association of State Highway and Transportation Officials' (AASHTO) standard specifications. At the conclusion of SHRP, selected test methods will be submitted to AASHTO for adoption into its standard specifications.

1. SCOPE

1.1 This method describes the mixing and compaction procedures to produce large slab specimens (approximately 101.6 mm H x 762 mm W x 762 mm L) of bituminous concrete in the laboratory by means of a mechanical rolling wheel compactor. It also describes the procedure for determining the air void content of the specimens obtained.

2. APPLICABLE DOCUMENTS

2.1 *AASHTO Test Methods:*

T 11-85	Amount of Material Finer than 75-µm Sieve in Aggregate
T 27-84	Sieve Analysis of Fine and Coarse Aggregates
T 246-81	Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus

2.2 *ASTM Test Methods:*

C 117-90	Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
C 136-84a	Sieve Analysis of Fine and Coarse Aggregates
D 1561-81a	Preparation of Bituminous Mix Test Specimens by Means of California Kneading Compactor
D 2041-78	Test Method for Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures
D 2493-91	Standard Viscosity Temperature Chart for Asphalts

3. APPARATUS

3.1 *Rolling Wheel Compactor* - A mechanical, self-propelled rolling wheel compactor with forward/reverse control such as that shown in Figure C.1 for compaction of asphalt concrete mixtures. It must weigh a minimum of 1,000 kg and possess the capability of increasing the weight to 1,500 kg. The load applied must be in the static mode.

3.2 *Mold* - A mold to hold the bituminous mix as shown in Figure C.2. The mold is composed of one lift 101.6 mm (4 in.) thick.

3.3 *Ovens* - Forced-draft electric ovens of sufficient size, capable of maintaining a uniform temperature between 100 ± 3°C to 200 ± 3°C (212 ± 37.4°F to 392 ± 37.4°F). It is preferable to have ovens with a capacity of 28 to 42 dm^3 (1.0 to 1.5 ft^3) for asphalts and 700 to 850 dm^3 (25 to 30 ft^3)for aggregates.

3.4 *Specimen Mixing Apparatus* - Suitable mechanized mixing equipment is required for mixing the aggregate and the bituminous material. It must be capable of maintaining the bituminous mixture at the selected mixing temperature, and allow the aggregate to be uniformly and completely coated with asphalt during the mixing period (approximately 4 minutes). It is preferable to have a mixer with a capacity of 70 to 85 dm^3 (2.5 to 3 ft^3). A conventional concrete mixer fitted with infrared propane heaters has been found to be suitable.

3.5 *Coring and Saw Cutting Equipment* - Mechanized coring and saw cutting equipment capable of coring 101.6 mm to 203.2 mm (4 to 8 in.) diameter specimens and beams of different sizes from an asphalt concrete slab. It is preferable to dry-cut the cores and beams.

3.6 *Balance* - Two balances are required; one with a capacity of 5 kg or more and sensitive to 1.0 g or less, and the other with a capacity between 45 to 120 kg, and sensitive to 0.5 kg or less.

3.7 *Miscellaneous Apparatus*:

3.7.1 Digital thermometers with thermocouple probe
3.7.2 Spatulas, trowels, scoops, spades, rakes
3.7.3 Heat resistant gloves
3.7.4 Metal pans
3.7.5 Socket wrench, sockets, screw drivers, crescent wrench
3.7.6 Lubricant for mold (eg. PAM cooking oil or equivalent)
3.7.7 Tape measure
3.7.8 Parafilm (manufactured by American National Can Co., Greenwich, CT)

4. MATERIAL PREPARATION

4.1 *Aggregate* - Aggregate to be used for specimen preparation should be prepared in accordance with AASHTO T-11 and T-27. After the aggregate has dried to a constant weight, remove the aggregate from the oven, and cool to room temperature. Then sieve into the separate size fractions necessary for accurately recombining into test mixtures conforming with specified grading requirements.

4.2 *Determine material quantities* - Calculate the quantity of material required to achieve the desired air void content. These calculations are shown in Section 7.

4.3 *Mixing Temperature* - Set the oven to the mixing temperature. For mixes employing unmodified asphalt cements, the temperature of the aggregate and the asphalt at the time mixing begins shall be in accordance with the temperatures specified in AASHTO T 246-82 or ASTM D 1561-81a. Alternatively, for either an unmodified or modified asphalt, the mixing temperatures can be estimated from a Bitumen Test Data Chart (Figure C.3). The temperature selected should correspond to a viscosity of 170 ± 20 cS (based on the original asphalt properties). The procedure utilizing the BTDC is the recommended procedure.

4.4 *Heating the asphalt cement* - For asphalts supplied in 5 gal. (19 l) epoxy coated containers, it must first be heated to 135°C (275°F) in a forced draft oven. The container should be loosely covered with a metal lid. This first heating is to subdivide the 5 gal. (19 l) sample into smaller containers for subsequent use. After approximately 1.5 h, remove the sample from the oven, and stir with a large spatula or metal rod. The sample should be stirred every half hour to ensure uniform heating. Typically, a 5 gal. (19 l) sample will require approximately 5 h for the entire heating cycle.

Note 1: Watch for signs of blue smoke from the asphalt. This would indicate overheating. If a noticeable quantity of smoke is observed, then the oven temperature should be reduced by 10° to 15°F.

Place paper or newsprint on the floor in a well-ventilated area. Place empty and clean 1 liter containers on the paper in a sequence convenient for pouring the hot asphalt. Different sized containers may also be used. It is important that the containers be properly labelled with self-adhesive labels or a diamond-tipped pencil prior to pouring.

Remove the 5 gal. (19 l) container from the oven and stir the asphalt for approximately 1 minute. Fill all the containers on the floor, taking care that the labels on the containers are not obliterated. After filling, close all containers tightly, and allow to cool to room temperature, then store at a temperature of 10°C (50°F). Closing the containers prior to cooling will produce a vacuum seal.

4.5 Prior to mixing, set the oven to the mixing temperature as determined in Section 4.3. Place a sufficient number of 1 liter cans (with a total weight greater than that calculated in Section 7.8) of asphalt in the oven at least 2 hours prior to mixing. Monitor the temperature of the asphalt periodically. When the temperature approaches the mixing temperature, transfer the asphalt into a large pot (e.g. a 12 qt. stock pot) and at the same time weigh the amount of asphalt added to the pot. Transfer enough asphalt to equal the amount calculated in Section 7.8 plus an extra 80 g (to account for the quantity retained in the pot after asphalt has been added to the aggregate). Then place the pot in the oven and continue to monitor the temperature periodically.

Note 2: This constitutes the second heating of the asphalt. Any asphalts that have been heated more than twice must be discarded.

4.6 *Mixing* - Preheat the mixer approximately 1 hour prior to mixing. Place coarse aggregate in the mixer followed by the fine aggregate and then the asphalt. Mix for approximately 4 minutes to ensure uniform coating of the aggregate.

4.7 *Short Term Aging* - After mixing, remove the mixture from the mixer and place it in metal pans. Place the mixture in an oven set at a temperature of 135° ± 1°C (275°F) for 4 h ± 1 min. Stir the mixture once an hour.

5. COMPACTION

5.1 Assemble the mold as shown in the schematic illustrated in Figure C.2. Preheat the mold with a "tent" equipped with infrared heat lamps (see Figure C.4).

5.2 Check the oil and fuel levels in the rolling wheel compactor and refill if necessary. Start the compactor and allow it to warm up. Spray a mild soapy solution on the rollers.

5.3 Apply sparingly a light oil (e.g. PAM cooking oil) to the base and sides of the mold.

5.4 Remove a pan of mixture from the oven and place it in the center of the mold. Level the mixture using a rake while at the same time avoiding any segregation of the mixture (i.e. avoid any tumbling of the coarse aggregate). Repeat this process until the mold is filled with the required quantity of material to achieve the target air void content. This should be all of the pre-weighed material. Tamp the mixture to achieve as level a surface as possible.

5.5 Monitor the temperature of the mixture at the surface, at mid-depth, and at the bottom in various locations. Allow the mixture to cool until the coolest temperature corresponds to the pre-established compaction temperature.

Note 3: The field compaction temperature should be used. As general guide, the compaction temperature to be used for most typical asphalt cements (AC-5 to AC-30) should correspond to an equiviscous temperature of 280 ± 30 cS (based on original binder properties) as described in Section 4.3. If necessary, the mixture should be placed in an oven until it reaches a uniform temperature.

Note 4: Lower compaction temperatures in the range between 240° to 280°F (115°C to 138°C) may be necessary depending on the compactibility of the mixtures used under the rolling wheel compactor.

5.6 Compact the mixture until the rollers bear down on the compaction stops (steel channels with depths equal to slab thickness inserted in the mold as shown in Figure C.2). When compacting, each pass of the roller must extend from the ramp to the platform in a continuous motion, with no stops on the mixture. After the first few passes, it may be necessary to scrape bituminous mixture off the rollers and reshape the mixture.

5.7 When compaction is complete, let the slab cool overnight (typically 15 to 16 hours) before removing the mold. If the slab is still warm to the touch, do not remove the mold. Do *not* place any weights on top of the slab.

5.8 After the slab is completely cooled, remove the slab from the mold together with the removable base of the mold (constructed of particle board) before placing on a pallet jack.

5.9 The slab should then be dry cored and sawn into the desired specimen shapes as soon as possible. Note that the specimens should not be taken from the outside edges (2 to 2.5 in (5 to 6.3 cm)) of the slab. This is approximately 2 to 2.5 times the nominal top size of the aggregate used. Store approximately 3 kg of the wasted mix for the determination of the theoretical maximum specific gravity as described in Section 6.

6. CALCULATE THE AIR VOID CONTENT

6.1 Weigh the dry, unwrapped, room temperature stabilized specimen and record this as *Mass in Air*, A.

6.2 Wrap the specimen in parafilm so that it is completely watertight with no air bubbles between the parafilm and the specimen. Use the minimum amount of parafilm necessary. Weigh the specimen in air and record this as *Mass in Air with Parafilm*, B.

6.3 Weigh the wrapped specimen suspended in water at 25°C (77°F), taking the reading as soon as the balance stabilizes. Record this as the *Mass in Water with Parafilm*, C.

6.4 Determine the specific gravity of parafilm at 25°C (77°F) or assume a value of 0.9. Record this as D.

6.5 Calculate the bulk specific gravity of the specimen as follows:

$$G_{mb} = \left[\frac{A}{B - C - \left(\frac{B-A}{D}\right)}\right] \qquad (3)$$

where:

A	=	Mass of dry uncoated specimen in air, g
B	=	Mass of parafilm coated specimen in air, g
C	=	Mass of parafilm coated specimen in water, g
D	=	Specific gravity of parafilm at 25°C (77°F)

6.6 Determine the theoretical maximum specific gravity, G_{mm}, in accordance with ASTM D 2041.

6.7 Calculate the air void content as follows:

$$Air\ Voids = \left[1 - \left(\frac{G_{mb}}{G_{mm}}\right)\right] * 100\% \qquad (4)$$

7. CALCULATE THE QUANTITY OF BITUMINOUS MIX REQUIRED

7.1 Measure the dimensions (height, length and width) of the compaction mold that will contain the compacted slab. Record this as H, L and W in dm.

7.2 Determine the volume (V) of the mold in units of dm^3.

7.3 Determine the maximum specific gravity of the bituminous mix at the desired asphalt content in accordance with ASTM D 2041. Record this as G_{mm}.

7.4 Determine target bulk specific gravity for compacted slab based on the target air voids content:

$$G_{mb} = G_{mm}\left[1 - \frac{\%AV}{100}\right] \qquad (5)$$

where:

G_{mb} = target bulk specific gravity of the compacted slab
$\%AV$ = target air voids of the compacted slab

7.5 Determine the unit mass (density) of the compacted slab:

$$\rho = G_{mb}\,\rho_w \qquad (6)$$

where:

ρ = unit mass of the compacted slab, kg/m^3
ρ_w = unit mass of water, kg/m^3

7.6 Determine the mass, M (kg) of the compacted slab:

$M = \rho\ V$

7.7 Determine the mass of the aggregate required for compaction as shown below in Equations 5 and 6. Equation 5 uses the asphalt content based on the dry mass of the aggregate, whereas Equation 6 uses the asphalt content based on total mass of the mixture.

$$M_{aggr} = \left[\frac{M}{\left(1+\frac{\%AC}{100}\right)}\right] \tag{7}$$

$$M_{aggr} = M\left[1-\frac{\%AC}{100}\right] \tag{8}$$

where:

M_{aggr} = total mass of aggregate, kg
%AC = asphalt content

7.8 Determine the mass of asphalt binder required for compaction as shown in Equations 7 and 8 below. Equation 7 uses the asphalt content based on the dry mass of the aggregate, whereas Equation 8 uses the asphalt content based on total mass of the mixture.

$$M_{AC} = M_{aggr}\left[\frac{\%AC}{100}\right] \tag{9}$$

$$M_{AC} = M\left[\frac{\%AC}{100}\right] \tag{10}$$

where:

M_{AC} = mass of asphalt binder, kg

8. REPORT

8.1 The report shall include the following information:

8.1.1 *Bituminous Mixture Description* - bitumen type, bitumen content, aggregate type, aggregate gradation, and air void percentage.
8.1.2 Mix and compaction temperatures, °C.
8.1.3 Mass of specimen in air, g (A)
8.1.4 Mass of specimen in air with parafilm, g (B)
8.1.5 Mass of specimen in water with parafilm, g (C)
8.1.6 Specific gravity of parafilm (D)

8.1.7 Bulk specific gravity, G_{mb}
8.1.8 Maximum Specific gravity, G_{mm}
8.1.9 Air void content of specimen, %
8.1.10 Dimensions of mold, dm
8.1.11 Volume of mold, dm^3
8.1.12 Unit mass of compacted slab, kg/dm^3
8.1.13 Mass of mix required for compaction, kg
8.1.14 Mass of aggregate required for compaction, M_{aggr} (kg)
8.1.15 Weight of asphalt required for compaction, M_{AC} (kg)
8.1.16 Time of mixing, min
8.1.17 Time of compaction, min

