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Field Validation of the Environmental Conditioning System

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Abstract

This research, conducted as part of the SHRP A-003A contract at Oregon State University (OSU), was designed to validate that the Environmental Conditioning System (ECS) can differentiate among asphalt concrete mixtures that will perform well or poorly in the field with regard to water sensitivity. Twelve test sections were identified, at least two in each of the four SHRP environmental regions: Wet-Freeze, Dry-Freeze, Wet-No Freeze and Dry-No Freeze. From these 12 sections, specimens were prepared using the original mix design (or mix design as identified by extractions), original aggregates, asphalt and admixtures. Specimens were tested using three procedures: (1) ECS, (2) the OSU wheel tracker, and (3) the Elf asphalt wheel tracker. Cores were taken from the field test sections to evaluate performance of the mixture in the pavement.

The performance of the mixtures in each of the test procedures was compared in an attempt to develop a correlation among procedures. Results indicate that the ECS test procedure can distinguish among the relative performance of mixtures, with regard to water sensitivity, as measured in the field and by the OSU and Elf wheel trackers. However, the age of the sections in the field is still relatively young, and water damage is expected to manifest itself in the future in those pavements identified as water sensitive.

Executive Summary

The work was completed by the A-003A contractor to the Strategic Highway Research Program (SHRP) for Task C.5 on the evaluation of water sensitivity of asphalt concrete mixtures. The testing included three phases: (1) laboratory development of procedures and criteria, (2) validation of the laboratory testing with accelerated laboratory "torture" tests, and (3) field verification of both the laboratory testing program and the accelerated laboratory test. This document reports the findings from the third phase, field verification.

The first stage of the A-003A work conducted at Oregon State University (OSU) involved the development of the Environmental Conditioning System (ECS), which subjects asphalt mixture specimens to a series of conditioning cycles, including water flow, elevated or lowered temperature, and repeated axial loading (Terrel and Al-Swailmi 1992). Phase two included validation of the ECS procedure with the OSU wheel tracker (French Laboratoire Central des Pont et Chaussees rutting tester) and the SWK/UN rutting tester, as simulations of the effect of traffic loading on the mixture (Scholz et. al. 1992). Specimens prepared for the OSU wheel tracker were water and temperature conditioned in a manner analogous to that of the ECS procedure.

The final phase of the project involved developed correlations among the ECS, OSU wheel tracker, and the field specimens to verify that ECS can discriminate among different performance levels of mixtures in the field, and that the OSU wheel tracker is an appropriate simulation of field conditions. Additional wheel tracking tests were performed by Elf Asphalt in Terre Haute, Indiana, on several of the mixtures. This information is included to represent a different type of wheel tracking test apparatus.

The purpose of this portion of the SHRP A-003A program was to demonstrate that the ECS test can accurately discriminate between superior and inferior asphalt concrete mixtures determined by their performance in full-scale field test sections. In addition, the correlation among the performance of mixtures in the ECS, OSU wheel tracker, and field sections was also verified. The verification effort differs from the previous work conducted under this portion of the A-003A project in that all the mixtures used were designed by the local authority in whose jurisdiction the field section was placed. Other asphalt-aggregate mixtures tested in the SHRP program were prepared according to mix designs developed by the SHRP A-003A team at the University of California, Berkeley.

This document presents the testing procedures, results, and analysis of data for the twelve asphalt-aggregate mixtures tested in the ECS, OSU wheel tracker, Elf wheel tracker, and full-scale field test sections. The analysis of data correlates the performance of these mixtures when subjected to the four types of moisture conditioning inherent in either the test apparatus or geographical location in which the asphalt mixture was used.

Twelve field sites were selected for the A-003A water sensitivity field validation effort. Sites were selected on the basis of availability of a minimum of 300 lbs. of usable blended aggregate, 3 gals. (11.4 l) of asphalt cement, required admixtures, mix design information, and cooperation from the presiding authority for field coring. Also, at least two sites were selected from each of the four SHRP environmental zones. Furthermore, the sites chosen had to be as old as possible so that there would be several seasons of natural environmental conditioning in the field.

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

The testing program for the A-003A field validation of water sensitivity of asphalt concrete mixtures involves specimens manufactured by three methods and tested in one or more of test procedures. Specimens were fabricated using one of the following: a laboratory kneading compactor, a laboratory roller compactor, or field compaction in place at the test section site. Laboratory-compacted specimens were manufactured at OSU, and field cores were obtained by the cooperating agencies.

The specimens manufactured at OSU were made from mix designs obtained by SHRP from the agency responsible for paving the site. Original aggregate, asphalt and admixtures were obtained and processed prior to mixing and compacting the specimens. Two mixing processes were used to prepare laboratory specimens for the field validation of water sensitivity effort. Individual, 4 in. × 4 in. (101.6 mm × 101.6 mm) specimens were mixed using protocols developed by the SHRP A-003A study team based upon ASTM D-1561-81a. Large slabs were mixed using protocols developed for the roller-compacted test specimens. Eight individual specimens and one large slab were manufactured for 11 of the 12 test mixtures. (There was not enough material available from one section for construction of OSU wheel tracker beams.) Two OSU wheel tracker beams, 19 in. × 6-1/2 in. × 4 in. (482.6 mm × 165.1 mm × 101.6 mm) and eight cores for use in the ECS were sawed from each large slab.

In addition, the governing agency for each site was requested to take cores from the site during the 1990-1991 period as the sites were identified. Eight cores were requested from each site, four from the outside wheel path, and four from between the wheel paths.

Each program under SHRP A-003A Task C.5 (ECS, OSU wheel tracking, Elf wheel tracking, and field) employed specimen conditioning in its test procedure, that subjected the specimen to water damage, followed by measurement of rutting (OSU and Elf wheel trackers) or reduction in modulus (ECS, rutted beam, and field) and visual evaluation of the degree of stripping. The performance indicator used for each test procedure was rutting—a ratio of conditioned to unconditioned modulus—which develops correlations among test procedures.

The analysis of the data from the testing program resulted in specifications for the use of ECS in a mix design program. Three levels of mix design are under consideration in the proposed SHRP mix design program (Superpave): **level 1**, low-traffic-volume roads; **level 2**, secondary routes, intermediate-traffic-volume roads; and **level 3**, primary state routes, high-speed and high-volume roads.

As designed in the laboratory, mixtures selected in the preliminary volumetric mix design will be subjected to short-term oven aging before compaction into specimens for ECS. The preliminary mixture design will determine the aggregate and asphalt type to be used, 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. These air void levels were chosen in accordance with the pessimum voids theory proposed by Terrel and Al-Swailmi (1992). Two specimens will be compacted at each level.

Two specimens of a given mixture and equal air void level will be run through the ECS procedure, using three or four cycles. The fourth or freeze cycle is optional for use in environments that 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 that performed well in ECS, OSU wheel tracker, and the field from those that showed deterioration in the OSU wheel tracker or the field. It is therefore recommended that the following procedure be used for Superpave:

Level 1 If the final ECS modulus ratio is < 0.7, the mixture should be treated for moisture susceptibility and the treated mixture retested in the ECS. If the final ECS modulus ratio is greater 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, treatment for moisture sensitivity should be considered, because these mixtures may experience moisture damage, though at a slower rate than those with final ECS modulus ratios of less than 0.7.

Level 2 For the mixture specimens with air void contents of 7 % ± 1 %, the criterion is the same as in level two. For the specimens with air voids content of 10 % ± 1%, the mixture should be treated for moisture susceptibility if the final ECS modulus ratio is < 0.6. Again, the slope of the curve between cycle 1 and cycle 3 is an indicator of continued but delayed water 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. Simple shear tests will be performed on both conditioned and unconditioned ECS test specimens with a requirement for acceptability of the mixture. If the mixture does not meet the simple shear criteria, it will be redesigned to improve its performance. Evaluation of mixtures with the ECS test procedure should eliminate the placement of mixtures that could experience water damage within the first several years of life.

The conclusions drawn from the analysis are summarized as follows:

- ECS can discriminate between mixtures that will perform well and those that will perform poorly with regard to water sensitivity of the asphalt mixture.
- The ECS modulus ratio allows for separation of mixtures into performance categories. Typically, mixtures that have final ECS modulus ratios of greater than 0.7 will perform well in the field. Those with lower final ECS ratios should be considered for redesign or treatment with admixtures.
- The slope of the modulus ratio curve between cycle 1 and cycle 3 is an indicator of the rate of water damage occurring to the specimen. Specimens that have acceptable ECS modulus ratios after three cycles may have slopes that indicate potential water susceptibility problems in the long term.
- Significant change in the modulus ratio occurs in some mixtures between cycle 1 and cycle 3, moving them from acceptable to unacceptable or questionable in terms of water sensitivity. The ECS test procedure should not be limited to one cycle.
- Of the variables considered (mixture type, air voids, initial modulus, air permeability, and water permeability), mixture type, initial modulus, and air voids have the strongest influence on the final ECS modulus ratio of the mixture.
- The mixtures tested have not been in the field long enough to allow a correlation between the cycles of conditioning the ECS and the corresponding period of field conditioning.
- The evaluation of visual stripping and migration of asphalt binder in the specimen is extremely subjective.

- For new pavements, the increase in resilient modulus caused by long-term aging in the field may overshadow the reduction in resilient modulus associated with the early stage of water damage to the pavement mixture.

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

- A strong correlation between ECS performance and number of years of expected field performance has not been made because of 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.

- There should be a controlled program of materials collection, construction of field sections, and continued coring to provide a larger data base for ECS criteria. Enough asphalt and aggregate should be sampled at the time of construction to allow manufacture of both OSU wheel tracker beams (at least four) and ECS specimens. Several of the mixtures tested in the SHRP A-003A program should have been replicated because of anomalous results from the OSU wheel tracker. Because of a lack of original aggregates, however, there was no opportunity to complete this work.

- The procedure for evaluating visual stripping of 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.

- ECS should be used to provide a systematic look at the effects of variations in volumetric mixture proportions, such as gradation and asphalt content, on the performance of mixtures.

- Inclusion of the ECS equipment and procedure per the specification guidelines is recommended for any mix design system proposed.

1

Introduction

Background

The original proposal by the A-003A contractor to the Strategic Highway Research Program (SHRP) included Task C.5 on the evaluation of water sensitivity of asphalt concrete mixtures. The program 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 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 the A-003A contractor for the investigation of 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, and (3) field verification of both the laboratory testing program and the accelerated laboratory test. This document includes the findings from the third phase, field verification.

The first stage of the A-003A work conducted at Oregon State University (OSU) involved the development of the Environmental Conditioning System (ECS), which subjects asphalt mixture specimens to a series of conditioning cycles, including water flow, elevated or lowered temperature, and repeated axial loading (Terrel and Al-Swailmi 1992). Phase two included validation of the ECS procedure with the French Laboratoire Central des Ponts et Chaussees rutting tester (referred to as the OSU wheel tracker in this report), and the SWK/UN rutting tester, as simulations of the effect of accelerated traffic loading on the mixture (Scholz et al. 1992). Specimens prepared for the OSU wheel tracker were water and temperature conditioned in a manner analogous to that of the ECS procedure.

The final phase of the project involved developing correlations among ECS, OSU wheel tracker, and field specimens to verify that ECS can discriminate among different performance levels of mixtures in the field and that the OSU wheel tracker is an appropriate simulation of environmental and traffic-loading conditions in the field. Additional wheel tracking tests were performed by Elf Asphalt in Terre Haute, Indiana, on several of the mixtures tested. This information is included to represent the response of a different type of wheel tracking test apparatus. Additional information on the water sensitivity of asphalt mixtures may be found in a preliminary literature review conducted by Terrel and Shute (1989).

Purpose

The purpose of this portion of SHRP A-003A was to demonstrate that the ECS test can accurately discriminate between superior and inferior asphalt concrete mixtures by demonstrating their performance in full-scale, field test sections. In addition, the correlation among the performance of mixtures in the ECS, OSU wheel tracker, and field sections was also verified. The verification effort differs from the previous work conducted under this portion of the A-003A project in that all the mixtures used were designed by the local authority in whose jurisdiction the field section was placed. Other asphalt-aggregate mixtures tested in the SHRP program were prepared according to mix designs developed by the SHRP A-003A team at the University of California, Berkeley.

This document presents the testing procedures, results, and analysis of data for the 12 asphalt-aggregate mixtures tested in the ECS, OSU wheel tracker, Elf wheel tracker, and full-scale field test sections. The analysis of data correlates the performance of these mixtures when subjected to the four types of moisture conditioning inherent in either the test apparatus or geographical location in which the asphalt mixture was used. Based on the data from this effort, criteria for the use of ECS data in a mix design development program will be proposed.

2

Experimental Program

In 1990, Oregon State University (OSU) began acquiring materials from various agencies for use in the field validation of the Environmental Conditioning System (ECS) test procedure. As field sites with available materials were identified, and as early testing with ECS progressed, a program of materials collection, specimen preparation, and testing emerged. This chapter discusses the resulting test program used to validate the ECS test equipment with materials and data from in-service field sections.

Overview

Figure 2.1 presents an overview of the testing program for the A-003A Task C.5 work. Specimens were subjected to one of three distinct treatments: ECS, the OSU wheel tracker, or the field test section. Each treatment consisted of a conditioning procedure unique to that system and one or more testing techniques to measure the performance of the test specimen. Testing with the Elf Asphalt wheel tracker was performed in addition to the main test plan.

The 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. From large, roller-compacted slabs, beam specimens were cut for use in the OSU wheel tracker, and specimens were cored for use in ECS. Field specimens were cored from field test sections for evaluation in the laboratory. Elf manufactured specimens according to its own procedures.

The following seven modes of performance are monitored:

1. Triaxial resilient modulus as measured by ECS.
2. Change in hydraulic conductivity or the coefficient of water permeability of the specimen, as measured in 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.
7. MTS diametral modulus.

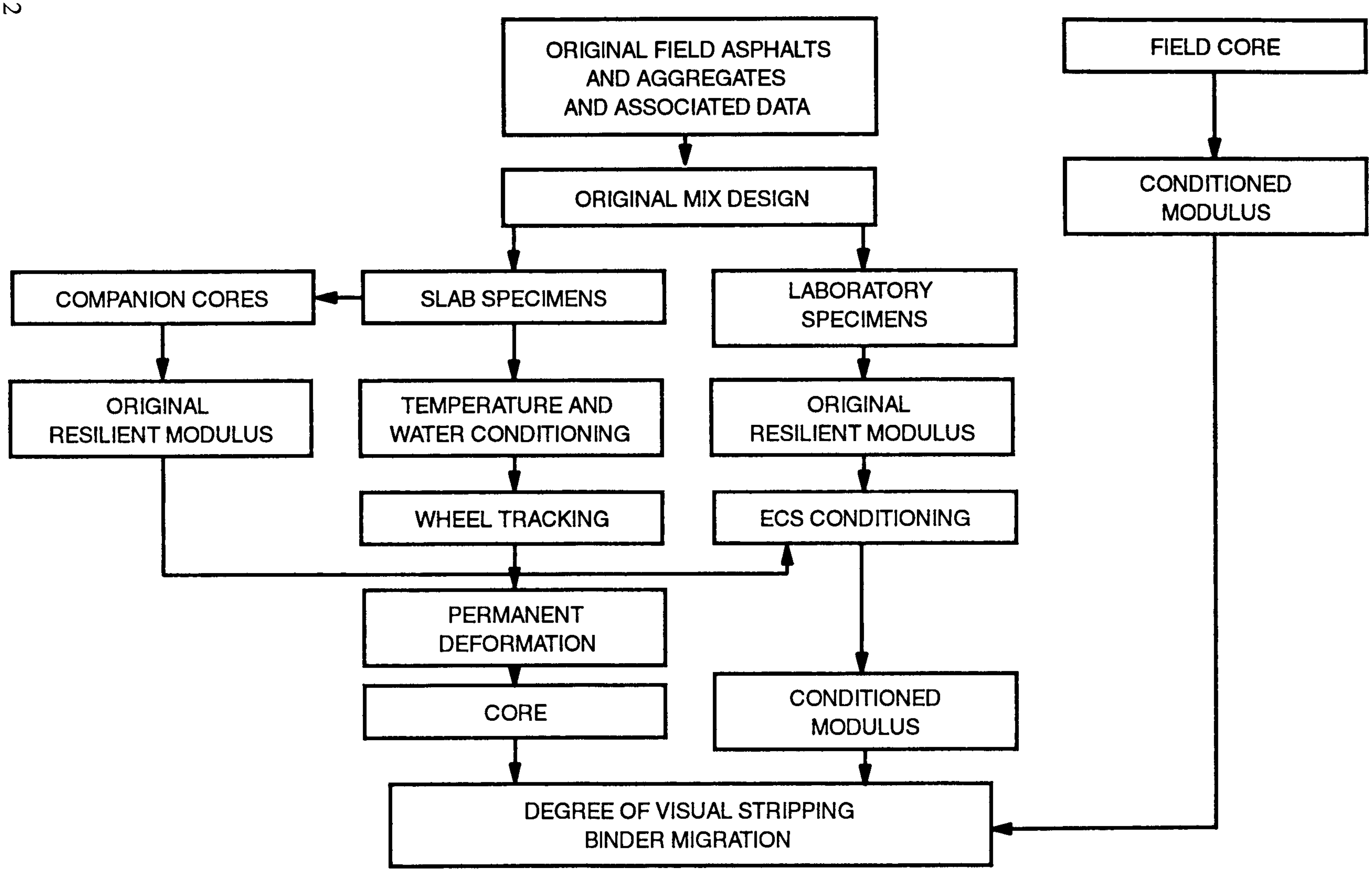


Figure 2.1. Field validation of water sensitivity, test program

Table 2.1 summarizes this information. Test procedures are described more fully later in this chapter and in appendixes B and D.

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/rutted beam	Rut depth MTS modulus Visual evaluation of stripping Visual evaluation of binder migration
Field	Field exposure	MTS modulus Visual evaluation of stripping Visual evaluation of binder migration

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

Cores taken from rutted OSU wheel tracking beams are not tested in the ECS apparatus. They were tested using the MTS apparatus, either diameterally or both diameterally and triaxially, depending on core height. If the cores were significantly less that 4 in. (101.6 mm) in height, triaxial modulus values were considered invalid, and correlations were made with diametral modulus values.

Field core specimens were also tested only in the MTS apparatus. Because of the variable thickness of constructed layers, some of these specimens were tested in only the diametral mode (specimens significantly under 4 in. (101.6 mm) in height). If the specimen was nominally 4 in. (101.6 mm) high, it was tested in both the diametral and triaxial configurations.

In order to develop stiffness ratios for the OSU wheel tracking and the field specimens, diametral and triaxial modulus data from laboratory roller and kneading-compacted specimens with similar air void values were used. Using a linear regression, the modulus values for the laboratory specimens were related to air void levels. 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 received evaluation for the visual degree of stripping and binder migration, regardless of specimen type or testing procedure. These procedures are described later in this chapter.

The definition of replicate specimen has changed somewhat between Task D.2.e and this portion of the water sensitivity work. In previous SHRP work, the goal was to produce specimens of two air void levels, 4 percent and 8 percent for the laboratory kneading-compacted specimens, and 8 percent for the OSU wheel tracking specimens. In this task, the goal was to create as wide a range of air voids as possible in order to bracket the air voids of specimens from the field. 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 later in chapter 2 and in appendix A of this document. Roller-compacted specimens were targeted at 8 percent air voids to match the previous work in D.2.e. However, because of limited amounts of material available and the natural variability in the specimens produced by the mixing and compaction procedures used, some of the beam specimens do not meet the 8 percent void criteria.

Selection of Field Sites

Twelve field sites were selected for the A-003A water sensitivity field validation effort. Sites were selected on the basis of availability of a minimum of 300 lbs. (136 kg) of usable blended aggregate, 3 gals. (11.4 l) of asphalt cement, required admixtures, mix design information, and cooperation from the presiding authority for field coring. Also, at least two sites were selected from each of the four SHRP environmental zones. Furthermore, the sites chosen had to be as old as possible so that there would be 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 their willingness to cooperate in the SHRP program and on the availability of retained materials. 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 itself 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. MRL also provided material from three of the four National Cooperative Highway Research Program'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 requires the cooperation of the host state because 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.

The 12 sites selected, the three-character site designator (e.g., CAB, CAG, WA1) used in this document, the governing agency for the site, and any local mixture designation used are listed in table 2.2. Table 2.3 lists the route number and construction date and indicates the environmental zone in which each site is located. Figure 2.2 indicates the approximate locations of the selected sites.

The construction dates indicate the unavailability of older sites with retained materials. 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 would typically have been 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 the type of construction the pavement was placed as (e.g., overlay), the layer thicknesses, the number of lifts, and the lift thickness. More information on the individual mix designs is given in later in this chapter.

In addition to the original materials and cores required from each field site, several other types of data were required to further characterize the test section and provide information about the performance of the mixture in the field. Data on the environmental conditions, temperature and precipitation, traffic loading, and pavement condition (summer 1992, if possible) at the site were requested from several agencies.

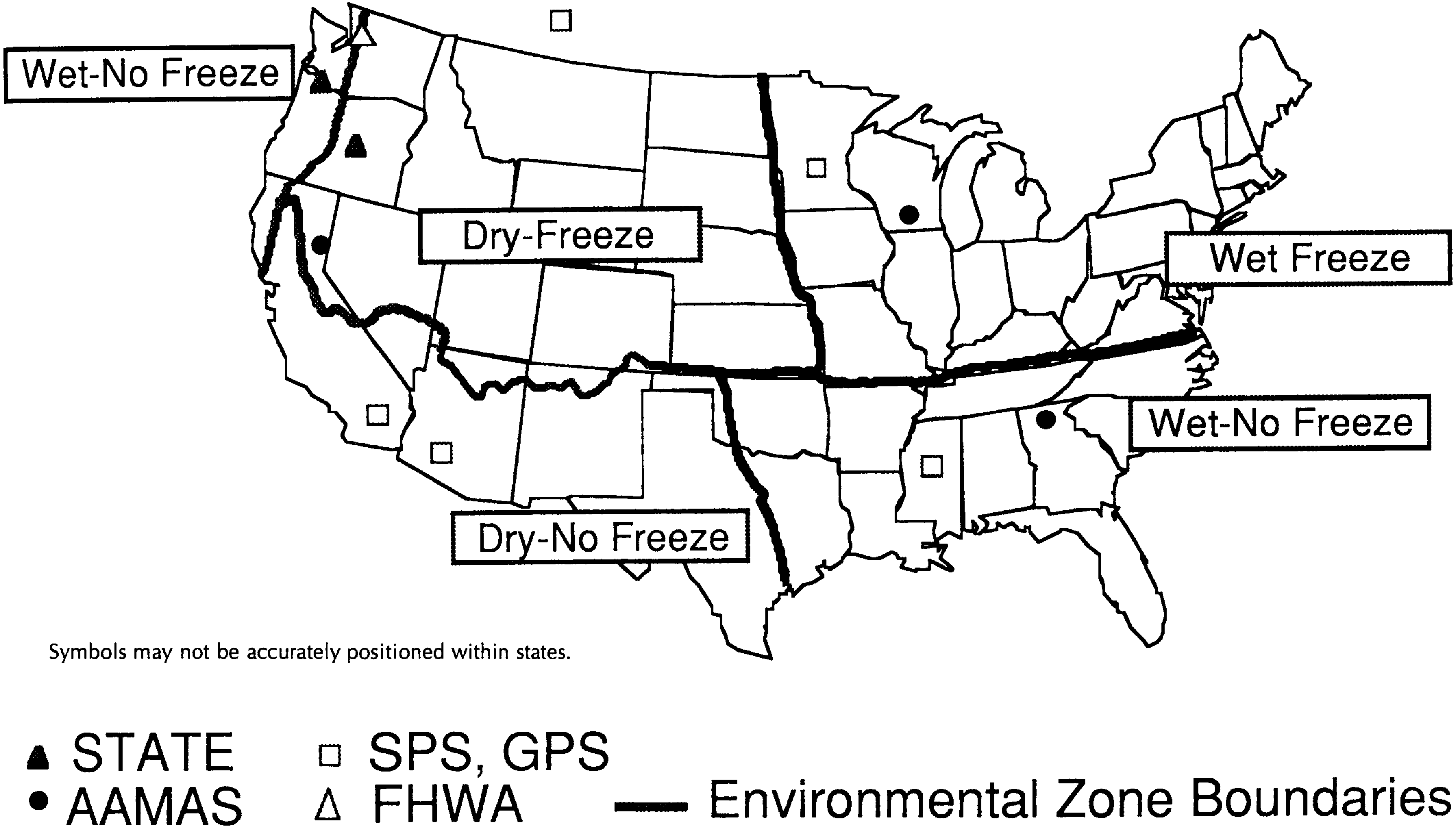
The field sites are grouped according to the four SHRP environmental zones. However, precipitation and temperatures vary widely in any given zone designation. Since 11 of the 12 sites used in the program were not SHRP GPS sites, the SHRP climatic data base did not contain information for these sites. Weather data for the United States was obtained from the National Climatic Data Center from two report series: *Climatological Data Annual Summary* and *Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days, 1961-1990* (National Oceanic and Atmospheric Administration 1990, Owenby and Ezell 1992).

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 location

Site	Route Number	Construction Date	Environmental Zone
AB5	Highway 16 from Edson to east 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	US 76 approximately three miles west of Hiawassee, GA	1989	Wet-no freeze
MN5	US 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	US 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	US 51 from Jct Highway 60 north to Poynette city limits	1989	Wet-freeze



Symbols may not be accurately positioned within states.

Figure 2.2. Water sensitivity field validation 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	Antistrip
OR1	AC-15	McCall Asphalt, Portland, OR	NA	None
OR2	PAC-20	Albina Asphalt Portland, OR	NA	Polymer, Antistrip, hydrated lime, fly ash
WA1	PMA-60	Chevron USA, Richmond Beach, WA	NA	Polymer
WIA	AC-5	Koch Asphalt	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	Normal 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	4.5[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 - 1.5-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.

Weather data for Canada were obtained from the Canadian Climate Centre (Environment Canada 1991-1992).

For a specific test section, the nearest recording weather station with monthly precipitation and temperature data was used to indicate what kind of weather the test section could expect. Table 2.6 indicates the recording station used for each test section. The approximate distance between the weather station and the test section is also indicated.

It is understood that the weather at a particular site may be significantly different from that of the nearest recording weather station. This is especially true for the WA1 site, which is located on a mountain roadway. The site is significantly higher in elevation (at approximately 4,300 ft) than the nearest recording weather station (690 ft) and is also on the western slope of Mt. Baker, which is subject to much different precipitation conditions than the recording station, which is located in a valley area. However, no other weather station exists that can provide data more appropriate for the site.

For the 12 sites used in the A-003A field validation effort, no traffic data were to be collected by SHRP. Traffic data were requested from the state agency with jurisdiction for the roadway that contained the test section. ADT and percent trucks were requested.

In order to qualify the performance of the mixtures 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 one case, WA1, the OSU A-003A team performed manual distress surveys. In addition, the Pasco surveys for 1992 were requested for those sites surveyed under that program. For the SHRP test sections, the manual distress and Pasco 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.

Rutting and other signs of asphalt stripping were the distress types that were watched for in the distress evaluations of the test sections.

Specimen Preparation

The testing program for the A-003A field validation of water sensitivity of asphalt-concrete mixtures involved specimens manufactured by three methods and tested in one or more of four test procedures. Specimens were fabricated using one of the following: the laboratory kneading compactor, the laboratory roller compactor, or field compaction in place 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.

Laboratory Aggregate Preparation

The specimens manufactured at OSU were made from mix designs obtained by SHRP from the agency responsible for paving the site. Original aggregate, asphalt, and admixtures were obtained and processed prior to mixing and compacting specimens.

Table 2.6. Nearest recording weather station

Site	Recording Climatic Station	Elevation (ft)	Approximate Distance from Site (mi)
AB5	Edson	3,022	2
AZ5	CasaGrande	1,395	5
CAB	Doyle 4 SSE	4,390	9
CAD	Doyle 4 SSE	4,390	9
CAG	El Centro 2 SSW	-30	11.6
GAA	Blairsville Experimental Station	1,917	19
MN5	Bemidji	1,340	10
MS5	Yazoo City 5 NNE	107	12
OR1	Clatskanie St. Helens RFD	22 102	17 17
OR2	Redmond FAA Airport	3,060	2
WA1	Upper Baker Dam	690	21
WIA	Portage	800	13

Example Code: AB5R801

AB5 = 3-character site designator (e.g., 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
01 = specimen number in group

Note: Specimens tested by Elf are designated by their site designator, the letters ELF, and a number 01 or 02 (e.g., AB5ELF01)

Figure 2.3. Specimen identification code

Original aggregate from each site typically arrived in 5-gal. (18.95-l) drums or 50-lb. (≈23-kg) bags. Though several were nominally mixed to the correct gradation, the aggregates were resieved and recombined according to protocols for aggregate processing developed by SHRP in order to eliminate any potential for segregation during shipping and handling.

The aggregates were shaken 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 U.S. sieve numbers 4 and 30. Each fraction was then treated as a separate source bin for recombination. The aggregate passing the number 4 and retained on the number 30 and the aggregate passing the number 30 were wet-sieved to obtain an accurate grain-size distribution of those portions.

The aggregate was re-combined using a least-sum-of-error-squared method to produce gradations that 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 12 test sections and the gradations are plotted in figures 2.4 through 2.15. The aggregates were batched into quantities for preparation of 4 in. × 4 in. (101.6 mm × 101.6 mm) kneading compactor specimens, approximately 4.23 lb. (1920 grams), or 24 in. × 24 in. × 4 in. (609.6 mm × 609.6 mm × 101.6 mm) roller-compacted slabs of approximately 195 lbs. (88.5 kg).

Any 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 a 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 fly ash were stirred into the aggregate without the addition of water. Admixtures used are summarized in table 2.8.

Laboratory Asphalt Preparation

Asphalt materials obtained from the MRL and other sources typically arrived in 1- or 5-gal. (3.8 or 19 l) pails. For ease of use, each large container was broken down into 1-qt. (0.95 l) containers, following the SHRP protocols for dividing asphalt. At this time, four penetration tins of asphalt were also obtained 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 this data. The mixing temperature corresponds to the temperature at which the asphalt being used has a viscosity of 170 ± 20 centiStokes (0.263 $\text{in.}^2/\text{sec}$). The compaction temperature corresponds to the temperature at which the asphalt being used has a viscosity of 665 ± 80 centiStokes (1.031 in^2/s). Table 2.9 presents the viscosity data and mixing and compaction temperatures for each asphalt.