9. PRECISION

9.1 A precision statement has not yet been developed for this test method.

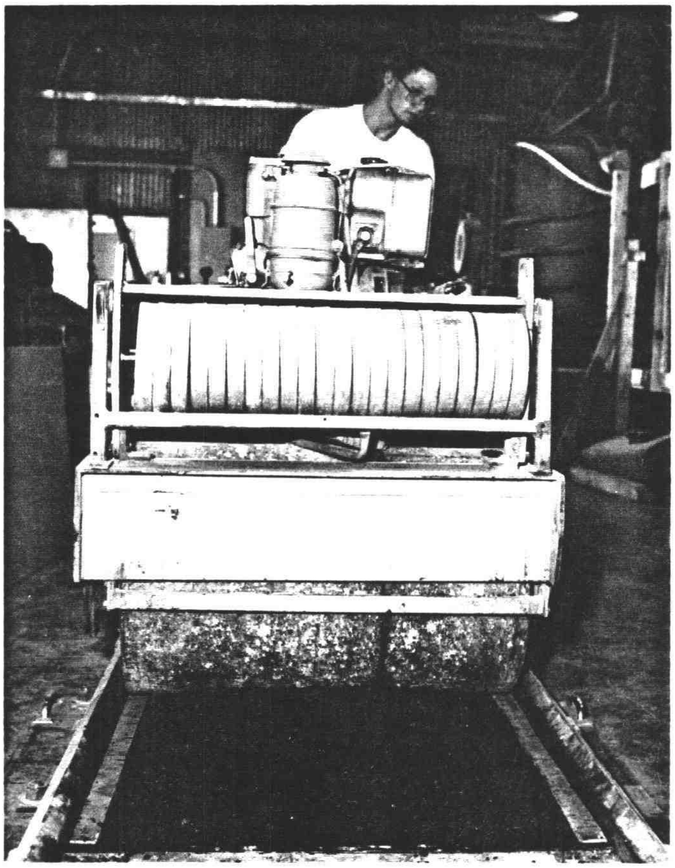

Figure C.1. Rolling wheel compactor

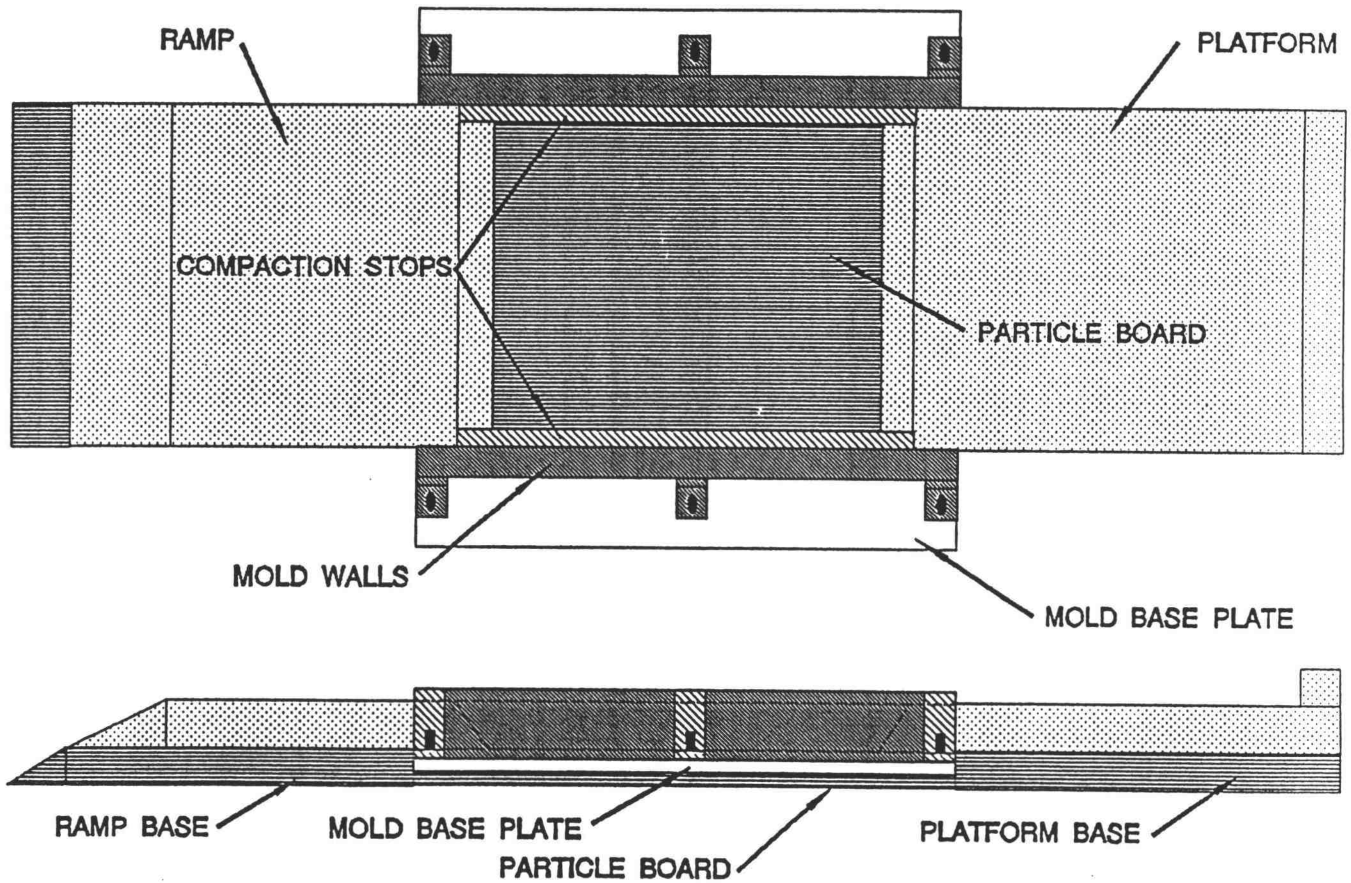

Figure C.2. Schematic of mold for slab

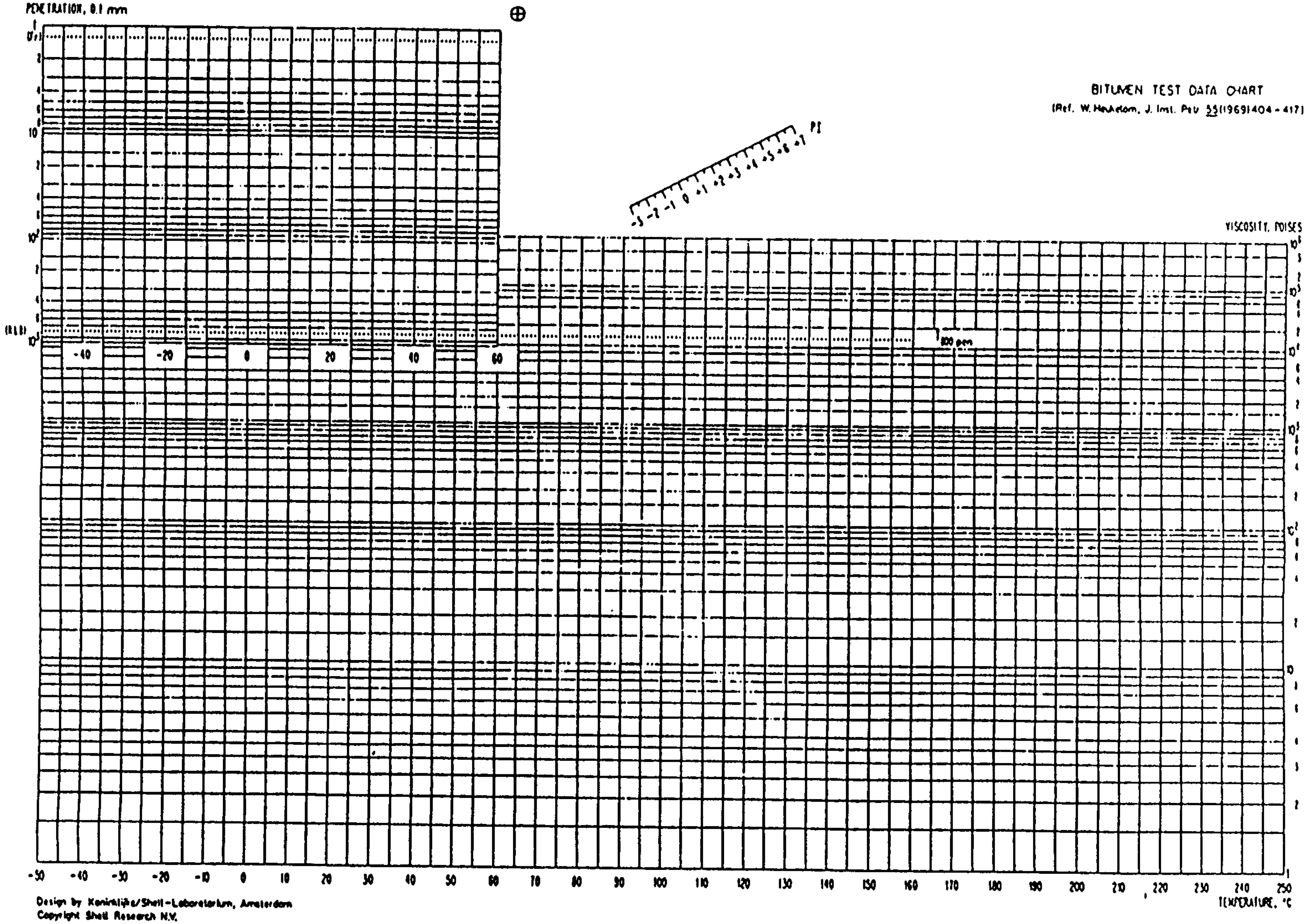

Figure C.3. Bitumen test data chart

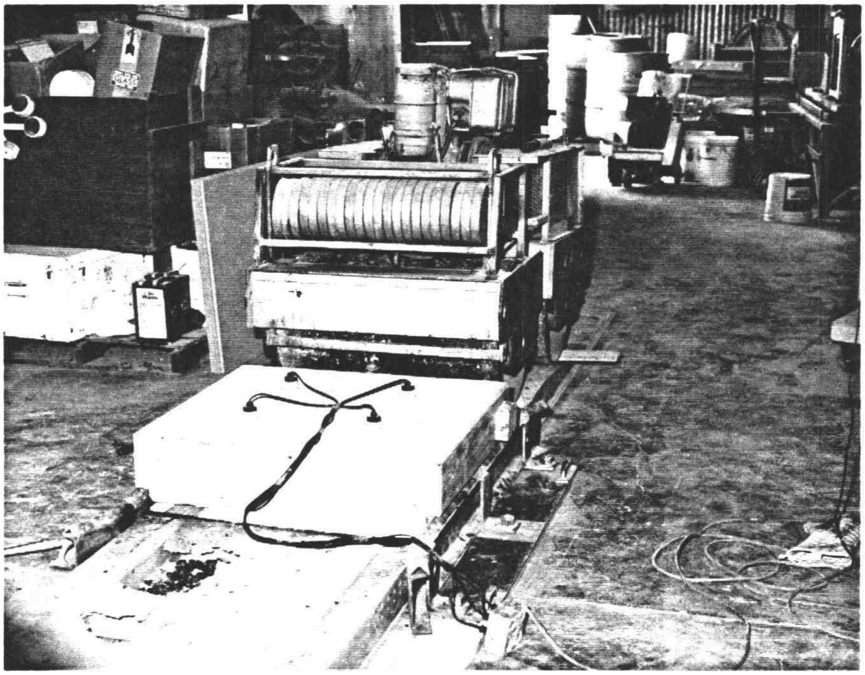

Figure C.4. Preheating the mold

Appendix D

Standard Method of Test for

Determining the Water Sensitivity Characteristics of Compacted Asphalt Concrete Mixtures Subjected to Hot and Cold Climatic Conditions

AASHTO DESIGNATION: T ###-YY
(ASTM DESIGNATION: D ####-YY)

This document is the draft of a test method being developed by researchers at Oregon State University for the Strategic Highway Research Program (SHRP). The information contained herein is considered interim in nature and future revisions are expected. It is also recognized that this document may lack details with respect to the test equipment (schematics, dimensions, etc.); more details will be provided after the test procedure is finalized. This version represents the state of the test procedure as of ***March 1, 1993****.*

The test method is in a format similar to the test methods contained in the American Association of State Highway and Transportation Officials' (AASHTO) standard specifications. At the conclusion of SHRP, selected test methods will be submitted to AASHTO for adoption into its standard specifications.

1. SCOPE

1.1 This method determines the water sensitivity or stripping characteristics of compacted asphalt concrete mixtures under warm and cold climatic conditions.

1.2 *This standard may involve hazardous materials, operations and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

1.3 The values stated in SI units are to be regarded as the standard. The values in parentheses are for information only.

2. REFERENCED DOCUMENTS

2.1 *AASHTO Documents:*

M ###	Specification for Performance Graded Asphalt Binders
R 11	Practice for Indicating Which Places of Figures are to be Considered Significant in Specifying Limiting Values
T 2	Method for Sampling Aggregates
T 40	Method for Sampling Bituminous Materials
T 27	Method for Sieve Analysis of Fine and Coarse Aggregates
T 164	Method for Quantitative Extraction of Bitumen from Paving Mixtures
T 167	Method for Compressive Strength of Bituminous Mixtures
T 168	Method of Sampling Bituminous Paving Mixtures
T 247	Method for Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
T ###	Practice for Preparation of Asphalt Concrete Specimens by Means of the Rolling Wheel Compactor
T ###	Practice for Short Term Aging of Asphalt Concrete Mixtures

2.2 *ASTM Documents:*

D 8	Standard Definitions of Terms Relating to Materials for Roads and Pavements
D 3549	Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens

3. TERMINOLOGY

3.1 Definitions for many terms common to asphalt are found in the following documents:

3.1.1 Standard Definitions D 8
3.1.2 Performance Graded Asphalt Binder M ###

4. SUMMARY OF PRACTICE

4.1 Compacted asphalt concrete test specimens are subjected to a water and temperature conditioning process. The water sensitivity characteristics of the compacted mixtures are determined based upon measurements of percent stripping, the ECS modulus, and the coefficients of permeability for air and water flow.

5. SIGNIFICANCE AND USE

5.1 The measured water sensitivity characteristics may be used to evaluate or characterize asphalt concrete mixtures.

5.2 The water sensitivity characteristics of asphalt concrete mixtures can be used to determine its suitability for use as a highway paving material. This information may also be used to compare and select various asphalt binders, asphalt modifiers, asphalt concrete mixtures, asphalt concrete additives and asphalt concrete aggregates.

6. APPARATUS

6.1 *Environmental Conditioning System (ECS)* - Any closed-loop computer controlled test system which meets the minimum requirements outlined in Table D.1. The ECS must be capable of increasing the temperature within an asphalt concrete specimen to 100°C and decreasing it to -20°C within 2 hours. It must be capable of pulling air and distilled water through a specimen at specified vacuum levels. The ECS must be capable of applying axial load pulses (220 ± 5 N (50 ± 1 lbf) static and 6700 ± 25 N (1506 ± 5 lbf) dynamic) in a haversine wave form with a load duration of 0.1 s and a rest period of 0.9 s between load pulses. The system must also be capable of measuring axial deformations and be equipped with computer software which can compute axial compressive stress and recoverable axial strain at various load cycles. In addition, the ECS must be capable of applying stresses sufficient to obtain deformations between 50 to 100 μstrain in compacted asphalt concrete specimens. The ECS is illustrated in Figures D.1, D.2, and D.3.

6.2 *Testing Machine* - a pneumatic or hydraulic testing machine that meets the requirements outlined in 4.3 of T 167.

6.3 *Specimen End Platens* - two aluminum end platens which are 102 ± 2 mm in diameter by 51 ± 2 mm thick. Each end platen will have a drainage hole at its center that is 4.8 ± 0.5 mm in diameter and one side of each end platen will be patterned with grooves as shown in Figure D.4. In addition, the platen must have a groove around its perimeter at mid height which is of sufficient width and depth to hold the O-rings described in 6.6.2.

6.4 *Perforated Teflon Disks* - As shown in Figure D.5. The perforations must coincide with the grooving pattern in the specimen end platens.

6.5 *Yoke and Spacer Assembly* - Used for mounting 2 vertical linear variable transducers (LVDTs) on the test specimen as shown in Figure D.2. Spacers should not be more than 51 mm for a 102 mm specimen.

6.6 *Miscellaneous Apparatus:*

6.6.1 150 mm (6 in.) of 100 mm (4 in.) diameter rubber membrane
6.6.2 Two 102 mm (4 in.) O-Rings
6.6.3 Caulking gun for applying silicone sealant
6.6.4 Calipers capable of measuring 150 ± 1 mm
6.6.5 Steel Spatula
6.6.6 Vacuum Source
6.6.7 Distilled Water Source

7. MATERIALS

7.1 The following materials are required:

7.1.1 Clear silicone sealant
7.1.2 Compressed air

8. SAMPLING

8.1 Asphalt binder shall be sampled in accordance with T 40.

8.2 Aggregate shall be sampled in accordance with T 2.

8.3 Asphalt concrete mixtures shall be sampled in accordance with T 168.

8.4 Compacted roadway test specimens from a newly laid pavement may be sampled and tested if the cores meet the dimension requirements specified in 9.4, however, the top and bottom of the cores must not sustain cut surfaces.

9. SPECIMEN PREPARATION

9.1 Prepare an asphalt concrete mixture sample in accordance with T ###, Preparation of Test Specimens of Bituminous Mixtures by Means of Laboratory Kneading Compaction or T ###, Preparation of Test Specimens of Bituminous Mixtures by Means of Rolling Wheel Compactor.

Note 1: Plant mixed asphalt concrete samples are not to be subjected to short term aging as described in T ###.

Note 2: The top and bottom of a specimen cored from a slab must not sustain cut surfaces.

9.2 Determine the air void content of the specimen in accordance with T ### or T ###.

9.3 Measure the diameter and height of the specimen at three locations as described in D 3549. Record the average measurement as the diameter and height of the specimen within ± 1 mm.

9.4 Place the specimen inside the 150 mm long rubber membrane, centering the specimen within the membrane so that there is a 25 mm extension at each end. Inject a continuous line of silicone cement around the specimen at mid height between the membrane and the specimen. Inject sufficient silicone to ensure that the entire surface area of the specimen will be sealed. Use a spatula to smooth and spread the silicone to a thin uniform layer. Allow the specimen to stand at room temperature, overnight or longer, until the silicone is dry.

10. PROCEDURE

10.1 *Test Set-Up*

10.1.1 Place a perforated teflon disk on top of the grooved surface of the bottom end platen inside the load frame.

10.1.2 Place the specimen vertically on top of the teflon disk and bottom end platen.

Note 3: Field cores shall be positioned such that the top of the specimen corresponds with the top of the pavement.

10.1.3 Place a perforated teflon disk on top of the specimen and place the top end platen on top of the disk, with the grooved surface facing the disk and specimen.

10.1.4 Seal the rubber membrane around the specimen platen assembly by placing an O-ring in each groove of the end platens, over the rubber membrane.

10.1.5 To ensure that the system is airtight, close the system to the water and air supplies by selecting vacuum with the Water-Vacuum-Air valve. Open the vacuum valve and adjust the vacuum regulator until the specimen inlet and outlet pressures read 510 ± 25 mm Hg (20 ± 1 in. Hg). Close the vacuum valve. Close the bypass valve so that any air in the specimen is removed. Monitor the specimen inlet and outlet pressure gages for 5 min. If both gage readings remain constant throughout the 5 min, the system is airtight and testing may continue. If either gage reading decreases, the system is not airtight and adjustments must be made to the system prior to continuing testing.

10.1.6 Attach the yoke with the spacers and the LVDTs to the specimen.

10.2 *Coefficient of Permeability For Air Flow*

10.2.1 Set and establish the temperature of the environmental control chamber to 25 ± 0.5°C.

10.2.2 Open the vacuum valve and select air from the Water-Vacuum-Air valve. Turn the air valve on. Apply the lowest differential pressure possible (typically 6 to 7 kPa) by adjusting the vacuum regulator. Record the air flow through the test specimen. Record the pressure differential reading.

10.2.3 Repeat 10.2.2 for three additional differential pressures. The pressures selected will vary depending upon the void content of the specimen being tested. Specimens with low air voids will require higher pressures. A constant interval between the differential pressures must be selected (e.g. 20, 30, 40, and 50 kPa (3, 4.4, 5.8, and 7.3 psi)). Any range of pressures may be selected that provides measurable flows on the air flow meters and which results in a range of air flows which are within + 10% of the air flow for the 4 pressures selected.

10.2.4 Calculate the coefficient of permeability for air flow of the test specimen as described in 11.2.1 for each of the pressures applied in 10.2.2 and 10.2.3. Calculate and report the average of the four results.

10.2.5 Close the vacuum valve.

10.3 *ECS Modulus Test*

10.3.1 Maintain the temperature of the environmental chamber at 25 ± 0.5°C. Remove the spacers from the yoke.

10.3.2 Apply a static load of 130 ± 25 N (30 ± 5 lbf) and an axial compressive repeated load of approximately 2200 N (494 lbf) to the test specimen. The repeated load should be in a haversine wave form with a load duration of 0.1 s and a rest period of 0.9 s between load pulses.

10.3.3 Adjust the specimen and/or yoke assembly until the readings from the two LVDTs are within 15% of each other.

10.3.4 If the strain is less than 50 μstrain, increase the magnitude of the repeated load until a strain level between 50 and 100 μstrain is reached. If the strain is more than 100 μstrain, decrease the repeated load until a strain level between 50 and 100 μstrain is reached. Record the final loads applied and utilize the same loading levels ± 25 N for subsequent ECS modulus testing after conditioning is applied to the specimen as described in 10.7.

Note 4: Typically, a load of 4000 N (9000 lbf) may be required to achieve a strain level of 100 μstrain.

10.3.5 Measure the peak axial load and recoverable vertical deformations for the load interval from the last 5 cycles. Record the peak axial load and recoverable vertical deformations at each load cycle for the last five load cycles applied. Calculate the ECS moduli as outlined in 11.3.3 and 11.3.4.

Note 5: Do not exceed 250 load cycles when performing the ECS modulus test as this will damage the specimen.

10.3.6 Remove the load from the specimen after the last load cycle. Close the valves of the inlet and outlet gages.

10.4 *Vacuum Conditioning*

10.4.1 Open the bypass valve.

10.4.2 Open the vacuum valve and close the bypass valve. Apply a vacuum of 510 ± 25 mm Hg (20 ± 1 in. Hg) for 10 ± 1 min.

10.4.3 Open the bypass valve. Close the vacuum valve.

10.5 *Wetting*

10.5.1 Maintain the temperature of the environmental chamber at 25 ± 0.5°C. Establish the temperature of the distilled water source at 25 ± 3°C. Open the bypass valve.

10.5.2 Select water from the Vacuum-Water-Air valve. Turn on the vacuum valve and adjust the vacuum regulator until a level of 510 ± 25 mm Hg is measured at the specimen outlet gage.

10.5.3 Wait about 1 min or until the distilled water has been drawn into the tubing and the system. Close the bypass valve and allow the distilled water to be pulled through the test specimen for 30 ± 1 min.

10.6 *Coefficient of Permeability For Water Flow*

10.6.1 Set the vacuum level to approximately 40 kPa (5.8 psi) differential pressure by adjusting the vacuum regulator. Record the water flow through the test specimen. Record the pressure differential reading.

10.6.2 Repeat 10.6.1 for three additional pressures. The pressures selected will vary depending on the void content of the specimen being tested. Specimens with low air voids will require higher pressures. The pressures may range from 20 to 40 kPa (3 to 6 psi) differential pressure. A constant interval between the pressures must be selected (e.g. 20, 30, 40, and 50 kPa (3, 4.4, 5.8, and 7.3 psi)). Any range of pressures may be selected that provide measurable flow on the water flow meter and which results in a range of water flows which are within + 10% of the water flow for the 4 pressures selected.

10.6.3 Calculate the coefficient of permeability for water flow as described in 11.5.1 for each pressure. Calculate and report the average result.

10.7 *Water Conditioning*

10.7.1 Conduct water conditioning for either the warm or cold climate conditions as described in 10.7.2 or 10.7.3, respectively. Figure D.6 summarizes the procedure described in 10.7.2 and 10.7.3.

10.7.2 *Warm Climate Conditioning*

10.7.2.1 Open the vacuum valve and set the vacuum pressure to 254 ± 25 mm Hg (10 ± 1 in. Hg) at the specimen outlet gage. Set the water flow to 4 ± 1 cm^3/min. Close the bypass valve.

10.7.2.2 Set the temperature of the environmental cabinet to 60 ± 0.5°C for 6 hr ± 5 min. followed by a temperature of 25 ± 0.5° C for at least 2 hours (but not more than 6 hours).