Table 2.7. Aggregate gradations, field section 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

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

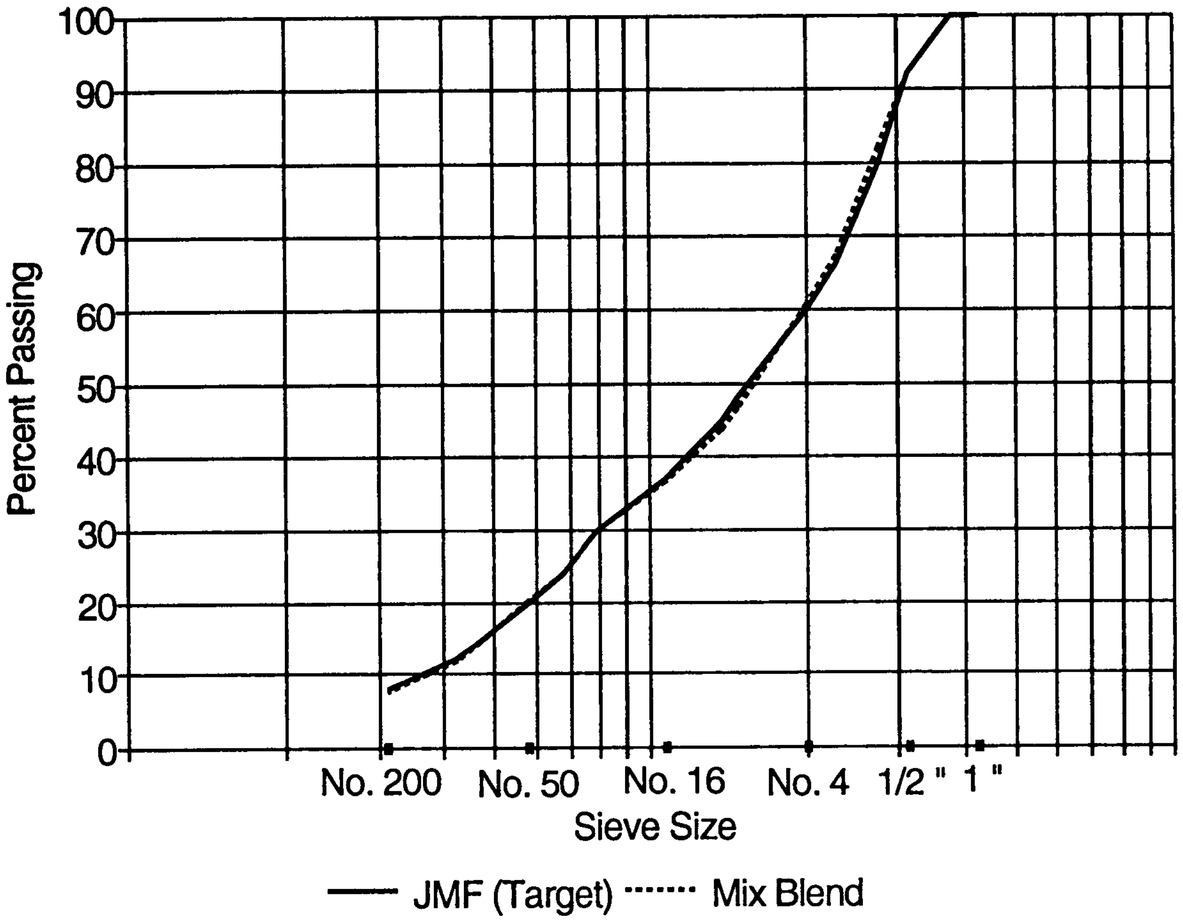


Figure 2.4. Aggregate gradation for Alberta, SPS-5 (AB5)

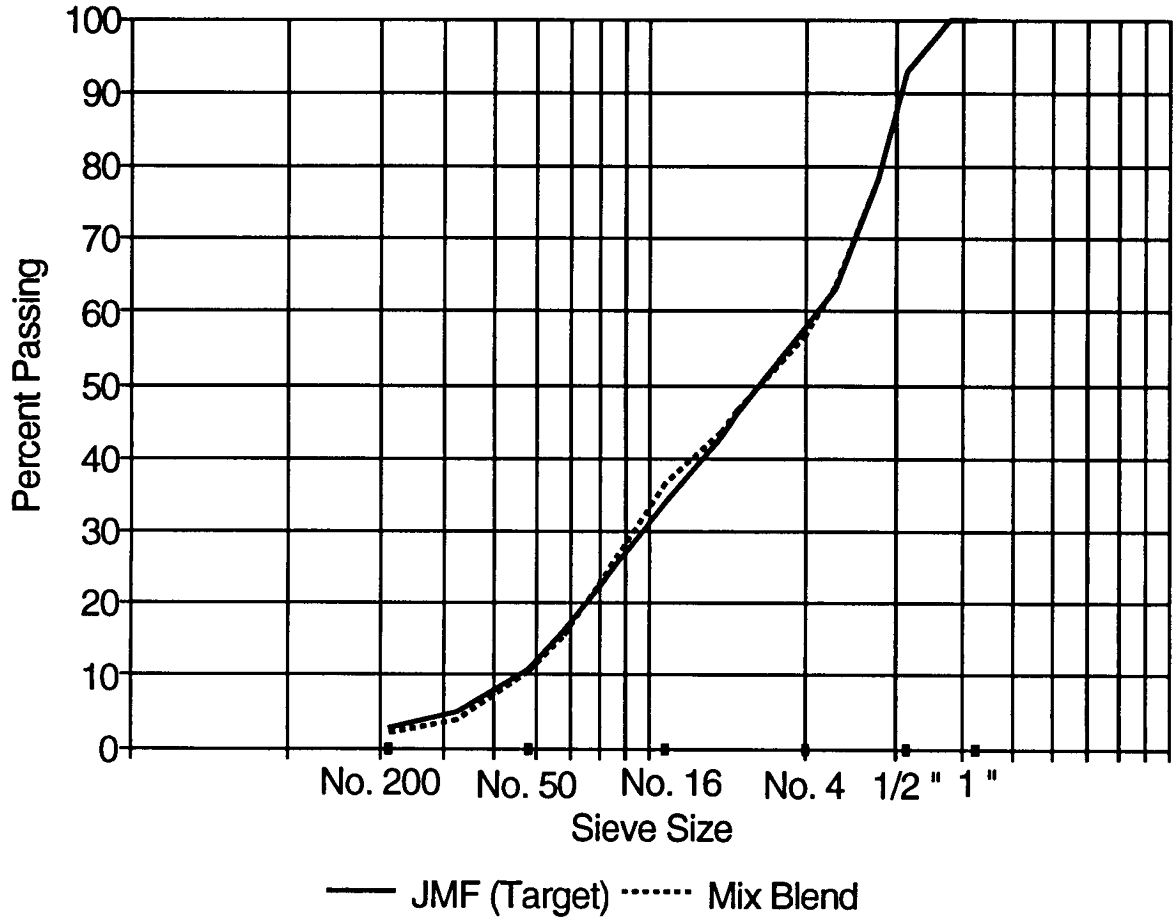


Figure 2.5. Aggregate gradation for Arizona, SPS-5 9 (AZ5)

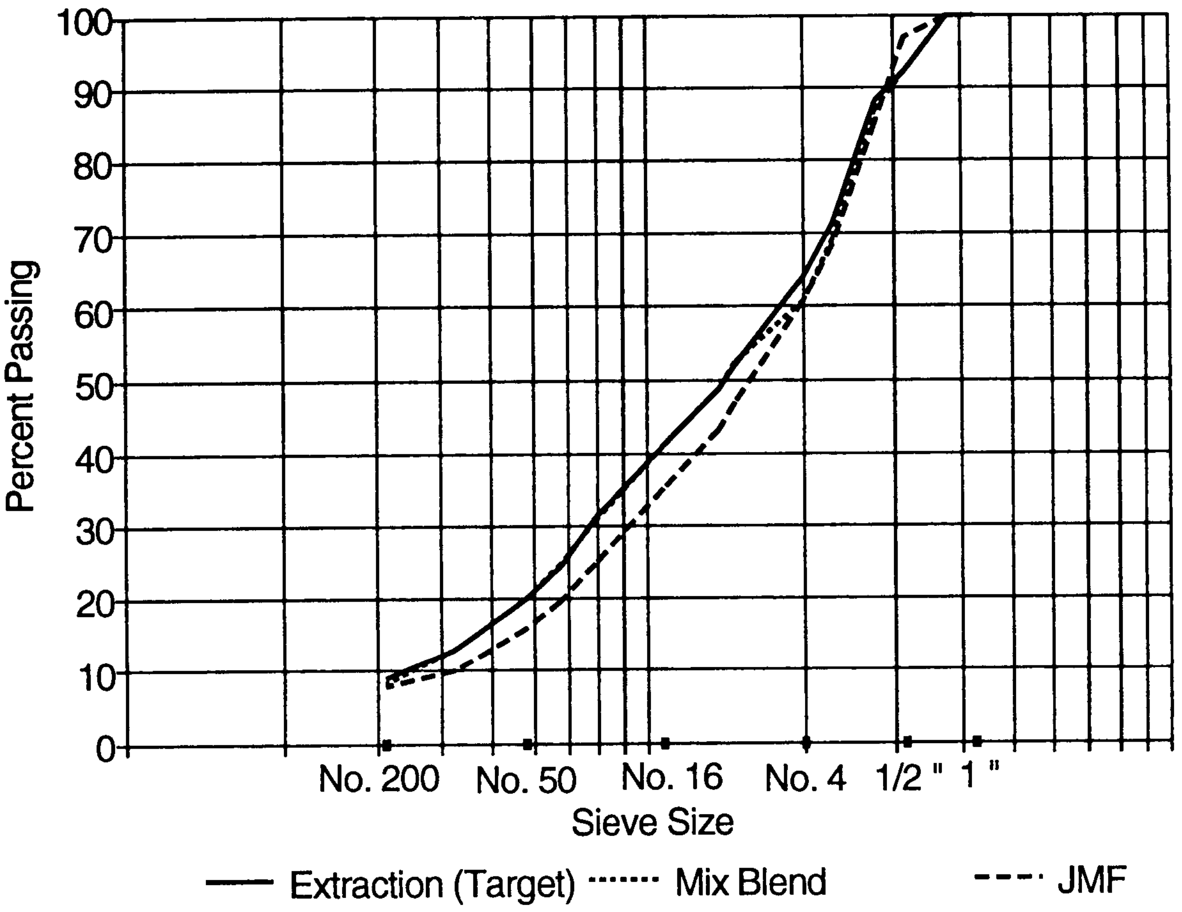


Figure 2.6. Aggregate gradation for California, AAMAS Batch (CAB)

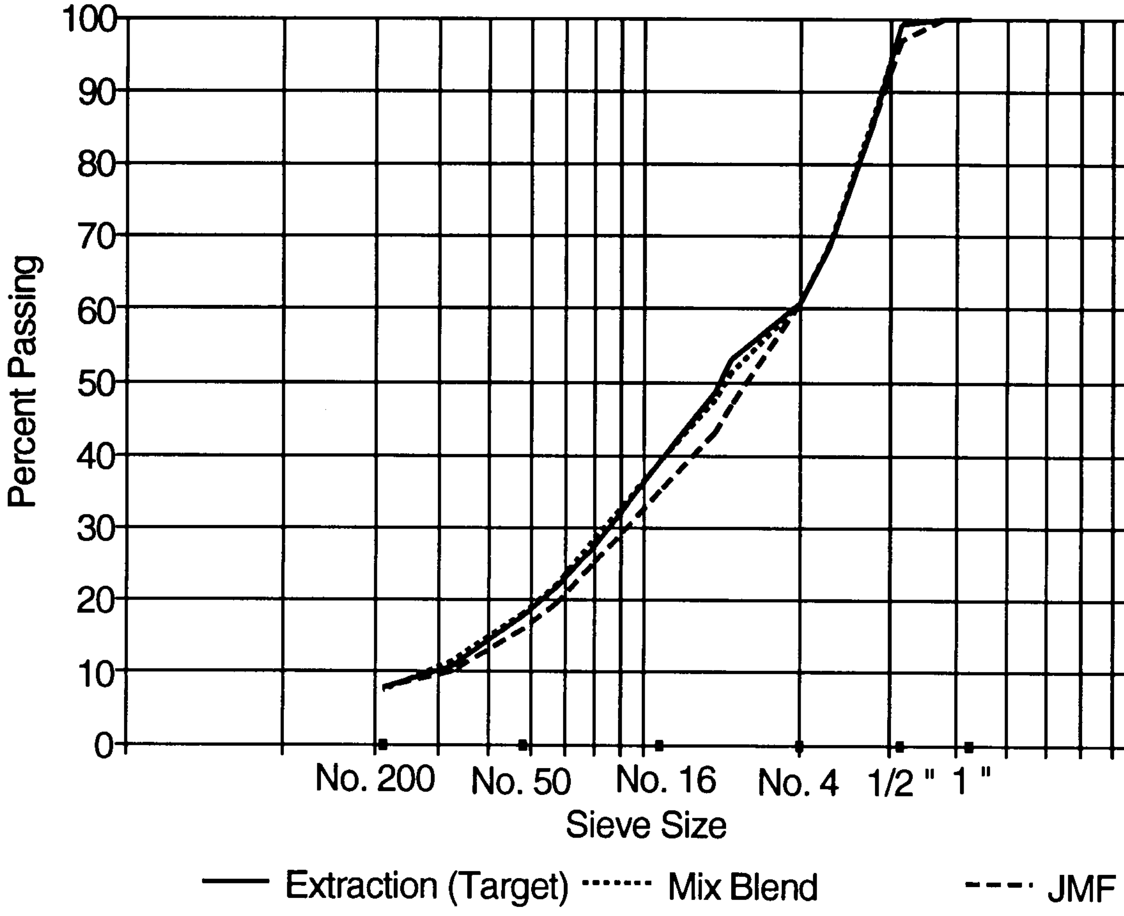


Figure 2.7. Aggregate gradation for California, AAMAS Drum (CAD)

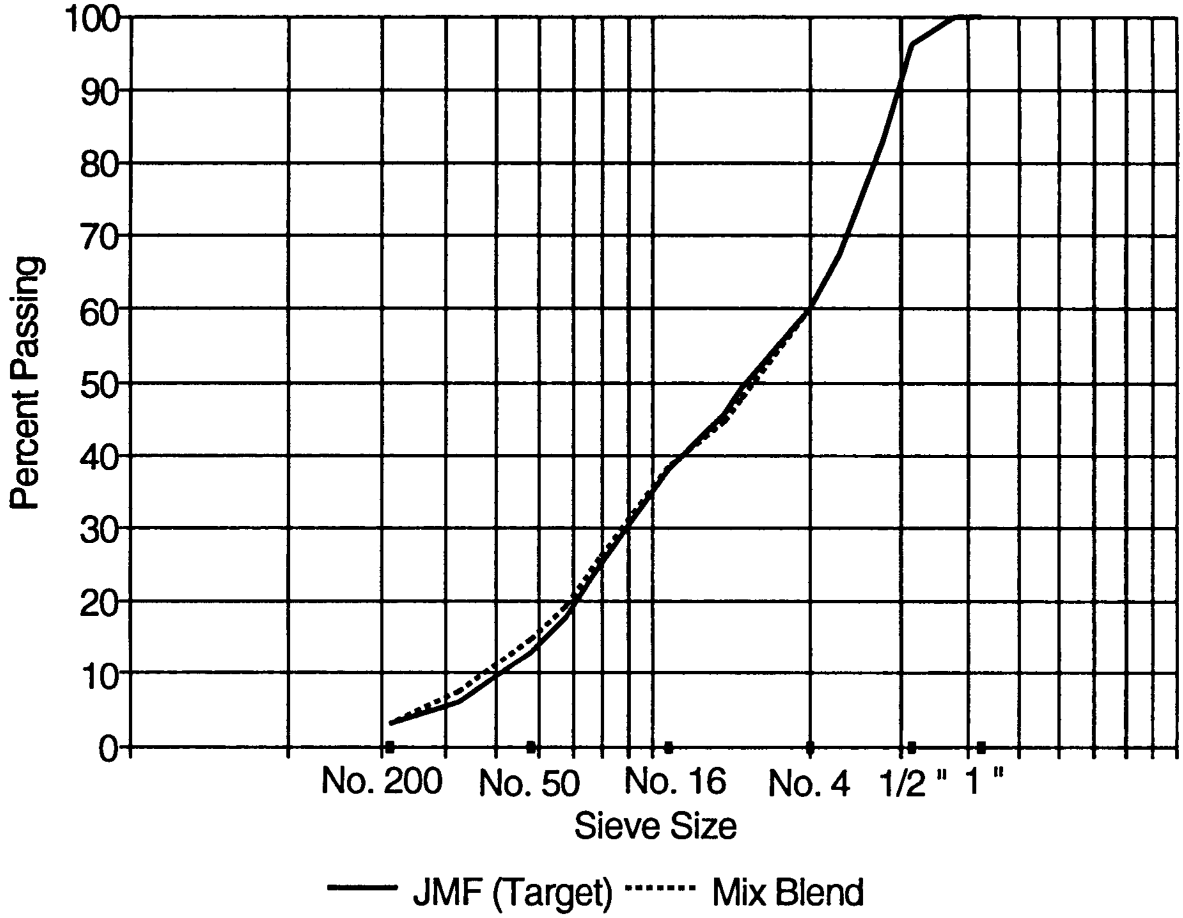


Figure 2.8. Aggregate gradation for California, GPS-6b (CAG)

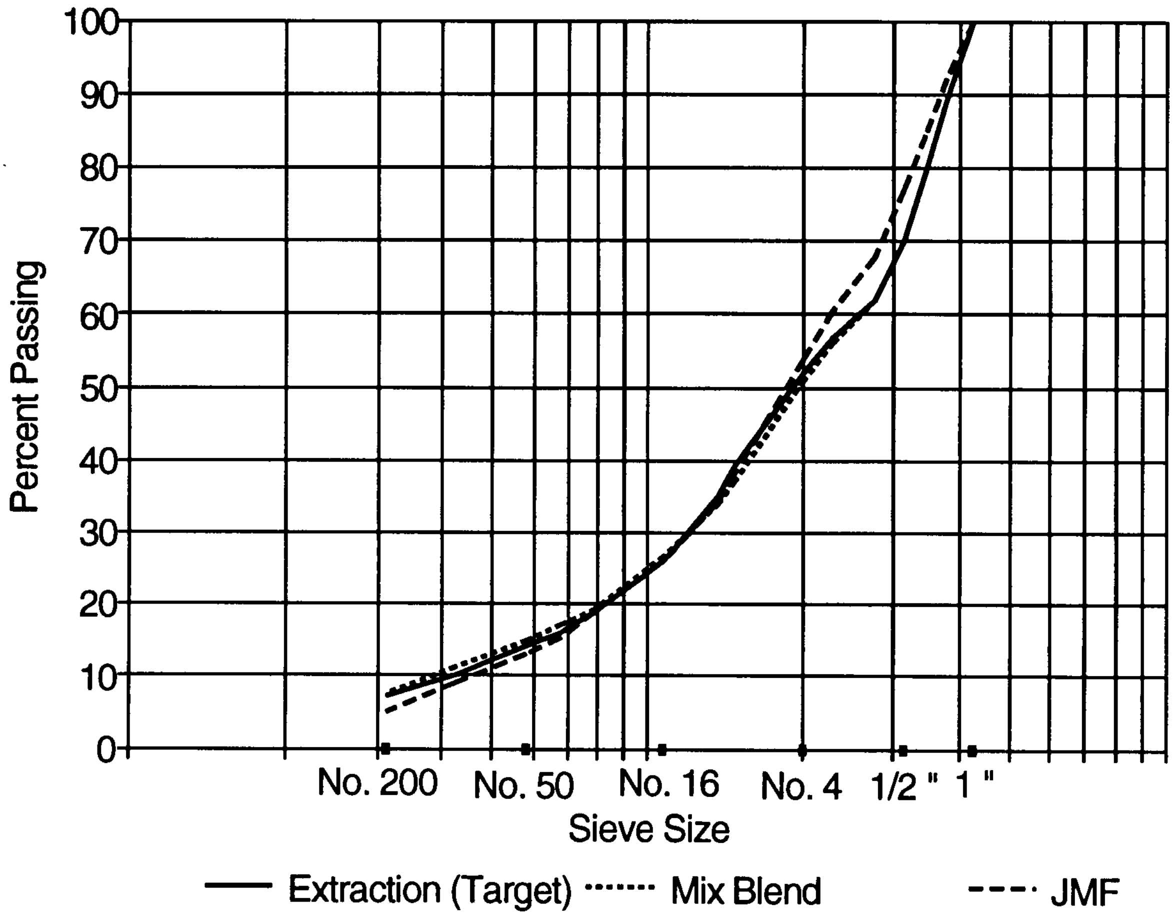


Figure 2.9. Aggregate gradation for Georgia, AAMAS (GAA)

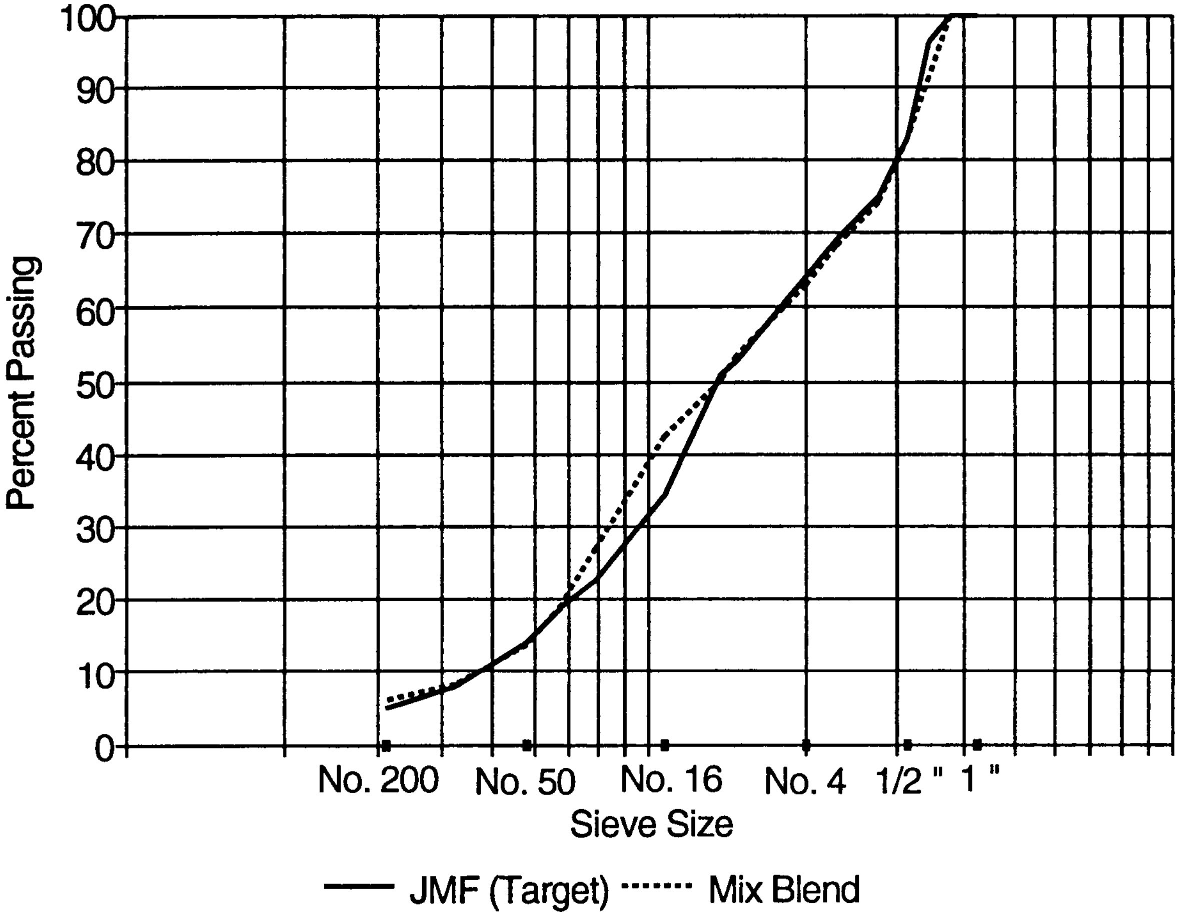


Figure 2.10. Aggregate gradation for Minnesota, SPS-5 (MN5)

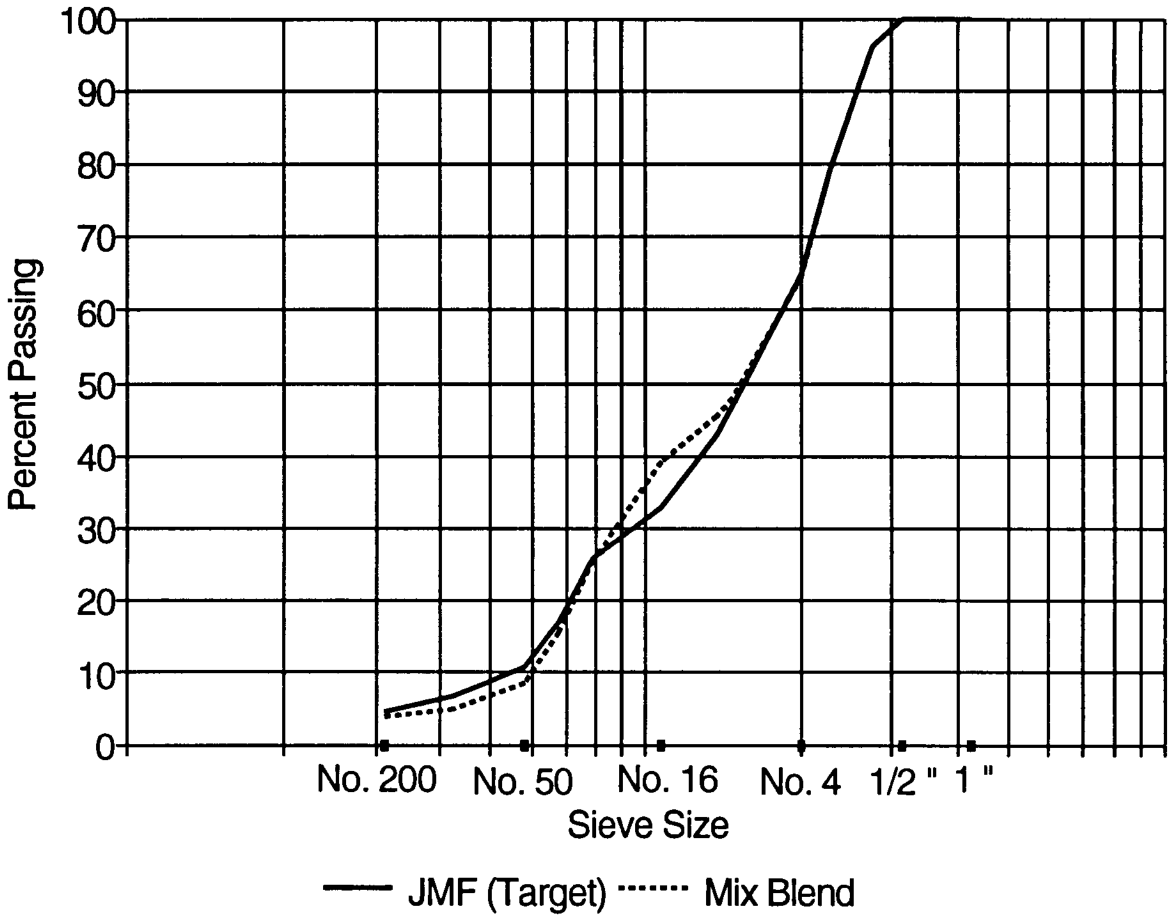


Figure 2.11. Aggregate gradation for Mississippi, SPS-5 (MS5)

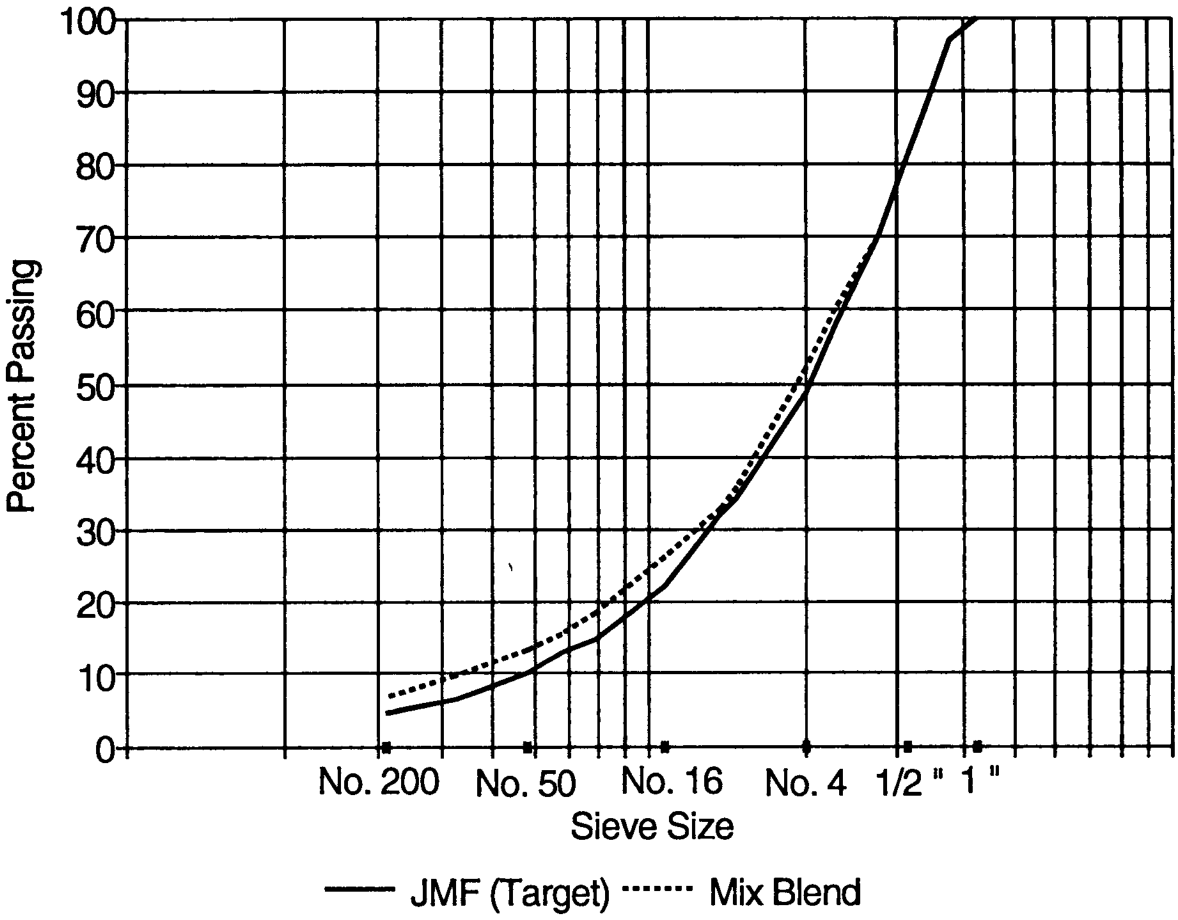


Figure 2.12. Aggregate gradation for Rainier, Oregon (OR1)