10.7.2.3 Apply an axial compressive load of 90 ± 5 N static (20 ± 1 lbf) and 900 ± 25 N (202 ± 5 lbf) dynamic to the test specimen, in a haversine wave form with a load duration of 0.1 s and a rest period of 0.9 s between load pulses. Continuous application of the load is to occur throughout the hot conditioning period (i.e., 6 hours at 60° C)

Note 6: For open-graded mixes, the loads may need to be reduced to avoid damage to specimen.

10.7.2.4 After 6 h, terminate the load applications.

10.7.2.5 After 8 h or more (no more than 12 hours), close the vacuum valve, open the bypass valve and open the system to atmospheric pressure. Continue to maintain the temperature setting of the environmental chamber at 25 ± 0.5°C. Determine the ECS moduli as described in 10.3.2 to 10.3.6.

10.7.2.6 If excessive deformation (>5%) of the specimen is experienced after a conditioning cycle, terminate further conditioning. Record all information collected as specified in 12.1. Conduct the stripping evaluation as described in 10.8. Note in data recorded that failure of the specimen was encountered during conditioning.

10.7.2.7 Continue to maintain temperature setting of the environmental chamber at 25 ± 0.5°C and determine the coefficient of permeability for water flow as described in 10.6.

10.7.2.8 Apply a second hot conditioning cycle by repeating 10.7.2.1 to 10.7.2.6.

10.7.2.9 Apply a third hot conditioning cycle by repeating 10.7.2.1 to 10.7.2.6.

10.7.3 *Cold Climate Conditioning*

10.7.3.1 Complete the three hot conditioning cycles as described in 10.7.2.

10.7.3.2 Turn the vacuum valve on and set the vacuum pressure to 250 ± 25 mm Hg (10 ± 1 in. Hg) at the outlet gage and set the water flow to 4 ± 1 cm^3/min. Terminate the loads applied. Check that the bypass valve is closed.

10.7.3.3 Set the temperature of the environmental chamber to -18 ± 0.5°C for 6 hours ± 5 min followed by a temperature of 25 ± 0.5°C for at least 2 h (no more than 6 hours).

10.7.3.4 After 8 h or more (not more than 12 hours), close the vacuum valve, open the bypass valve and open the system to atmospheric pressure. Continue to maintain the temperature setting of the environmental chamber at 25 ± 0.5°C. Determine the ECS modulus as described in 10.3.2 to 10.3.6.

10.7.3.5 Continue to maintain the temperature setting of the environmental chamber at 25 ± 0.5°C and determine the coefficient of permeability for water flow as described in 10.6.

10.8 *Stripping and Binder Migration Evaluation*

10.8.1 At the conclusion of the last conditioning cycle, remove the specimen from the environmental chamber. Remove the membrane from the specimen and place the specimen in a diametral position between two bearing plates of a loading jack on a mechanical or hydraulic testing machine.

10.8.2 Apply a load sufficient to induce a vertical crack in the specimen.

10.8.3 Remove the test specimen and pull the two halves apart.

10.8.4 Estimate the percentage of stripping which has occurred by making a relative comparison to the standard patterns of stripping shown in Figure D.7.

10.8.5 Estimate the level of binder migration which has occurred by making a relative comparison to the standards shown in Figure D.8.

11. CALCULATIONS

11.1 Calculate the following:

11.1.1 *Cross Sectional Area (m^2):*

$$A = \frac{\pi d^2}{40\,000} \tag{11}$$

where:

d = Average diameter of the test specimen, in cm
π = 3.14159

11.2 After conducting the air permeability testing outlined in 10.2, calculate the following:

11.2.1 *Coefficient of Permeability for Air Flow (cm/s)*

$$k_a = \frac{Q\,H}{\Delta h\,A} \tag{2}$$

where:

k_a	=	coefficient of permeability for air flow, cm/s
Q	=	flow rate of air at mean pressure across specimen, cm^3/s
H	=	average height of the test specimen, cm
Δh	=	difference in piezometric head across the specimen, cm
A	=	cross sectional area of the specimen, cm^2

Note 7: Equation 2 is only applicable for test specimens which are 102 ± 2 mm in diameter and for air supply testing temperatures which are 25 ± 30°C. It is also only applicable for the units above.

11.3 After applying each of the last five load cycles as specified in 10.3.5, calculate the following:

11.3.1 *Peak Stress (kPa) per load cycle:*

$$\sigma_{i-n} = \left(\frac{V_{i-n}}{A}\right) \tag{13}$$

where:

V_{i-n} = peak load applied by the vertical actuator over a load cycle, in N
i = number of conditioning cycles applied (i.e. 0, 1,...4)
n = number of load cycles applied (i.e. 1, 2,...5)

11.3.2 *Recoverable Axial Strain (mm/mm) per load cycle:*

$$e_{i-n} = \frac{\sigma_{ri-n}}{h} \tag{14}$$

where:

δ_{ri-n} = peak recoverable vertical deformation over a load cycle, in mm
h = gage length, the distance over which deformations are measured (i.e. distance between yoke rings), in mm

Note 8: The recoverable deformation is the portion of the total deformation that disappears (or is recovered) upon unloading the specimen as shown in Figure D.9.

11.3.3 *ECS Modulus (kPa) per load cycle:*

$$M_{i-n} = \left(\frac{\sigma_{i-n}}{e_{i-n}}\right) \tag{15}$$

11.4 After calculating ECS modulus for the last five load cycles as described in 11.3.5, calculate the following:

11.4.1 *Average ECS Modulus (kPa) per conditioning cycle:*

$$M_{Ai} = \frac{\sum_{n=1}^{5} (M_{i-n})}{\Delta n} \tag{16}$$

where:

Δn	=	the number of load cycle included in M_{Ai} calculation (for last five load cycles, Δn = 5)

11.5 After conducting the water permeability testing outlined in 10.6, calculate the following:

11.5.1 *Coefficient of Permeability For Water Flow (cm/s):*

$$k_w = \frac{Q\,H}{\Delta h\,A} \qquad (7)$$

where:

k_w	=	coefficient of permeability for water flow, cm/s
Q	=	flow rate of water at pressure across specimen, in cm^3/s
H	=	average height of the test specimen, cm
Δh	=	difference in piezometric head across the specimen, cm
A	=	cross sectional area of the specimen, cm^2

Note 9: Equation 7 is only applicable for test specimens which are 102 ± 2 mm in diameter and for water supply testing temperatures which are 25 ± 30°C. It is also only applicable for the units above.

11.6 After completing each conditioning cycle (i), compute the following:

11.6.1 *ECS Modulus Ratio:*

$$MR_i = \left(\frac{M_{Ai}}{M_{A0}}\right) \qquad (18)$$

where: M_{A0} = initial ECS modulus, in kPa

12. REPORT

12.1. Report the following information:

12.1.1 *Asphalt Binder Grade*

12.1.2 *Asphalt Binder Content* - in % to the nearest 0.1%

12.1.3 *Aggregate Type and Gradation*

12.1.4 *Mixing and Compaction Conditions* - the following information as applicable:

12.1.4.1 *Plant Mixing Temperature* - in °C to the nearest 1°C
12.1.4.2 *Laboratory Mixing Temperature* - in °C to the nearest 1°C
12.1.4.3 *Laboratory Compaction Temperature* - in °C to the nearest 1°C
12.1.4.4 *Laboratory Compaction Method*
12.1.4.5 *Compacted Specimen Height* - in cm to the nearest 0.10 cm
12.1.4.6 *Compacted Specimen Diameter* - in cm to the nearest 0.10 cm
12.1.4.7 *Compacted Specimen Area* - in m^2 to the nearest 0.0002 m^2
12.1.4.8 *Compacted Specimen Density* - in kg/m^2 to the nearest 1 kg/m^2
12.1.4.9 *Compacted Specimen Air Voids* - in % to the nearest 0.1%

12.1.5 *Coefficient of Permeability for Air Flow* - a table listing of the following results for each differential pressure applied:

12.1.5.1 *Chamber Testing Temperature* - in °C to the nearest 0.5°C
12.1.5.2 *Differential Pressure* - kPa to the nearest 1 kPa
12.1.5.3 *Air Flow* - in cm^3/min to the nearest 2 cm^3/min
12.1.5.4 *Coefficient of Permeability For Air Flow* - in cm/s to the nearest 2 cm/s

12.1.6 *Average Coefficient of Permeability for Air Flow* - in cm/s to the nearest 2 cm/s

12.1.7 *ECS Modulus Results* - a table listing the following results for each load cycle (last five cycles) prior to any conditioning cycles and after each conditioning cycle:

12.1.7.1 *Chamber Testing Temperature* - in °C to the nearest 0.5°C
12.1.7.2 *Static Load Applied* - in N to the nearest 5 N
12.1.7.3 *Dynamic Load Applied* - in N to the nearest 5 N
12.1.7.4 *Peak Stress* - in kPa to the nearest 0.1 kPa
12.1.7.5 *Recoverable Axial Strain* - in mm/mm to the nearest 10^{-6} mm/mm
12.1.7.6 *ECS Modulus* - in kPa to the nearest 5 kPa

12.1.8 *Initial ECS Modulus* - in kPa to the nearest 5 kPa

12.1.9 *Coefficient of Permeability for Water Flow* - a table listing the following results for each differential pressure applied prior to applying any condition cycles and after each conditioning cycle is applied:

12.1.9.1 *Chamber Testing Temperature* - in °C to the nearest 0.5°C
12.1.9.1 *Water Temperature* - in °C to the nearest 0.5°C

12.1.9.2 *Differential Pressure* - in kPa to the nearest 1 kPa
12.1.9.3 *Water Flow* - in cm^3/min to the nearest 2 cm^3/min
12.1.9.4 *Coefficient of Permeability for Water Flow* - in cm/s to the nearest 10^{-4} cm/s

12.1.10 *Initial Average Coefficient of Permeability for Water Flow* - in cm/s to the nearest 10^{-4} cm/s

12.1.11 *Average Coefficient of Permeability for Water Flow after Each Conditioning Cycle Applied* - in cm/s to the nearest 10^{-4} cm/s

12.1.12 *Water Conditioning Results* - a table listing the following results for each conditioning cycle:

12.1.12.1 *Average ECS Modulus* - in kPa to the nearest 5 kPa
12.1.12.2 *ECS Modulus Ratio*

12.1.13 *Stripping Rate* - in percent to the nearest 5 percent
12.1.14 *Binder Migration* - single letter designation

13. PRECISION

13.1 Data to support a precision statement for this test method are not available.

13.2 Since there is no accepted reference value, the bias for this test method cannot be determined.

14. KEYWORDS

14.1 Asphalt concrete, bituminous paving mixtures, water sensitivity, stripping potential, ECS modulus, permeability.

Table D.1. Minimum test system requirements

Measurement and Control Parameters	Range	Resolution	Accuracy
Load (compression)	0 to 4400 N	≤ 0.5%	± 1%
Axial Deformation	0 to 6.35 mm	≤ 0.0001 mm	± 0.0001 mm
Chamber Temperature	-20 to +100°C	≤ 0.5°C	± 0.5°C
Vacuum Pressure	0 to 635 mm Hg	≤ 25 mm Hg	± 25 mm Hg
Air Flow	20 to 20 000 cm^3/min	≤ 5%	± 3%
Water Flow	0 to 2525 cm^3/min	≤ 2 cm^3/min	± 1 cm^3/min
Water Reserve Temperature	25 ± 3°C	≤ 0.5°C	± 0.5°C

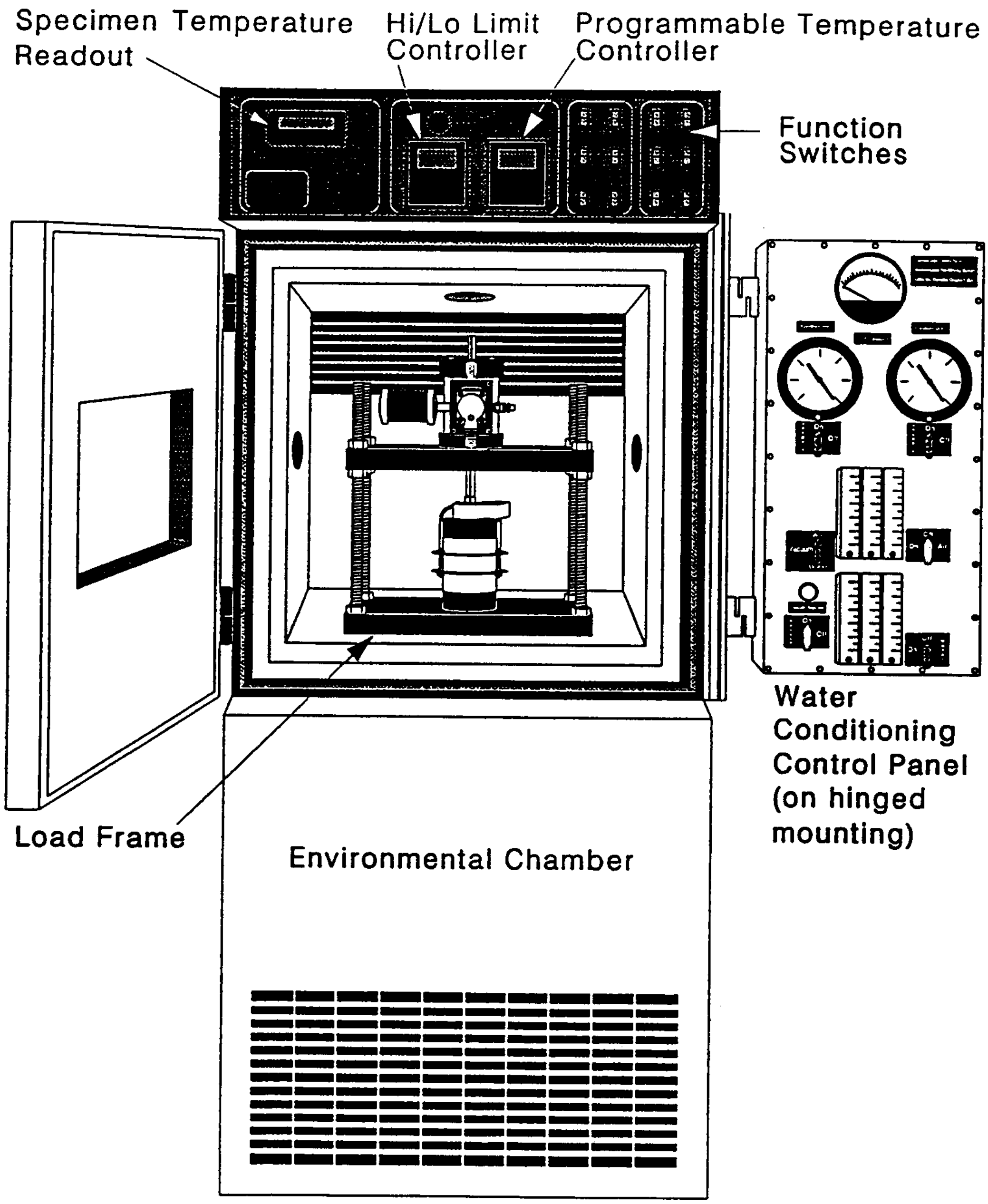

Figure D.1. Environmental conditioning system (front view)

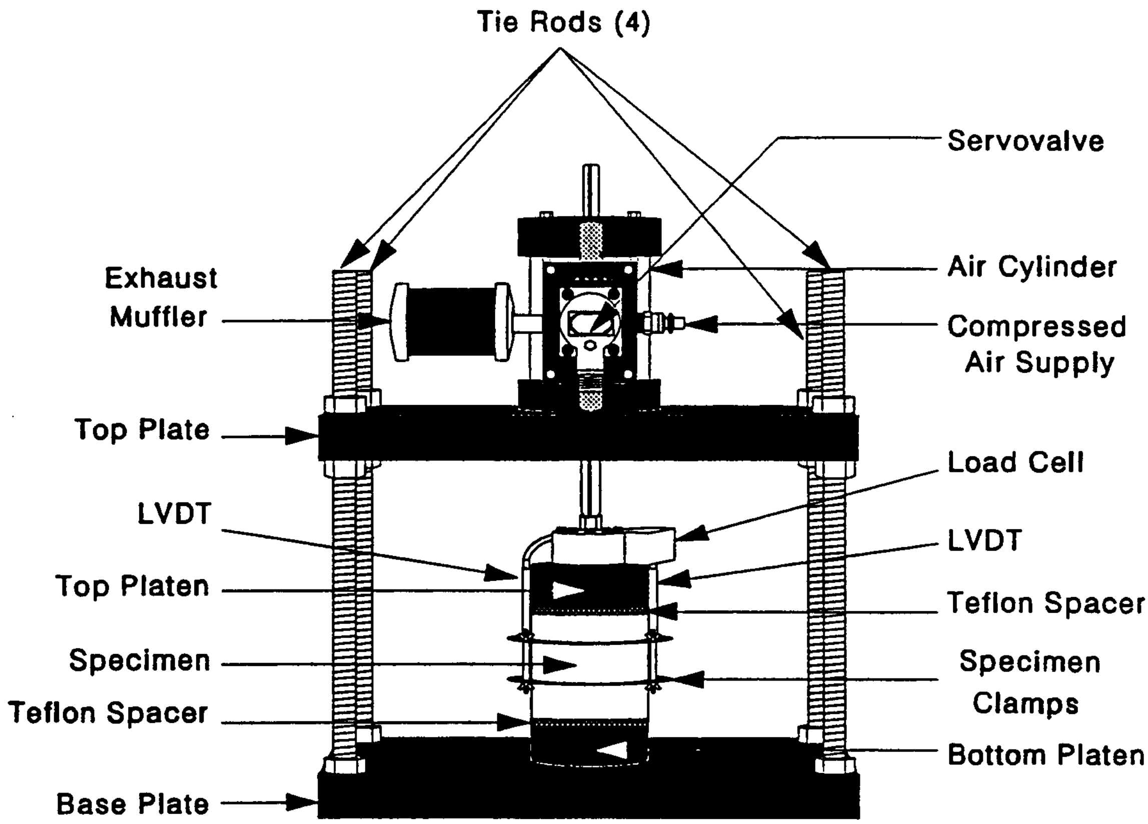

Figure D.2. Load frame with specimen

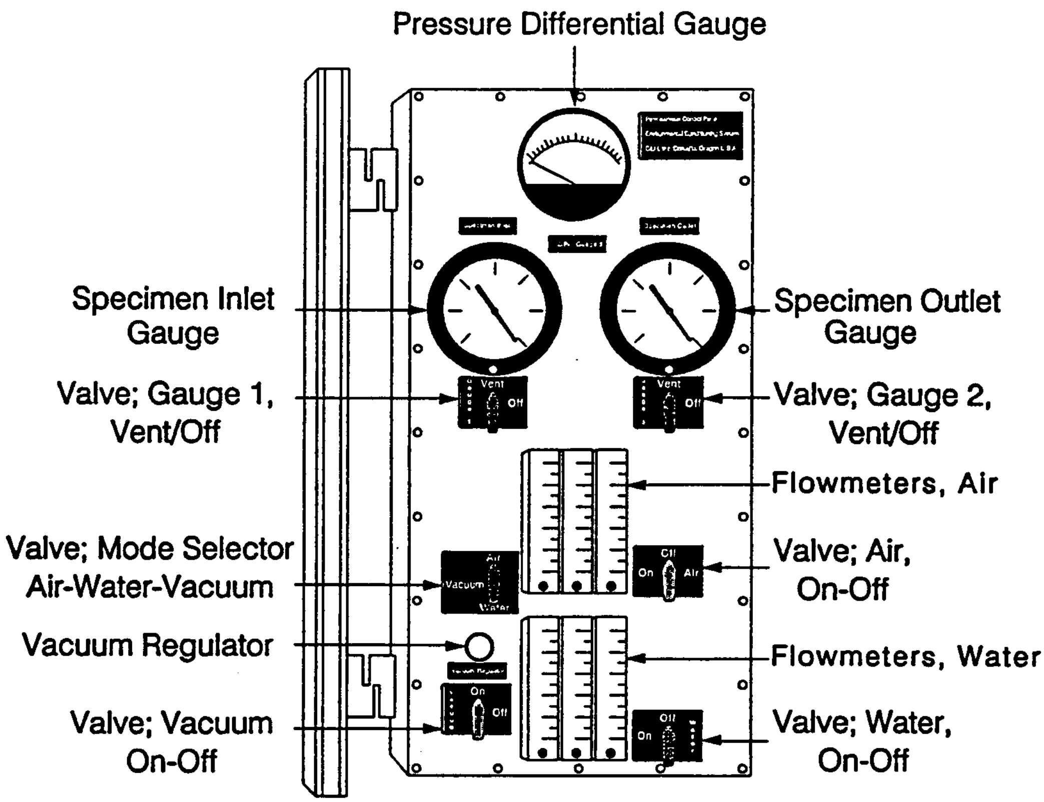

Figure D.3. Control panel

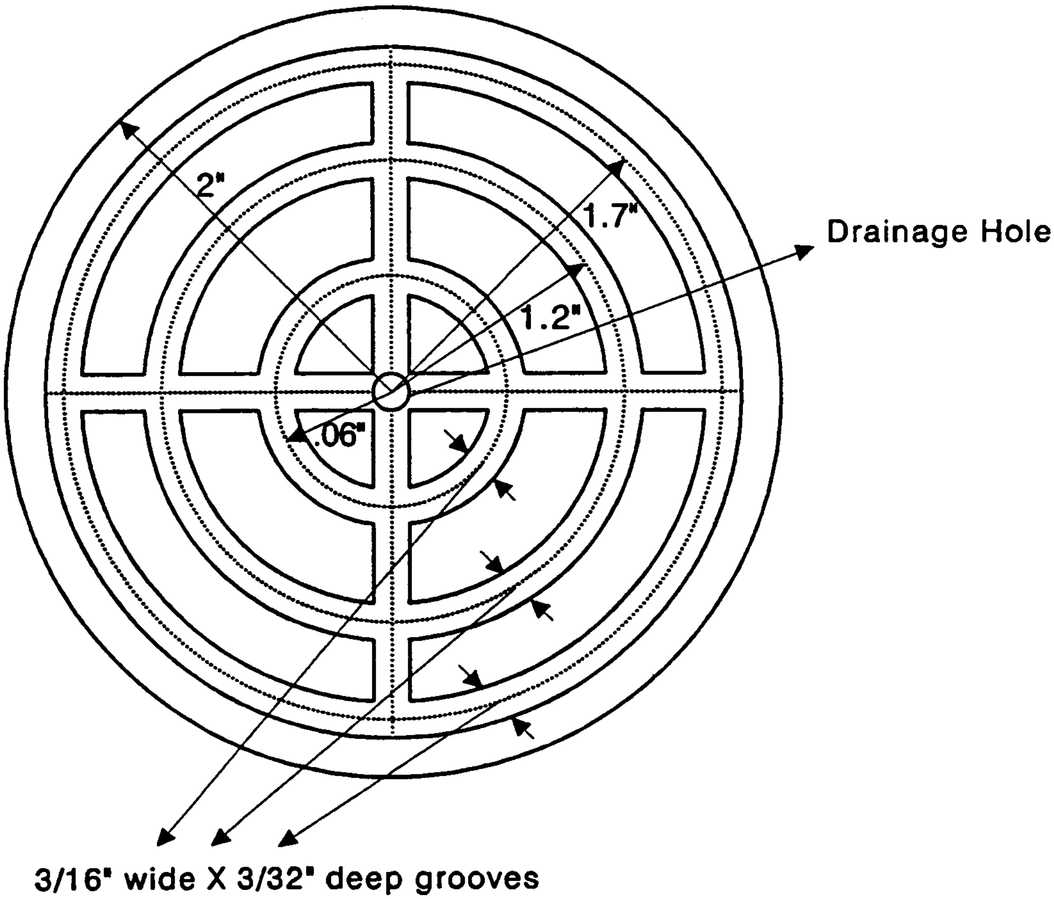

Figure D.4. Groove pattern for end platens

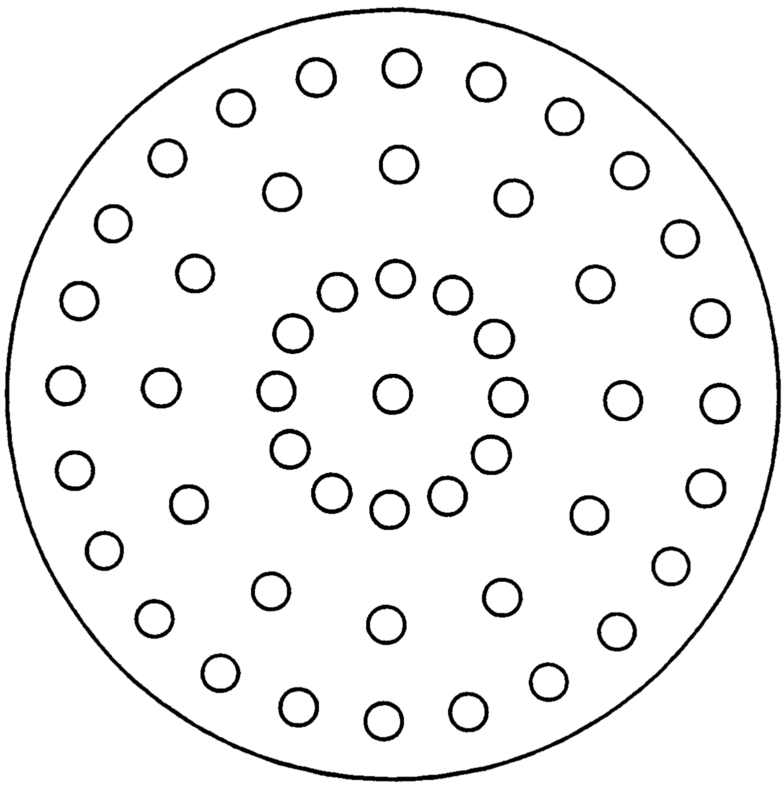

Figure D.5. Perforated teflon spacers

CONDITIONING FACTOR	WETTING *	CONDITIONING STAGE			
		CYCLE-1	CYCLE-2	CYCLE-3	CYCLE-4
Vacuum Level (mm. Hg):	510	250	250	250	250
Repeated Loading	NO	YES	YES	YES	NO
Ambient Temp. (C) **	25	60	60	60	-18
Duration (hr.)	0.5	6	6	6	6

Conditioning Procedure for Warm Climate (WETTING through CYCLE-3)

Conditioning Procedure for Cold Climate (WETTING through CYCLE-4)

* WETTING: Wetting the specimen prior to the conditioning cycles

** Inside the Environmental Cabinet

Notes:

1. The conditioning procedure for a warm climate is wet then 3 hot cycles
2. The conditioning procedure for a cold climate is wet then 3 hot cycles plus one cold cycle

Figure D.6. Conditioning cycles for warm and cold climates

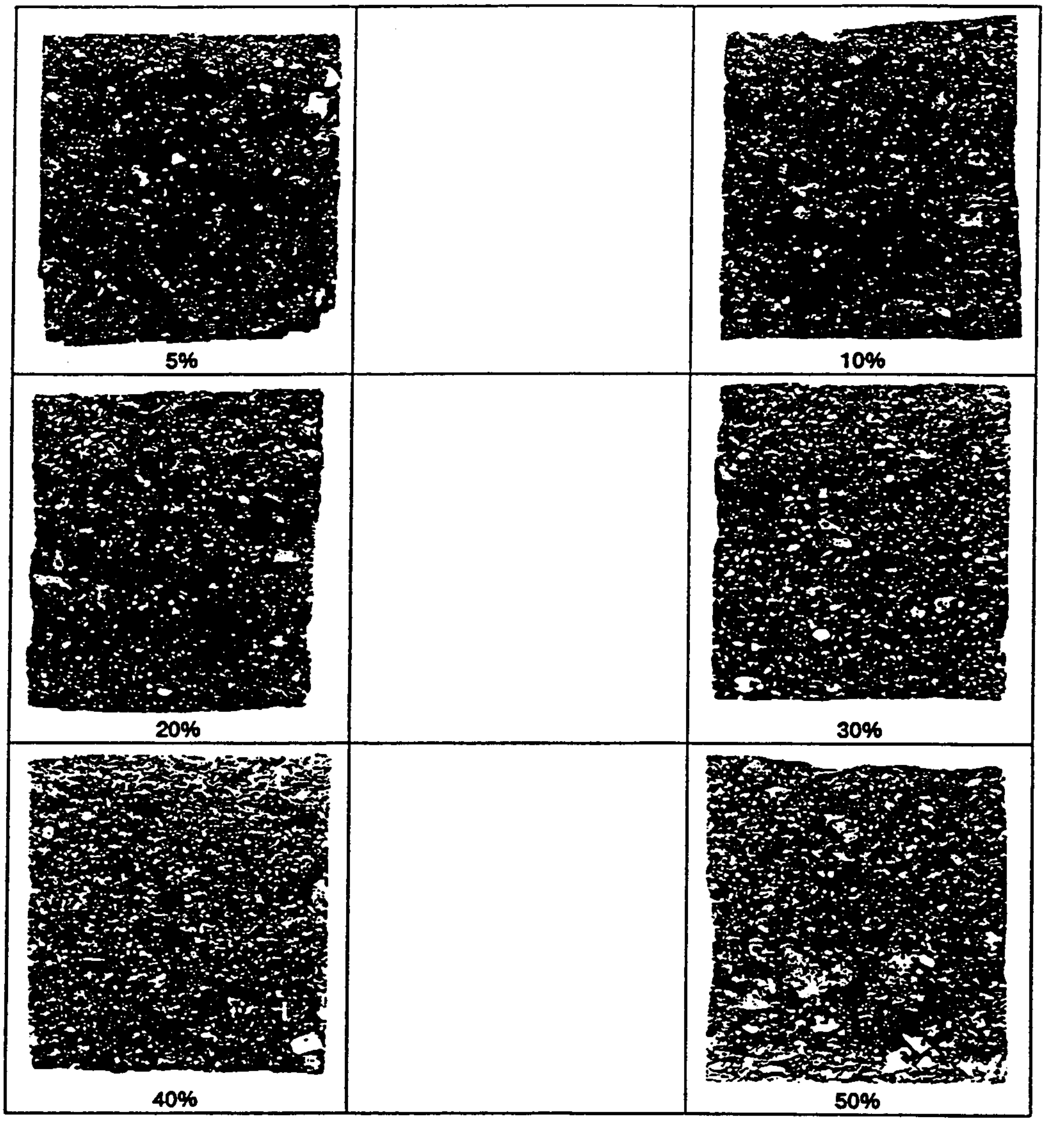

Figure D.7. Stripping rate standards

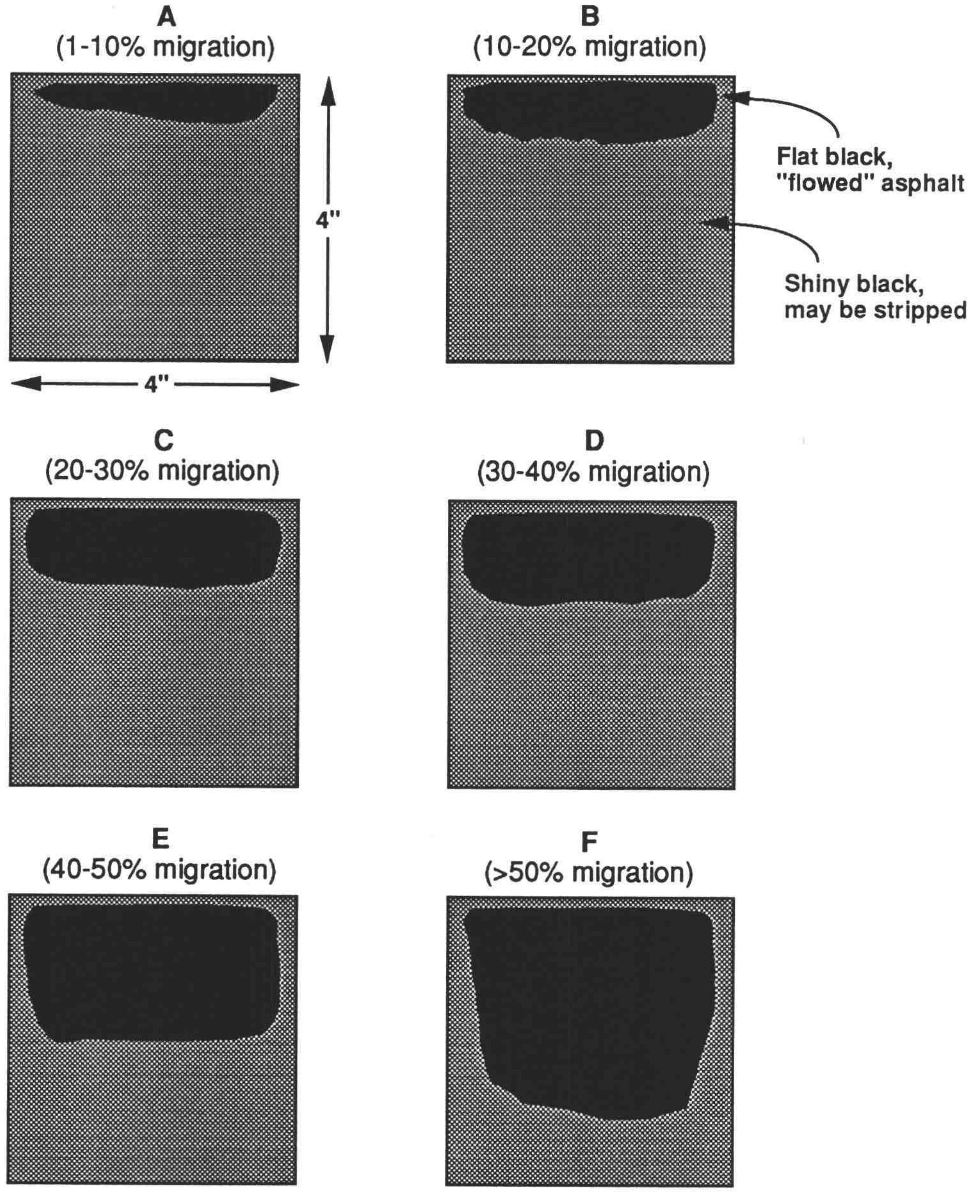

Figure D.8. Binder migration standards

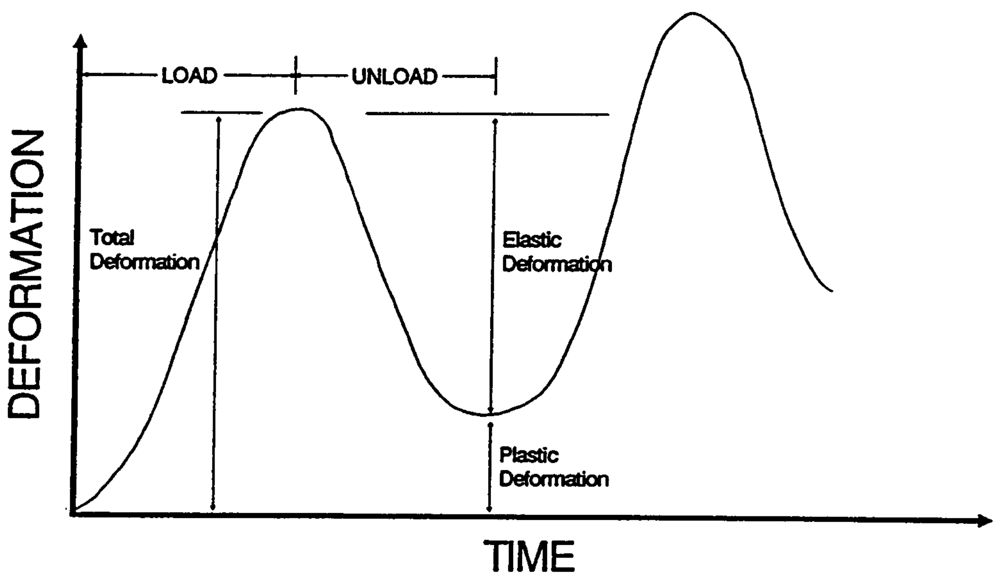

Figure D.9. Illustration of specimen deformation resulting from application of load

Appendix E

Standard Method of Test for

Asphalt Pavement Rutting Test with the OSU Wheel Tracker

AASHTO DESIGNATION: T ###-YY
(ASTM DESIGNATION: D ####-YY)

This document is the draft of a test method being developed by researchers at Oregon State University for the Strategic Highway Research Program (SHRP). The information contained herein is considered interim in nature and future revisions are expected. It is also recognized that this document may lack details with respect to the test equipment (schematics, dimensions, etc.); more details will be provided after the test procedure is finalized. This version represents the state of the test procedure as of March 1, 1993.

The test method is in a format similar to the test methods contained in the American Association of State Highway and Transportation Officials' (AASHTO) standard specifications. At the conclusion of SHRP, selected test methods will be submitted to AASHTO for adoption into its standard specifications.

1. SCOPE

1.1 This method determines the rutting susceptibility of water and temperature conditioned asphalt concrete beam specimens. The amount of rutting is used a measure of the performance of the mixture in terms of water sensitivity.

2. APPLICABLE DOCUMENTS

2.1 *AASHTO Test Methods:*

T ### Practice for Preparation of Asphalt Concrete Specimens by Means of the Rolling Wheel Compactor

2.2 *ASTM Test Methods:*

D 8	Standard Definitions of Terms Relating to Materials for Roads and Pavements
D 3549	Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens

3. SUMMARY OF PRACTICE

3.1 Compacted asphalt concrete test specimens are subjected a water and temperature conditioning process. The water sensitivity characteristics of the compacted mixtures are determined based upon measurements of percent stripping, binder migration and the amount of rutting.

4. APPARATUS

4.1 *LCPC Rutting Tester* - Also known as the OSU Wheel Tracker, described in Table E.1.

4.2 *Specimen Conditioning System* - A system capable of pulling a vacuum of 25 in. Hg (635 mm) through the beam specimen.

4.3 *Hot Water Bath* - A hot water bath capable of holding two 20 x 7.5 x 4 in. (508 x 190.5 x 101.6 mm) specimen containers. The bath will be capable of maintaining a temperature of 140°F ± 9°F (60°C ± 5°C).

4.4 *Temperature Controlled Cabinet* - A hot water bath capable of holding two 20 x 7.5 x 4 in. (508 x 190.5 x 101.6 mm) specimen containers. The cabinet will be capable of maintaining a temperature of -0.4°F ± 9°F (-18°C ± 5°C).

4.5 *Miscellaneous Apparatus:*

4.5.1 Specimens Holders
4.5.2 Compressed Air Source
4.5.3 Vacuum Source

5. MATERIALS

5.1 The following materials are required:

5.1.1 Clear silicone sealant
5.1.2 Latex rubber sheeting

6. SPECIMEN PREPARATION

6.1 Prepare two asphalt concrete mixture specimens in accordance with T ### "Standard Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of Rolling Wheel Compactor."

6.2 Determine the air void content of the specimens in accordance with Section 6 of T ###.

6.3 Place an 1 in. band of latex rubber sheeting around the circumference of each beam specimen at mid-height, using silicon rubber sealant. Allow to cure overnight (24 hours).