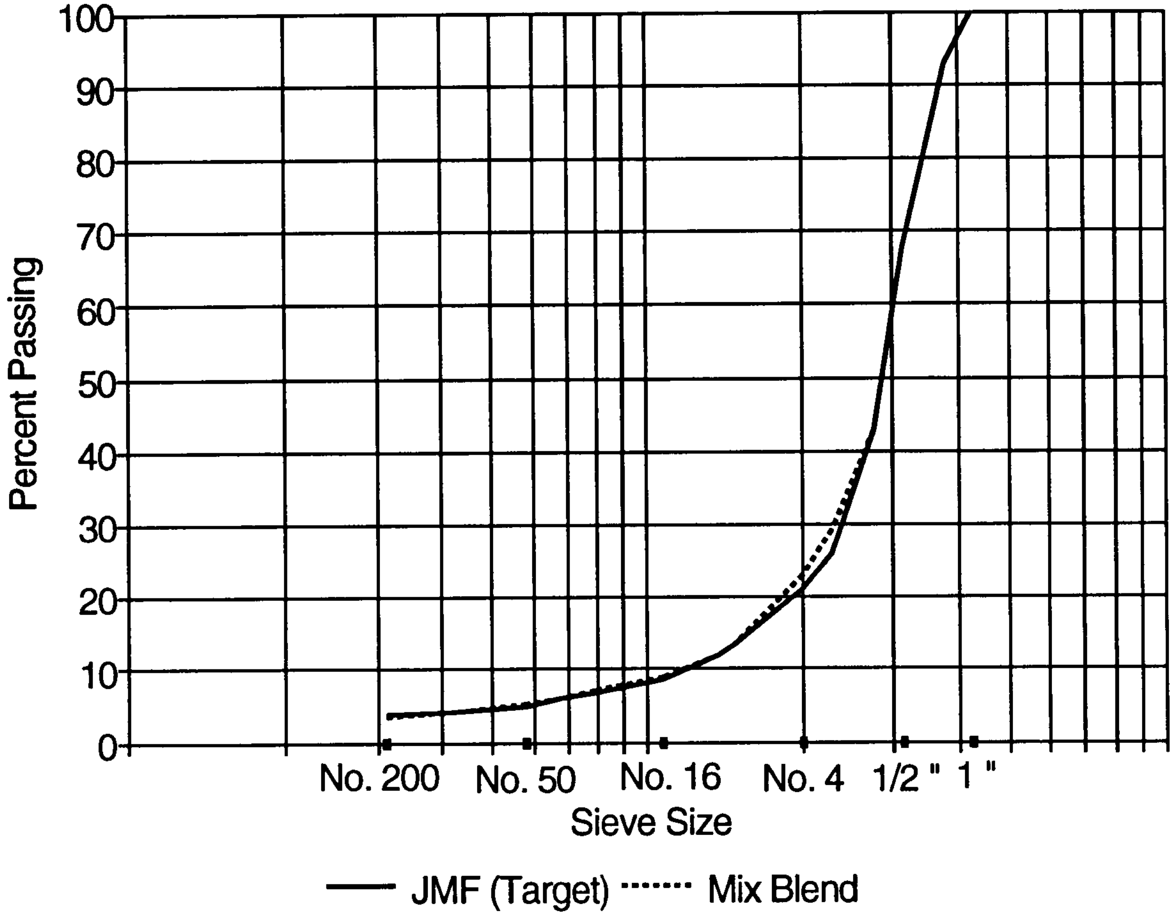


Figure 2.13. Aggregate gradation for Bend-Redmond, Oregon (OR2)

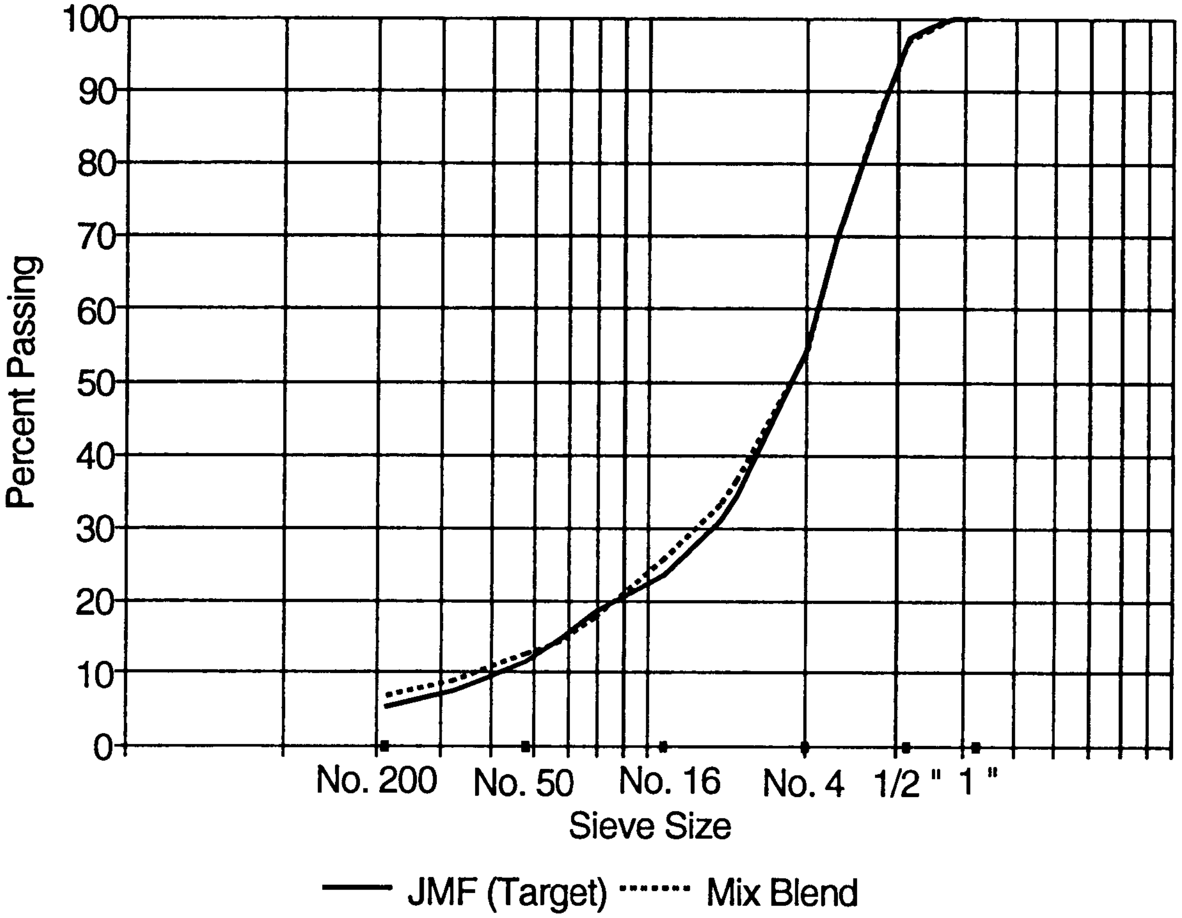


Figure 2.14. Aggregate gradation for Mount Baker, Washington (WA1)

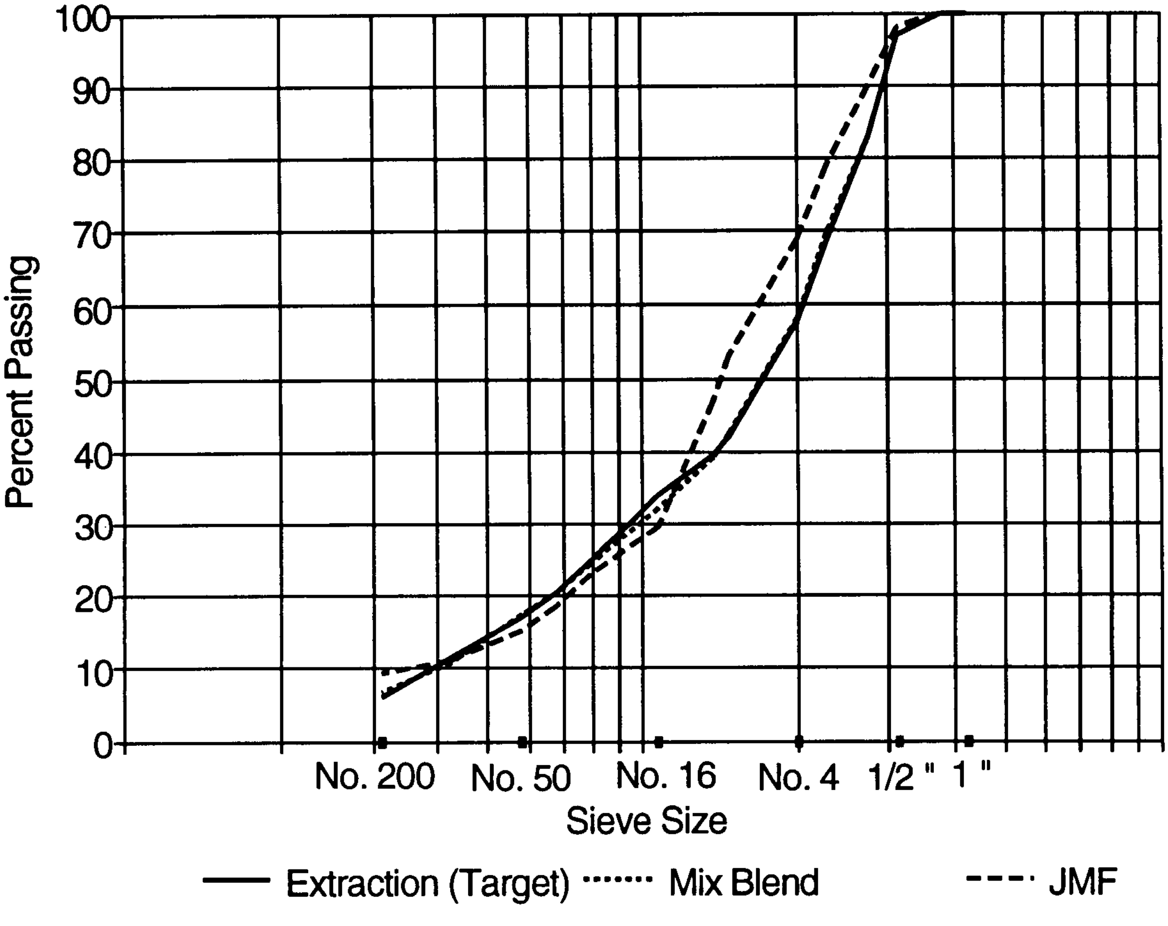


Figure 2.15. Aggregate gradation for Wisconsin, AAMAS (WIA)

Table 2.8. Asphalt and admixture contents

Site	Asphalt Content[1]	Admixture Content
AB5	5.4 JMF	
AZ5	4.7 JMF	2% type II Portland cement[2]
CAB	5.61 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% Perma-Tac[3]
OR1	5.20 JMF	
OR2	5.80 JMF	0.62% lime[2] 1.0% fly ash[2] 0.25% antistrip[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	4,140	411	151	128
CAB	2,050	286	151	127
CAD	2,050	286	151	127
CAG	1,180	278	144	120
GAA	3,150	528	157	132
MN5	608	223	141	116
MS5	3,670	592	160	134
OR1	1,620	224	140	118
OR2	2,230[1]	581[1]	160	134
WA1	70[2]	656	163	136
WIA	392	187	137	112

[1] Original asphalt, no antistrip.

[2] Penetration at 60°C.

Laboratory Mixing and Compaction

Two mixing processes were used to prepare laboratory specimens for the field validation of water sensitivity. Individual, 4 in. × 4 in. (101.6 mm × 101.6 mm) specimens were mixed using protocols developed by the SHRP A-003A study team, based upon ASTM D-1561-81a. Large slabs were mixed using protocols developed for the roller-compacted test specimens (SHRP-A-379). 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. Specimens were tested in the Elf wheel tracker. The mix designs were the same as those used at OSU.

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 gms. 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 asphalt was spread into metal baking pans for short-term aging, a simulation of the aging that occurs in asphalt mixtures prior to compaction. At the time of mixing, an extra specimen was mixed for use as a Rice maximum specific gravity sample (ASTM D-2041).

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. 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 for between 12 and 24 hours at room temperature. This variation of the standard protocol was necessary because of time constraints. Typically, the mixture is not allowed to cool before heating for compaction begins.

Two hours before 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. 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 from 12 to 24 hours at room temperature before extrusion from the compaction molds. The specimens were labeled at this time, placed in Ziploc plastic bags, and stored at 59°F (15°C) until testing.

Preparation of the large slabs for use in the OSU wheel tracker (Laboratoire Central des Ponts et Chaussees [LCPC] rutting tester) involved a variation of the above process. Table 2.11 gives a brief summary of the procedure. The slab preparation process is shown schematically in figure 2.16. 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 200 lb. to 215 lb. (90 kg to 98 kg), was mixed at one time. Once the aggregate and asphalt were both placed in the mixer, mixing continued for four minutes.

Table 2.10. Compaction levels

Compaction Effort	Seating Load	Compaction Pressure
Low	20 blows @ 250 psi (1,724 kPa)	150 blows @ 150 psi (1,034 kPa)
Medium	20 blows @ 250 psi (1,724 kPa)	150 blows @ 300 psi (2,067 kPa)
High	20 blows @ 250 psi (1,724 kPa)	150 blows @ 500 psi (3,445 kPa)
Dense	20 blows @ 250 psi (1,724 kPa)	200 blows @ 500 psi (3,445 kPa)

Table 2.11. Summary of specimen preparation procedure for roller-compacted slabs (SHRP A-003A Task C.5)

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 200 lbs. and 215 lbs. (90 and 98 kN) at an air void content of 8% ± 1%.
2	Prepare the asphalt and aggregate for mixing.
3	Heat the materials to the mixing temperature for the asphalt (170 cS ± 20 cS). Mixing temperatures ranged between 279°F and 320°F (137°C and 163°C).
4	Mix the asphalt and aggregate for four 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 hours, stirring the mixture every hour, to represent the amount of aging that occurs in the mixing plant.
6	Assemble the compaction mold and preheat it 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 overcompaction of the mixture. Compaction temperatures (based on 665 cS ± 80 cS) ranged between 234°F and 271°F (112°C 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 beams for the OSU wheel tracker. Dry cut four cores for the ECS.

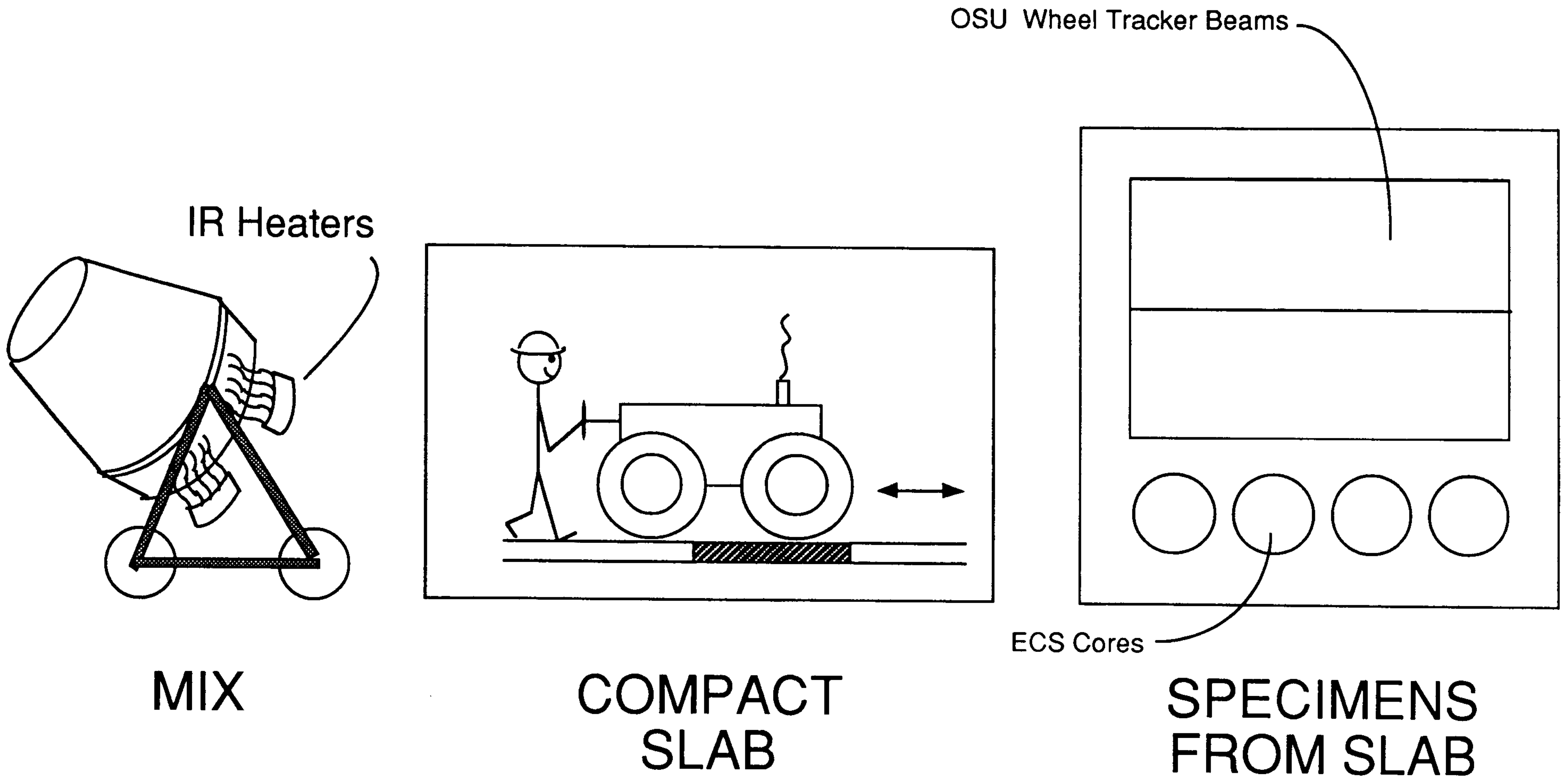


Figure 2.16. Schematic of the specimen preparation process

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 3,260 lb. (1,480 kg). The compacted slab was then allowed to cool overnight (approximately 16 hours) after which it was removed from the mold.

Two beam specimens, 19 in. × 6-1/2 in. × 4 in. (482.6 mm × 165.1 mm × 101.6 mm), for use in the OSU wheel tracker, were sawed from the compacted slab, as well as a sample for Rice specific gravity. Four 4-in.-high × 4-in.-diameter (101.6 mm × 101.6 mm) cores were dry cored using an 4-in. (101.6 mm) inside diameter diamond core bit for testing in the ECS apparatus.

Field Cores

The governing agency for each site was requested to take cores from the site during the 1990-1991 period 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.-diameter (101.6 mm), 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. (152.4 mm) core bit and later recorded at OSU with either a dry-core machine, or a wet-core machine if the sample was too tall for the dry-coring set up. The CAB and CAD samples were cored to a 3.75-in. diameter (95.25 mm) 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 representative lift of the mixture within the core. Data provided by the local agency and the SHRP regional contractors typically allowed for determination of which portion of the core contained the mixture that was under investigation. In one case (GAA), the mixture of interest is the base for a 2-in. (50.8 mm) surface-wearing course. The OR1 mixture is also the base lift of the surface course, and has a 2-in. (50.8 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 how many lifts the mixture was placed in. In some cases, if it was difficult to identify the lift with the appropriate mixture, specimens made from the mixture in the laboratory were cut in half to give a reference for identifying the mixture in the field core.

For the CAD specimens, a line of excess asphalt was noted between the second and third lifts of the surface. This portion of the core also had fine-grained soil in the voids. The assumption was made that traffic was allowed on the section prior to placement of the top lifts and that the excess asphalt and soil were the results of the tack coat and traffic. This was not observed in the CAB samples.

Several sites had cores that exhibited debonding between either lifts within the overlay or between the overlay and the existing pavement. When 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 in. (101.6 mm), but several of the pavements had lifts of significantly less. The OR2 pavement lift was nominally 2 in. (50.8 mm), and after trimming many of these specimens were under 2 in. (50.8 mm) in height. If the mixture layer was thick enough to allow it, the top 1/4 in. (6.35 mm) was also removed to get rid of overly oxidized or consolidated material and material that might be contaminated with typical roadway substances. All sample trimming used a carbon dioxide cooled, dry-cut, diamond-blade saw to eliminate introduction of additional moisture into the samples. After trimming, the samples were labeled, bagged, and stored at 59°F (15°C) until further testing.

Table 2.12. Coring dates for 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. Experiment design for testing of 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. Experiment design for testing of 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.

Specimens Cored from Rutted Beams

At the completion of OSU wheel tracking tests, three cores are drilled from each beam—one from the center of the beam, centered in the rut path, and two from either side of the path. The tops of these specimens were trimmed to remove the uneven surface. The specimens were allowed to dry for seven days before further testing using MTS.

Testing Procedures

Each program under SHRP A-003A Task C.5 (ECS, OSU wheel tracking, Elf wheel tracking, and field) employed specimen conditioning in its test procedure, which subjected the specimen to water damage, followed by measurement of rutting (OSU and Elf wheel trackers) or reduction in modulus (ECS, rutted beam, and field) and visual evaluation of the degree of stripping and binder migration.

However, before the specimens were subjected to ECS and OSU wheel tracking procedures, a series of tests to establish the original conditions of the specimen were required. These tests were conducted on all 4-in.-high × 4-in.-diameter (101.6 mm × 101.6 mm) cylindrical specimens and beam specimens for the OSU wheel tracker, with the exception of modulus testing, which is not performed on beam specimens prior to testing the OSU wheel tracker. Elf specimens were tested at Elf according to its procedures.

Cores cut from rutted beam specimens and field cores were subjected to these tests after they had been removed from the wheel tracker beam or pavement. Data from corresponding laboratory specimens were used to estimate the original unconditioned properties of field and rutted beam specimens.

This section briefly describes the testing performed prior to ECS and OSU wheel tracking procedures; ECS, OSU wheel tracker, and Elf wheel tracker test procedures; and the visual degree of stripping and binder migration evaluations. The treatment that field cores undergo within the pavement test section is not described because it is self-evident.

Information on the climate conditions at the location of each of the test sections is given in chapter 3. Detailed test methods are provided in appendixes A, B, C, D, and F.

Volumetric Properties

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

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

where Wt_A = weight of dry sample in air
Wt_C = weight of sample coated in Parafilm in air
Wt_W = weight of sample coated in Parafilm, submerged in water

Two samples of loose mixture were used to determine the theoretical maximum specific gravity G_{MM} (Rice specific gravity), one from the kneading-compacted 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

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

It is understood that rutted beam specimens and field cores have been wet and 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.

Specimens tested by Elf were tested according to ASTM D-2726 bulk specific gravity and density of compacted bituminous mixtures, using saturated surface-dry specimens.

MTS Diametral Resilient Modulus

The diametral resilient modulus (ASTM D-4123) was used to screen sets of laboratory cores prior to testing in ECS and for final stiffness testing of rutted beam cores and field sections. Diametral modulus testing is performed on a closed-loop hydraulic system run by computer software, which performs the test and calculates the modulus value for each specimen.

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. A static load of 10 lb. (44.5 N) was applied to restrain the specimen in the test apparatus. A pulse load was then applied for 0.1 sec. with a 0.9-sec. 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 as 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 the calculated values differed by more than 10 percent from their average, the specimen was retested.

The diametral resilient modulus was calculated using the following equation:

$$\text{Diametral } M_R = 0.6183 \frac{P}{(d * t)} \tag{2.3}$$

where M_R = resilient modulus (psi)
P = load (pounds)
d = deformation (inches)
t = thickness (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 the output 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 modulus and hard-copy output.

MTS Triaxial Resilient Modulus

Each specimen nominally 4 in. (101.6 mm) in height was also tested to determine resilient modulus in the triaxial configuration with the MTS apparatus. This test was performed with a 30-lb. (133.5 N) static load. The pulse loading was increased until either 100 μ-strain or 40 psi (275 kPa) of loading was reached. A value of triaxial resilient modulus was then calculated by the computer software. The specimen was then further loaded until the second condition was reached, and the modulus again calculated. The constant stress and constant strain readings were taken for use in comparison to the ECS resilient modulus, which was taken as constant stress, and the resilient modulus generated by the aging group, which was taken at constant strain.

ECS Test

The test procedure for ECS involves inducing and monitoring the water damage to a 4-in.-high × 4-in.-diamter (101.6 mm × 101.6 mm) asphalt-concrete specimen. The specimen was prepared either by the kneading compactor method or by coring from a roller-compacted slab. The procedure for ECS is briefly described in table 2.14. Specimens tested with the ECS are identified in table 2.15.

Figure 2.17 shows a schematic of the equipment used to perform the ECS test program. 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 ECS, specimens undergo testing for volumetric properties and MTS diametral and triaxial resilient modulus as described previously in this chapter. The dry (unconditioned) specimen is then encased in a latex rubber membrane and placed within the ECS. The dry (unconditioned) ECS modulus and air permeability are determined. The modulus test performed by ECS was a triaxial resilient modulus test with a zero confining pressure (i.e., $\sigma_2 = \sigma_3 = 0$). The loading, in the form of a true haversine waveform having a duration of 0.1 sec. followed by a dwell time of 0.9 sec., was targeted to be 40 psi (275 kPa). Sufficient loading was applied to the specimen to ensure a constant stress condition before a resilient modulus value was calculated.

The specimen was vacuum conditioned by applying a vacuum of 20 in. (508 mm) Hg to the outlet from the specimen in order to evacuate as much air as possible from the specimen. The specimen was then "wetted" by pulling distilled water through it under the action of the 20-in. (508 mm) Hg vacuum for 30 minutes. Upon completion of the wetting process, the water permeability of the specimen was determined. The specimen was then subjected to one of two programs of thermal conditioning cycles.

For specimens that came from environments designated as no-freeze, the specimen was subjected to three "hot" cycles by heating the specimen to 140°F (60°C) for six hours. During this time, the specimen was subjected to repeated loading of approximately 200 lb. (890 N). Between cycles, the specimen was brought to 77°F (25°C) for at least four hours and tested for resilient modulus and water permeability. All resilient modulus testing took place with the specimen at 77°F (25°C).

For specimens that came from environmental zones with a freeze designation, an additional "freeze" cycle was added at the end of the third hot cycle. The cycle cooled the specimen to 0°F (-18°C) for six hours without repeated loading. After the specimen was brought to 77°F (25°C) for at least four hours, the resilient modulus and water permeability were again measured.

Table 2.14. Summary of the ECS test procedure

Step	Description
1	Prepare test specimens per SHRP protocol.
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 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 specimen to 140°F (60°C) for six hours under repeated loading. This is a hot cycle.
10	Cool specimen to 77°F (25°C) for at least four hours. Measure triaxial resilient modulus and water permeability.
11	Repeat steps 9 and 10 for two more hot cycles.
12	Cool specimen to 0°F (-18°C) for six hours without repeated loading. This is a freeze cycle.
13	Heat specimen to 77°F (25°C) for at least four hours and measure the triaxial resilient modulus and water permeability.
14	Split specimen and perform a visual evaluation of stripping and binder migration.
15	Plot the ECS resilient modulus ratio.

Source: Scholz et al. 1992.

Table 2.15. Experiment design for the ECS testing for SHRP A-003A Task C.5

Mixture Number	Mixture 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. Experiment design for the ECS testing for SHRP A-003A Task C.5 (continued)

Mixture Number	Mixture 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

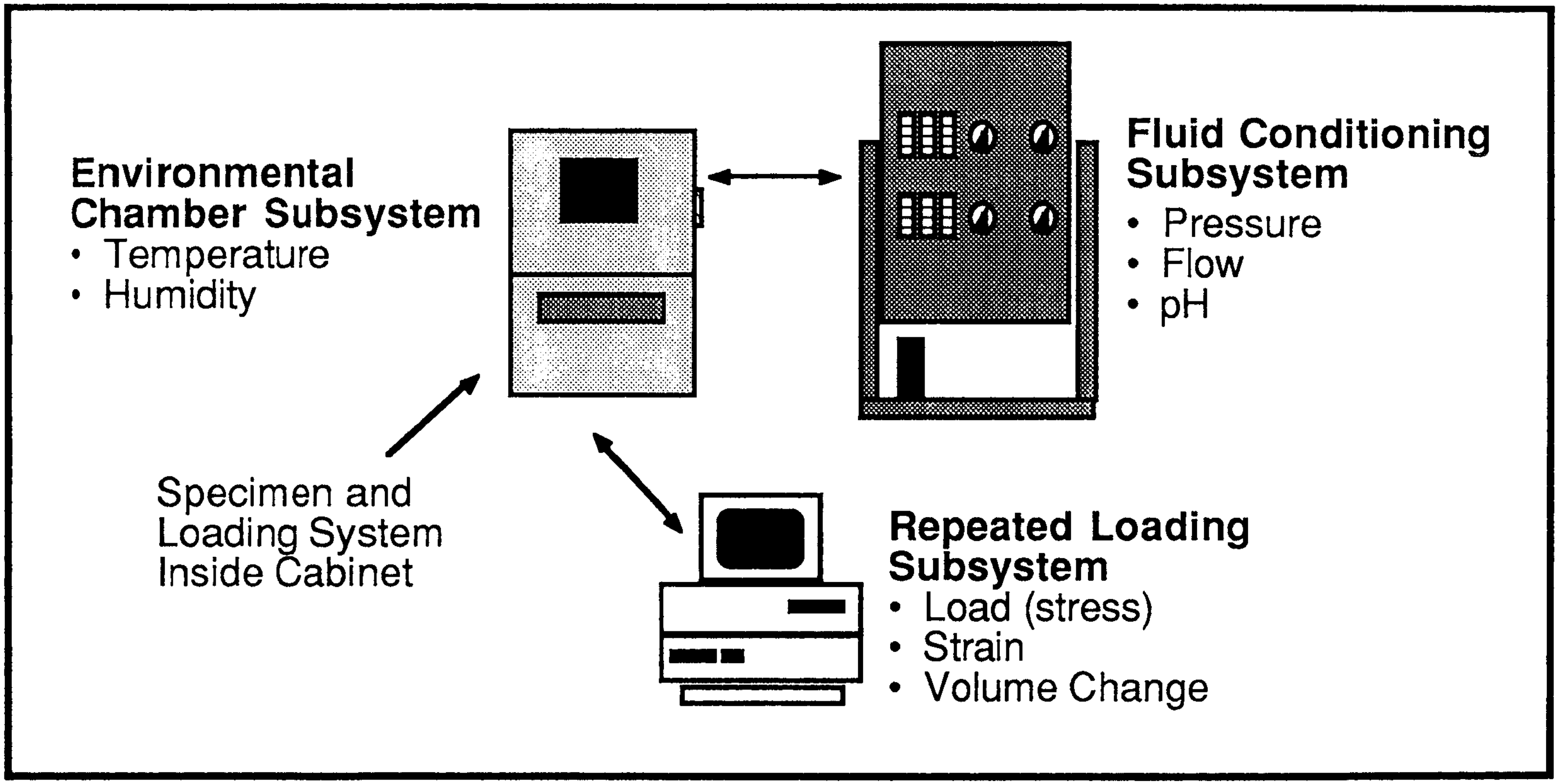


Figure 2.17 Schematic of the environmental conditioning system (ECS)

At the completion of either three or four conditioning cycles, the specimen membrane was removed, and the specimen was split diametrally using MTS. A visual evaluation of stripping and binder migration was made from the two split faces of the specimen.

OSU Wheel Tracking Test

The procedure for the OSU wheel tracking test involved conditioning beams of asphalt-aggregate mixtures to induce water damage and then testing them under repeated loading of the OSU wheel tracker. Rut depth was the response mode monitored. Figure 2.18 shows a schematic of the OSU wheel tracker. The procedure is briefly outlined in table 2.16. The beam specimens tested under this conditioning procedure and their associated rutted beam specimens are identified in table 2.17.