6.4 *Vacuum Conditioning*

6.4.1 Verify the dry weight of specimen and air void content of the specimen were determined in accordance with T ####.

6.4.2 Place the beam specimen on the bottom platen of the vacuum conditioning apparatus.

6.4.3 Place the top platen of the vacuum conditioning system on the specimen.

6.4.4 Fit the latex rubber membrane of the vacuum conditioning up over the specimen and top platen. Secure with appropriate clamping ring.

6.4.5 Set vacuum level to 23 in. Hg (584 mm). Allow specimen to draw water for 30 minutes.

6.4.6 Remove the specimen from the vacuum apparatus.

6.4.7 Weight the specimen and determine the degree of saturation.

6.4.8 If the saturation level is less than 60 percent, repeat steps 6.4.2 through 6.4.7 until the saturation level exceeds 60 percent, but not more than three additional times. The total conditioning time is not to exceed two hours.

6.4.9 Repeat steps 6.4.1 through 6.4.8 with companion specimen.

6.4.10 Place each specimen in a specimen holder and fill the holder with distilled water to cover the specimen.

6.4.11 Place the specimens in their holders in the hot water bath set at 60°C (140°F). Allow the specimens to condition for six hours.

6.4.12 Remove the specimens from the hot water bath and allow the specimens to cool to 25°C (140°F) for ten hours. Refill the specimen holder with distilled water as necessary.

6.4.13 Place the specimens into the 60°C (140°F) hot water bath again. Allow the specimens to condition for six hours.

6.4.14 Remove the specimens from the hot water bath and place in the cold cabinet. Allow the specimens to cool to -20°C (-4°F) for eight hours.

6.4.15 Remove the specimens from the cold cabinet and place in the 60° C (140° F) hot water bath. Allow the specimen to condition for ten hours.

6.4.16 Remove the specimen from the hot water bath and allow the specimen to cool to 25° C (140° F) for ten hours.

6.4.17 Wrap the specimen in plastic wrap to avoid moisture loss. The specimen are now ready to test in the OSU wheel tracker. The testing should take place immediately.

7. TEST PROCEDURE

7.1 Lubricate the platens of the OSU wheel tracker with a spray lubricant such as Pam.

7.2 Place 19 x 6-1/2 in. (482.6 x 165.1 mm) teflon sheet on the platen.

7.3 Place the asphalt concrete beam in the rutting tester, on the teflon sheet. Do not rip the plastic wrap.

7.4 Place the rutting tester mold over the specimen and teflon sheet. Do not rip the plastic wrap.

7.5 Place thin expanded foam sheets between the specimen and the walls of the mold on all four sides of the specimen. The foam sheets will be cut to the side dimensions of the beam specimen.

7.6 Bolt the mold to the platen of the OSU wheel tracker.

7.7 Repeat steps 7.1 through 7.6 to place the other beam on the opposite side of the OSU wheel tracker.

7.8 Close the doors of the OSU wheel tracker.

7.9 Connect the OSU wheel tracker to power and compressed air.

7.10 Power on the fan/temperature controller and adjust the setpoint temperature to 104°F (40°C). Allow the actual temperature to reach the setpoint temperature before proceeding further.

7.11 Remove the plastic wrap from the top of the specimen. Using a 15/64-in. bit, drill a hole 2-in deep each beam in the outer front corner. Insert the temperature probe in the hole. Manually move the carriage to ensure the tire does not make contact with the temperature probe.

7.12 When the actual temperature reaches the setpoint temperature check the pressure in each tire. Ensure that each tire is pressured to 100 psi.

7.13 Spread the top of the specimen with chalk dust to prevent sticking between the tire and specimen surface.

7.14 *Precondition the test specimens as follows:*

7.14.1 With the pressure switches in the off (arret) position, set each piston pressure to 50 psi.

7.14.2 Set the counter to 25. The counter value is the number of cycles the carriage will travel: one cycle equals two wheel passes; thus, a counter value of 25 cycles equals 50 wheel passes.

7.14.3 Set the pressure switches in the on (marche) position and ensure the pressure for each piston reads 50 psi. If not, adjust the pressure to 50 psi.

Note 1: When adjusting the pressure, always bring the pressure up to the setpoint pressure, never reduce the pressure to the setpoint pressure.

7.14.4 Start the carriage in motion by pressing the on (marche) push button.

7.14.5 Immediately after 50 wheel passes have been applied to the test specimens (when the carriage stops), release the pressure of each piston by turning the pressure switches to the off (arret) position.

7.15 Take measurements of the test specimen using the finger apparatus and software.

7.16 With the pressure switches still in the off (arret) position, adjust the pressure for each piston to 90 psi. Set the counter to apply the number of wheel passes for the next data set, as shown by the software. Wait for the actual temperature to reach the setpoint temperature before proceeding further.

7.17 When the actual temperature reaches the setpoint temperature, load the test specimens by turning the pressure switches to the on (marche) position. Ensure each piston pressure is 90 psi. If not, adjust the pressure to 90 psi.

Note 2: When adjusting the pressure, always bring the pressure up to the setpoint pressure; never reduce the pressure to the setpoint pressure.

7.18 Start the carriage in motion by pressing the on (marche) push button.

7.19 Immediately after the wheel passes have been applied (when the carriage stops) release the pressure to each piston by turning the pressure switch to the off (arret) position.

7.20 Take measurements of the test specimen using the finger apparatus and software.

7.21 Repeat Steps 7.16 though 7.20 for all data sets given in the software package.

7.22 At the completion of the test, leave the doors to the rutting tester open and allow the test specimens to cool to room temperature. Once cooled, remove the test specimens and store them for photographing and coring.

7.23 Take a photographic record of the specimen.

7.24 Dry core three cores from the specimen into three cores. The cores will be laterally centered in the wheel path, and one core will be taken from the direct center of the length of the wheel path. No cores should be taken from the end of the wheel path where the OSU wheel tracker tire changes direction.

8. DATA ANALYSIS

Analysis of the data obtained from the rutting tester should consist of the following as a minimum:

8.1 *Calculation of the average rut depth versus number of wheel passes* - This accomplished by taking the average of the finger reading after a certain number of wheel passes, *i*, minus the average reading of data set *0*. That is,

$$\text{rut depth} = \frac{P12_i + P13_i + P14_i + P22_i + P23_i + P24_i + P32_i + P33_i + P34_i}{9}$$

$$- \frac{P12_0 + P13_0 + P14_0 + P22_0 + P23_0 + P24_0 + P32_0 + P33_0 + P34_0}{9}$$

where:

PXY = gage reading at position XY.

8.2 *Calculate the average shove (on each side of the rut) versus number of wheel passes* - This is accomplished by taking the average of the finger readings after certain number of wheel passes, *i*, minus the average of the finger readings for zero wheel passes. That is,

$$\text{shove}_{\text{left}} = \frac{P11_i + P21_i + P31_i}{3} - \frac{P11_0 + P21_0 + P31_0}{3}$$

and

$$\text{shove}_{\text{right}} = \frac{P15_i + P25_i + P35_i}{3} - \frac{P15_0 + P25_0 + P35_0}{3}$$

where:

PXY = gage reading at position XY.

8.3 *Plot the average rut depth and the average shove (both sides) versus number of wheel passes.*

Table E.1. Specifications of the LCPC rutting tester

Applied Load	0 to 500 N (0 to ≈ 1120 lb)[a]
Carriage Velocity (maximum)	1.6 m/s (≈ 5.25 ft/s)
Carriage Acceleration (maximum)	10 m/s^2 (≈ 32.8 ft/s^2)
Carriage Travel	360, 410, 450, or 500 mm (≈ 14, 16, 18, or 20 in.)
Travel Frequency	1 Hz (carriage cycle is forward and back in 1 s)
Number of Tires	2[b]
Tire Pressure	7 kg/cm^2 (≈ 100 psi)
Tire Yaw	0 to 10°
Temperature Range	35 to 60° C (39 to 140° F) (can run at ambient temperature without temperature regulation)
Test Criterion	Rut depth at a predetermined number of cycles (1 cycle equals 2 wheel passes). The number of cycles is controlled by a mechanical counter. It is possible to monitor the propagation of rut depth by making intermediate measurements (this requires temporarily stopping the test).

[a] The OSU wheel tracker can attain loads of up to 1700 lb

[b] Tire size: 8.0 in. (203 mm) inside diameter (ID)
16.0 in. (406 mm) outside diameter (OD) (at 100 psi [689 kPa], no load)
4.0 in. (102 mm) width (3.25 in. [82.5 mm] tread width)

Appendix F

Flow System Calibration Data

Table F.1. Calibration for flow system A

12 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	14	0.02056
2000	1	15	0.02083
3000	1	15	0.02083
4000	1	15	0.02083
5000	1	15	0.02083
6000	1	15	0.02083
			0.02079

flow(gph)= 12.75

74.83 avg secs

11 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	24	0.02333
2000	1	24	0.02333
3000	1	23	0.02306
4000	1	24	0.02333
5000	1	24	0.02333
6000	1	24	0.02333
			0.02329

flow(gph)= 11.38

83.83 avg secs

10 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	31	0.02528
2000	1	30	0.02500
3000	1	31	0.02528
4000	1	32	0.02556
5000	1	33	0.02583
6000	1	34	0.02611
			0.02551

flow(gph)= 10.39

91.83 avg secs

9 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	42	0.02833
2000	1	43	0.02861
3000	1	44	0.02889
4000	1	43	0.02861
5000	1	44	0.02889
6000	1	42	0.02833
			0.02861

flow(gph)= 9.26

103.00 avg secs

8 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	55	0.03194
2000	1	55	0.03194
3000	1	55	0.03194
4000	1	56	0.03222
5000	1	57	0.03250
6000	1	56	0.03222
			0.03213

flow(gph)= 8.25

115.67 avg secs

7 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	12	0.03667
2000	2	12	0.03667
3000	2	11	0.03639
4000	2	14	0.03722
5000	2	13	0.03694
6000	2	15	0.03750
			0.03690

flow(gph)= 7.18

132.83 avg secs

6 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	31	0.04194
2000	2	33	0.04250
3000	2	37	0.04361
4000	2	36	0.04333
5000	2	36	0.04333
6000	2	35	0.04306
			0.04296

flow(gph)= 6.17

154.67 avg secs

5 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	53	0.04806
2000	2	55	0.04861
3000	3	0	0.05000
4000	3	2	0.05056
5000	2	59	0.04972
6000	3	2	0.05056
			0.04958

flow(gph)= 5.34

178.50 avg secs

4 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	3	23	0.05639
2000	3	25	0.05694
3000	3	22	0.05611
4000	3	24	0.05667
5000	3	24	0.05667
6000	3	32	0.05889
			0.05694

flow(gph)= 4.65

205.00 avg secs

3 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	4	19	0.07194
2000	4	24	0.07333
3000	4	9	0.06917
4000	4	14	0.07056
5000	4	29	0.07472
6000	4	36	0.07667
			0.07273

flow(gph)= 3.64

261.83 avg secs

2 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	6	14	0.10389
2000	6	28	0.10778
3000	6	38	0.11056
4000	6	40	0.11111
5000	6	47	0.11306
6000	7	1	0.11694
			0.11056

flow(gph)= 2.40

398.00 avg secs

Regression Output

Constant		0.412745992
Std Err of Y Est		0.208618893
R Squared		0.998439309
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	0.9982443	
Std Err of Coef.	0.019891	

Actual (gph)	Reading (gph)	Regression (gph)
2.40	2.00	2.41
3.64	3.00	3.41
4.65	4.00	4.41
5.34	5.00	5.40
6.17	6.00	6.40
7.18	7.00	7.40
8.25	8.00	8.40
9.26	9.00	9.40
10.39	10.00	10.40
11.38	11.00	11.39
12.75	12.00	12.39

Table F.1. Calibration for flow system A (continued)

30 cc/min

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	3	46	0.06278
2000	3	17	0.05472
3000	3	43	0.06194
4000	3	19	0.05528
5000	3	42	0.06167
6000	3	33	0.05917
			0.05926

flow(cc/min)= 28.21

213.33 avg secs

20 cc/min

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	5	38	0.09389
2000	5	13	0.08694
3000	5	25	0.09028
4000	4	16	0.07111
5000	5	41	0.09472
6000	5	26	0.09056
			0.08792

flow(cc/min)= 19.01

316.50 avg secs

10 cc/min

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	10	58	0.18278
2000	10	27	0.17417
3000	6	49	0.11361
4000	9	20	0.15556
5000	10	41	0.17806
6000	11	30	0.19167
			0.16597

flow(cc/min)= 10.07

597.50 avg secs

Regression Output:

Constant		0.96112
Std Err of Y Est		0.103249
R Squared		0.999935
No. of Observations		3.00
Degrees of Freedom		1
X Coefficient(s)	0.90687858555	
Std Err of Coef.	0.00730081887	

Actual (cc/min)	Reading (cc/min)	Regression (cc/min)
10.07	10.00	10.03
19.01	20.00	19.10
28.21	30.00	28.17

Table F.2. Calibration for flow system B

12 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	19	0.02194
2000	1	19	0.02194
3000	1	19	0.02194
4000	1	18	0.02167
5000	1	19	0.02194
6000	1	17	0.02139
			0.02181

flow(gph)= 12.15

78.50 avg secs

11 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	28	0.02444
2000	1	26	0.02389
3000	1	27	0.02417
4000	1	26	0.02389
5000	1	28	0.02444
6000	1	27	0.02417
			0.02417

flow(gph)= 10.96

87.00 avg secs

10 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	34	0.02611
2000	1	36	0.02667
3000	1	37	0.02694
4000	1	35	0.02639
5000	1	36	0.02667
6000	1	35	0.02639
			0.02653

flow(gph)= 9.99

95.50 avg secs

9 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	1	49	0.03028
2000	1	48	0.03000
3000	1	49	0.03028
4000	1	50	0.03056
5000	1	49	0.03028
6000	1	50	0.03056
			0.03032

flow(gph)= 8.74

109.17 avg secs

8 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	1	0.03361
2000	2	1	0.03361
3000	2	0	0.03333
4000	1	59	0.03306
5000	1	59	0.03306
6000	2	0	0.03333
			0.03333

flow(gph)= 7.95

120.00 avg secs

7 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	26	0.04056
2000	2	28	0.04111
3000	2	26	0.04056
4000	2	25	0.04028
5000	2	22	0.03944
6000	2	22	0.03944
			0.04023

flow(gph)= 6.59

144.83 avg secs

6 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	2	45	0.04583
2000	2	45	0.04583
3000	2	38	0.04389
4000	2	38	0.04389
5000	2	36	0.04333
6000	2	38	0.04389
			0.04444

flow(gph)= 5.96

160.00 avg secs

5 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	3	11	0.05306
2000	3	9	0.05250
3000	3	13	0.05361
4000	3	14	0.05389
5000	3	13	0.05361
6000	3	13	0.05361
			0.05338

flow(gph)= 4.96

192.17 avg secs

4 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	3	53	0.06472
2000	4	0	0.06667
3000	4	4	0.06778
4000	3	51	0.06417
5000	3	52	0.06444
6000	3	53	0.06472
			0.06542

flow(gph)= 4.05

235.50 avg secs

3 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	5	11	0.08639
2000	5	13	0.08694
3000	5	1	0.08361
4000	5	3	0.08417
5000	4	55	0.08194
6000	4	50	0.08056
			0.08394

flow(gph)= 3.16

302.17 avg secs

2 gph

Weight	Time	Difference	Dec. Time
grams	min	secs	hr
1000	7	2	0.11722
2000	8	3	0.13417
3000	10	32	0.17556
4000	11	13	0.18694
5000	11	32	0.19222
6000	12	11	0.20306
			0.16819

flow(gph)= 1.58

605.50 avg secs

Regression Output

Constant		-0.175982
Std Err of Y Est		0.2059577
R Squared		0.996631
No. of Observations		11
Degrees of Freedom		9
X Coefficient(s)	1.01325565	
Std Err of Coef.	0.0196373	

Actual (gph)	Reading (gph)	Regression (gph)
1.58	2.00	1.85
3.16	3.00	2.86
4.05	4.00	3.88
4.96	5.00	4.89
5.96	6.00	5.90
6.59	7.00	6.92
7.95	8.00	7.93
8.74	9.00	8.94
9.99	10.00	9.96
10.96	11.00	10.97
12.15	12.00	11.98

Table F.2. Calibration for flow system B (continued)

30 cc/min

Weight grams	Time min	Difference secs	Dec. Time hr
1000	4	8	0.06889
2000	4	15	0.07083
3000	4	14	0.07056
4000	4	32	0.07556
5000	4	19	0.07194
6000	3	57	0.06583
			0.07060

flow(cc/min)= 23.68

254.17 avg secs

20 cc/min

Weight grams	Time min	Difference secs	Dec. Time hr
1000	6	1	0.10028
2000	5	22	0.08944
3000	5	31	0.09194
4000	5	13	0.08694
5000	7	32	0.12556
6000	5	19	0.08861
			0.08924

flow(cc/min)= 18.73

321.25 avg secs

10 cc/min

Weight grams	Time min	Difference secs	Dec. Time hr
1000	12	9	0.20250
2000	11	50	0.19722
3000	12	8	0.20222
4000	8	59	0.14972
5000	12	0	0.20000
6000	11	24	0.19000
			0.19028

flow(cc/min)= 8.79

685.00 avg secs

Regression Output:

Constant		2.173328
Std Err of Y Est		2.042635
R Squared		0.963737
No. of Observations		3.00
Degrees of Freedom		1
X Coefficient(s)	0.7446054809	
Std Err of Coef.	0.144436132	

Actual (gph)	Reading (gph)	Regression (gph)
8.79	10.00	9.62
18.73	20.00	17.07
23.68	30.00	24.51

Table F.3. System blank calibration

System A

Delta P (psi)	Flow (gph)	Flow (m3/s)	Press (Pa)	Reg. Pres. (Pa)
2	2.1	2.21E-06	13789.51	12940.99
3	3.2	3.36E-06	20684.27	21314.86
4	4	4.21E-06	27579.03	27404.94
5	5	5.26E-06	34473.79	35017.54
6	5.9	6.2E-06	41368.54	41868.88
7	6.8	7.15E-06	48263.3	48720.23
8	7.5	7.89E-06	55158.06	54049.05

Regression Output:

Constant		-3045.47
Std Err of Y Est		791.5335
R Squared		0.997647
No. of Observations		7
Degrees of Freedom		5
No. of Observations		6
X Coefficient(s)	7.24E+09	4
Std Err of Coef.	1.57E+08	
X Coefficient(s)	0.032867	

System B

Delta P (psi)	Flow (gph)	Flow (m3/s)	Press (Pa)	Reg. Pres. (Pa)
2	4.5	4.73E-06	13789.51	12940.93
3	7.3	7.68E-06	20684.27	21957.91
4	9.2	9.67E-06	27579.03	28076.58
5	10.9	1.15E-05	34473.79	33551.18

Regression Output:

Constant		-1550.65
Std Err of Y Est		1311.683
R Squared		0.985523
No. of Observations		4
Degrees of Freedom		2
X Coefficient(s)	3.06E+09	
Std Err of Coef.	2.62E+08	

Table F.4. Pressure gage calibration

System A

Delta P (psi)	Press. (N/m2)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Ave. Man. (in. Hg) (up scale)	Ave. Man. (in. Hg) (down scale)	Ave. Man. (in. Hg)	Ave. Man. (n/m2)	Man. Reg. (n/m2)
8	55158.06	14.95	14.8	14.65	14.85					14.83	14.80	14.81	50114.39	49768.51
7	48263.30	13.1	13.1	13.2	13.3					13.20	13.15	13.18	44574.32	43646.95
6	41368.54	11.2	10.95	11.1	11.05					11.00	11.15	11.08	37469.49	37525.38
5	34473.79	8.6		8.85		8.65	9.2	8.6	8.65	8.93	8.68	8.80	29772.60	31403.81
4	27579.03					6.95	7.15	6.95	7.25	7.20	6.95	7.08	23936.49	25282.24
3	20684.27					6	6.1	5.75	6.1	6.10	5.88	5.99	20257.21	19160.67
2	13789.51					3.85	4.3	3.55	4.5	4.40	3.70	4.05	13702.16	13039.11

Regression Output:

Constant		795.97
Std Err of Y Est		1191.36
R Squared		0.993282
No. of Observations		7
Degrees of Freedom		5
X Coefficient(s)	0.8878584073	
Std Err of Coef.	0.0326546474	

System B

Delta P (psi)	Press. (N/m2)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Man (in. Hg) (down scale)	Man (in. Hg) (up scale)	Ave. Man. (in. Hg) (up scale)	Ave. Man. (in. Hg) (down scale)	Ave. Man. (in. Hg)	Ave. Man. (n/m2)	Man. Reg. (n/m2)
8	55158.056	17.7	16.2	18	17	17	17					16.73	58022.74	59776.59
7	48263.299	16.35	14.3	16.2	15.8	15.5	15.7					15.27	52919.67	51843.07
6	41368.542	13.4	12.25	13.3	14.35	13.05	14.35					13.65	45504.71	43909.55
5	34473.785	10.75	10.2	10.25	10.45	10.25	10.5	11.05	10.5	10.1	10.3	10.39	35304.21	35976.03
4	27579.028	7.7	7.7					9.3	9.1	8.7	9	8.60	29039.56	28042.51
3	20684.271	6	6.1					5.2	5.5	5.15	5.55	5.72	18889.81	20108.99
2	13789.514	4.3	4.6					3.1	3.2	3.1	3.25	3.68	12151.51	12175.47

Regression Output:

Constant		-3691.57
Std Err of Y Est		1393.702
R Squared		0.994519
No. of Observations		7
Degrees of Freedom		5
X Coefficient(s)	1.1506598225	
Std Err of Coef.	0.0382007534	

Appendix G

ECS Laboratory Test Data

Table G.1. Alberta, SPS-5 (AB5) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
AB5R803	05/30/92	5.40	5.55	3.89E-06	202.5	194.0	202.0	A	0	40.5	180.5	224.6	1.00	5.36E-05	5	NO	
									1	40.9	204.0	200.5	0.89	7.85E-05			0.0587
									2	40.8	204.5	200.0	0.89	8.19E-05			0.0721
									3	40.9	213.5	191.1	0.85	6.22E-05			0.0844
									4	40.0	219.0	183.9	0.82	5.16E-05			
AB5R804	03/09/92	5.40	5.30		187.5	262.0	253.0	A	0	42.4	207.5	204.6	1.00	1.70E-05	5	NO	
									1	44.0	239.5	183.8	0.90	4.88E-05			0.0929
									2	44.5	271.5	163.9	0.80	5.46E-05			0.1122
									3	44.4	269.0	164.9	0.81	5.55E-05			0.1323
									4	44.7	270.0	165.8	0.81	4.97E-05			
AB5KL01	02/23/92	5.40	5.98		164.0		195.0	A	0	34.9	135.5	257.5	1.00	9.49E-06	5	C	
									1	38.1	216.5	176.5	0.69	4.20E-05			0.0807
									2	36.9	230.0	160.9	0.62	3.54E-05			0.1034
									3	37.3	236.5	158.4	0.62	2.40E-05			0.1236
									4	37.7	260.0	144.9	0.56	2.36E-05			
AB5KM03	03/14/92	5.40	4.36		198.0		203.0	B	0	40.6	158.5	256.2	1.00		5	D	
									1	41.2	204.0	201.7	0.79	1.37E-05			0.0518
									2	41.4	209.0	197.8	0.77	1.73E-05			0.0654
									3	41.3	228.0	181.0	0.71	1.54E-05			0.0757
									4	36.1	237.0	173.7	0.68	1.53E-05			
AB5KH06	02/23/92	5.40	2.77		257.5		268.0	B	0	40.3	136.0	296.5	1.00		5	E	
									1	41.1	146.0	281.4	0.95				0.0832
									2	40.7	164.0	248.3	0.84				0.1286
									3	40.8	173.5	234.5	0.79				0.1705
									4	40.7	170.5	238.6	0.80				
AB5KD08	03/14/92	5.40	2.58		271.0		273.0	A	0	36.8	138.0	266.0	1.00		5	E	
									1	40.2	147.5	272.8	1.03	9.86E-06			0.0831
									2	39.5	155.0	254.1	0.96	9.86E-06			0.0967
									3	39.8	171.5	231.3	0.87	7.86E-06			0.1169
									4	41.5	178.0	232.9	0.88	7.86E-06			

Table G.2. Arizona, SPS-5 (AZ5) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
AZ5R803	05/28/92	4.70	8.28	4.67E-05	844.0	1378.0	1070.0	B	0	40.3	55.2	731.0	1.00	1.46E-04	20	NO	
									1	40.0	79.1	506.0	0.69	7.44E-05			0.0652
									2	39.5	77.1	514.0	0.70	4.66E-05			0.0770
									3	39.7	75.7	524.9	0.72	3.23E-05			0.0794
AZ5R805	03/06/92	4.70	8.16	2.91E-05	946.0	741.0	731.0	B	0	41.9	56.8	737.2	1.00	6.78E-05	20	NO	
									1	42.3	79.4	532.7	0.72	1.21E-04			0.0979
									2	41.9	78.0	537.3	0.73	9.38E-05			0.1050
									3	42.6	77.5	550.3	0.75	5.24E-05			0.1058
AZ5KL01	02/18/92	4.70	8.37	1.2E-05	803.5		994.0	B	0	42.9	51.6	831.1	1.00	4.37E-05	20	NO	
									1	43.1	69.2	622.0	0.75	7.65E-05			0.0544
									2	42.8	68.4	626.4	0.75	1.00E-04			0.0627
									3	42.2	65.0	649.7	0.78	5.94E-05			0.0648
AZ5KM04	02/18/92	4.70	8.00	3.93E-06	797.5		905.0	A	0	35.7	33.3	1074.9	1.00	1.38E-05	20	NO	
									1	36.8	49.1	757.3	0.70	5.78E-05			0.0613
									2	36.0	50.9	707.3	0.66	8.51E-05			0.0751
									3	37.8	48.8	775.8	0.72	4.22E-05			0.0923
AZ5KH05	06/07/92	4.70	6.17		962.5	1119.0	1118.0	B	0	41.7	37.1	1125.2	1.00		20	C	
									1	39.9	43.6	918.5	0.82				0.0548
									2	40.5	53.0	763.4	0.68	1.41E-05			0.0669
									3	41.3	53.6	769.7	0.68				0.0771
AZ5KH06	03/12/92	4.70	6.30		988.0		1300.0	B	0	42.8	35.8	1197.6	1.00		20	C	
									1	43.0	46.7	920.1	0.77	5.04E-05			0.0497
									2	43.0	48.9	880.0	0.73	3.93E-05			0.0618
									3	42.9	53.1	807.8	0.67	2.16E-05			0.0687

Table G.3. California, AAMAS Batch (CAB) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
CABKL02	04/05/92	5.61	7.41	7.08E-06	601.5	729	755	B	0	41.6	59.8	694.5	1	2.61E-05	5	C	
									1	42.2	87.6	481.7	0.69	2.30E-05			0.0338
									2	42.1	91.2	462.7	0.67	1.97E-05			0.0419
									3	40.6	88.6	458.8	0.66	1.86E-05			0.0496
									4	40.4	104	389.1	0.56	1.26E-05			
CABKM12	04/03/92	5.61	4.88		830.0	969.0	925.0	B	0	42.9	48.5	886.5	1.00		5	D	
									1	42.8	57.7	741.6	0.84				0.0388
									2	43.5	58.5	742.7	0.84				0.0401
									3	43.2	59.2	733.2	0.83				0.0457
									4	41.5	66.9	620.8	0.70				
CABKM14	04/05/92	5.61	6.04		732.0	1129.0	1042.0	A	0	39.1	20.7	1888.9	1.00		5	E	
									1	37.1	34.6	1072.9	0.57	1.65E-05			0.0332
									2	38.7	52.9	731.2	0.39	1.50E-05			0.0458
									3	37.9	56.3	673.4	0.36	1.93E-05			0.0606
									4	38.9	69.9	557.8	0.30	1.30E-05			
CABKH04	06/05/92	5.61	4.14		743.5	1102.0	1038.0	A	0	40.5	36.3	1117.6	1.00		5	D	
									1	40.7	43.0	949.3	0.85	7.64E-06			0.0367
									2	40.3	47.2	854.3	0.76	7.17E-06			0.0573
									3	39.3	41.5	947.8	0.85	7.58E-06			0.0727
									4	40.2	46.6	861.2	0.77				
CABKD05	04/03/92	5.61	4.02		857.5	861.0	970.0	A	0	38.7	19.7	1969.3	1.00		5	C	
									1	38.5	36.7	1053.9	0.54				0.0484
									2	39.5	28.1	1405.7	0.71				0.0800
									3	39.9	35.8	1116.1	0.57				0.1088
									4	40.6	47.2	864.0	0.44				

Table G.4. California, AAMAS Drum (CAD) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
CADR804	03/16/92	4.54	9.39	1.23E-04	875.0	943.0	914.0	A	0	45.4	36.5	1246.4	1.00	3.17E-05	5	NO	
									1	47.1	79.3	596.0	0.48	6.95E-05			0.0687
									2	46.9	93.4	502.5	0.40	4.73E-05			0.0831
									3	47.2	93.3	473.9	0.38	3.72E-05			0.0928
									4	46.4	146.5	317.4	0.25	3.31E-05			
CADR806	03/16/92	4.54	9.75	1.23E-04	816.5	710.0	678.0	B	0	42.2	56.8	711.1	1.00	1.57E-04	5	NO	
									1	42.3	92.7	456.5	0.64	3.85E-05			0.0690
									2	42.5	96.6	440.1	0.62	3.20E-05			0.0725
									3	42.5	98.0	433.4	0.61	3.14E-05			0.0718
									4	41.8	136.5	306.4	0.43	3.17E-05			
CADKL02	04/01/92	4.54	9.49	8.99E-05	690.0	802.0	790.0	B	0	43.4	66.2	655.1	1.00	2.67E-04	5	NO	
									1	43.6	84.7	515.0	0.79	9.46E-05			0.0176
									2	43.7	86.5	505.0	0.77	1.17E-04			0.0172
									3	44.2	94.2	469.5	0.72	7.55E-05			0.0153
									4	43.6	114.0	382.2	0.58	6.62E-05			
CADKM0	03/19/92	4.54	9.11	6.43E-05	756.5	820.0	811.0	B	0	43.2	70.0	616.8	1.00	1.25E-04	5	NO	
									1	42.9	84.4	508.8	0.82	4.72E-05			0.0226
									2	43.0	93.1	462.2	0.75	3.68E-05			0.0269
									3	42.9	91.5	468.7	0.76	4.74E-05			0.0311
									4	42.1	107.5	392.7	0.64	3.47E-05			
CADKH05	06/03/92	4.54	7.78	3.30E-05	821.0	1177.0	1070.0	A	0	39.3	29.6	1325.8	1.00	8.97E-05	5	NO	
									1	39.4	46.4	847.9	0.64	4.38E-05			0.0273
									2	40.0	47.6	839.7	0.63	4.06E-05			0.0380
									3	40.5	52.0	779.2	0.59	3.54E-05			0.0479
									4	40.2	64.5	623.9	0.47	2.67E-05			
CADKD07	03/19/92	4.54	8.49	2.84E-05	810.00	1130.00	1046.00	A	0	39.6	23.0	1709.5	1.00	6.14E-05	5	NO	
									1	38.9	46.3	844.5	0.49	1.23E-05			0.0299
									2	38.7	56.5	685.1	0.40	1.50E-05			0.0432
									3	38.9	68.8	564.6	0.33	1.97E-05			0.0550
									4	39.9	89.5	449.0	0.26	1.51E-05			
CADKD08	04/01/92	4.54	7.69	2.62E-05	734.00	832.00	813.00	A	0	37.5	39.2	955.4	1.00	4.79E-05	5	NO	
									1	38.7	60.3	643.2	0.67	2.02E-05			0.0366
									2	38.5	48.1	802.4	0.84	2.04E-05			0.0447
									3	38.7	58.2	693.3	0.73	2.59E-05			0.0535
									4	39.2	72.5	540.9	0.57	1.99E-05			

Table G.5. California GPS-6b (CAG) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
CAGR803	04/24/92	5.21	11.00	9.97E-05	234.0	246.0	249.0	A	0	39.6	153.0	259.0	1.00	9.07E-04	20	NO	
									1	41.1	330.0	124.7	0.48	3.56E-04			0.1138
									2	40.9	376.0	108.5	0.42	2.54E-04			0.1377
									3	40.8	380.0	107.4	0.41	1.68E-04			0.1510
CAGR805	04/24/92	5.21	10.66	9.27E-05	235.5	230.0	233.0	B	0	38.6	192.5	199.9	1.00	4.55E-04	20	NO	
									1	38.5	305.0	126.3	0.63	1.61E-04			0.0637
									2	38.8	343.5	112.7	0.56	1.49E-04			0.0732
									3	38.5	364.0	105.5	0.53	9.34E-05			0.0787
CAGKL01	05/08/92	5.21	9.26	4.90E-05	193.5	331.0	337.0	B	0	40.2	176.0	228.7	1.00	1.74E-04	30	NO	
									1	40.0	338.5	117.9	0.52	5.97E-05			0.0490
									2	39.4	375.5	105.0	0.46	4.40E-05			0.0552
									3	39.5	416.0	94.8	0.41	3.24E-05			0.0618
CAGKM0	05/07/92	5.21	8.82	2.77E-05	269.5	322.0	324.0	B	0	39.7	121.5	326.3	1.00	9.39E-05	20	NO	
									1	38.5	282.5	136.4	0.42	4.87E-05			0.0449
									2	38.6	320.0	120.5	0.37	3.53E-05			0.0575
									3	39.8	335.5	118.6	0.36	2.83E-05			0.0627
CAGKD06	05/07/92	5.21	7.82	5.39E-06	280.5	363.0	360.0	A	0	41.0	86.1	476.5	1.00	3.26E-05	30	A	
									1	39.7	203.5	194.8	0.41	3.58E-05			0.0468
									2	41.3	229.0	180.2	0.38	2.42E-05			0.0636
									3	39.6	236.5	167.3	0.35	2.19E-05			0.0753
CAGKD07	05/08/92	5.21	7.04	7.91E-07	349.0	441.0	461.0	A	0	40.1	95.3	420.3	1.00	1.85E-05	20	B	
									1	40.8	170.5	239.2	0.57	2.19E-05			0.0516
									2	40.5	194.5	207.7	0.49	2.01E-05			0.0676
									3	39.8	201.0	198.2	0.47	1.87E-05			0.0815

Table G.6. Georgia, AAMAS (GAA) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
GAAR803	04/07/92	4.33	7.62	3.29E-05	429.0	683.0	614.0	A	0	40.8	92.2	443.2	1.00	1.51E-04	0	NO	
									1	41.0	106.0	387.3	0.87	4.94E-05			0.0449
									2	42.1	122.5	343.5	0.78	4.12E-05			0.0597
									3	40.1	115.0	348.8	0.79	4.75E-05			0.0710
GAAR806	04/07/92	4.33	9.09	1.13E-04	464.5	321.0	317.0	B	0	39.5	85.6	467.4	1.00	1.58E-03	0	NO	
									1	39.7	100.8	394.4	0.84	1.03E-03			0.0388
									2	40.0	105.0	381.3	0.82	8.67E-04			0.0394
									3	40.3	100.7	399.8	0.86	7.86E-04			0.0417
GAAKL12	06/07/92	4.33	9.84	7.42E-05	390.0	325.0	337.0	A	0	39.4	116.3	338.7	1.00	5.76E-04	5	NO	
									1	39.4	121.0	325.9	0.96	2.40E-04			0.0280
									2	39.3	113.5	345.8	1.02	2.01E-04			0.0359
									3	39.5	113.5	348.7	1.03	2.17E-04			0.0428
GAADM1	04/23/92	4.33	9.19	6.56E-05	449.0	376.0	374.0	B	0	40.6	118.0	343.7	1.00	2.96E-04	0	NO	
									1	39.9	97.1	410.3	1.19	1.80E-04			0.0081
									2	39.6	101.5	389.7	1.13	1.55E-04			0.0062
									3	39.5	101.1	390.4	1.14	1.31E-04			0.0042
GAAKH04	04/23/92	4.33	7.48	3.19E-05	505.0	663.0	587.0	A	0	39.8	36.1	1105.2	1.00	6.97E-05	0	NO	
									1	38.8	46.9	827.0	0.75	3.81E-05			0.0207
									2	39.5	45.5	868.0	0.79	2.78E-05			0.0293
									3	39.0	47.4	823.6	0.75	2.29E-05			0.0355
GAAKD01	04/12/92	4.33	6.36	1.21E-05	494.5	458.0	466.0	A	0	37.9	77.8	488.0	1.00	2.59E-05	5	NO	
									1	39.0	73.0	535.0	1.10	5.88E-05			0.0211
									2	39.5	77.2	511.8	1.05	4.68E-05			0.0315
									3	39.2	76.3	513.4	1.05	6.49E-05			0.0434

Table G.7. Minnesota, SPS-5 (MN5) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
MN5R803	04/19/92	5.60	11.27	6.33E-05	129.5	131.0	118.0	B	0	41.1	243.0	169.0	1.00	4.40E-04	5	NO	
									1	42.5	329.0	129.1	0.76	3.26E-04			0.0878
									2	40.0	324.0	123.5	0.73	2.09E-04			0.0960
									3	40.1	320.5	125.1	0.74	1.99E-04			0.0955
									4	41.0	430.0	95.1	0.56	1.92E-04			
MN5R804	04/21/92	5.60	10.62	8.82E-05	126.5	120.0	132.0	A	0	40.6	313.0	129.6	1.00	6.56E-04	5	NO	
									1	43.4	373.0	116.1	0.90	5.74E-04			
									2	40.9	358.0	114.0	0.88	5.20E-04			
									3	39.9	354.5	112.5	0.87	4.21E-04			
									4	40.9	436.0	93.8	0.72	3.97E-04			
MN5R806	04/21/92	5.60	11.74	8.48E-05	115.5	201.0	192.0	B	0	40.0	231.5	173.0	1.00	5.61E-04	5	NO	
									1	40.2	355.0	113.2	0.65	4.67E-04			
									2	40.6	330.5	122.9	0.71	4.00E-04			
									3	40.6	337.0	120.5	0.70	3.36E-04			
									4	41.1	430.0	95.5	0.55	3.03E-04			
MN5KL03	04/17/92	5.60	6.50	3.06E-06	230.0		236.0	B	0	39.0	158.5	245.8	1.00	2.32E-05	5	D	
									1	38.9	208.5	186.4	0.76	4.82E-05			0.0482
									2	39.0	225.0	172.9	0.70	3.44E-05			0.0700
									3	38.2	251.0	152.1	0.62	3.16E-05			0.0815
									4	41.0	314.0	130.5	0.53	3.29E-05			
MN5KM0	04/19/92	5.60	5.61		287.5		300.0	B	0	39.8	149.5	265.8	1.00		5	D	
									1	39.6	176.0	225.4	0.85	1.59E-05			0.0728
									2	38.8	196.5	197.5	0.74	1.41E-05			0.0939
									3	38.4	210.5	182.5	0.69	1.36E-05			0.1268
									4	39.6	237.0	166.5	0.63	9.73E-06			
MN5KD08	04/17/92	5.60	4.40		340.5		382.0	A	0	39.3	94.9	413.3	1.00		5	D	
									1	40.5	121.5	332.8	0.81	1.01E-05			0.0485
									2	40.3	156.0	258.4	0.63	1.20E-05			0.0887
									3	40.9	195.5	209.0	0.51	1.24E-05			0.1422
									4	40.9	228.0	179.2	0.43	1.03E-05			
MN5KD09	04/19/92	5.60	3.04		394.0		455.0	A	0	39.9	72.4	550.9	1.00		5	D	
									1	40.2	103.5	387.4	0.70	1.05E-05			0.0506
									2	40.7	133.0	306.2	0.56	7.37E-06			0.0906
									3	41.7	175.5	237.9	0.43	1.02E-05			0.1396
									4	40.9	199.0	205.4	0.37	9.51E-06			