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

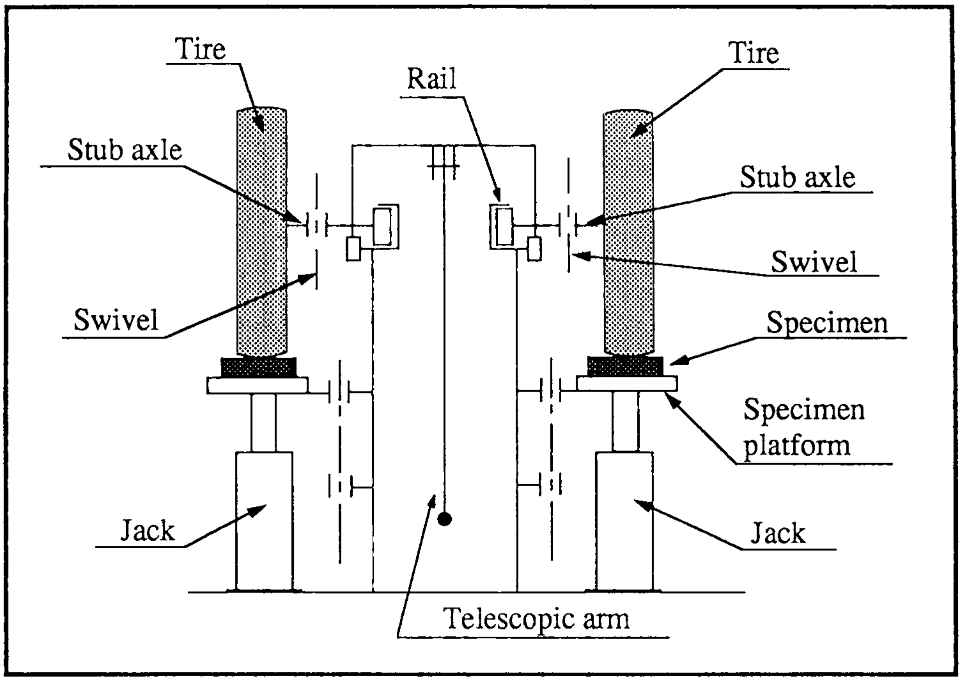
1. The wetting procedure for the beam specimens employed a slightly higher vacuum level and was significantly longer than that employed in ECS. This was to ensure that specimens achieved a saturation of between 60 percent and 80 percent.

2. The duration of some of the conditioning cycles was longer than in the ECS procedure because of scheduling constraints for the equipment used for thermal conditioning.

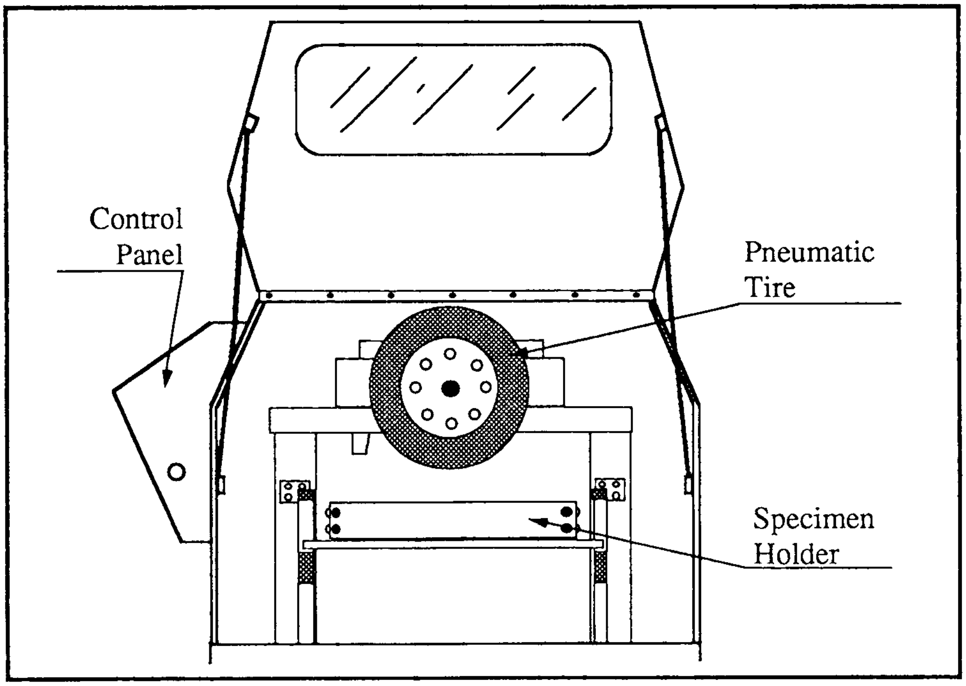
3. The order of the conditioning cycles was slightly different for the wheel tracking test program relative to the ECS test program. Again, this was due to scheduling constraints on the equipment used for thermal conditioning.

Once the beam had undergone water and thermal conditioning, it was wrapped in plastic, to prevent moisture loss and placed in 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. An 1/8-in.-thick (3 mm) 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 placed in the OSU wheel tracker, bolted into place, and the system was brought up to the test temperature of 104°F (40°C) for at least two hours.

After the specimen reached 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.



Schematic



Side View

Figure 2.18 Schematic of the OSU wheel tracker

Table 2.16 Summary of OSU wheel tracking test procedure

Step	Description
1	Prepare test specimen as described in Table 2.11.
2	Determine the gravimetric properties of the beam.
3	Place a latex and silicone sealant seal around the circumference of the beam at midheight 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 6 hours. Cool the specimen to 77°F (25°C) in a distilled water bath for 10 hours. Heat the specimen to 140°F (60°C) in a distilled water bath for 6 hours. Cool the specimen to -4°F (-20°C) in a distilled water bath for 8 hours. Heat the specimen to 140°F (60°C) in a distilled water bath for 10 hours. Cool the specimen to 77°F (25°C) in a distilled water bath for 10 hours.
6	Wrap the specimen in plastic (e.g., Saran Wrap) to retain moisture 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 taking 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 so as to obtain cores for evaluation. Split the cores and perform a visual evaluation of stripping and binder migration.

Source: Scholz et al. 1992.

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

Table 2.17 Experiment design for the OSU wheel tracking for the SHRP A-003A Task C.5

Mixture Number	Mixture Code	Site	Replicate
1	AB5R801[1]	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

[1] Each beam resulted in three cored, rutted beam specimens (e.g., AB5R801A, AB5R801B, AB5R801C).

A preconditioning wheel load of 50 wheel passes at 92 psi (634 kPa) was 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 obtained electronically (i.e., via computer), using a displacement transducer designed specifically for these measurements, or manually, using the caliper provided by LCPC. Figure 2.19 shows the 15 positions at which the surface profile measurements were obtained. Note that the measurement positions were concentrated near the center of the beam along its longitudinal axis so as to avoid measurement of high plastic deformations that occur in the region where the rolling wheel slows down, stops, and reverses 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, alternatively, until failure occurred (as established by a sudden and significant increase in plastic deformation). After accumulation of 100, 200, 500, 1,000, 2,000, and 5,000 wheel passes the load was temporarily halted and the surface profile measured. After 10,000 wheel passes or when loading was terminated because of failure, a final surface profile was measured. The beam was then cored into three, 4-in.-diameter (101.6 mm) rutted beam specimens.

Elf Wheel Tracking Test

The procedure for the Elf wheel tracking test involved testing a specimen immersed in a water bath at elevated temperatures. A brief summary of the test procedure is given in table 2.18. Appendix F provides the detailed test protocol. Mixtures tested in this procedure are listed in table 2.19.

The Elf wheel tracker employed an 8-in.-diameter (203.6 mm), 1.85-in.-wide (47.0 mm) steel wheel. The wheel was applied to the surface of the specimen with a 156-lb. (697 N) force. The wheel reciprocated over the specimen, making 50 passes per minute, at a maximum speed of 1.1 ft./sec. (340 mm/sec.), reached at the midpoint of the specimen. The configuration resulted in a 0.1-sec. loading period and a 1.0-sec. relaxation period at the midpoint of the specimen. An LVDT was mounted to measure the movement of the wheel downward as the rut depth increased.

The test specimens were 10.24 in. ± 0.1 in. (260 mm ± 2 mm) wide, and 12.6 in. ± 0.1 in. (320 mm ± 2 mm) long. The thickness of the specimen was typically twice the maximum nominal aggregate size, ranging from 1.5 in. to 3.9 in. (38 mm to 100 mm). The specimen was mounted so that it is surrounded on all sides by a minimum of 0.79 in. (2 cm) of free-circulating water.

Elf identifies the following additional data, as well as rut depth:

- Postcompaction consolidation. The depth of impression that rapidly accumulates during the first 1,000 ± 500 wheel passes.

- Creep slope. The inverse rate of deformation expressed in units of wheel passes per millimeter of deformation. This rate is calculated after the postcompaction consolidation but before the onset of moisture damage.

- Stripping inflection point. The number of wheel passes necessary to induce moisture damage to the specimen. After moisture damage begins, the rate of deformation increases rapidly, and uncoated aggregate particles emerge from the surface of the specimen.

- Stripping slope. The inverse rate of deformation measured after the stripping inflection point until the end of the test.

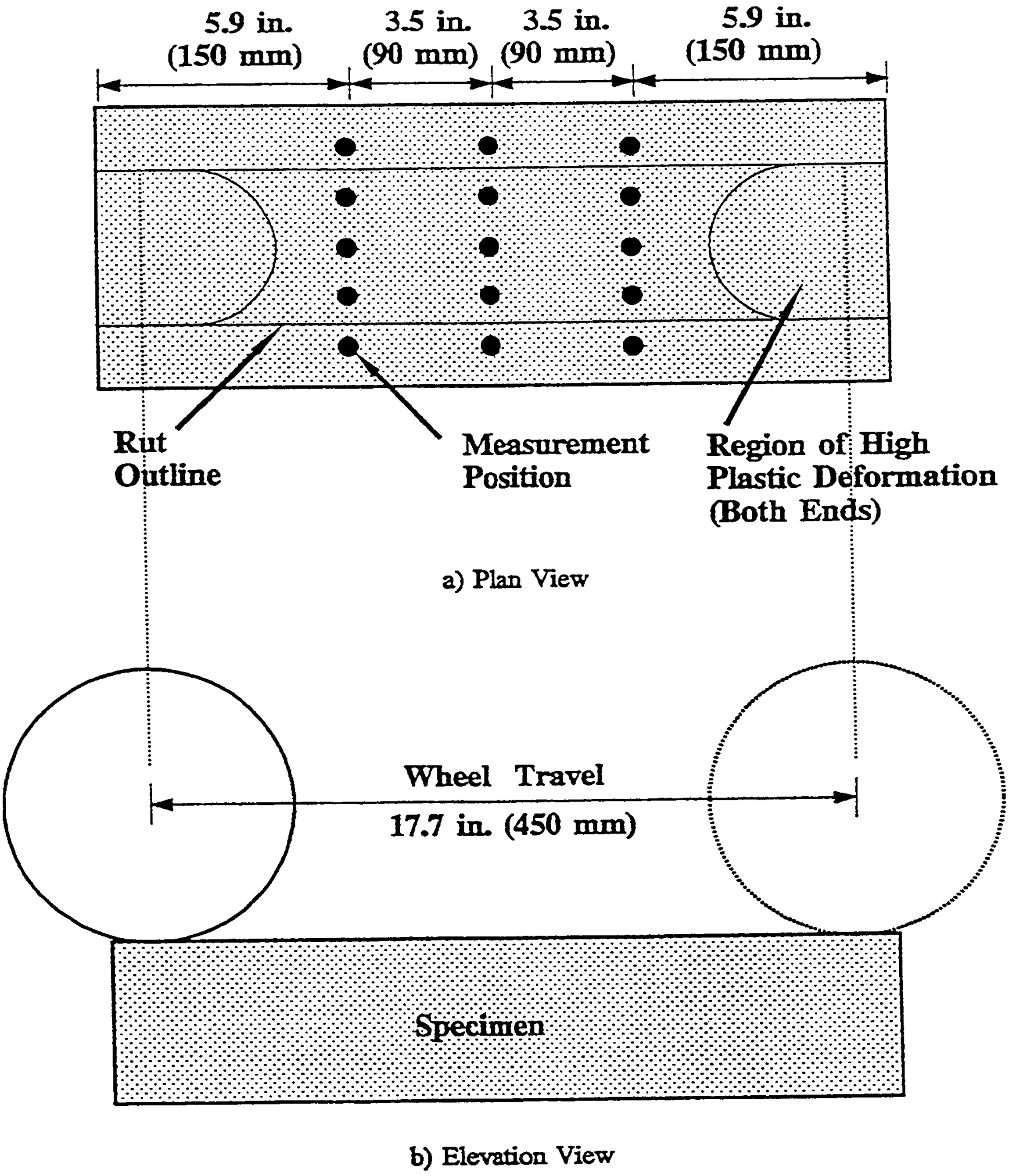


Figure 2.19 Measuring positions for rut depth

Table 2.18 Summary of the Elf wheel tracking procedure

Step	Description
1	Prepare test specimen according to standard Elf Protocol (appendix E).
2	Determine the gravimetric properties of the specimen.
3	Mount the specimen into the test mounting tray using plaster of paris.
4	Bolt the specimen tray into the wheel tracker, introduce water into the machine.
5	Determine test temperature: 104°F (40°C) for binders of viscosity grade AC-10 (penetration grade 120/150) or softer 122°F (50°C) for all harder grade of binder
6	Stabilize water bath temperature at test temperature. Condition specimen by soaking at test temperature for 30 ± 5 minutes.
7	Lower wheel onto specimen and begin testing. Ten wheel passes is used as the test zero.
8	Record rut depth after at least every 100 wheel passes. Note number of passes at which stripped aggregate particles are ejected from the specimen into the water bath.
9	Conclude testing after 20,000 passes, or when a 20 mm rut depth is reached.

Table 2.19 Experiment design for the Elf wheel tracker

Mixture Number	Mixture Code	Site
1	AB5ELF01	AB5
2	AZ5ELF01 AZ5ELF02	AZ5
3	OR1ELF01 OR1ELF02	OR1
4	OR2ELF01 OR2ELF02	OR2
5	WIAELF01 WIAELF02	WIA

Visual Evaluation of Stripping and Binder Migration

After each testing procedure was completed, and the specimen had been tested for resilient modulus with either MTS or ECS, a visual evaluation was performed. Specimens were split in half by applying a diametral static load. The two broken faces were examined to determine what percentage of the surface area of the face had been stripped of asphalt. The percentage of stripping was reported to be: 0, 5, 10, 20, 30, 40, or 50, as shown in figure 2.20. Fractured faces were neglected in the identification of aggregate faces that had lost their asphalt covering.

In addition to percent of stripped aggregate, it became evident early in the testing program that some of the field validation mixtures had experienced displacement of the asphalt binder in the direction of water flow through the specimen during the ECS test procedure. This phenomenon, termed binder migration, is described by giving the specimen a letter rating, each letter corresponding to a level of binder movement, as represented in figure 2.21.

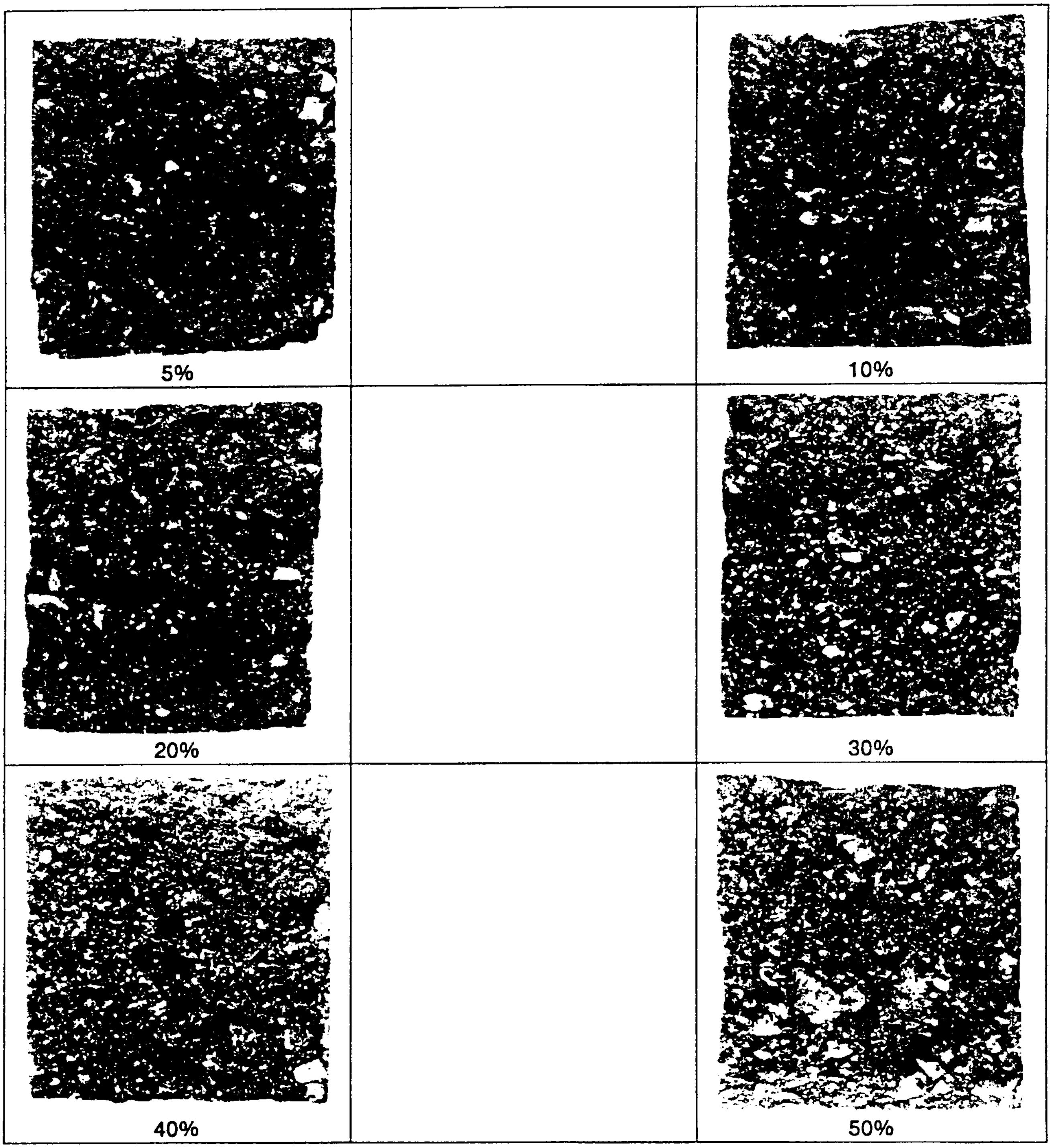


Figure 2.20. Visual stripping rating chart

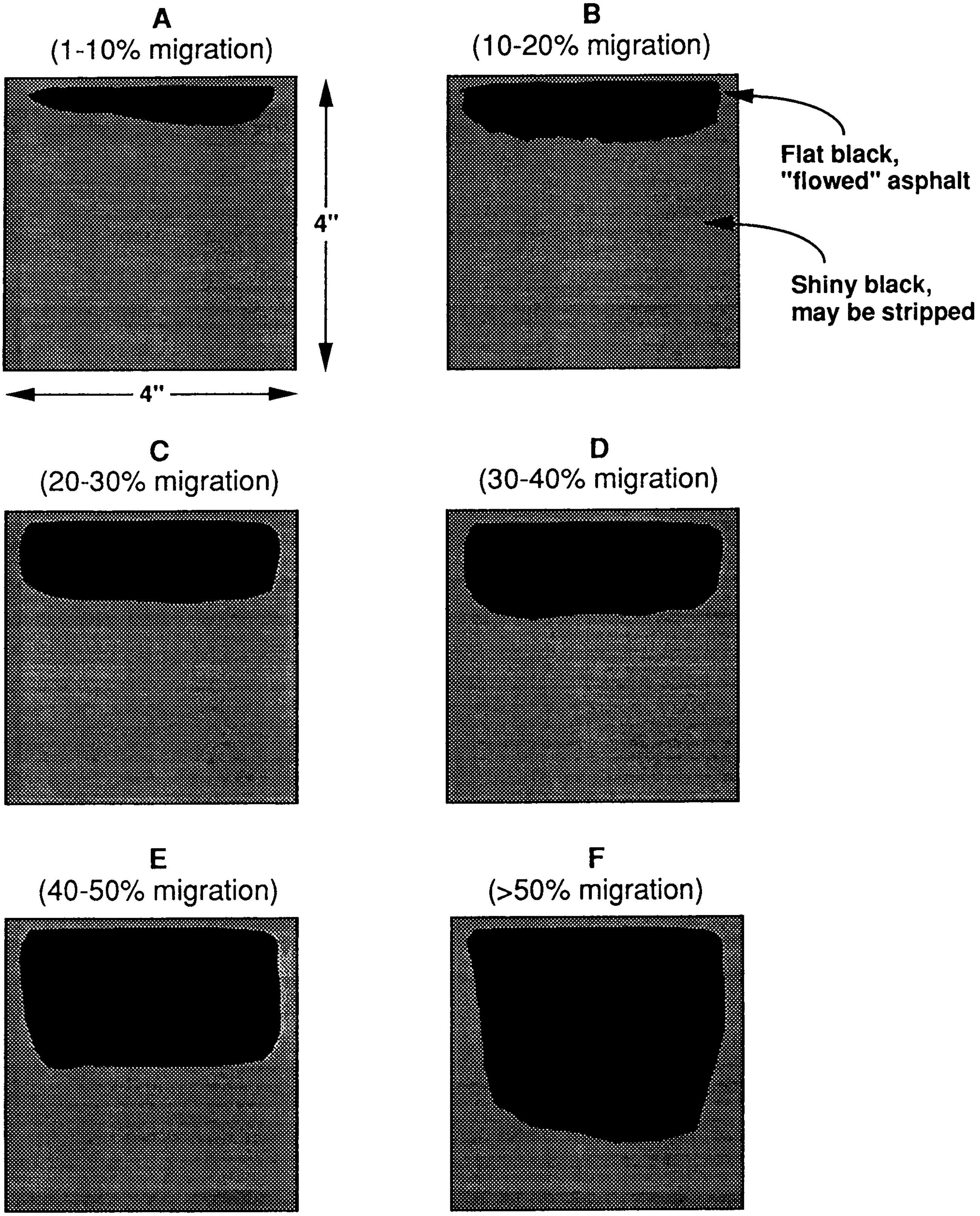


Figure 2.21. Binder migration rating chart

3

Results

This chapter presents the results of the field validation effort for water sensitivity. Included are results obtained in the Environmental Conditioning System (ECS) and the Oregon State University (OSU) wheel tracking programs conducted at OSU, as well as those obtained by the Elf Asphalt wheel tracking program. Resilient modulus data, both diametral and triaxial, from cores taken from in-service field test sections are also presented.

ECS Test Program

The specimens tested in the ECS program are summarized in table 3.1. The initial test program included six specimens from each mixture, with the exception of CAB, for which there were four specimens. Additional specimens were added to investigate mixtures that had data that varied within the mixture set. The test results for the ECS testing program are shown graphically in figures 3.1 through 3.12.

ECS Modulus Data

Each data curve in figures 3.1 through 3.12 represents a single ECS specimen. The curves define the change in retained resilient modulus (termed ECS-modulus ratio) as a function of the conditioning level (each cycle represents a conditioning cycle within ECS with the first three cycles being "hot" cycles and the fourth cycle being the "freeze" cycle)[1]. 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 the specimens caused by water damage relative to the dry, unconditioned stiffness of the specimen. Water damage as measured by the decrease in the ECS modulus

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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 zero confining stress (i.e., $\sigma_2 = \sigma_3 = 0$) conducted on a 4-in.-diameter (102 mm) × 4-in.-high (102 mm) asphalt-aggregate mixture test specimen.

Table 3.1. ECS test specimens

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	
AB5KM03	4.4	5	D	
AB5KH06	2.8	5	E	
AB5KD08	2.6	5	E	
AZ5R803	8.3	20	No	
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 3.1. ECS test specimens (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	
GAAKM11	9.2	0	No	
GAAKH04	7.4	0	No	
GAAKD01	6.4	5	No	
MN5R803	11.3	5	No	
MN5R804	10.6	5	No	
MN5R806	11.7	5	No	
MN5KL03	6.5	5	D	
MN5KM05	5.6	5	D	
MN5KD08	4.4	5	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 1st cycle-loading continued[2]
MS5KH07	4.1	20	C	Failed 1st cycle-sample removed[2]
MS5KD08	3.5	20	C	Failed 1st cycle-loading continued[2]
OR1R803	8.3	5	No	
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	
OR2R804	20.2	5	No	
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 3.1. ECS test specimens (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 1st cycle-loading discontinued[2]
WIAKM08	1.8	5	No	
WIAKH15	1.4	5	No	Failed 2nd cycle-loading continued[2]
WIAKD18	0.6	5	No	
WIAKD19	0.7	5	No	

[1] Figure 2.21 illustrates the rating scale for binder migration.

[2] Failed because of excessive deformation under repeated axial loading.

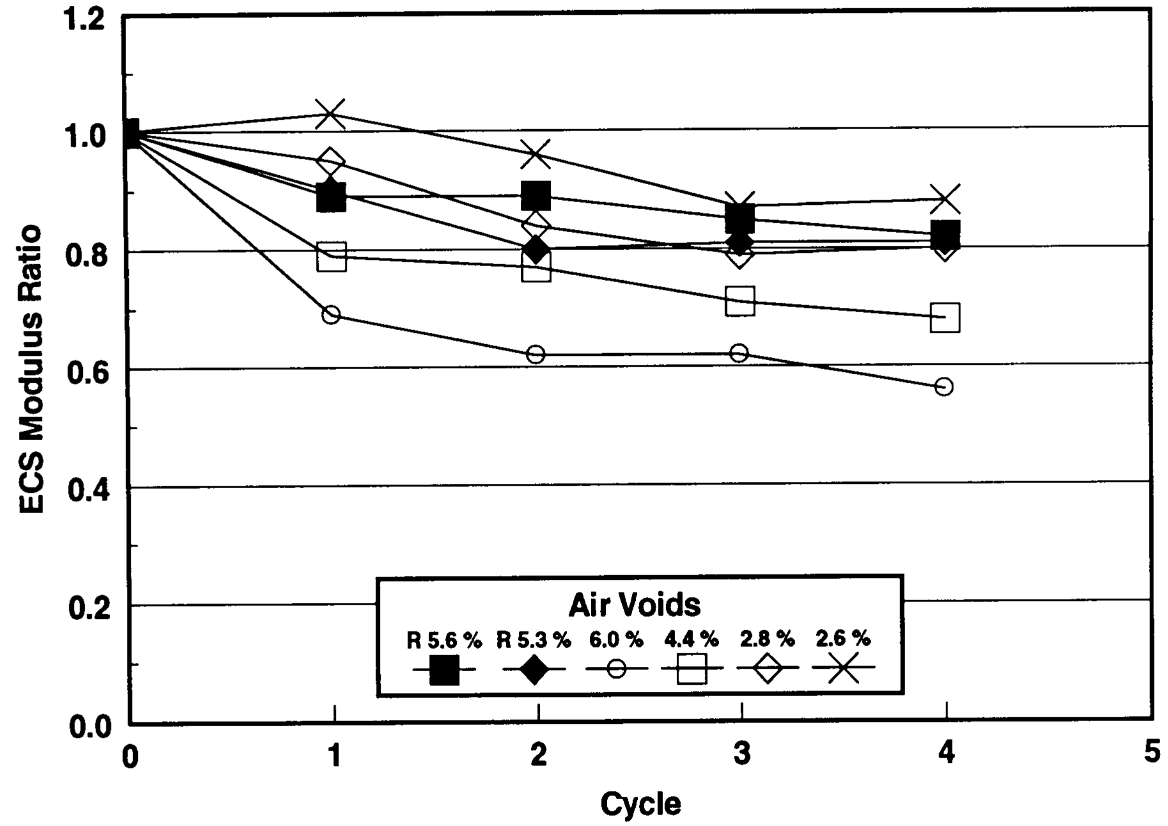


Figure 3.1. AB5 ECS results

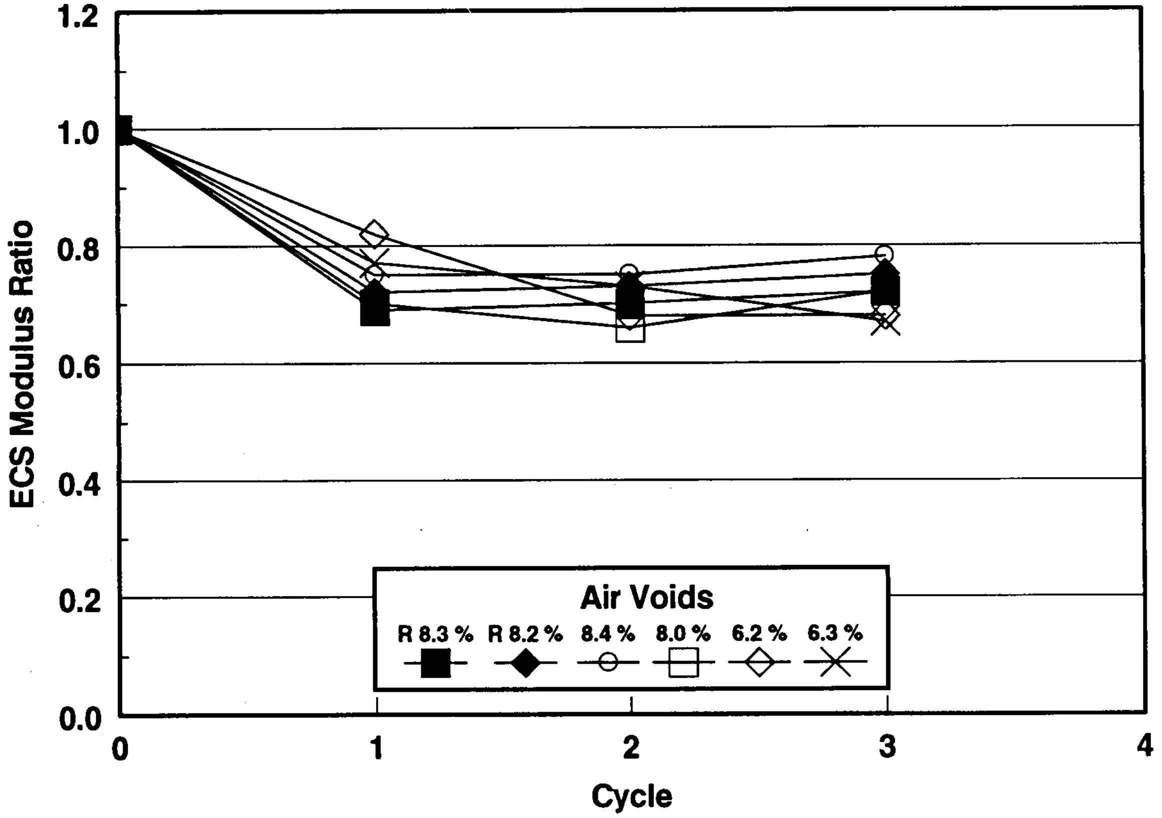


Figure 3.2. AZ5 ECS results

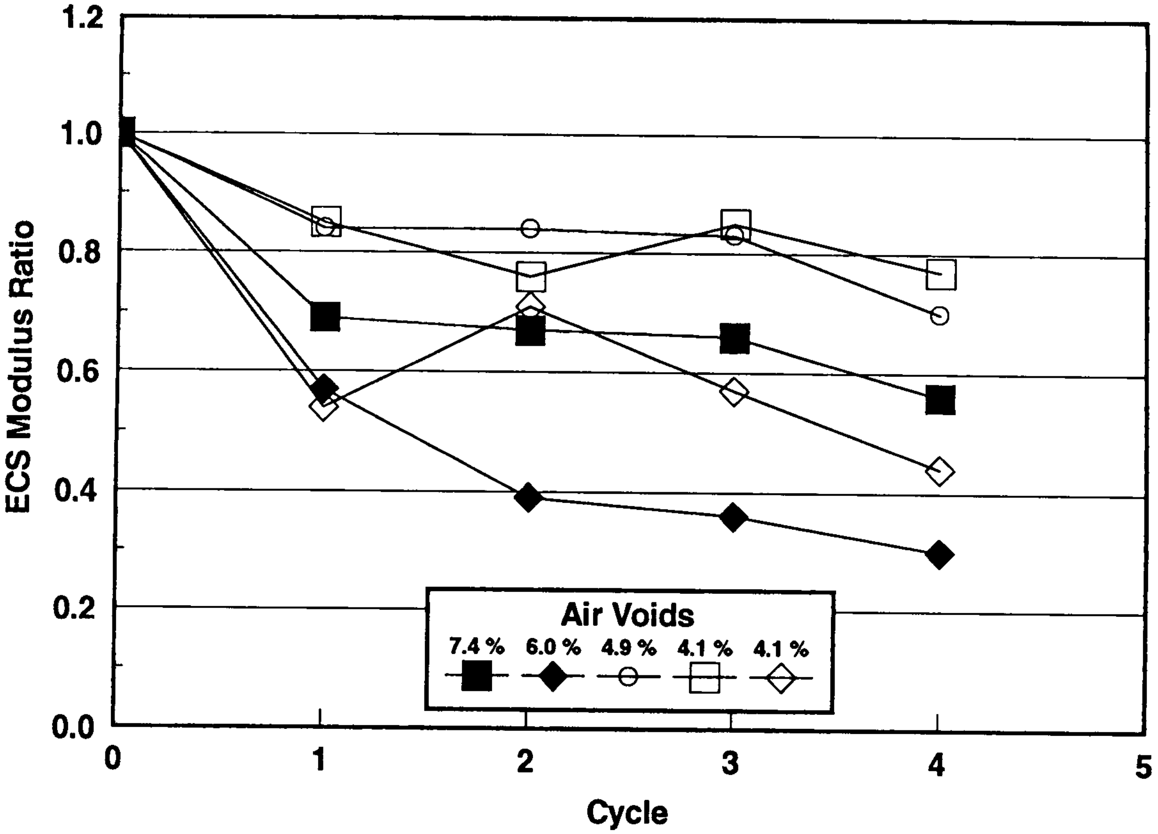


Figure 3.3. CAB ECS results

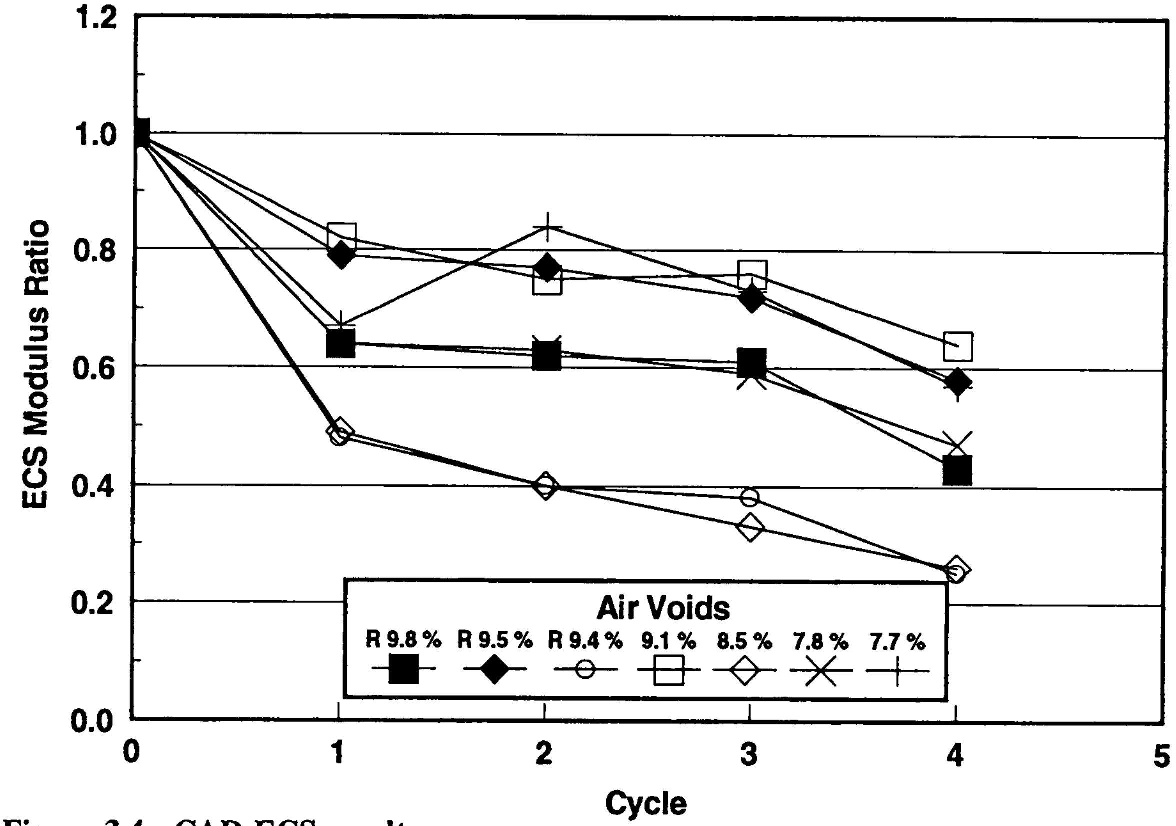


Figure 3.4. CAD ECS results

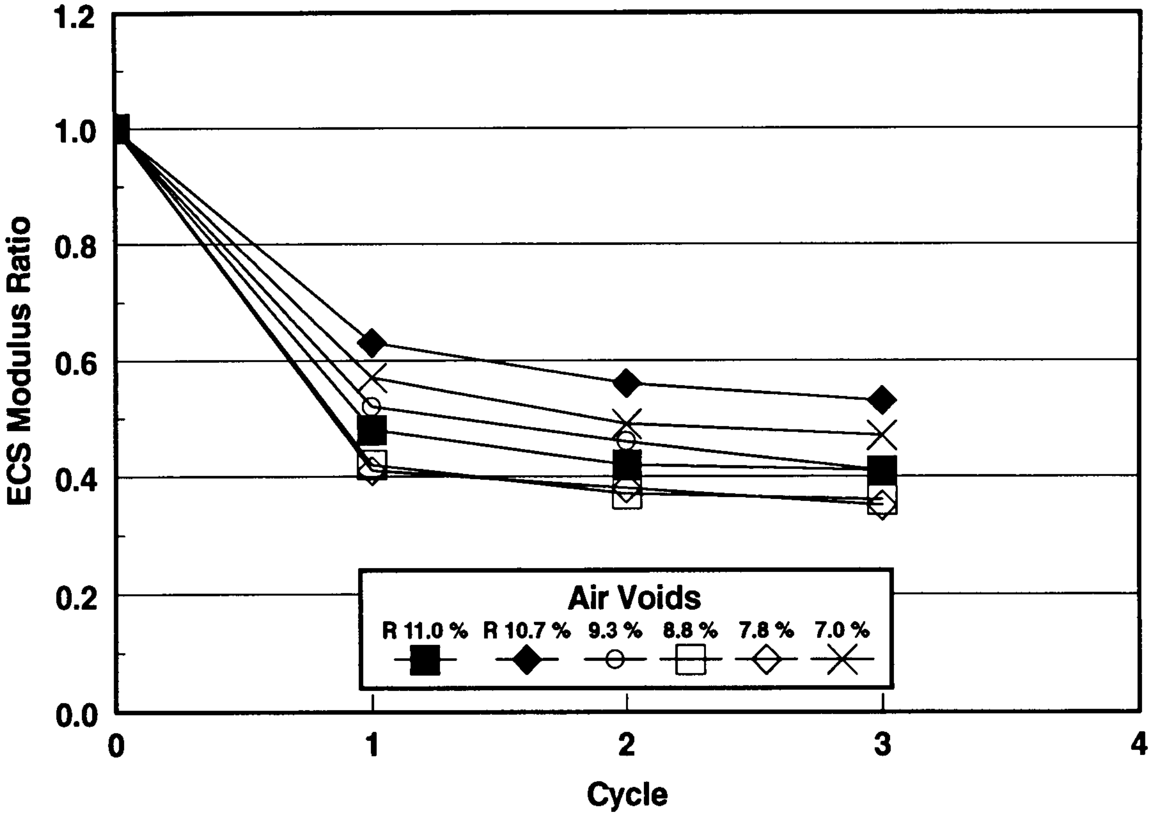


Figure 3.5. CAG ECS results

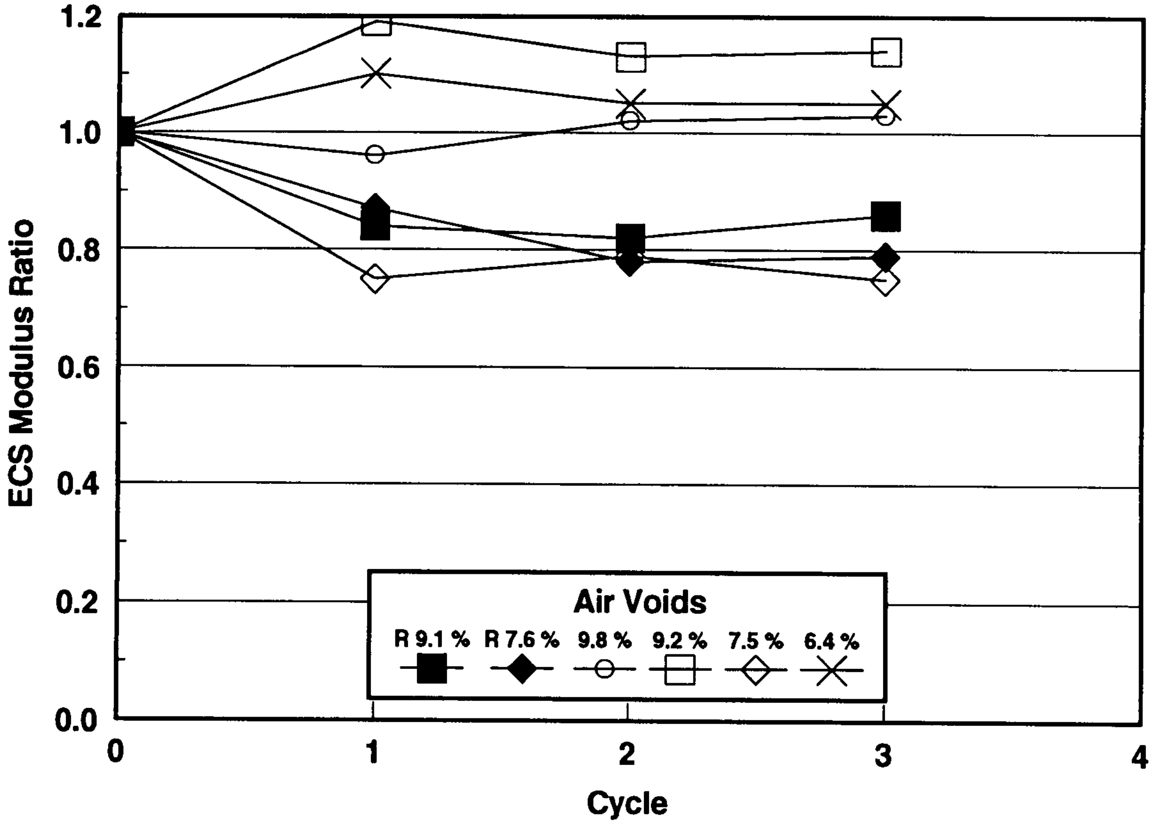


Figure 3.6. GAA ECS results

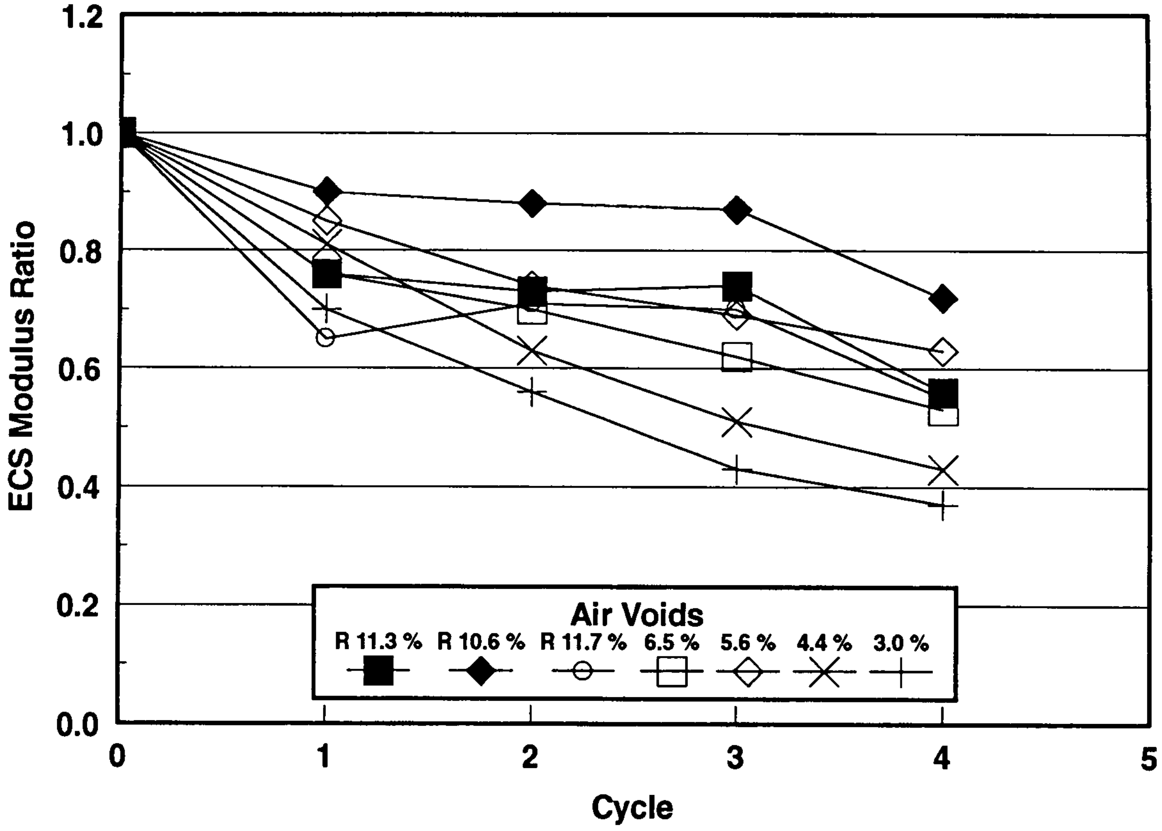


Figure 3.7. MN5 ECS results

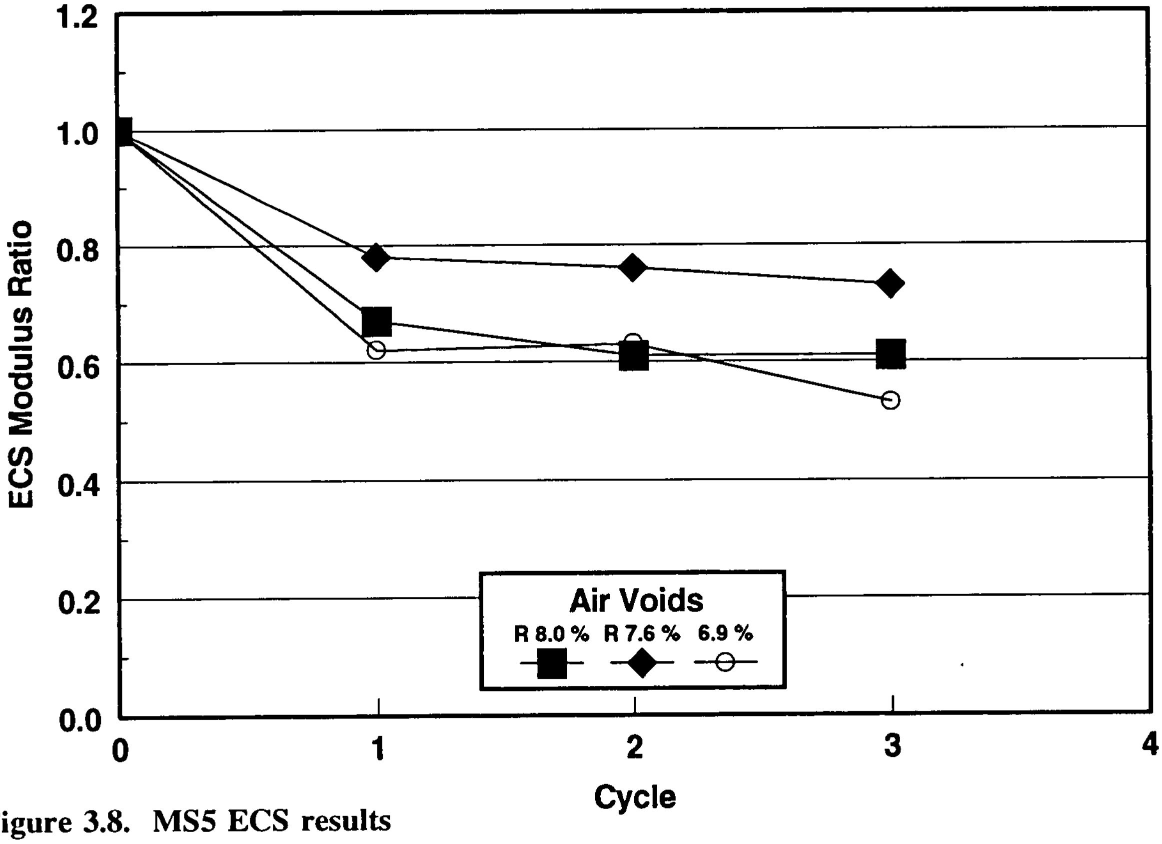


Figure 3.8. MS5 ECS results

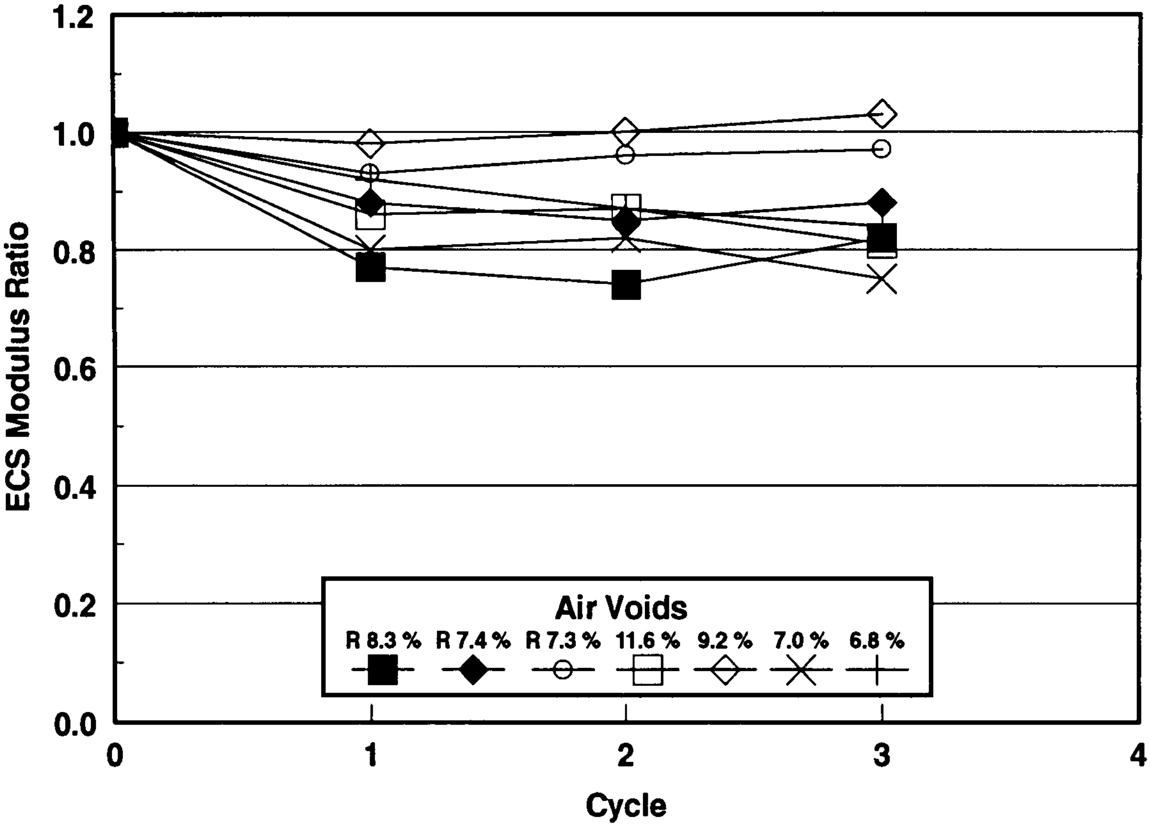


Figure 3.9. OR1 ECS results

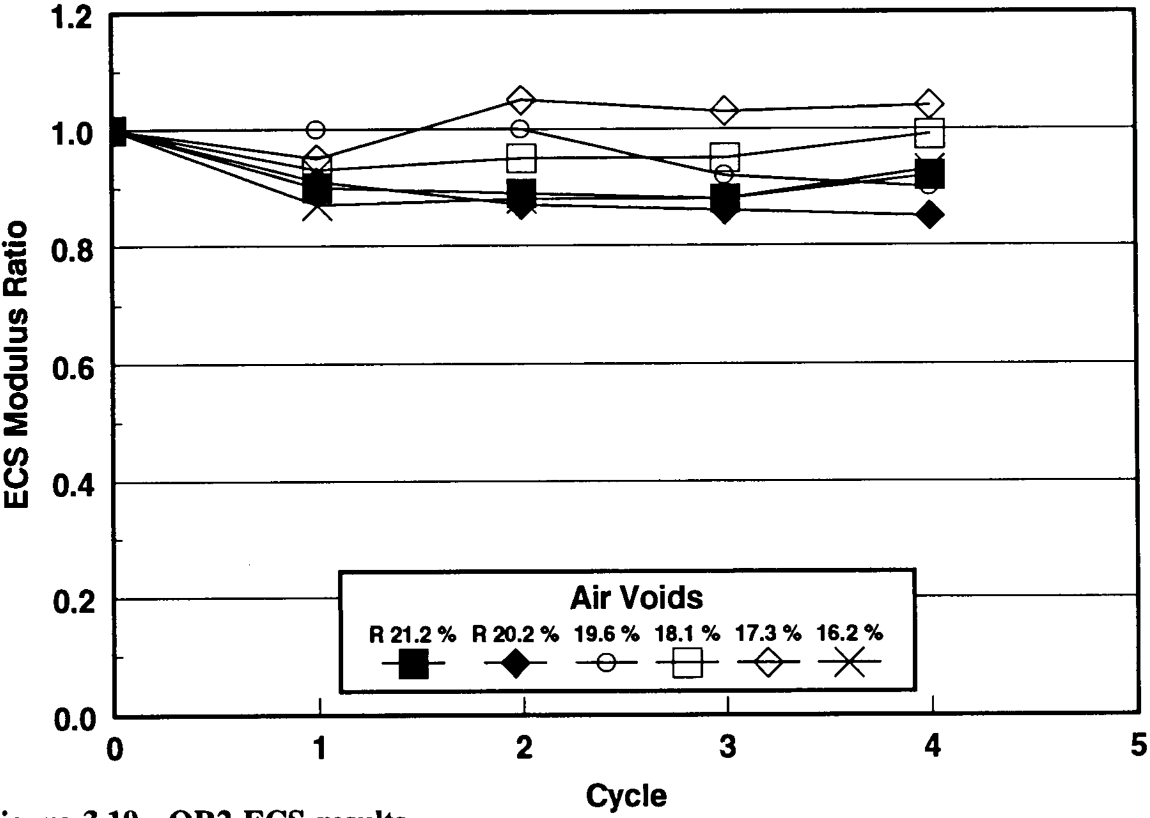


Figure 3.10. OR2 ECS results

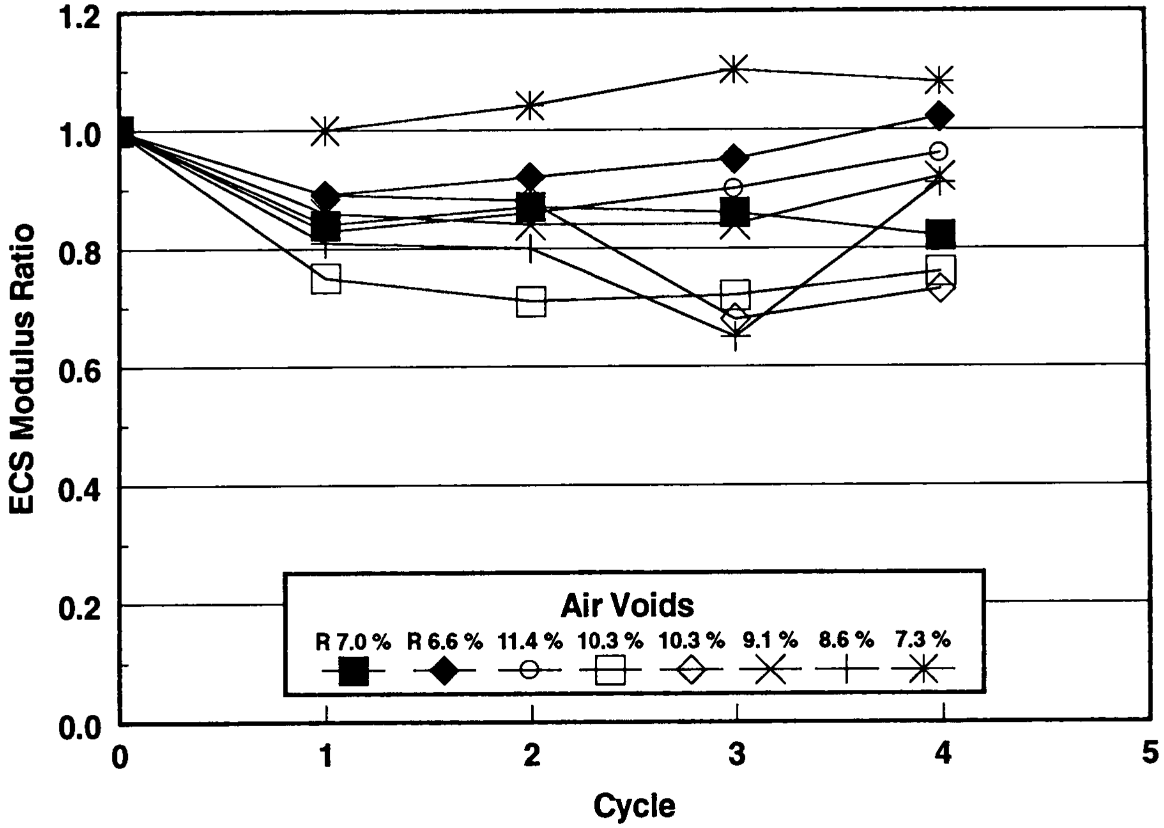


Figure 3.11. WA1 ECS results

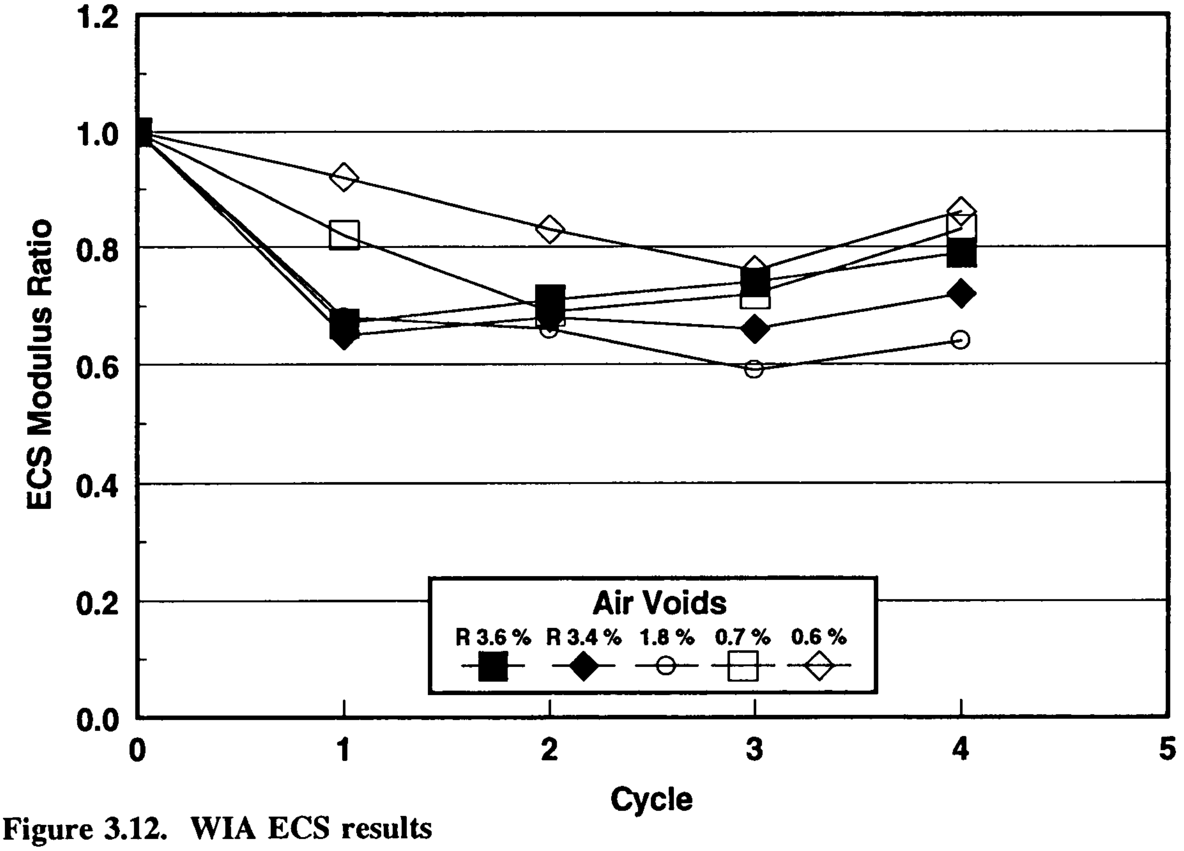


Figure 3.12. WIA ECS results

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 ECS, specimens of two mixtures experienced excessive deformation during the “hot” cycles of the test: WIA and MS5. This behavior had not occurred during the previous work with the Strategic Highway Research Program (SHRP) core 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 percent to 15 percent, so that the yoke that holds the linear variable differential transducers (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, and the specimen was further conditioned without loading, with modulus testing taking place between cycles. The data for these specimens also appear in appendix C. The specimens that experienced failure because of excessive deformation within the ECS test apparatus are identified in table 3.1.

Visual Degree of Stripping and Binder Migration Data

The visual degree of stripping, as evaluated after the completion of the ECS procedure, indicates the level of adhesion loss between the asphalt binder and the aggregate in a specimen. Binder migration may be the result of both a loss of adhesion between the asphalt binder and the aggregate and a loss of cohesion in the asphalt binder. In order for asphalt binder particles to migrate within the specimen, the particles must first debond from all surrounding material. This debonding 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 C.