Table G.8. Mississippi, SPS-5 (MS5) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
MS5R804	02/29/92	5.90	7.62		255.50	245.00	236.00	B	0	405.5	150.5	269.5	1.00	4.88E-05	20	NO	
									1	41.2	196.5	209.9	0.78	2.22E-04			0.1503
									2	41.6	204.0	203.8	0.76	2.71E-04			0.1599
									3	41.6	212.5	195.5	0.73	2.14E-04			0.1652
MS5R805	02/29/92	5.90	8.03	9.57E-06	209.00	222.00	224.00	A	0	41.9	131.5	319.0	1.00	8.24E-05	20	NO	
									1	45.8	215.0	213.2	0.67	2.64E-04			0.1973
									2	46.1	235.5	195.4	0.61	3.02E-04			0.2356
									3	45.8	236.5	193.6	0.61	2.64E-04			0.2505
MS5KL03	02/22/92	5.90	6.87		284.00	326.00	337.00	A	0	36.0	86.3	416.9	1.00		20	A	
									1	36.9	145.0	257.5	0.62	5.56E-05			0.1590
									2	39.0	148.0	264.0	0.63	7.37E-05			0.2096
									3	38.0	171.0	221.6	0.53	5.42E-05			0.2364
MS5KM04	02/25/92	5.90	5.91		343.00	355.00	371.00	B	0	40.8	96.0	425.0	1.00		20	C	
									1					3.80E-05			0.1718
									2					4.29E-05			0.2443
									3					4.03E-05			0.2955
MS5KH07	02/22/92	5.90	4.05		359.00	445.00	448.00	B	0	40.9	81.4	504.2	1.00		20	C	
									1								
									2								
									3								
MS5KD08	02/25/92	5.90	3.53		381.50	679.00	635.00	A	0	39.0	44.0	887.7	1.00		20	C	
									1								0.1707
									2								0.3403
									3								0.5247

Table.9. Rainier, Oregon (OR1) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
OR1R803	03/11/92	5.20	8.29	3.09E-05	560.0			A	0	44.1	76.6	578.0	1.00	6.25E-04	5	NO	
									1	46.3	103.5	444.8	0.77	7.64E-04			0.0701
									2	44.8	104.4	430.0	0.74	6.57E-04			0.0871
									3	46.5	97.9	474.3	0.82	5.26E-04			0.0974
OR1R804	05/18/92	5.20	7.41	2.35E-05	519.5	789.0	768.0	A	0	40.7	43.0	948.7	1.00	5.46E-04	0	NO	
									1	40.3	48.1	836.4	0.88	8.29E-04			0.0730
									2	40.9	50.7	806.8	0.85	8.08E-04			0.0912
									3	40.9	48.8	838.7	0.88	7.01E-04			0.1047
OR1R806	03/11/92	5.20	7.33	2.34E-05	519.0			B	0	60.4	79.2	530.2	1.00	3.52E-04	5	NO	
									1	42.7	173.4	492.5	0.93	5.03E-04			0.0543
									2	42.7	83.9	508.7	0.96	5.14E-04			0.0596
									3	42.8	455.7	512.3	0.97	4.59E-04			0.0622
OR1KL02	03/18/92	5.20	11.60	8.37E-05	478.0	469.0	468.0	B	0	42.6	85.6	497.7	1.00	1.43E-04	5	NO	
									1	42.7	99.7	427.7	0.86	6.06E-04			0.0519
									2	42.5	98.6	430.9	0.87	5.33E-04			0.0676
									3	42.8	106.5	401.3	0.81	5.88E-04			0.0727
OR1KM04	03/07/92	5.20	9.21		575.5	519.0	519.0	B	0	41.0	81.5	502.2	1.00	6.60E-04	0	B	
									1	41.2	83.8	492.0	0.98	1.03E-04			0.0545
									2	41.5	82.6	502.9	1.00	7.56E-05			0.0611
									3	41.3	81.9	515.0	1.03	5.11E-05			0.0672
OR1KH07	03/18/92	5.20	6.97		741.5	576.0	576.0	A	0	41.8	46.8	894.1	1.00		0	C	
									1	43.0	59.9	718.1	0.80	3.67E-05			0.0431
									2	43.0	58.5	733.9	0.82	2.13E-05			0.0528
									3	41.0	60.8	674.7	0.75	1.59E-05			0.0652
OR1KD08	03/07/92	5.20	6.76		760.0	620.0	650.0	A	0	38.1	51.1	745.5	1.00		0	C	
									1	39.8	58.3	682.5	0.92	7.98E-06			0.0455
									2	39.4	60.9	647.8	0.87	9.83E-06			0.0606
									3	19.7	63.5	626.0	0.84	8.48E-06			0.0720

Table G.10. Bend-Redmond, Oregon (OR2) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
OR2R803	05/13/92	5.80	21.25		68.0	110.0	128.0	B	0	38.5	440.5	87.4	1.00		10	NO	
									1	38.0	485.5	78.2	0.90	3.19E-03			
									2	38.0	486.5	78.0	0.89	2.73E-03			
									3	37.4	484.5	77.3	0.88	2.34E-03			
									4	37.9	474.0	80.0	0.92	2.25E-03			
OR2R804	06/01/92	5.80	20.23		79.0	185.0	197.0	B	0	39.9	38.8	103.0	1.00		5	NO	
									1	40.2	43.0	93.6	0.91	6.11E-04			
									2	40.2	45.0	89.6	0.87	8.16E-04			
									3	39.5	44.4	89.0	0.86	1.08E-03			
									4	41.4	47.1	87.9	0.85	1.07E-03			
OR2KL02	06/03/92	5.80	19.56	1.00E-04		127.0	146.0	B	0	44.7	35.8	124.9	1.00	1.39E-01	20	NO	
									1	39.1	31.3	124.9	1.00	5.51E+00			
									2	39.6	31.7	125.0	1.00	1.04E-01			
									3	41.6	36.4	114.4	0.92	7.00E-02			
									4	40.2	35.6	112.8	0.90	1.31E-01			
OR2KH05	05/05/92	5.80	17.30	8.04E-05	142.5	126.0	121.0	A	0	39.1	196.5	199.2	1.00	3.06E-03	5	NO	
									1	40.9	215.0	190.0	0.95	1.93E-03			
									2	40.2	192.5	208.5	1.05	1.46E-03			
									3	40.6	197.5	205.1	1.03	2.07E-03			
									4	39.4	190.5	206.6	1.04	2.37E-03			
OR2KH06	05/05/92	5.80	16.17	1.01E-04	171.0	195.0	205.0	B	0	40.9	228.5	178.4	1.00	4.27E-03	5	NO	
									1	39.5	254.0	155.6	0.87	2.90E-03			
									2	40.4	258.0	156.5	0.88	3.28E-03			
									3	40.0	254.0	157.2	0.88	2.35E-03			
									4	40.1	242.0	165.5	0.93	3.38E-03			
OR2KD08	05/13/92	5.80	18.09		120.0	168.0	173.0	A	0	38.9	182.0	213.8	1.00	9.78E-06	10	NO	
									1	39.9	200.0	199.1	0.93	8.55E-04			
									2	40.0	196.5	203.5	0.95	5.07E-04			
									3	39.7	195.0	203.8	0.95	6.21E-04			
									4	39.7	188.5	210.9	0.99	6.29E-05			
OR2KD09	06/01/92	5.80	16.73	4.25E-05	138.0	166.0	181.0	A	0	34.5	159.5	215.9	1.00	3.16E-04	5	NO	
									1	35.1	214.5	163.6	0.76	9.47E-04			
									2	35.0	211.0	166.1	0.77	8.21E-04			
									3	35.7	203.5	174.9	0.81	6.39E-04			
									4	35.4	210.5	167.9	0.78	6.20E-04			

Table G.11. Mount Baker, Washington (WA1) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/s)	Visual Stripping (%)	Binder Migration	Deformation (in.)
WA1R804	04/26/92	5.21	6.99	1.76E-05	238.0	294.0	286.0	A	0	39.8	123.0	322.9	1.00	4.15E-04	0	NO	
									1	40.2	148.0	270.9	0.84	1.83E-04			0.1105
									2	40.9	145.0	281.7	0.87	2.59E-04			0.1204
									3	40.9	148.0	276.3	0.86	2.42E-04			0.1298
									4	40.7	155.0	263.9	0.82	2.07E-04			
WA1R805	04/26/92	5.21	6.64	5.57E-06	240.5	283.0	291.0	B	0	39.2	169.0	232.2	1.00	6.81E-05	0	NO	
									1	38.9	188.0	206.6	0.89	1.41E-04			0.0632
									2	39.6	183.5	213.8	0.92	1.37E-04			0.0707
									3	39.5	180.0	219.6	0.95	1.45E-04			0.0729
									4	40.0	169.5	235.9	1.02	1.32E-04			
WA1KL20	04/28/92	5.21	11.42	6.89E-06	207.0	315.0	309.0	B	0	41.0	169.0	243.2	1.00	9.58E-05	5	D	
									1	39.3	195.0	201.7	0.83	1.21E-04			0.0138
									2	39.0	186.0	209.8	0.86	1.39E-04			0.0142
									3	39.2	180.0	217.8	0.90	2.04E-04			
									4	40.0	172.0	233.3	0.96	2.43E-04			
WA1KL21	04/30/92	5.21	10.33		252.0	299.0	315.0	B	0	41.2	149.0	277.0	1.00		5	E	
									1	39.5	159.0	247.8	0.89	6.90E-05			0.0217
									2	39.6	162.0	244.2	0.88	6.70E-05			0.0245
									3	39.5	208.5	189.4	0.68				0.0263
									4	40.9	201.0	203.2	0.73				
WA1KM22	05/26/92	5.21	10.34		235.0	300.0	302.0	A	0	41.0	100.5	405.8	1.00		5	E	
									1	40.5	133.0	303.5	0.75	5.44E-05			0.0265
									2	40.7	142.0	286.3	0.71	4.10E-05			0.0366
									3	40.6	138.0	293.8	0.72	5.03E-05			0.0457
									4	40.0	129.5	308.3	0.76	5.83E-05			
WA1KD07	04/28/92	5.21	7.28		342.0	511.0	487.0	A	0	42.0	104.5	402.3	1.00		5	E	
									1	41.8	104.0	402.5	1.00				0.0223
									2	41.1	98.0	418.1	1.04				0.0311
									3	40.7	91.9	442.1	1.10				
									4	41.2	95.0	434.0	1.08				
WA1KD26	04/30/92	5.21	8.59		322.0	378.0	383.0	A	0	40.2	91.9	437.2	1.00		5	F	
									1	39.9	112.0	354.9	0.81				0.0268
									2	39.1	112.0	348.2	0.80				0.0392
									3	37.6	132.5	283.3	0.65				0.0497
									4	36.0	90.2	399.8	0.91				
WA1KD27	05/26/92	5.21	9.07		328.0	374.0	371.0	B	0	40.1	141.5	283.5	1.00		5	F	
									1	39.2	160.0	244.8	0.86				0.0232
									2	38.7	163.5	236.8	0.84				0.0260
									3	39.4	164.5	238.6	0.84				0.0294
									4	40.0	153.5	259.8	0.92				

Table G.12. Wisconsin, AAMAS (WIA) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri. c. strn (ksi)	ECS Sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr Ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration	Deformation (in.)
WIAR804	03/04/92	5.30	3.40		268.5	338.0	338.0	A	0	42.8	137.0	311.8	1.00		5	NO	
									1	47.8	247.0	201.9	0.65	1.63E-05			0.1933
									2	49.3	233.5	210.9	0.68	1.77E-05			0.2493
									3	50.8	248.5	204.3	0.66	1.65E-05			0.2980
									4	50.9	226.5	224.7	0.72	1.50E-05			
WIAR805	03/04/92	5.30	3.46		281.5	293.0	303.0	B	0	41.0	126.5	323.6	1.00		5	NO	
									1	41.4	192.0	215.8	0.67	1.74E-05			0.1878
									2	41.9	183.0	229.2	0.71	1.90E-05			0.2393
									3	42.1	177.0	238.1	0.74	1.68E-05			0.2638
									4	42.0	165.0	254.2	0.79	1.80E-05			
WIAKL01	03/02/92	5.30	3.32		306.0	637.0	574.0	B	0	41.1	82.5	498.2	1.00		5	NO	
									1	41.7	167.5	248.9	0.50				
									2	41.8	151.0	277.6	0.56				
									3	41.9	134.5	311.4	0.62				
									4	41.8	130.0	320.6	0.64				
WIAKM08	03/02/92	5.30	1.81		349.0	421.0	446.0	B	0	42.2	107.0	394.1	1.00		5	NO	
									1	45.9	170.5	269.1	0.68				
									2	47.7	184.0	259.6	0.66				
									3	49.7	21.3	233.0	0.59				
									4	48.7	194.5	250.7	0.64	8.07E-06			
WIAKH15	02/27/92	5.30	1.37		315.0	476.0	475.0	B	0	41.1	81.2	505.4	1.00		5	NO	
									1	42.0	129.5	324.3	0.64				
									2	43.0	117.5	366.5	0.73				
									3								
									4								
WIAKD18	05/30/92	5.30	0.60		370.0	446.0	475.0	B	0	40.9	111.5	367.1	1.00		5	NO	
									1	39.9	118.0	338.0	0.92				0.1214
									2	40.1	131.0	306.3	0.83				0.1494
									3	40.5	145.5	277.5	0.76				0.1730
									4	41.6	131.5	316.8	0.86				
WIAKD19	02/27/92	5.30	0.69		366.5	475.0	473.0	A	0	42.8	100.9	424.5	1.00		5	NO	
									1	47.3	135.5	348.3	0.82	1.78E-05			
									2	53.8	184.0	293.3	0.69				
									3	56.7	185.5	306.6	0.72	7.20E-06			
									4	53.5	151.5	354.3	0.83	7.46E-06			

Table G.13. Arizona Slurry Seal (AZF) and Colorado A (COA) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
AZF06	1/24/93		3.3	--	492.5			A	0	46.1	64.5	717.5	1.00	--	40	10
									1	41.5	63.7	651.2	0.91	--		
									2	45.6	65.3	698.3	0.97	--		
									3	37.8	63.4	596.3	0.83	--		
AZF07	1/24/93		4.1	--	558.0			B	0	44.1	63.9	691.0	1.00	--	50	10
									1	25.6	64.6	398.3	0.58	--		
									2	24.9	66.2	375.9	0.54	--		
									3	17.8	60.8	292.2	0.42	--		
AZF08	3/17/93		3.6	--	447.0			B	0	38.8	108.0	359.3	1.00	--	20	20
									1	39.2	107.0	366.2	1.02	--		
									2	38.8	110.0	352.2	0.98	--		
									3	38.9	108.3	359.2	1.00	--		
COA05	11/29/92		8.3	2.80E-05	502.5	634.0	562.0	A	0	45.8	59.7	801.5	1.00	2.07E-05	5	NO
									1	45.1	124.0	363.6	0.45	1.77E-07		
									2	40.3	117.5	343.2	0.43	--		
									3	40.0	136.5	292.7	0.37	--		
									4	34.6	116.5	296.3	0.37	1.55E-07		
COA22	11/29/92		8.8	3.30E-05	516.0	461.0	453.0	B	0	33.6	79.6	421.6	1.00	7.3E-05	5	NO
									1	17.5	95.8	339.1	0.80	6.14E-05		
									2	28.9	88.3	326.8	0.78	5.25E-05		
									3	29.3	91.2	321.0	0.76	4.22E-05		
									4	29.4	93.2	315.4	0.75	2.31E-05		
COA33	12/17/92		8.3	8.09E-06	521.5	848	713	A	0	45.1	60.3	747.8	1.00	--	5	NO
									1	26.5	59.9	441.5	0.59	3.59E-06		
									2	25.2	66.1	381.7	0.51	3.59E-06		
									3	20.3	59.9	341.35	0.46	--		
									4	24.4	64.9	375.95	0.50	6.63E-06		

Table G.14. Colorado B (COB) and Colorado C (COC) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
COB27	12/1/92		5.4	--	775.0	1360.0	973.0	B	0	35.9	54.4	660.5	1.00	--	10	A
									1	38.6	52.4	736.9	1.12			
									2	38.3	56.5	677.7	1.03			
									3	38.2	55.1	693.0	1.05			
									4	39.3	46.0	648.5	0.98			
COB31	12/17/92		5.1	--	771.5	1204	941	B	0	38.0	52.3	729.0	1.00	--	10	A
									1	41.2	53.4	772.1	1.06			
									2	40.2	61.1	658.8	0.90			
									3	37.5	58.4	643.4	0.88			
									4	34.9	58.7	594.0	0.81			
COB34	12/1/92		4.5	--	770.0	1113.0	912.0	A	0	45.7	24.6	1871.1	1.00	--	10	A
									1	41.2	28.4	1453.3	0.78	--		
									2	41.6	29.8	1409.3	0.75	--		
									3	41.9	27.8	1531.9	0.82	8.43E-06		
									4	41.4	34.9	1188.8	0.64	9.66E-06		

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
COC12	1/20/93		11.1	3.50E-05	473.0			A	0	46.9	63.3	740.9	1.00	3.09E-06	20	NO
									1	26.3	62.1	422.9	0.57	1.55E-07		
									2	23.4	66.8	349.4	0.47	1.02E-06		
									3	21.5	66.8	322.2	0.43	7.31E-07		
									4	16.0	65.5	246.7	0.33	6.44E-06		
COC16	1/20/93		10.6	3.00E-05	478.5			B	0	43.0	95.3	450.8	1.00	1.74E-04	20	NO
									1	34.5	97.1	355.0	0.79	2.98E-05		
									2	33.4	101.5	329.6	0.73	1.47E-05		
									3	32.5	109.5	346.3	0.77	8.36E-06		
									4	28.4	107.0	264.5	0.59	5.64E-06		