Permeability Data

Average values of the coefficients of permeability and the intrinsic permeabilities for all mixtures are reported in table 3.2. The coefficients of air and water permeability were calculated using Darcy’s Law. The coefficient of permeability is dependent on both the media and the fluid used as a permeant. 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 = permeability (m^2)
γ = specific weight of the fluid (N/m^3)
μ = viscosity of the fluid ($N\text{-}s/m^2$)

Table 3.2. Average coefficients of permeability, intrinsic permeabilities for each mixture[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)	1.84E-05 (3)	1.68E-10 (3)
AZ5	2.29E-05 (4)	3.63E-09 (4)	7.82E-05 (4)	7.13E-10 (4)
CAB	7.08E-06 (1)	1.12E-09 (1)	1.41E-05 (1)	1.28E-10 (1)
CAD	6.97E-05 (7)	1.10E-08 (7)	1.60E-04 (7)	1.46E-09 (7)
CAG	4.59E-05 (6)	7.26E-09 (6)	2.18E-04 (6)	1.98E-09 (6)
GAA	5.50E-05 (6)	8.69E-09 (6)	3.40E-04 (6)	3.10E-09 (6)
MN5	5.98E-05 (4)	9.47E-09 (4)	3.55E-04 (4)	3.23E-09 (4)
MS5	9.57E-06 (1)	1.51E-09 (1)	6.30E-05 (2)	5.74E-10 (2)
OR1	4.04E-05 (4)	6.39E-09 (4)	5.82E-04 (5)	5.30E-09 (5)
OR2	8.10E-05 (4)	1.28E-08 (4)	1.78E-03 (5)	1.63E-08 (5)
WA1	1.00-05 (3)	1.59E-09 (3)	9.66E-05 (3)	8.80E-10 (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.

It was not uncommon for specimens to have coefficient of permeability values too low for the ECS equipment to measure, for both air and water. Of the 78 specimens tested, 37 were impermeable to air in the ECS apparatus and 32 were impermeable to water. The lower limits of the ECS permeability apparatus are approximately 1.14E-07in./sec. (7.90E-07 cm/sec.) for air and 7.87E-08in./sec. (2.00E-07 cm/sec.) for water. Also, five of the specimens tested were impermeable to air, and yet permeable to water after the 30-minute wetting procedure.

Figure 3.13 shows the relationship between the coefficient of permeability for air and the percent air voids. Similar data for the coefficient of permeability for water are shown in figure 3.14. 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 3.15 through 3.26 show the variation of the coefficient of permeability of water throughout the ECS test procedure.

OSU Wheel Tracking Program

Results from the OSU wheel tracking program are summarized in table 3.3 and are shown graphically in figure 3.27. Table 3.4 shows the data from the cores taken from the rutted beam specimens. 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 only used in figure 3.27 for illustration.

Two mixtures produced specimens that failed within the OSU wheel tracker, CAG, and MN5. Failure is defined as a rut depth of greater than 20 mm (0.79 in.). The beams made of the MN5 mixture failed within 1,000 wheel passes, and testing was discontinued. The beams manufactured using 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 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.

Elf Wheel Tracking Program

The results of the testing conducted by Elf Asphalt in Terre Haute, Indiana, are presented in table 3.5 (Hines 1992). Rut depths at wheel pass levels corresponding to those used in the OSU wheel tracking test have been plotted for each specimen tested by Elf in figure 3.28.

Field Data

Weather Data

Data from the nearest recording weather station for each field section are presented in tables 3.6 through 3.9. The most recent full year of data published by the National Climatic Data Center is 1990. Eleven of the 12 sites were in place during the full 1990 calendar year.

Project CAG was constructed in late summer of 1990. The 30-year data are presented to indicate more stabilized information from the site in case the 1990 data represent abnormal temperature or precipitation extremes.

Traffic Data

Traffic data for each field test section as reported by the local state agency are shown in table 3.10. Average daily traffic (ADT) and percentage of truck traffic were requested for the most recent full year of data available. In some cases, the data are for a year prior to the construction of the test section investigated in this program.

Manual Distress Surveys and Pasco Data

Table 3.11 indicates the condition of each field test section from the most recent distress survey, manual or Pasco, for the site. The type of survey and date performed are also indicated.

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 3.29 through 3.50. The MTS modulus values of newly manufactured, laboratory kneading compactor cores are shown as a reference. This modulus is termed the unconditioned modulus value because the specimens have not undergone any type of conditioning prior to this measurement of modulus. The results of the visual stripping evaluation are shown in table 3.12. The complete data from the cores are given in appendix D.

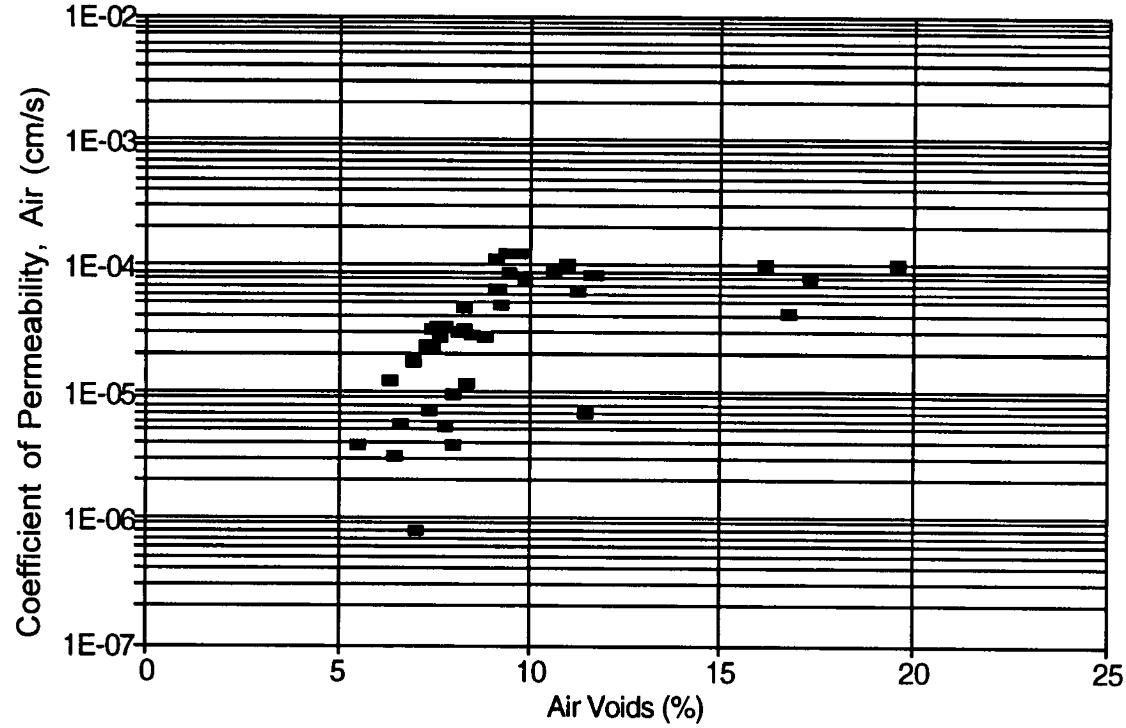


Figure 3.13. Variation in the coefficient of air permeability with air voids

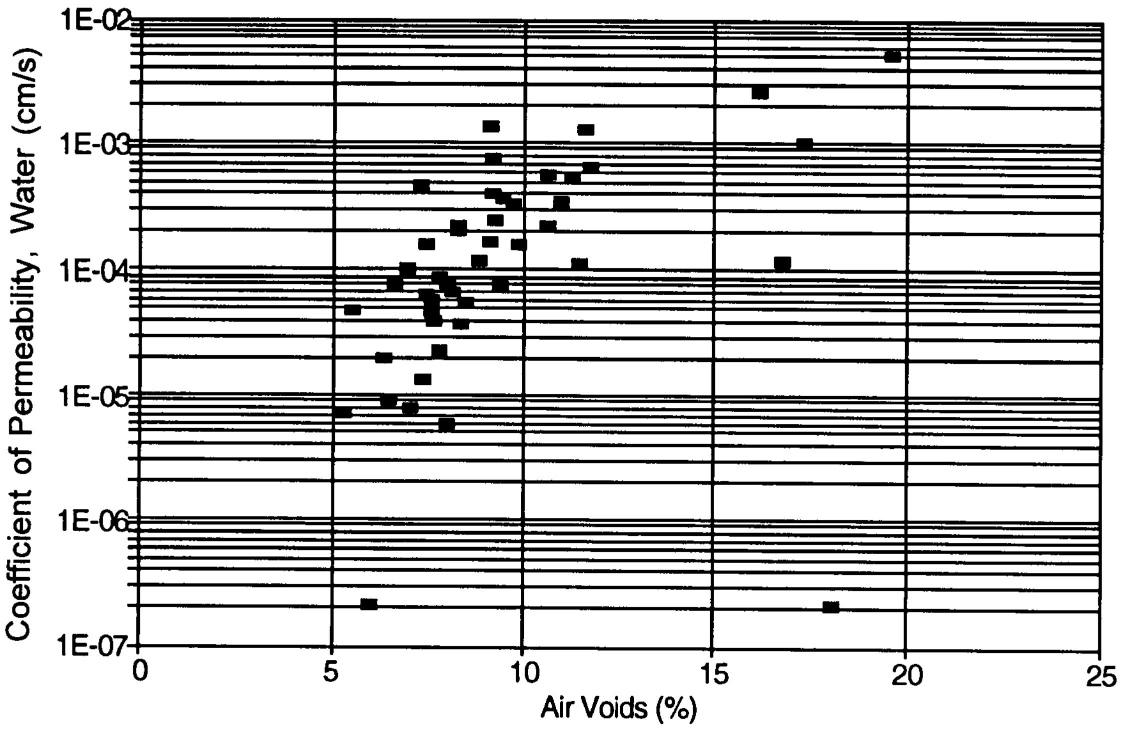


Figure 3.14. Variation in the coefficient of water permeability with air voids

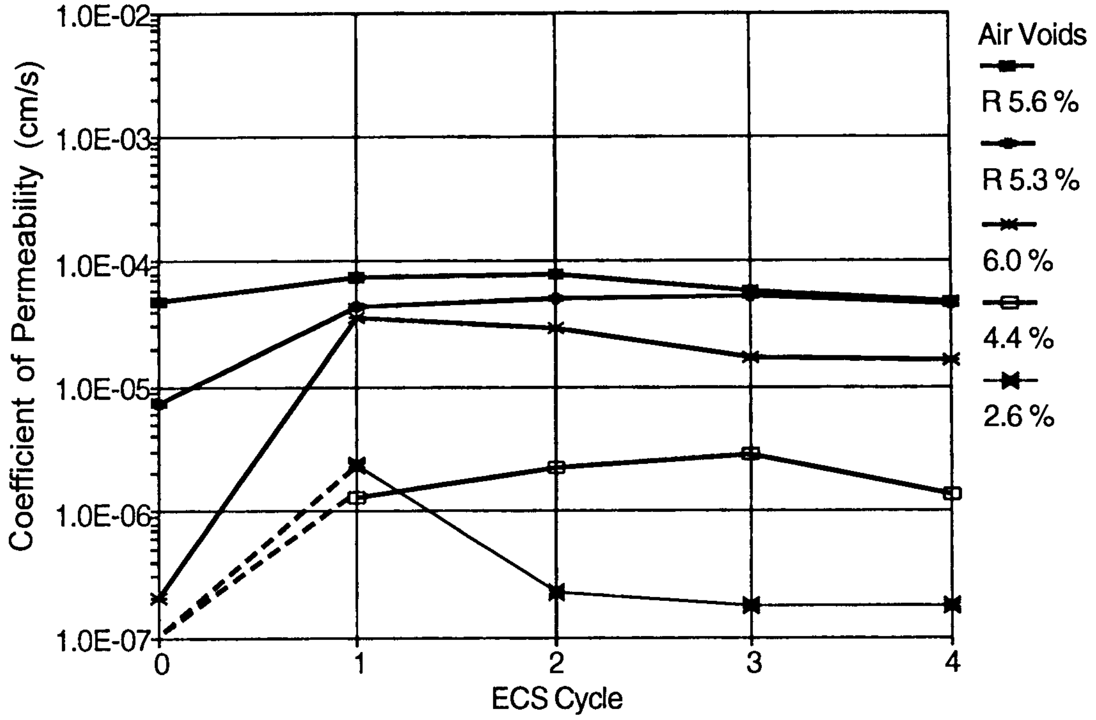


Figure 3.15. Variation in the coefficient of water permeability in the ECS procedure, AB5

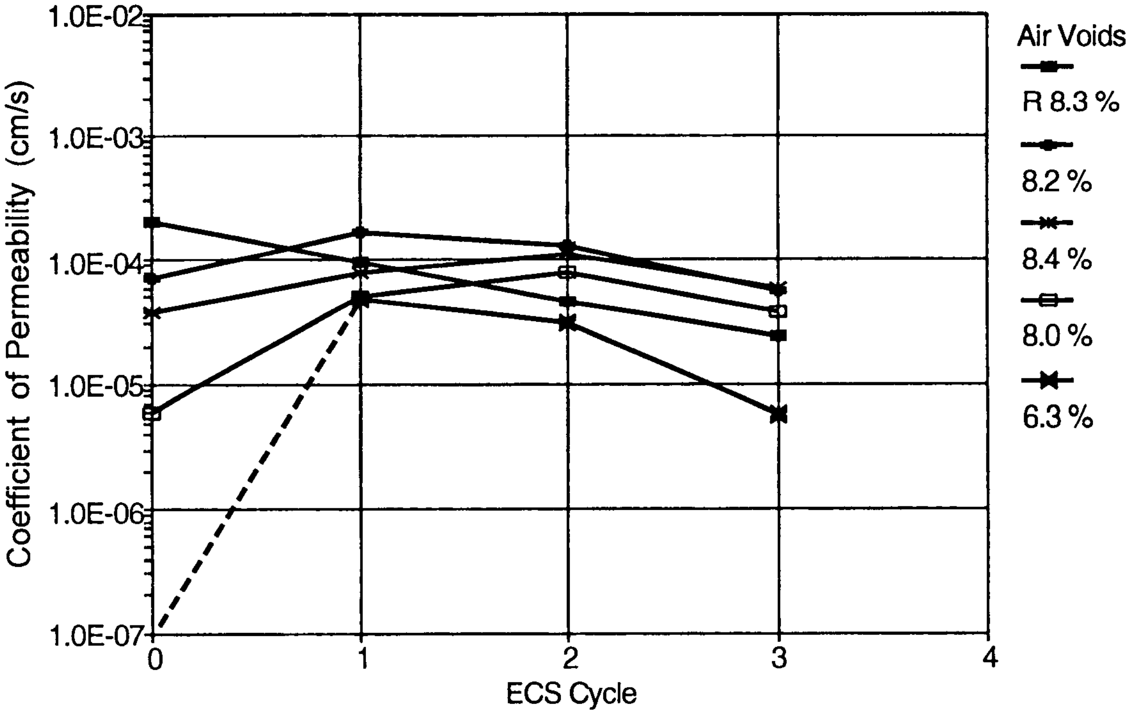


Figure 3.16. Variation in the coefficient of water permeability in the ECS procedure, AZ5

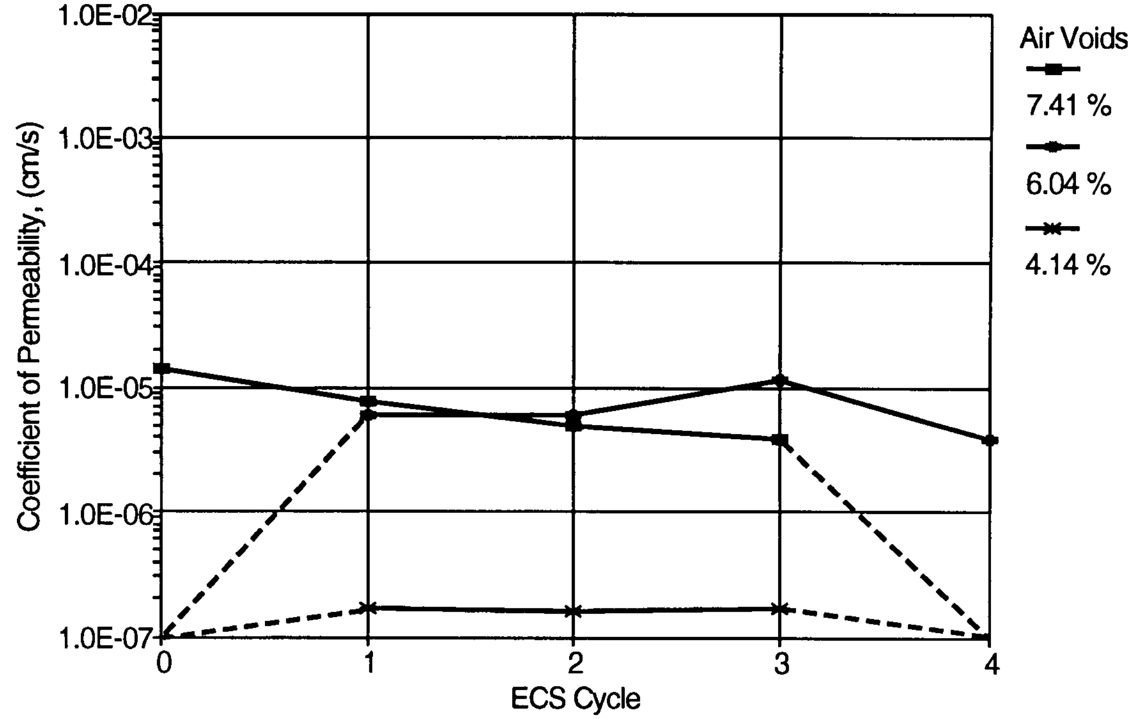


Figure 3.17. Variation in the coefficient of water permeability in the ECS procedure, CAB

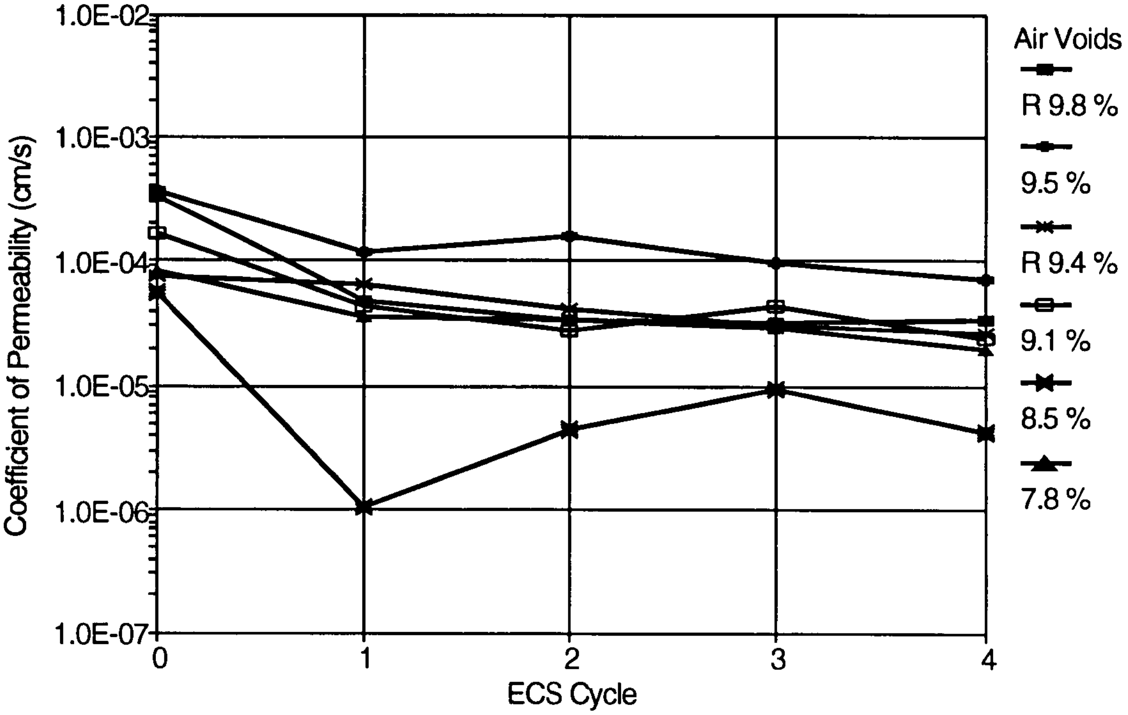


Figure 3.18. Variation in the coefficient of water permeability in the ECS procedure, CAD

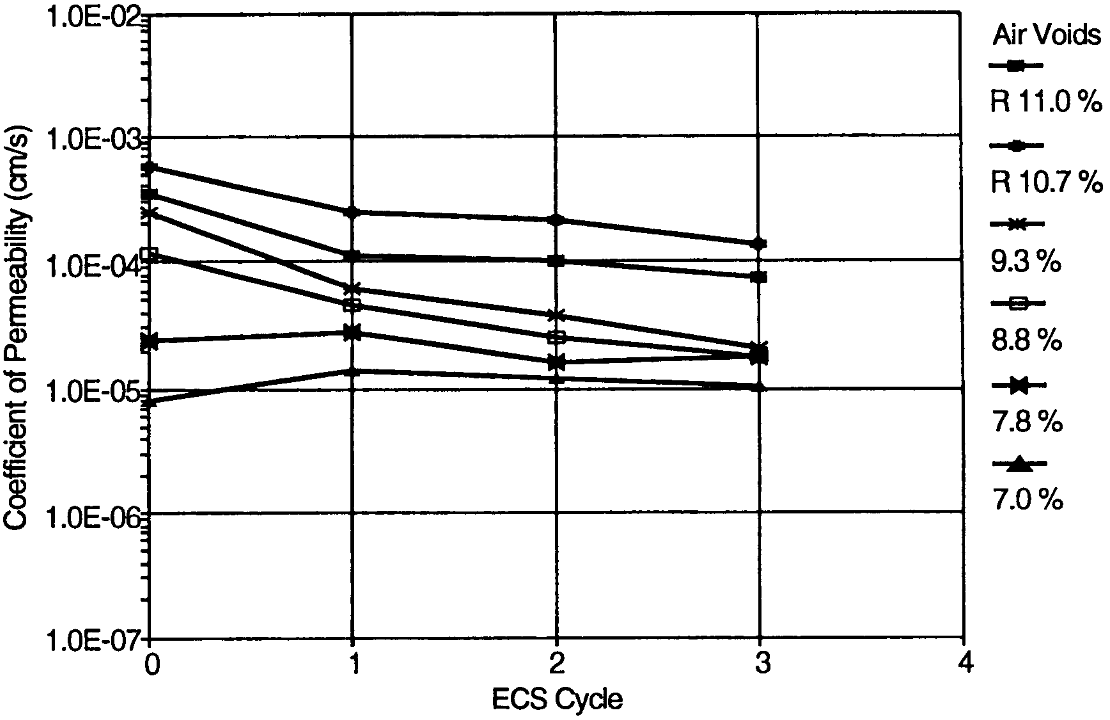


Figure 3.19. Variation in the coefficient of water permeability in the ECS procedure, CAG

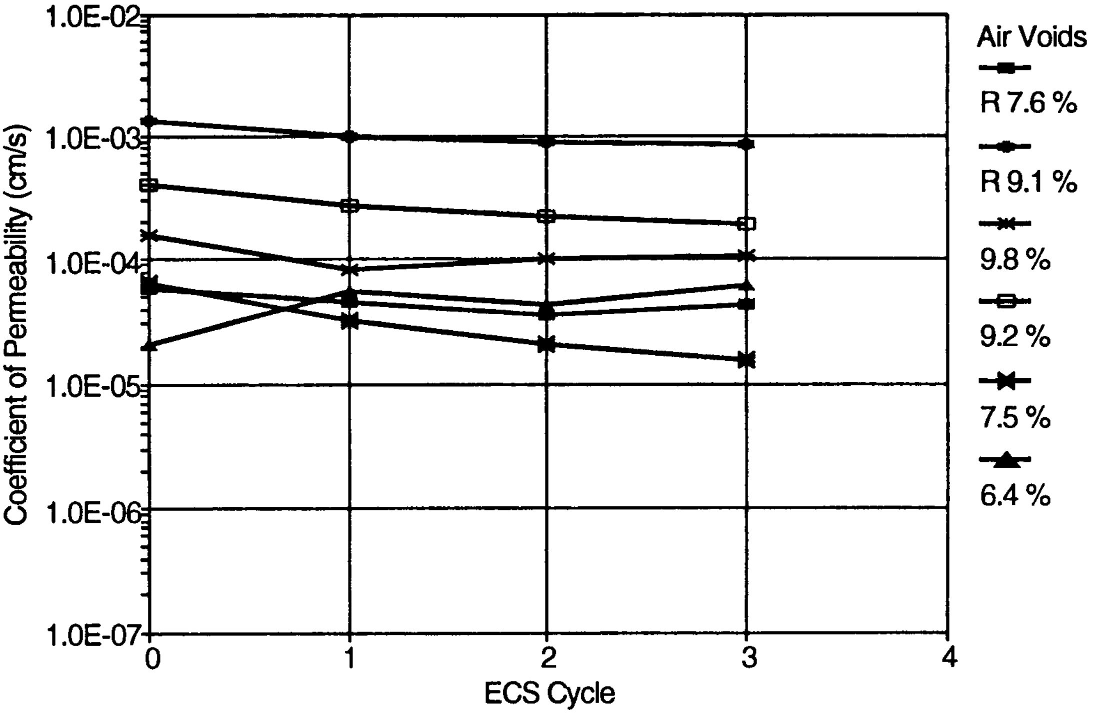


Figure 3.20. Variation in the coefficient of water permeability in the ECS procedure, GAA

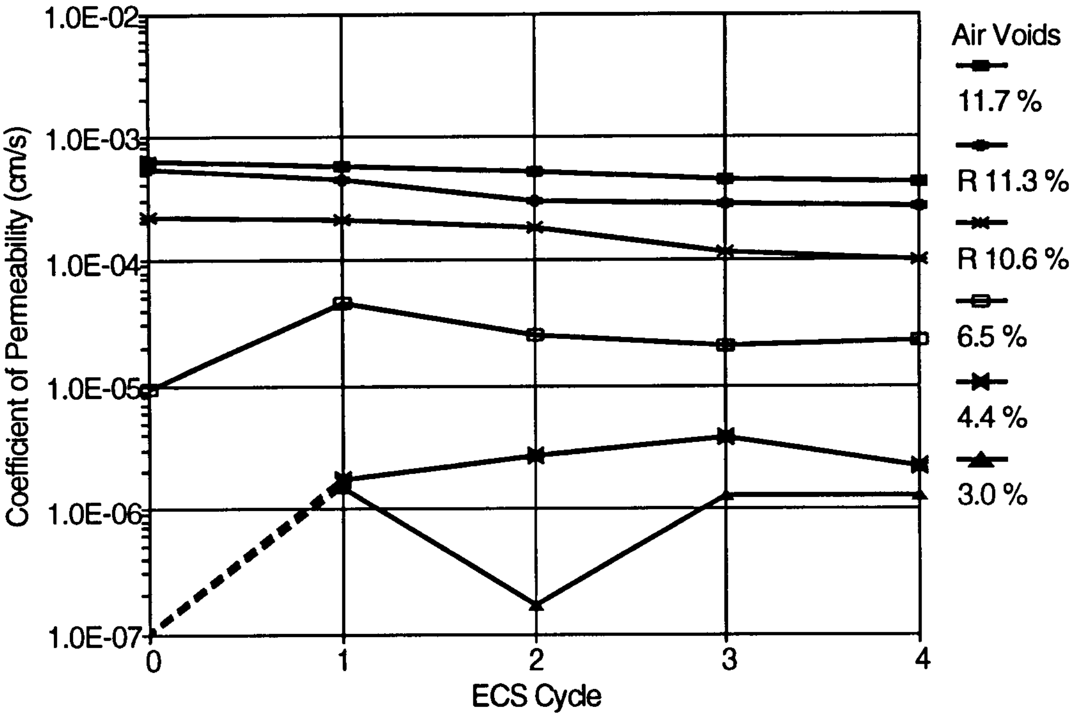


Figure 3.21. Variation in the coefficient of water permeability in the ECS procedure, MN5

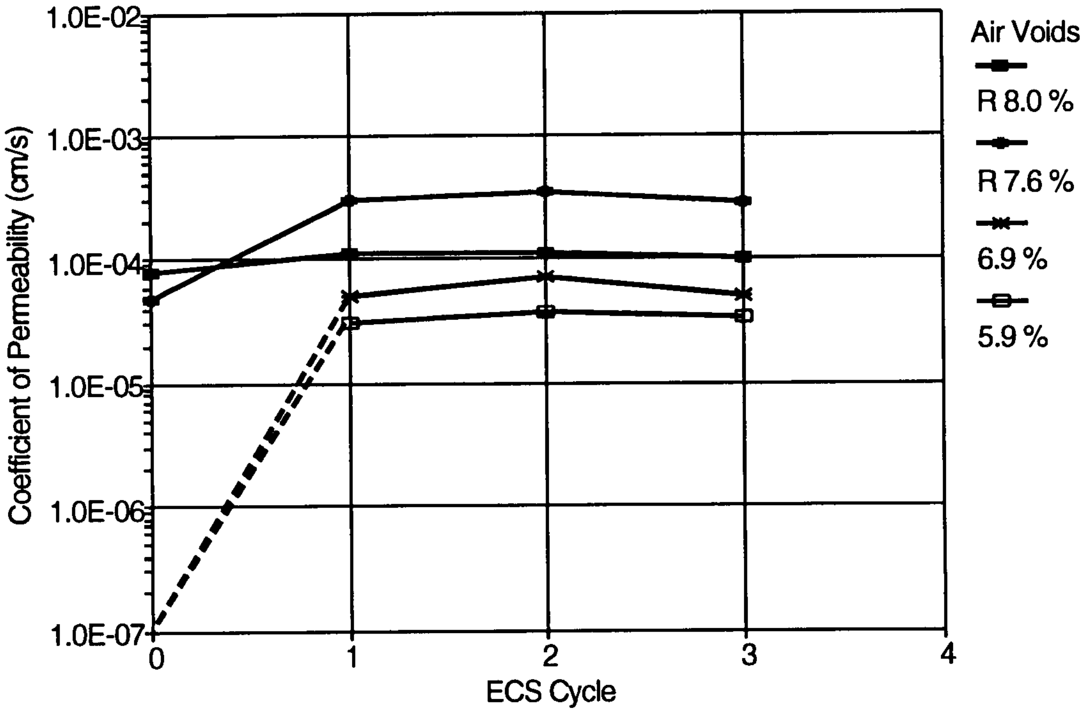


Figure 3.22. Variation in the coefficient of water permeability in the ECS procedure, MS5

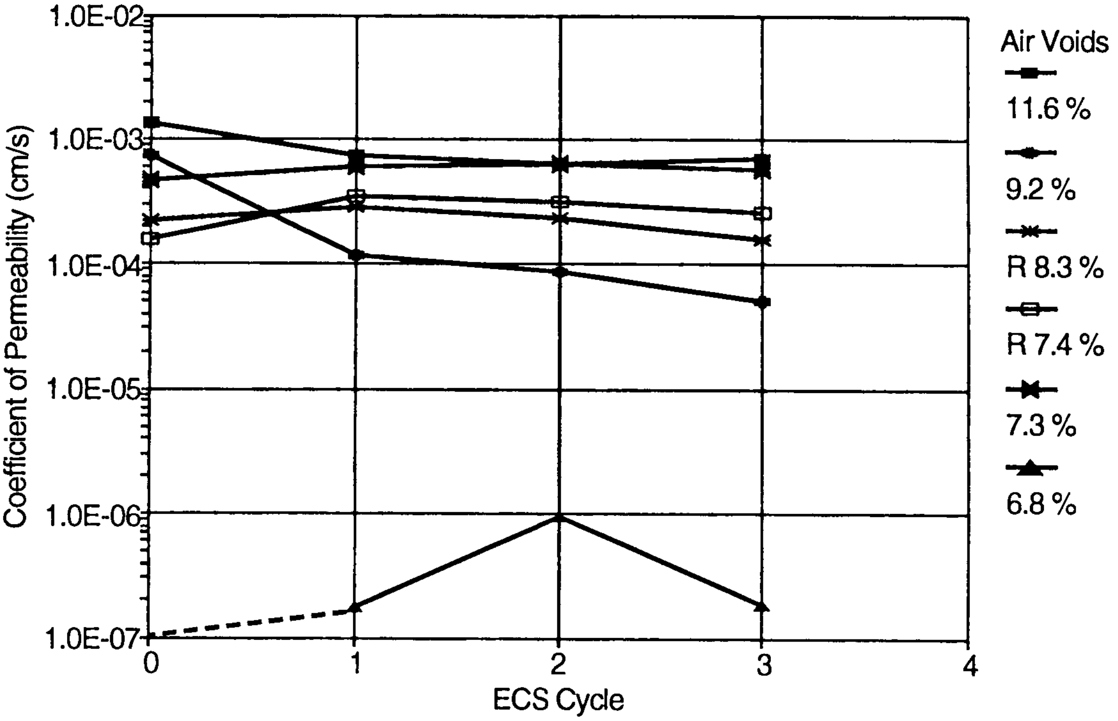


Figure 3.23. Variation in the coefficient of water permeability in the ECS procedure, OR1

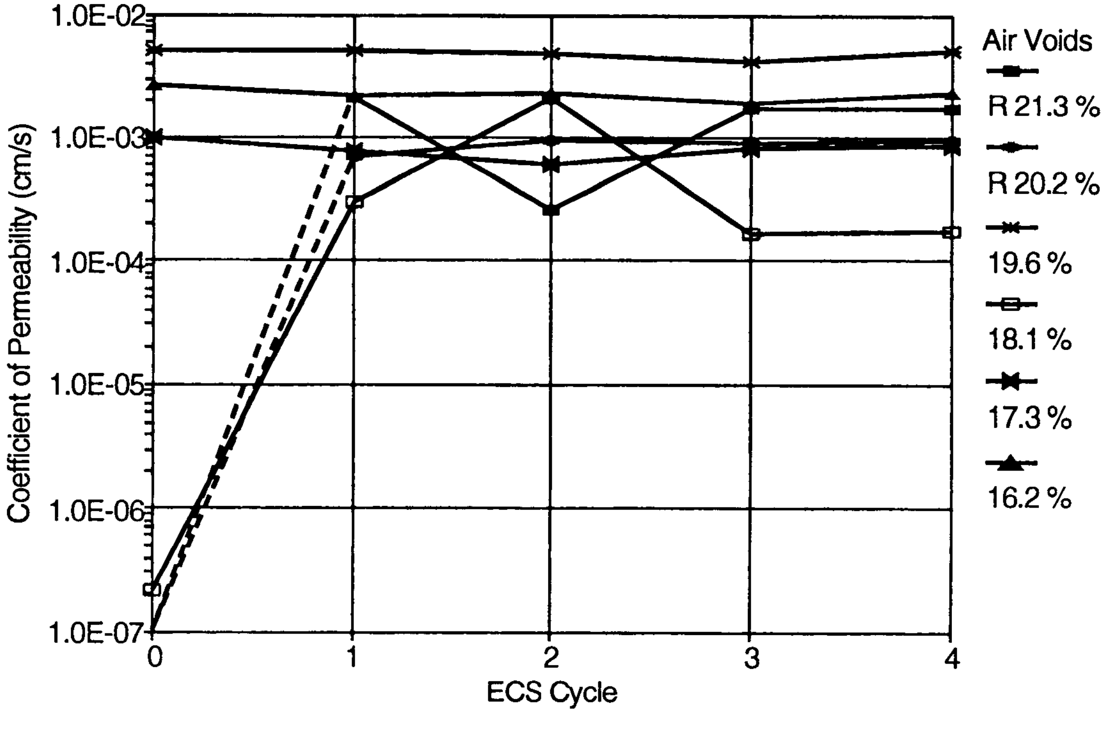


Figure 3.24. Variation in the coefficient of water permeability in the ECS procedure, OR2

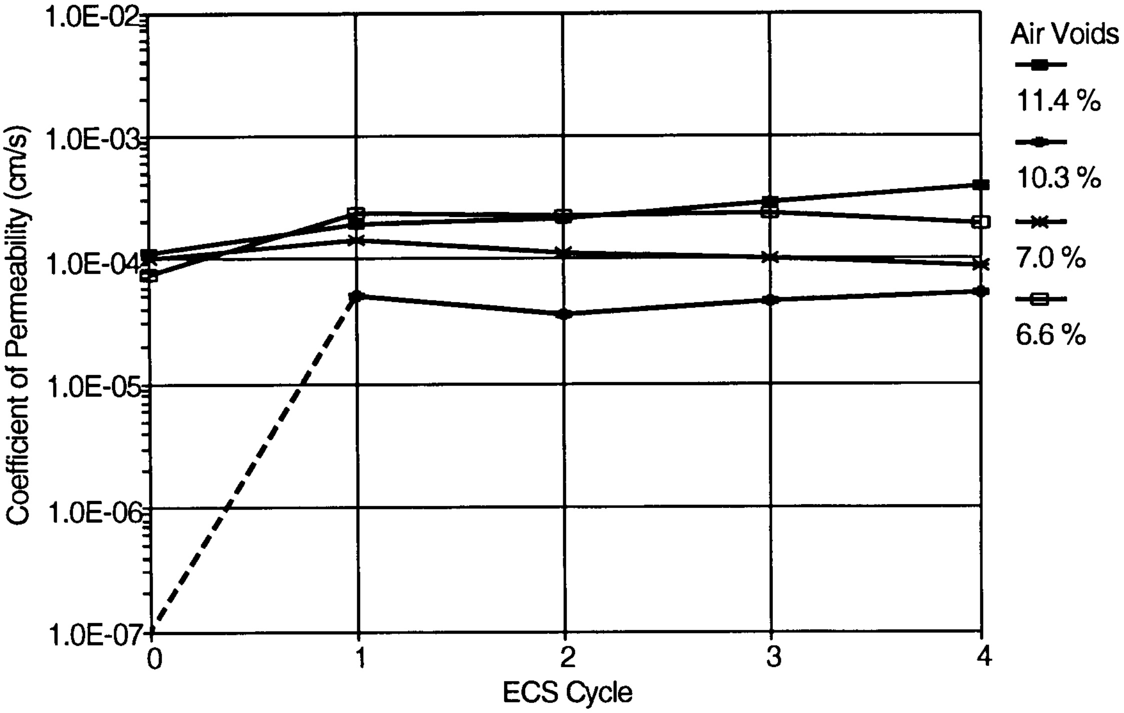


Figure 3.25. Variation in the coefficient of water permeability in the ECS procedure, WA1

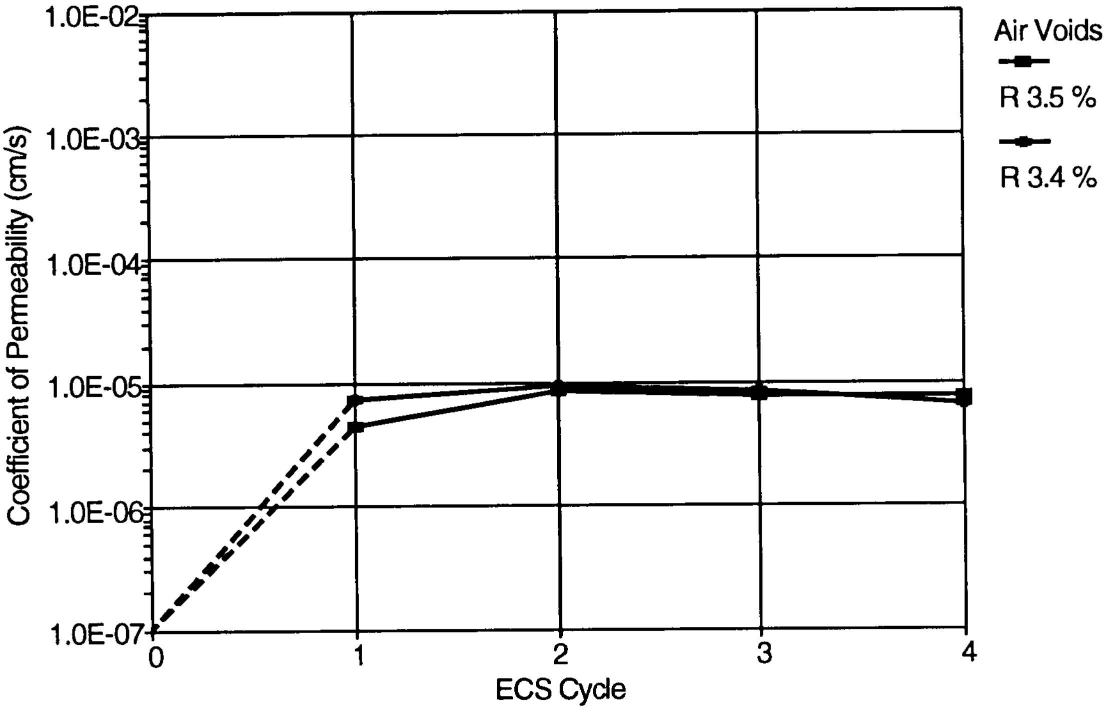


Figure 3.26. Variation in the coefficient of water permeability in the ECS procedure, WIA

Table 3.3. 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 because of migration of dust into specimen

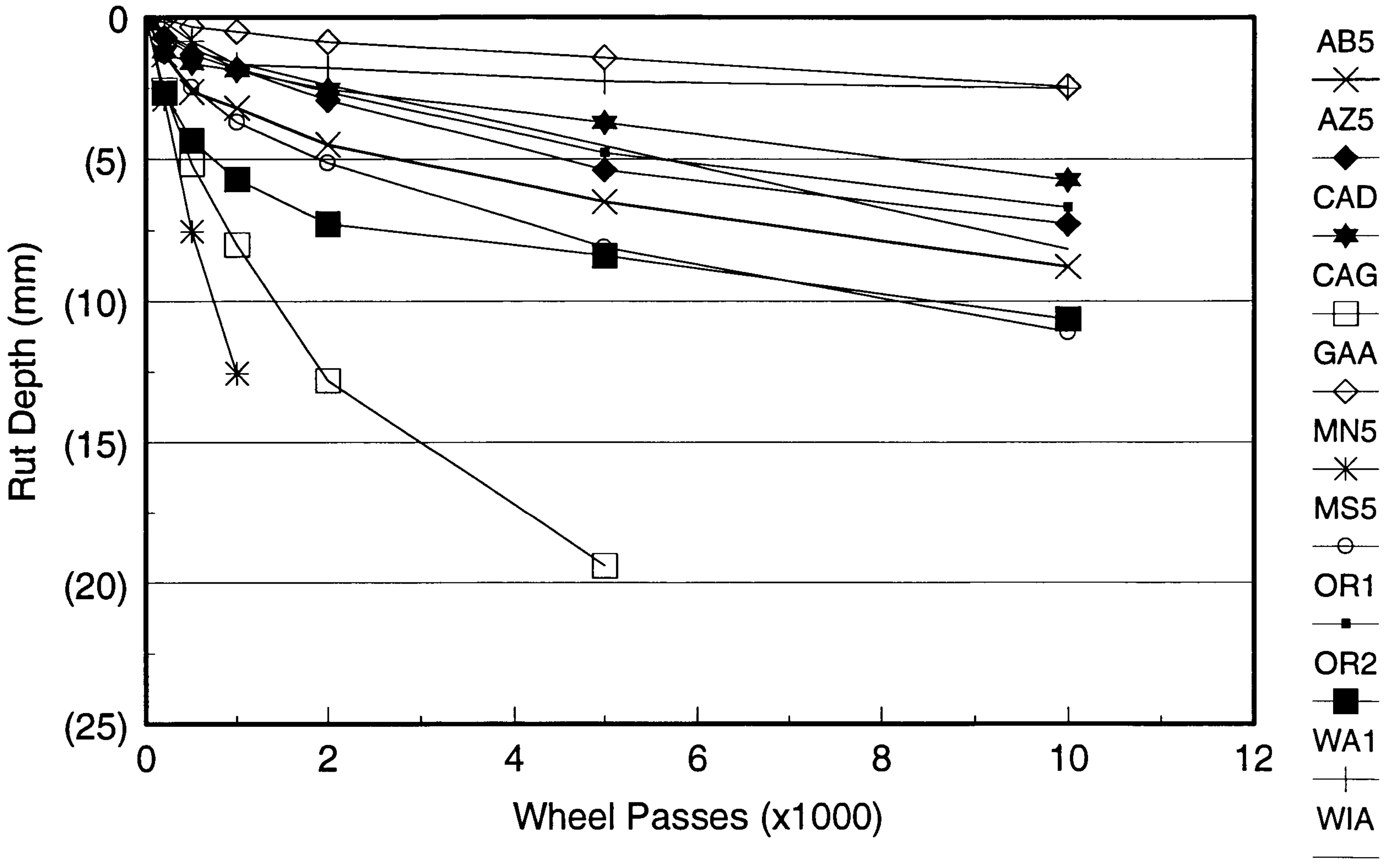


Figure 3.27. Average rut depths for OSU wheel tracking test program

Table 3.4. Summary of data from rutted beam cores

Specimen	Air Voids (%)	Height (in.)	MTS Diametral Modulus (ksi)
AB5R801A	4.5	3.453	162.0
AB5R801B	5.0	3.319	163.0
AB5R802A	4.5	3.094	170.0
AB5R802B	4.5	3.534	167.0
AZ5R801A	9.5	3.078	757.5
AZ5R801B	8.5	3.316	836.5
AZ5R802A	9.1	3.398	902.5
AZ5R802B	9.1	2.849	825.0
CADR801A	11.9	3.543	486.0
CADR801B	7.2	3.197	359.0
CADR802A	12.3	3.274	458.0
CADR802B	20.4	3.251	212.5
CAGR801A	6.7	2.979	270.5
CAGR801B	5.4	2.952	360.0
CAGR802A	6.1	2.96	350.5
CAGR802B	5.4	2.993	321.5
GAAR801A	7.7	3.272	426.0
GAAR801B	7.1	3.527	434.5
GAAR802A	6.4	3.768	417.5
GAAR802B	6.2	3.596	403.0
MN5R801A	5.2	2.795	238.5
MN5R801B	4.8	2.888	250.0
MN5R802A	5.7	2.935	228.0
MN5R802B	5.6	3.203	215.0
MS5R801A	8.3	3.139	206.5
MS5R801B	8.1	3.228	221.0
MS5R802A	7.7	3.398	192.5
MS5R802B	7.3	3.516	187.0
OR1R801A	9.0	3.504	358.5
OR1R801B	7.5	3.091	437.5
OR1R802A	8.5	3.402	454.5
OR1R802B	9.2	3.226	
OR2R801A	18.8	3.014	58.0
OR2R801B	24.0	2.893	39.5
OR2R802A	21.8	3.049	
OR2R802B	25.1	2.997	
WA1R801A	6.1	3.848	190.0
WA1R801B	5.3	3.735	221.0
WA1R802A	5.8	3.701	185.0
WA1R802B	5.5	3.716	200.5
WIAR801A	2.7	3.381	258.5
WIAR801B	2.5	3.544	279.5
WIAR802A	3.5	3.295	249.5
WIAR802B	2.4	3.563	274.0

Table 3.5. Results of the Elf wheel tracking program

Specimen	Test Temp. (°C)	Air Voids (%)	Post Compaction (mm)	Creep Slope (passes/mm)	Stripping Inflection (passes)	Stripping Slope (passes/mm)
AB5ELF01	50	3.7	0.7	780	1,600	200
AZ5ELF01	50	6.4	0.3	5,560	5,400	300
AZ5ELF02	50	7.9	0.3	3,570	3,800	135
OR1ELF01	40	5.9	1.2	21,950	No stripping	
OR1ELF02	50	5.9	1.0	1,770	8,000	508
OR2ELF01	40	8.0	0.7	12,670	No stripping	
OR2ELF02	50	8.0	0.98	2,475	14,500	570
WIAELF01	40	7.3	1.4	2,590	11,800	690
WIAELF02	50	7.3	1.4	150	No stripping	

Source: Hines 1992.

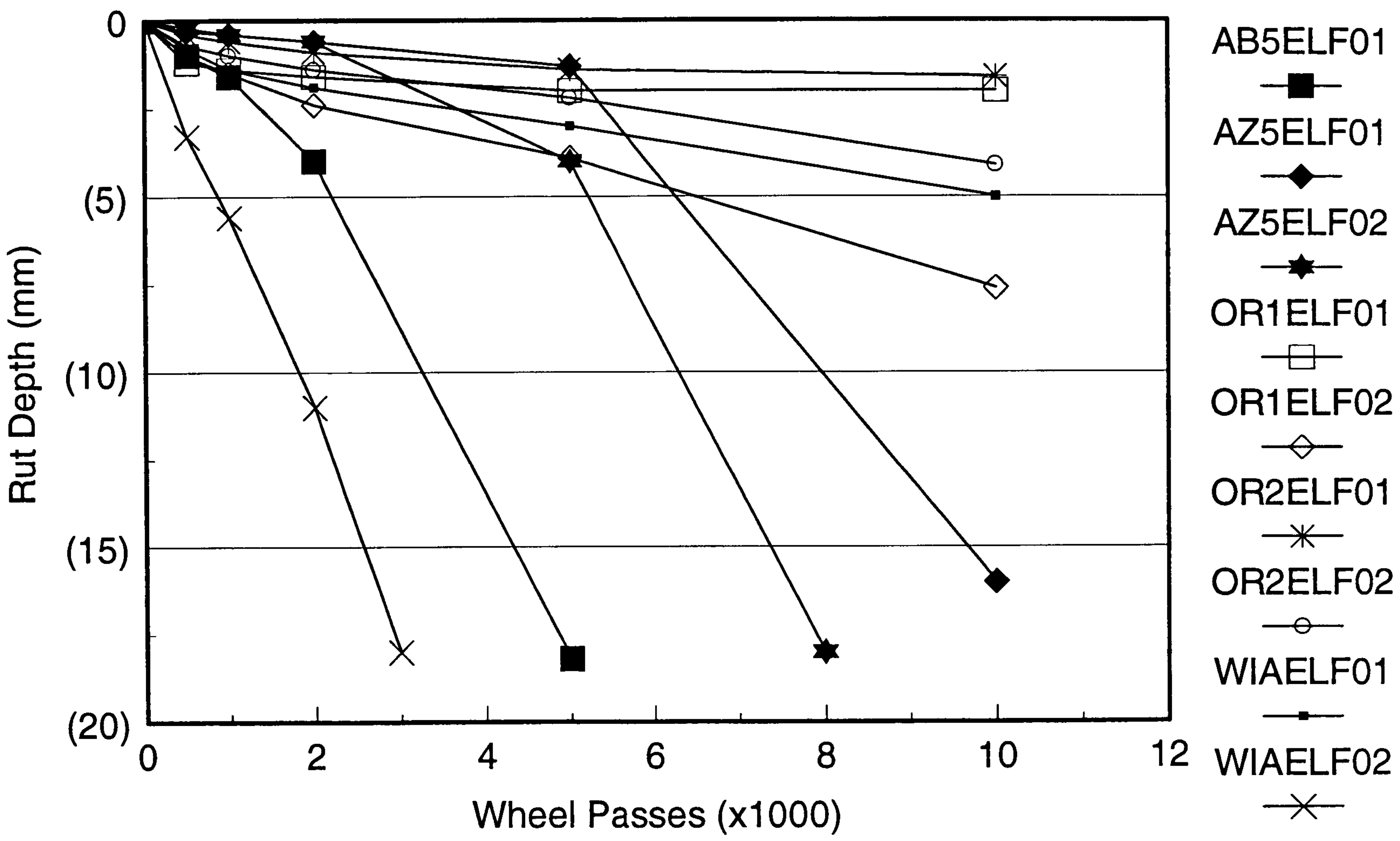


Figure 3.28. Elf wheel tracker results

Table 3.6. Monthly total precipitation[1] for the nearest recording station, 1990

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
AB5[2]	0.07	0.81	0.85	3.06	0.44	3.77	3.31	3.46	1.80	3.25	0.34	0.86	22.02
AZ5	1.17	0.72	0.19	0.04	0.20	0.10	1.40	4.21	1.86	--[3]	--[3]	0.60	10.49
CAB	0.68	0.75	0.38	0.81	0.75	0.06	1.73	0.08	0.51	0.10	0.38	0.63	6.86
CAD	0.68	0.75	0.38	0.81	0.75	0.06	1.73	0.08	0.51	0.10	0.38	0.63	6.86
CAG	0.18	0.00	0.00	0.02	0.00	0.08	0.25	0.91	0.53	0.00	0.00	0.00	1.97
GAA	7.82	9.62	9.92	3.00	4.12	1.60	7.57	2.32	4.51	7.26	1.86	7.65	67.25
MN5	0.35	0.58	1.34	1.51	0.68	4.77	1.88	0.97	1.15	2.85	0.20	--[3]	16.28
MS5	9.93	6.42	5.76	4.35	6.74	3.85	1.84	1.10	3.29	2.11	3.88	13.15	62.42
OR1	16.03 10.8	9.03 6.27	2.72 2.66	3.64 2.32	1.81 3.06	2.41 1.53	0.68 0.46	1.64 0.83	0.45 0.37	7.72 7.76	8.68 5.61	4.60 3.42	59.41 45.09
OR2	1.40	0.00	0.95	0.43	1.08	0.08	--[3]	--[3]	--[3]	--[3]	0.48	0.34	4.76
WA1	19.94	17.75	6.76	4.00	2.77	6.34	0.74	4.15	0.61	16.99	31.34	19.05	130.44
WIA	1.31	0.75	3.27	3.03	4.58	8.58	1.99	4.23	2.63	2.51	1.74	2.27	36.89

Sources: National Oceanic and Atmospheric Administration 1990; Environment Canada 1991.

[1] Values of precipitation in inches.

[2] Values for 1991.

[3] Data missing from official weather information source document.

Table 3.7. Monthly normal precipitation[1] for the nearest recording station, 30-year average, 1961-1990

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
AB5	1.00	0.57	0.84	0.84	2.28	4.43	4.42	3.16	2.46	0.81	0.78	0.78	22.35
AZ5	0.73	0.69	0.88	0.27	0.13	0.13	0.88	1.98	0.86	0.77	0.76	1.17	9.25
CAB	2.83	2.47	1.81	0.94	1.14	0.82	0.48	0.43	0.64	1.24	2.76	2.49	18.05
CAD	2.83	2.47	1.81	0.94	1.14	0.82	0.48	0.43	0.64	1.24	2.76	2.49	18.05
CAG	0.37	0.27	0.21	0.05	0.02	0.01	0.09	0.37	0.31	0.32	0.27	0.42	2.71
GAA	5.15	5.24	6.24	4.71	4.81	4.32	4.85	4.42	4.30	3.75	4.51	4.87	57.17
MN5	0.63	0.48	0.90	1.90	3.00	3.83	3.71	3.35	2.70	1.99	0.80	0.70	23.99
MS5	5.52	5.37	6.38	5.31	5.49	3.56	4.51	3.17	3.26	3.89	4.97	6.66	58.09
OR1	9.08 6.44	6.62 4.92	6.30 4.70	3.68 2.85	2.46 2.35	1.71 1.74	0.78 0.72	1.21 1.30	2.43 2.00	4.41 3.23	8.64 6.33	9.27 7.33	56.59 43.91
OR2	1.06	0.60	0.69	0.58	0.71	0.73	0.45	0.55	0.41	0.54	1.16	1.09	8.57
WA1[2]													
WIA	1.02	1.09	2.18	2.98	3.20	3.82	3.65	3.99	4.08	2.40	2.18	1.51	32.10

Sources: Owenby and Ezell 1992; Environment Canada 1992.

[1] Values of precipitation in inches.

[2] No recording station with this data in the vicinity of the site.

Table 3.8. Monthly average temperature[1] for the nearest recording station, 1990

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB5[2]	9.9	29.8	22.6	40.8	61.2	53.8	58.3	60.6	50.2	34.3	20.7	17.8
AZ5	51.1	52.7	62.5	71.2	76.5	89.3	90.2	86.2	84.0	--[3]	--[3]	49.4
CAB	33.7	28.3	43.5	52.2	53.1	61.8	70.3	67.6	63.0	53.3	38.0	20.7
CAD	33.7	28.3	43.5	52.2	53.1	61.8	70.3	67.6	63.0	53.3	38.0	20.7
CAG	55.0	57.6	65.6	72.4	76.5	88.0	92.3	89.3	86.7	76.0	63.5	52.4
GAA	43.3	46.7	51.3	53.5	62.9	70.3	72.8	73.3	67.2	57.4	49.1	44.7
MN5	16.0	10.6	25.3	38.4	50.2	--[3]	--[3]	--[3]	--[3]	--[3]	--[3]	--[3]
MS5	51.1	56.4	58.7	63.8	71.4	81.3	81.3	81.7	78.3	63.5	58.4	50.4
OR1	41.9 43.0	39.0 41.4	47.8 50.4	51.8 55.5	53.8 56.4	59.3 63.9	66.0 71.3	66.1 71.1	63.0 68.2	50.1 53.0	45.2 46.5	33.0 34.2
OR2	36.3	34.9	42.2	51.1	50.4	59.1	--[3]	--[3]	--[3]	--[3]	40.8	26.1
WA1	35.9	30.5	39.8	49.2	52.0	56.4	65.2	65.0	60.6	45.5	40.6	27.9
WIA	28.3	24.7	37.2	48.5	53.3	67.2	70.7	69.3	63.3	47.1	40.3	20.7

Sources: National Oceanic and Atmospheric Administration 1990; Environment Canada, 1991

[1] Temperatures in °F.

[2] Values for 1991.

[3] Data missing from official weather information source document.

Table 3.9. Monthly normal temperature[1] for the nearest recording station, 30-year average, 1961-1990

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB5[2]	10.8	14.9	25.3	37.9	47.7	54.7	58.6	56.7	47.7	38.5	20.7	10.9
AZ5	51.4	55.5	60.3	67.6	76.4	85.6	91.0	88.6	82.6	71.6	59.3	51.5
CAB	32.1	37.2	41.4	46.7	54.7	62.8	69.5	68.2	60.9	51.0	40.0	32.4
CAD	32.1	37.2	41.4	46.7	54.7	62.8	69.5	68.2	60.9	51.0	40.0	32.4
CAG	54.6	58.8	62.8	68.6	76.4	85.1	91.3	90.8	84.8	74.4	62.4	54.4
GAA	34.9	38.0	46.2	54.3	61.9	69.0	72.5	71.8	66.1	55.2	46.9	38.7
MN5	2.3	8.5	22.2	39.3	52.7	62.7	68.0	65.2	54.2	42.9	25.8	9.0
MS5	44.1	48.3	56.8	65.2	72.6	79.4	81.9	81.2	76.1	65.4	56.0	47.7
OR1	38.1 39.1	42.0 43.1	45.2 46.8	48.5 50.6	53.7 56.5	58.8 62.4	62.7 67.1	63.7 67.8	60.1 62.9	52.2 53.9	43.9 45.3	38.7 39.7
OR2	31.4	36.0	39.5	44.1	51.0	59.4	65.9	65.1	57.0	48.3	38.2	31.8
WA1[3]												
WIA	14.8	19.2	31.9	45.6	56.9	66.2	70.8	68.0	59.3	48.9	34.9	20.9

Sources: Owenby and Ezell 1992; Environment Canada 1992

[1] Temperatures in °F.

[2] 1970 to 1990.

[3] No recording station with this data in the vicinity of the site.

Table 3.10. Traffic volumes for the field test sections

Site	ADT	Percent Trucks	Date
AB5	4,480	14.7	1991
AZ5	4,500	25.0	1991
CAB	4,000	16.0	1989
CAD	4,000	16.0	1989
CAG	8,200	14.0	1991-1992
GAA	8,800	9.8	1991
MN5	4,900	13.4	1986
MS5	9,000	20.0	Prior to construction
OR1	6,400	10.5	1991
OR2	12,300	---[2]	1991
WA1	190[1] 285[1]	---[2] ---[2]	1986 Projected 2000
WIA	3,500	10.0	1991

[1] Seasonally adjusted.
[2] Unavailable.