Table G.15. Colorado E (COE) and Georgia Field (GAF) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
COE26	1/18/93		8.2	--	571.5			A	0	46.3	62.7	739.0	1.00	3.59E-06	20	NO
									1	41.5	65.4	634.1	0.86	4.33E-06		
									2	76.7	65.1	589.7	0.80	7.00E-06		
									3	35.6	64.5	553.0	0.75	5.99E-06		
									4	34.1	67.0	509.1	0.69	2.65E-06		
COE32	1/18/93		7.5	2.60E-06	571.0			B	0	42.3	87.0	485.4	1.00	2.84E-06	20	NO
									1	36.1	93.7	385.0	0.79	4.10E-06		
									2	34.2	95.3	358.4	0.74	3.16E-06		
									3	33.25	91.45	363.6	0.75	5.95E-06		
									4	32.7	93.9	348.0	0.72			
GAF04	1/25/93		11.7	6.40E-05	128.5			A	0	27.0	127.0	213.3	1.00	2.72E-04	20	NO
									1	6.7	119.0	55.6	0.26	9.69E-06		
									2	6.3	127.5	49.3	0.23			
									3	5.8	111.1	52.7	0.25			
GAF05	11/29/92		9.9	3.50E-05	136.5			B	0	21.2	100.2	212.3	1.00	6.24E-05	20	NO
									1	7.1	145.5	48.5	0.23			
									2	6.7	154.0	43.4	0.20			
									3	6.6	159.5	41.1	0.19			

Table G.16. Louisiana Field (LAF) and The Asphalt Institute Non-Stripping Mixture (TAI) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
LAF01B	12/3/92			–	541.0	439.0	416.0	A	0	46.7	64.4	726.4	1.00	–	5 gray agg. stripped	A
									1							
									2							
									3							
									4							
LAF03A	12/3/92			–	686.5	1023.0	847.0	B	0	43.3	65.7	657.8	1.00	–	30 Orange agg. stripped	B gray agg. no strip
									1	20.4	66.8	303.1	0.46			
									2	24.7	64.0	385.3	0.59			
									3	28.0	66.8	424.8	0.65			
									4							

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
TAI09	1/22/93		9.0	2.10E-05	487.0			A	0	47.9	64.3	745.3	1.00	5.12E-05	30	NO
									1	38.7	63.8	607.0	0.81	3.95E-06		
									2	36.7	62.8	587.7	0.79			
									3	32.1	62.1	517.0	0.69			
									4	37.3	65.8	567.3	0.76	6.30E-05		
TAI39	1/22/93		8.5	1.30E-05	493.5			B	0	44.1	74.0	596.2	1.00	5.55E-05	30	NO
									1	35.3	78.3	450.2	0.76	4.15E-04		
									2	30.7	74.3	414.9	0.70	3.77E-04		
									3	27.6	77.2	358.5	0.60	3.86E-04		
									4	27.9	77.5	360.2	0.60	3.24E-04		

Table G.17. Wyoming (WYO) ECS test data

Specimen ID	Date Tested	Asph. Cont. (%)	Air Voids (%)	Air Perm. (cm/sec)	MTS Dia. (ksi)	MTS Tri. c. strs (ksi)	MTS Tri c. strn (ksi)	ECS sys.	Cond. cycle	ECS Stress (psi)	ECS Strain (micro)	ECS Mr (ksi)	ECS Mr ratio	Water Perm. (cm/sec)	Visual Stripping (%)	Binder Migration
WYO02	11/17/92		8.6	2.50E-05	438.0	487.0	477.0	A	0	35.4	78.0	453.6	1.00	8.14E-05	40	NO
									1	20.6	91.7	224.9	0.50	6.43E-06		
									2	12.9	79.3	162.5	0.36			
									3	9.6	86.3	111.8	0.25			
									4	9.5	84.7	111.9	0.25			
WYO05	11/17/92		8.0	1.60E-05	492.5	482.0	456.0	B	0	30.3	80.2	376.8	1.00	7.02E-05	30	NO
									1	21.1	91.7	229.4	0.61	1.11E-05		
									2	15.1	100.7	149.1	0.40			
									3	9.3	104.0	84.3	0.22			
									4	8.7	98.7	88.7	0.24			

Appendix H

Field Core Data

Table H.1. Field core data

Core ID	Location	Air voids (%)	Height (in.)	MTS Dia. Mr (ksi)	MTS Tri. Mr c. strs (ksi)	MTS Tri. Mr c. strn (ksi)	Calc. int. MTS Dia. Mr (ksi)	Dia. Modulus Ratio	Calc. int. MTS Tri. Mr (strs) (ksi)	Tri. Modulus Ratio
AB5F01	bwp	1.25	2.273	138.0			293.8	0.47		
AB5F02	bwp	1.08	2.265	158.0			298.8	0.53		
AB5F01B	bwp	1.31	2.442	196.0			292.1	0.67		
AB5F02B	bwp	1.08	2.533	216.0			298.6	0.72		
AB5F05	bwp	1.17	3.950	140.0	190.0	176.0	296.1	0.47	302.3	0.63
AB5F06	bwp	1.54	2.302	162.0			285.5	0.57		
AB5F06B	bwp	2.12	2.427	192.0			269.0	0.71		
AB5F09	wp	0.98	4.010	160.0	278.0	289.0	301.4	0.53	306.9	0.91
AB5F10	wp	1.53	4.040	156.0	226.0	243.0	286.0	0.55	293.6	0.77
AB5F11	wp	1.58	4.003	150.5	234.0	252.0	284.6	0.53	292.4	0.80
AB5F12	wp	1.39	4.010	160.5	218.0	215.0	289.8	0.55	296.9	0.73
AZ5F01	bwp	5.50	4.044	1310.0	975.0	992.0	1038.1	1.26	1341.2	0.73
AZ5F02	bwp	4.77	3.73	1280.0	1098.0	1071.0	1098.2	1.17	1448.4	0.76
AZ5F03	wp	4.61	4.014	1171.0	711.0	1012.0	1110.8	1.05	1470.9	0.48
AZ5F04	bwp	5.06	3.887	1329.0	1506.0	1573.0	1074.5	1.24	1406.1	1.07
AZ5F05	bwp	5.19	4.032	1156.0	3169.0	2616.0	1063.4	1.09	1386.3	2.29
AZ5F06	wp	4.56	3.667	1259.0	1740.0	1850.0	1115.1	1.13	1478.5	1.18
AZ5F07	bwp	4.46	3.987	1201.0	1037.0	1300.0	1123.0	1.07	1492.6	0.69
AZ5F08	bwp	4.95	4.068	961.0	1975.0	1726.0	1083.7	0.89	1422.4	1.39
AZ5F09	wp	4.15	4.012	1108.0	1504.0	1599.0	1148.5	0.96	1538.0	0.98
AZ5F10	bwp	4.43	3.979	1248.0	961.0	1239.0	1125.8	1.11	1497.5	0.64
AZ5F11	bwp	4.86	3.95	1104.0	3279.0	2334.0	1090.9	1.01	1435.4	2.28
AZ5F12	wp	4.40	3.974	1230.0	2954.0	1707.0	1128.3	1.09	1501.9	1.97
CABF01	bwp	5.63	4.018	511.0	1192.0	1036.0	756.5	0.68	944.4	1.26
CABF02	bwp	5.59	3.985	529.0	733.0	728.0	760.3	0.70	946.7	0.77
CABF03	bwp	5.51	4.031	491.0	1395.0	1683.0	766.6	0.64	950.3	1.47
CABF04	bwp	5.68	3.995	464.0	1208.0	946.0	752.9	0.62	942.4	1.28
CABF05	bwp	5.77	4.024	481.0	375.0	405.0	745.2	0.65	937.9	0.40
CABF06	bwp	5.37	4.014	466.0	534.0	552.0	778.4	0.60	957.1	0.56
CABF07	wp	5.47	4.011	658.0	846.0	954.0	770.4	0.85	952.5	0.89
CABF08	wp	5.66	4.008	490.0	585.0	571.0	753.9	0.65	942.9	0.62
CABF09	wp	5.18	3.992	598.0	1085.0	928.0	793.9	0.75	966.1	1.12
CABF10	wp	5.30	4.018	697.0	642.0	635.0	784.0	0.89	960.4	0.67
CABF11	wp	5.75	3.975	624.0	1692.0	1101.0	746.7	0.84	938.8	1.80
CABF12	wp	5.14	4.017	566.0	841.0	820.0	797.5	0.71	968.2	0.87
CABF13	wp	4.98	3.995	587.0	773.0	695.0	810.9	0.72	976.0	0.79
CABF14	wp	4.78	3.986	619.0	2566.0	1630.0	827.4	0.75	985.6	2.60
CABF15	wp	5.57	9.932	494.0	948.0	993.0	762.1	0.65	947.6	1.00
CABF16	wp	5.94	3.973	550.0	546.0	571.0	731.1	0.75	929.7	0.59
CADF01	bwp	4.97	4.046	586.0	827.0	810.0	1050.0	0.56	1366.2	0.61
CADF02	bwp	5.31	4.066	681.0	1897.0	1445.0	1020.7	0.67	1326.2	1.43
CADF03	bwp	6.10	4.068	572.0	753.0	770.0	953.4	0.60	1234.3	0.61
CADF04	bwp	6.47	2.723	794.0			921.3	0.86		
CADF05	bwp	5.17	4.029	649.0	1646.0	1535.0	1032.7	0.63	1342.7	1.23
CADF06	bwp	5.46	2.73	780.0			1007.6	0.77		
CADF07	wp	6.01	4.04	560.0	1082.0	1053.0	961.0	0.58	1244.7	0.87
CADF08	wp	6.73	4.04	589.0	600.0	629.0	899.6	0.65	1160.8	0.52
CADF09	wp	7.03	4.039	617.0	71.0	822.0	874.0	0.71	1125.9	0.63
CADF10	wp	5.88	3.99	640.0	1039.0	934.0	971.8	0.66	1259.5	0.82
CADF11	wp	5.54	3.954	619.0	1015.0	1011.0	1000.8	0.62	1299.1	0.78
CADF12	wp	5.69	4.005	651.0	4106.0	2345.0	988.5	0.66	1282.2	3.20
CADF13	wp	6.16	4.022	646.0	1775.0	1216.0	947.6	0.68	1226.4	1.45
CADF14	wp	5.49	3.999	667.0	968.0	1002.0	1005.2	0.66	1305.1	0.74
CADF15	wp	5.96	3.97	669.0	1033.0	972.0	965.1	0.69	1250.3	0.83
CADF16	wp	6.42	1.953	814.0			925.6	0.88		

Table H.1. Field core data (continued)

Core ID	Location	Air voids (%)	Height (in.)	MTS Dia. Mr (ksi)	MTS Tri. Mr c. strs (ksi)	MTS Tri. Mr c. strn (ksi)	Calc. int. MTS Dia. Mr (ksi)	Dia. Modulus Ratio	Calc. int. MTS Tri. Mr (strs) (ksi)	Tri. Modulus Ratio
CAGF01	bwp	6.08	3.052	330.0			415.9	0.79		
CAGF02	bwp	5.75	3.000	388.0			436.7	0.89		
CAGF03	bwp	5.77	2.882	360.5			435.4	0.83		
CAGF04	bwp	6.31	3.080	332.0			401.3	0.83		
CAGF05	bwp	6.22	2.966	367.0			407.1	0.90		
CAGF06	bwp	6.17	2.921	363.0			409.9	0.89		
CAGF07	wp	6.37	3.113	352.0			397.3	0.89		
CAGF08	wp	5.77	3.034	354.5			435.5	0.81		
CAGF09	wp	5.22	2.656	396.5			469.6	0.84		
CAGF10	wp	5.32	2.670	360.5			463.8	0.78		
CAGF11	wp	5.07	2.517	373.5			479.1	0.78		
CAGF12	wp	5.29	2.721	381.5			465.2	0.82		
CAGF13	wp	5.05	2.655	428.0			480.8	0.89		
CAGF14	wp	4.88	2.699	444.0			491.4	0.90		
CAGF15	wp	5.19	2.587	441.5			471.6	0.94		
CAGF16	wp	4.75	2.738	395.5			499.5	0.79		
CAGF17	bwp	5.973	2.925	384.5			422.4	0.91		
CAGF18	bwp	6.243	3.101	402.5			405.5	0.99		
CAGF19	bwp	6.026	2.986	382.5			419.1	0.91		
CAGF20	bwp	6.668	2.987	423.5			378.7	1.12		
CAGF21	bwp	6.241	3.197	363			405.6	0.90		
CAGF22	bwp	5.942	2.913	419			424.4	0.99		
CAGF23	wp	4.744	2.843	472.5			499.8	0.95		
CAGF24	wp	5.205	2.809	455			470.8	0.97		
CAGF25	wp	5.071	2.701	494			479.2	1.03		
CAGF26	wp	5.559	2.716	444.5			448.5	0.99		
CAGF27	wp	6.455	2.693	479.5			392.1	1.22		
CAGF28	wp	5.255	2.651	501			467.6	1.07		
GAAF01A	wp	8.45	3.970	327.0	303.0	282.0	454.5	0.72	434.3	0.70
GAAF02A	wp	7.23	2.123	320.0			508.0	0.63		
GAAF03A	wp	7.23	3.948	361.0	368.0	363.0	508.3	0.71	515.9	0.71
GAAF04A	wp	7.17	2.795	319.0			510.6	0.62		
GAAF05A	wp	10.23	3.495	237.0	319.0	319.0	376.6	0.63	316.1	1.01
GAAF06A	wp	8.09	2.645	378.0			470.6	0.80		
GAAF01B	bwp	7.35	4.030	329.0	1010.0	663.0	503.0	0.65	507.8	1.99
GAAF02B	bwp	8.29	3.893	293.0	373.0	366.0	461.7	0.63	445.2	0.84
GAAF03B	bwp	7.38	2.587	352.0			501.6	0.70		
GAAF04B	bwp	7.02	2.858	360.0			517.5	0.70		
GAAF05B	bwp	9.78	3.880	229.0	384.0	377.0	396.2	0.58	345.9	1.11
GAAF06B	bwp	8.69	3.977	275.0	555.0	525.0	444.3	0.62	418.8	1.33
MN5F01	wp	4.76	4.087	286.5	544.0	487.0	306.1	0.94	350.9	1.55
MN5F03	wp	4.42	4.127	290.0	289.0	285.0	320.7	0.90	372.4	0.78
MN5F06	wp	4.76	3.957	284.5	535.0	503.0	306.2	0.93	351.1	1.52
MN5F07	wp	4.86	4.023	245.5	574.0	464.0	302.0	0.81	344.8	1.66
MN5F08	wp	4.34	4.012	283.0	511.0	459.0	324.3	0.87	377.7	1.35
MN5F15	wp	5.16	3.997	295.0	642.0	526.0	289.0	1.02	325.8	1.97
MN5F18	bwp	6.66	3.981	154.5	323.0	292.0	224.5	0.69	231.0	1.40
MN5F21	bwp	6.66	4.027	174.5	351.0	351.0	224.5	0.78	231.0	1.52
MN5F22	bwp	6.07	3.993	184.5	828.0	553.0	249.9	0.74	268.3	3.09
MN5F23	bwp	6.72	4.050	153.0	231.0	240.0	221.8	0.69	227.0	1.02
MN5F24	bwp	7.07	4.008	149.5	297.0	313.0	206.8	0.72	204.9	1.45
MN5F26	bwp	6.03	3.996	191.0	295.0	295.0	251.3	0.76	270.4	1.09
MS5F01	bwp	6.31	2.089	382.5			336.4	1.14		
MS5F02	wp	4.56	2.157	371.0			350.4	1.06		
MS5F03	bwp	6.31	2.093	365.5			336.4	1.09		
MS5F04	wp	4.27	1.993	389.5			352.7	1.10		
MS5F05	bwp	6.50	1.928	341.0			334.9	1.02		
MS5F07	bwp	6.25	2.090	386.0			336.9	1.15		
MS5F08	wp	4.33	1.961	373.5			352.2	1.06		

Table H.1. Field core data (continued)

Core ID	Location	Air voids (%)	Height (in.)	MTS Dia. Mr (ksi)	MTS Tri. Mr c. strs (ksi)	MTS Tri. Mr c. stm (ksi)	Calc. int. MTS Dia. Mr (ksi)	Dia. Modulus Ratio	Calc. int. MTS Tri. Mr (strs) (ksi)	Tri. Modulus Ratio
OR1F01	wp	6.39	2.253	319.5			744.3	0.43		
OR1F02	wp	7.58	2.318	394.5			689.1	0.57		
OR1F03	bwp	10.14	1.971	332.5			570.2	0.58		
OR1F04	bwp	9.14	1.868	348.0			616.4	0.56		
OR1F05	wp	12.60	1.832	586.5			455.8	1.29		
OR1F06	wp	11.69	2.008	519.5			497.9	1.04		
OR1F07	wp	14.50	1.910	197.0			367.4	1.01		
OR1F08	wp	13.38	1.769	307.5			420.6	1.07		
OR1F09	bwp	15.14	2.037	299.5			337.9	1.13		
OR1F10	bwp	17.43	1.997	177.5			231.2	1.52		
OR1F11	wp	13.76	1.931	224.5			402.1	0.91		
OR1F12	wp	14.10	1.810	243.0			386.1	1.01		
OR2F01	wp	13.19	1.898	147.0			209.4	0.70		
OR2F02	wp	14.81	1.910	157.0			182.6	0.86		
OR2F03	wp	14.45	1.942	132.5			188.5	0.70		
OR2F04	wp	14.89	1.910	140.5			181.3	0.78		
OR2F05	wp	13.74	2.178	138.5			200.2	0.69		
OR2F06	wp	12.85	2.117	126.0			214.9	0.59		
OR2F07	wp	12.82	2.155	100.5			215.3	0.47		
OR2F08	wp	14.03	2.255	109.0			195.5	0.56		
OR2F09	bwp	14.62	2.138	114.5			185.7	0.62		
OR2F10	bwp	14.91	2.132	88.0			180.9	0.49		
OR2F11	bwp	15.51	2.290	117.5			170.9	0.69		
OR2F12	bwp	14.97	2.078	102.0			179.9	0.57		
WA1F01	bwp	9.19	2.415	307.5			288.7	1.06		
WA1F02	bwp	8.67	2.604	308.0			302.8	1.02		
WA1F03	bwp	8.82	2.64	278.5			298.6	0.93		
WA1F04	bwp	9.85	2.654	335.5			270.9	1.24		
WA1F05	bwp	9.98	2.377	383.0			267.6	1.43		
WA1F06	bwp	9.92	2.368	360.5			269.1	1.34		
WA1F07	wp	7.67	2.559	330.5			329.7	1.00		
WA1F08	wp	7.51	2.374	328.5			333.9	0.98		
WA1F09	wp	7.75	2.837	307.5			327.4	0.94		
WA1F10	wp	7.58	2.638	326.0			332.1	0.98		
WA1F11	wp	7.73	2.474	335.5			328.0	1.02		
WA1F12	wp	7.70	2.787	297.5			328.7	0.91		
WIAF02	bwp	3.50	2.498	359.0			316.8	1.13		
WIAF03	bwp	3.64	2.669	366.0			314.4	1.16		
WIAF04	bwp	3.58	2.766	358.0			315.5	1.13		
WIAF05	bwp	4.46	2.633	374.0			301.3	1.24		
WIAF06	bwp	4.68	2.639	377.0			297.7	1.27		
WIAF07	wp	4.49	2.726	332.0			300.7	1.10		
WIAF08	wp	3.31	2.56	369.0			319.8	1.15		
WIAF09	wp	3.63	2.598	392.0			314.6	1.25		
WIAF10	wp	3.70	2.498	376.0			313.5	1.20		
WIAF11	wp	4.34	3.106	377.0			303.2	1.24		
WIAF12	wp	3.75	3.049	343.0			312.7	1.10		
WIAF13	wp	4.13	3.064	335.0			306.6	1.09		
WIAF14	wp	4.21	2.964	394.0			305.2	1.29		
WIAF15	wp	4.18	2.907	384.0			305.7	1.26		
WIAF16	wp	3.70	2.776	396.0			313.5	1.26		