Table 3.11. Summary of pavement condition surveys

Site	Survey Type	Survey Date	Comments
AB5	Manual	August 92	In good condition, small amount of cracking
AZ5	Manual	August 92	In good condition, some traffic densification
CAB	Manual	August 92	In good condition
CAD	Manual	August 92	In good condition
CAG	Manual	August 92	In good condition
GAA			Covered by wearing course
MN5	Manual	June 92	Some low-to-moderate-severity, transverse cracking, 5 mm-8 mm rutting, some low-to-moderate-severity bleeding
MS5	Manual		In bad condition, reflective cracking, scheduled for overlay
OR1			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	September 92	In good condition, no visible rutting
WIA	Manual	1991	In good condition, PDI=0, psi=4.3, 1/10 in. of rutting measured

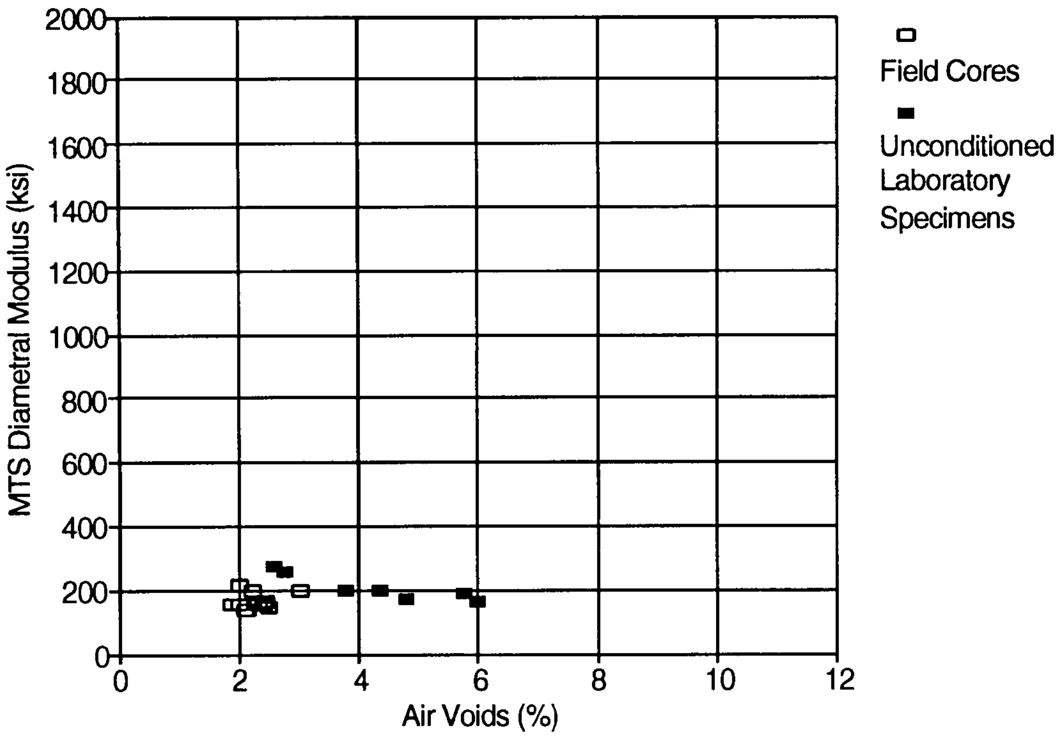


Figure 3.29. AB5 field cores, diametral modulus data

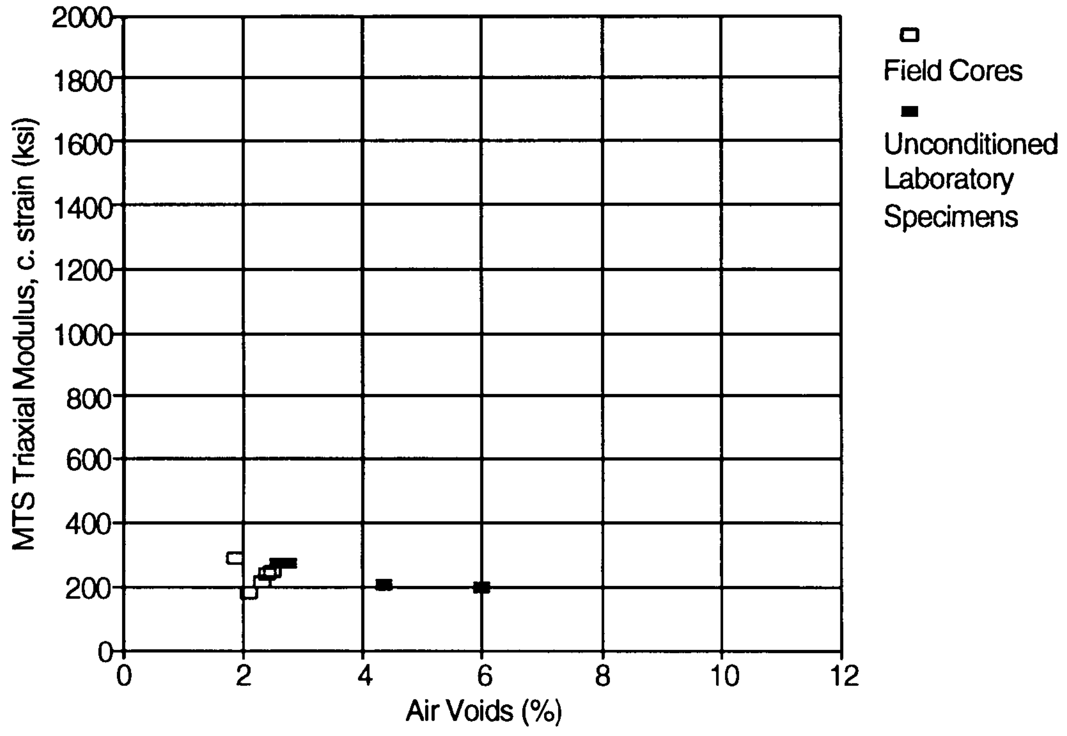


Figure 3.30. AB5 field cores, triaxial modulus data (tested at 100 μ-strain)

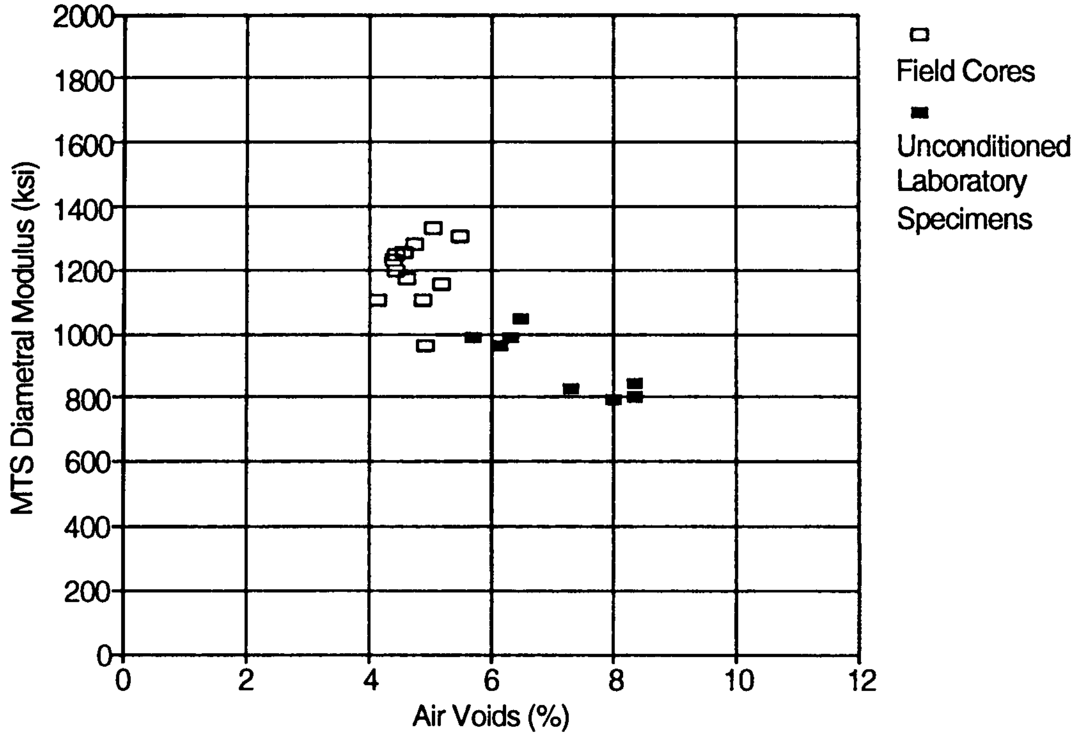


Figure 3.31. AZ5 field cores, diametral modulus data

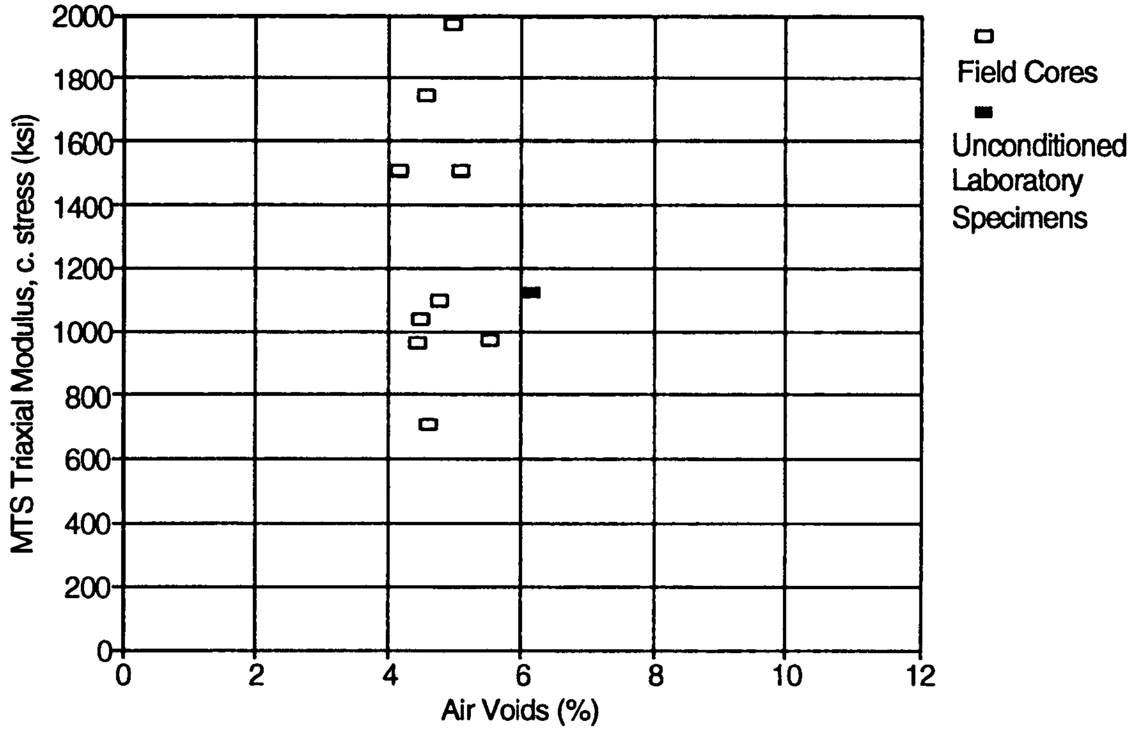


Figure 3.32. AZ5 field cores, triaxial modulus data (tested at 40 psi [275 kPa])

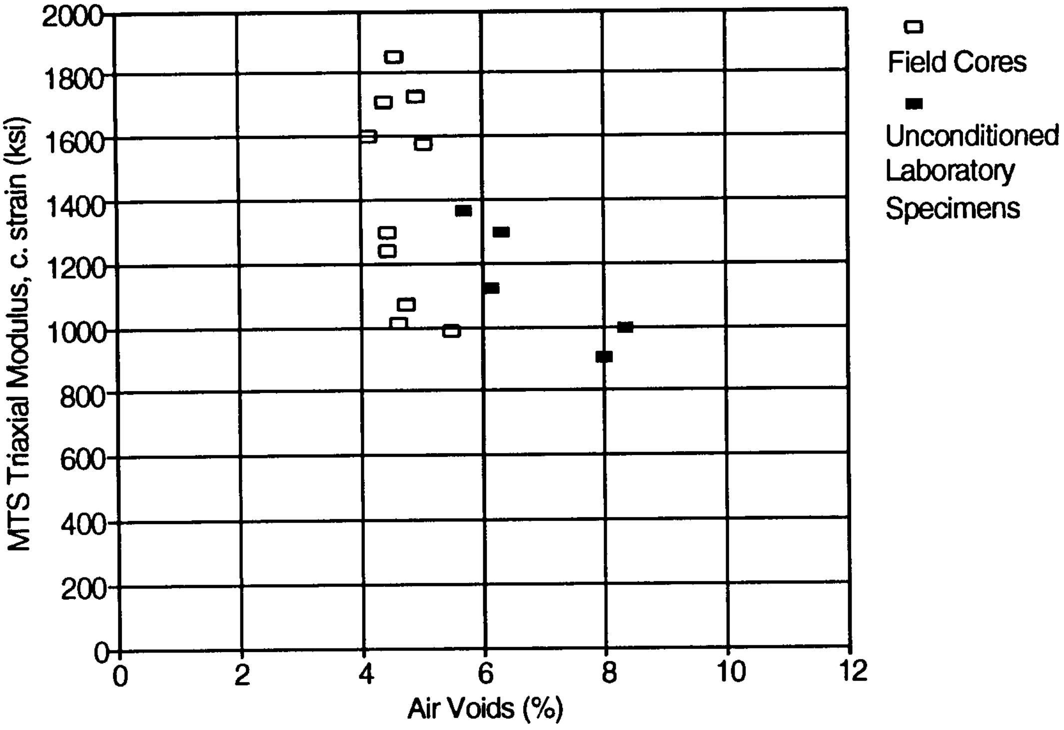


Figure 3.33. AZ5 field cores, triaxial modulus data (tested at 100 μ-strain)

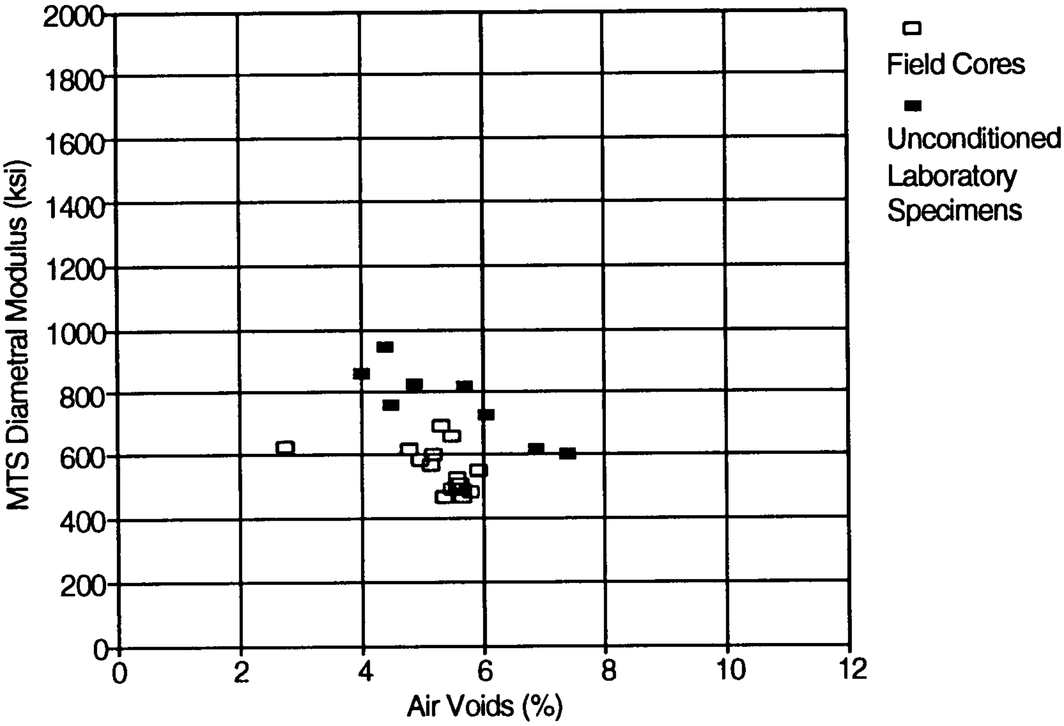


Figure 3.34. CAB field cores, diametral modulus data

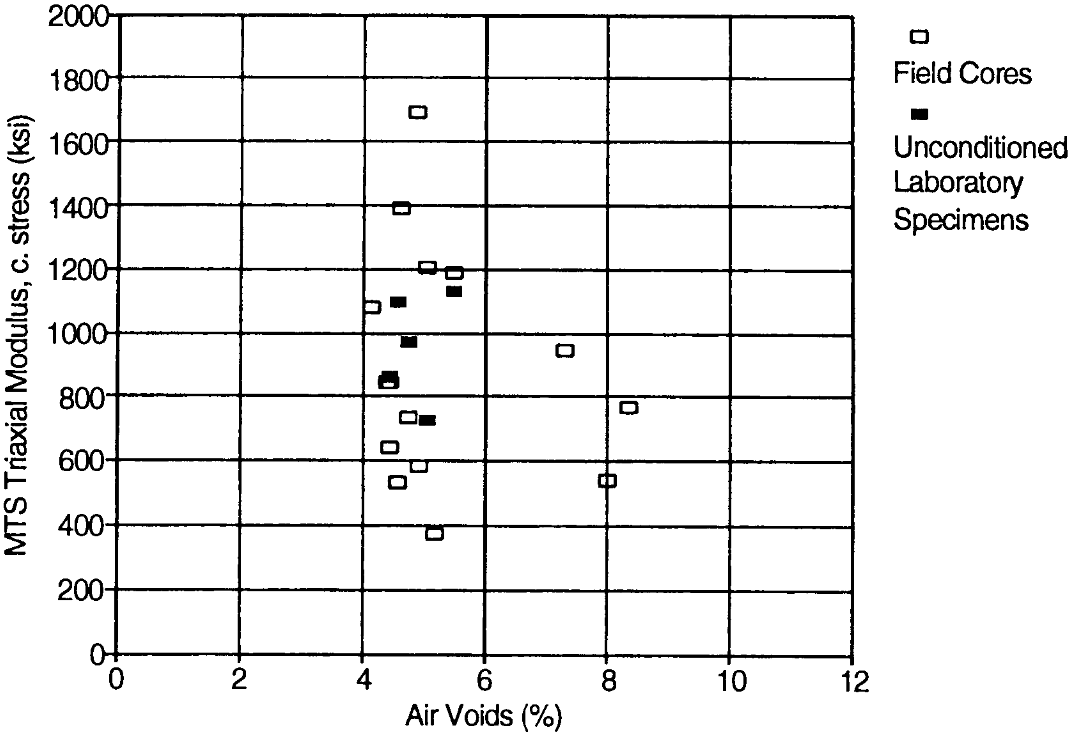


Figure 3.35. CAB field cores, triaxial modulus data (tested at 40 psi (275 kPa))

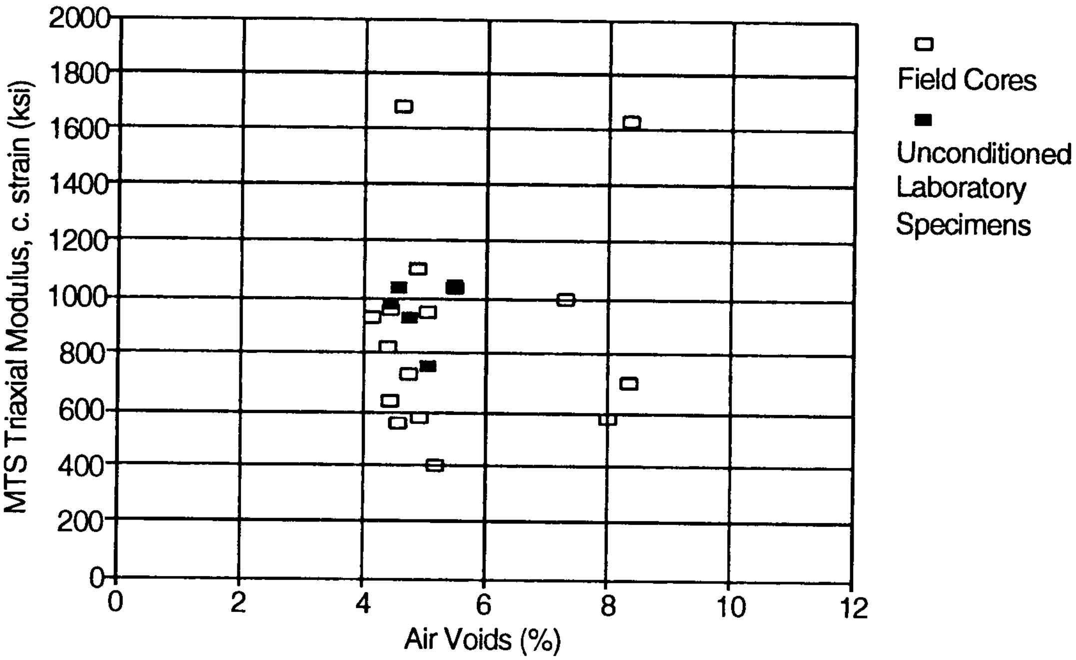


Figure 3.36. CAB field cores, triaxial modulus data (tested at 100 μ-strain)

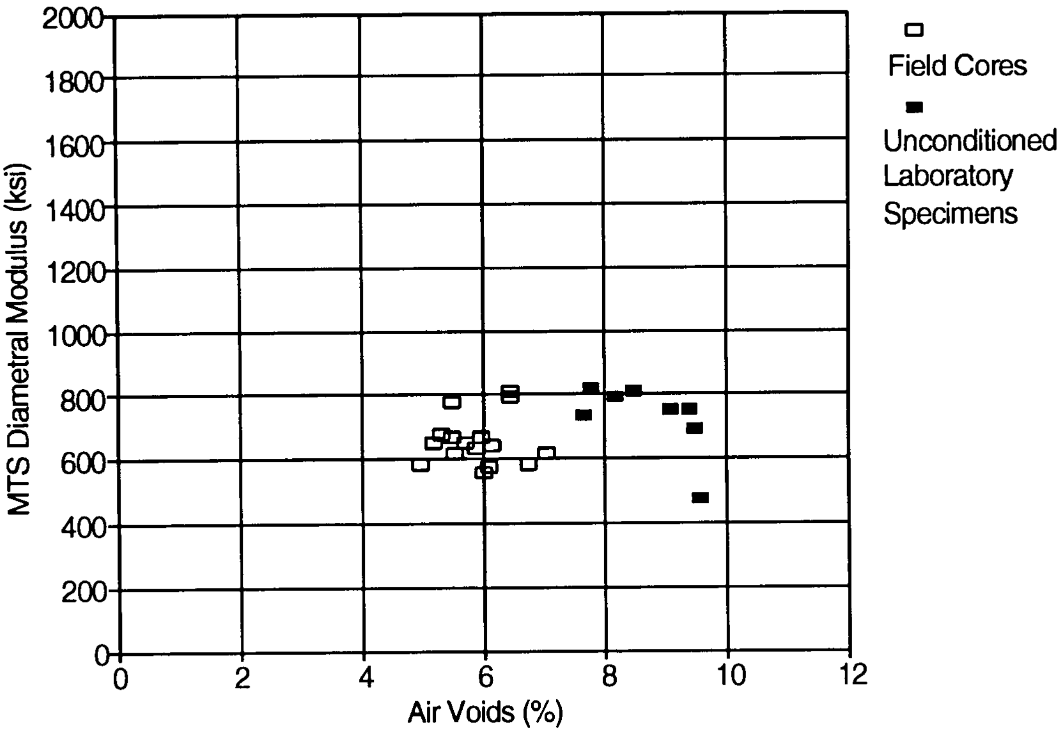


Figure 3.37. CAD field cores, diametral modulus data

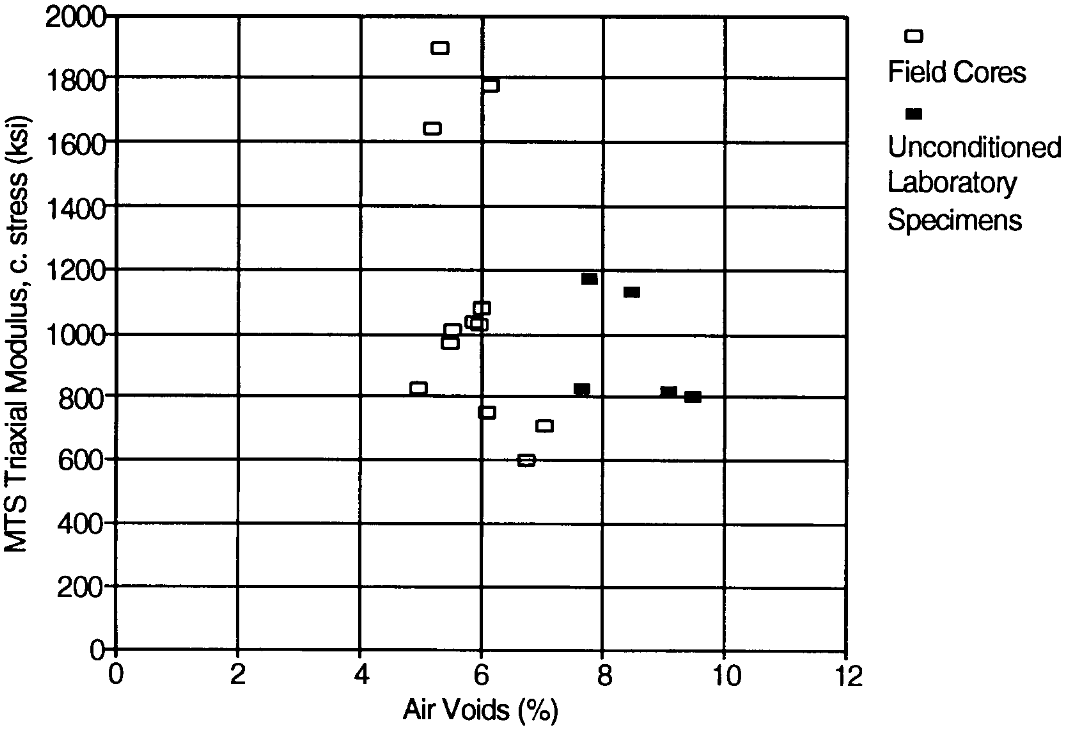


Figure 3.38. CAD field cores, triaxial modulus data (tested at 40 psi (275 kPa))

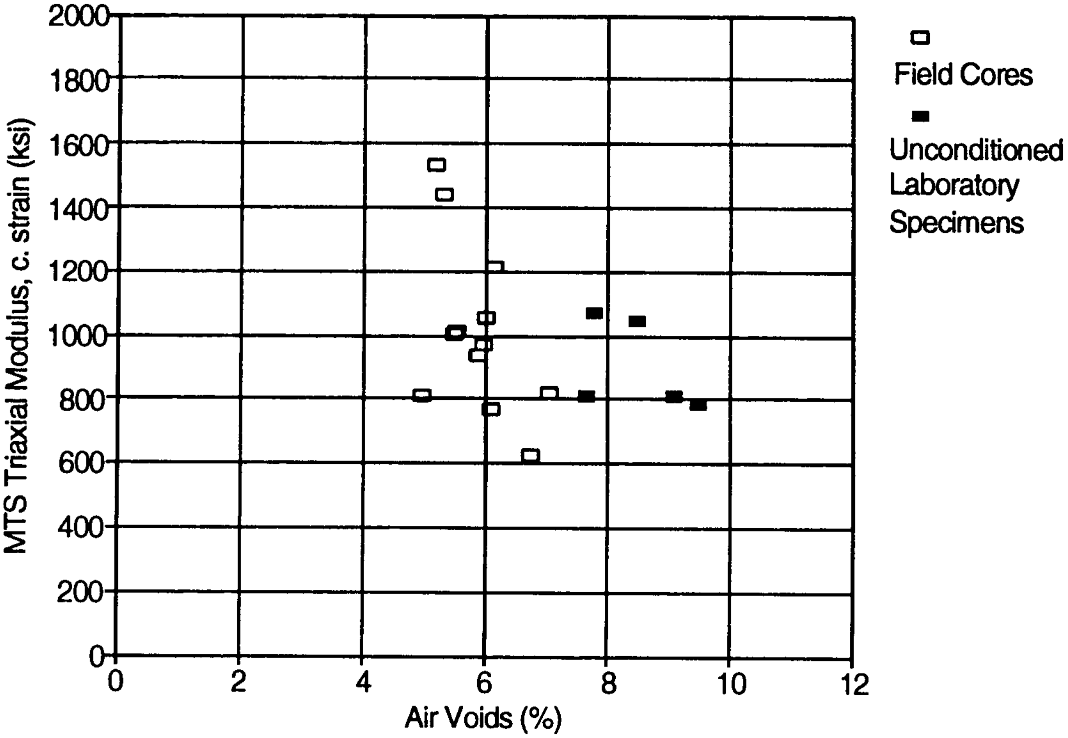


Figure 3.39. CAD field cores, triaxial modulus data (tested at 100 μ-strain)

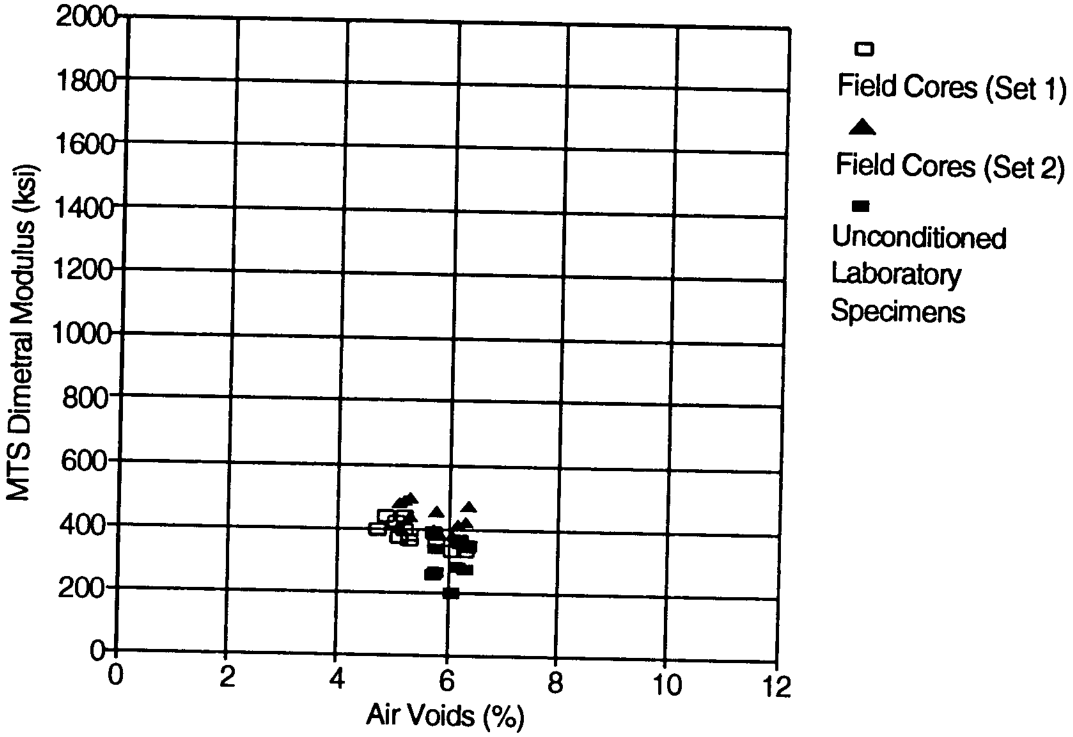


Figure 3.40. CAG field cores, diametral modulus data

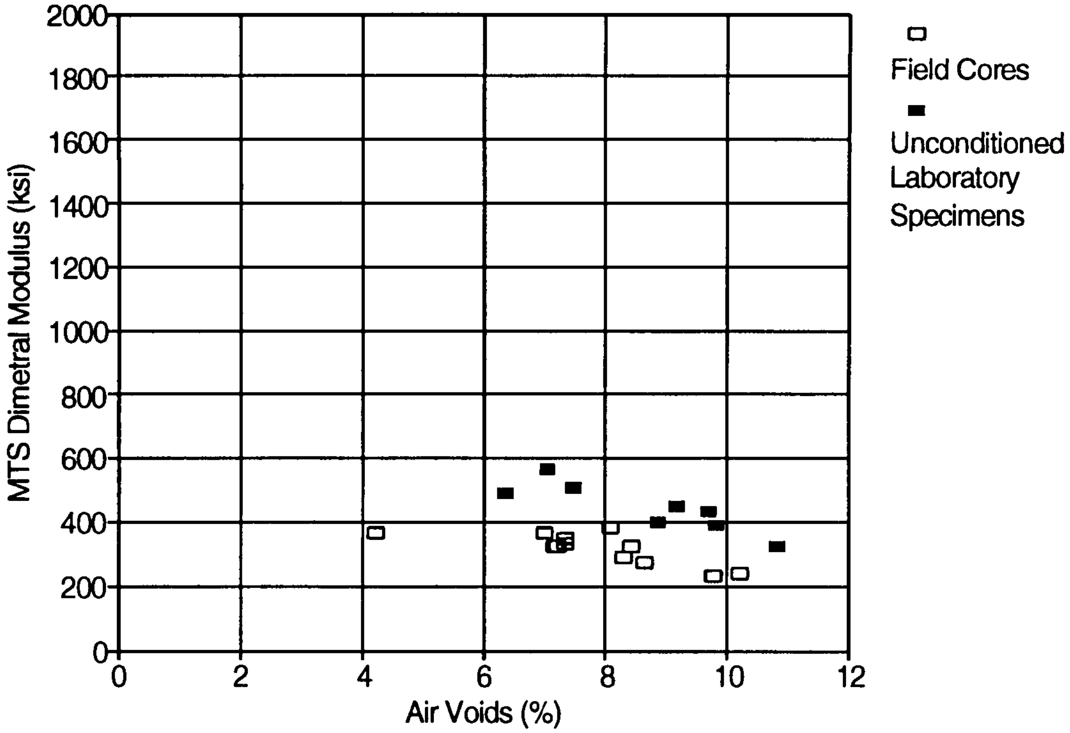


Figure 3.41. GAA field cores, diametral modulus data

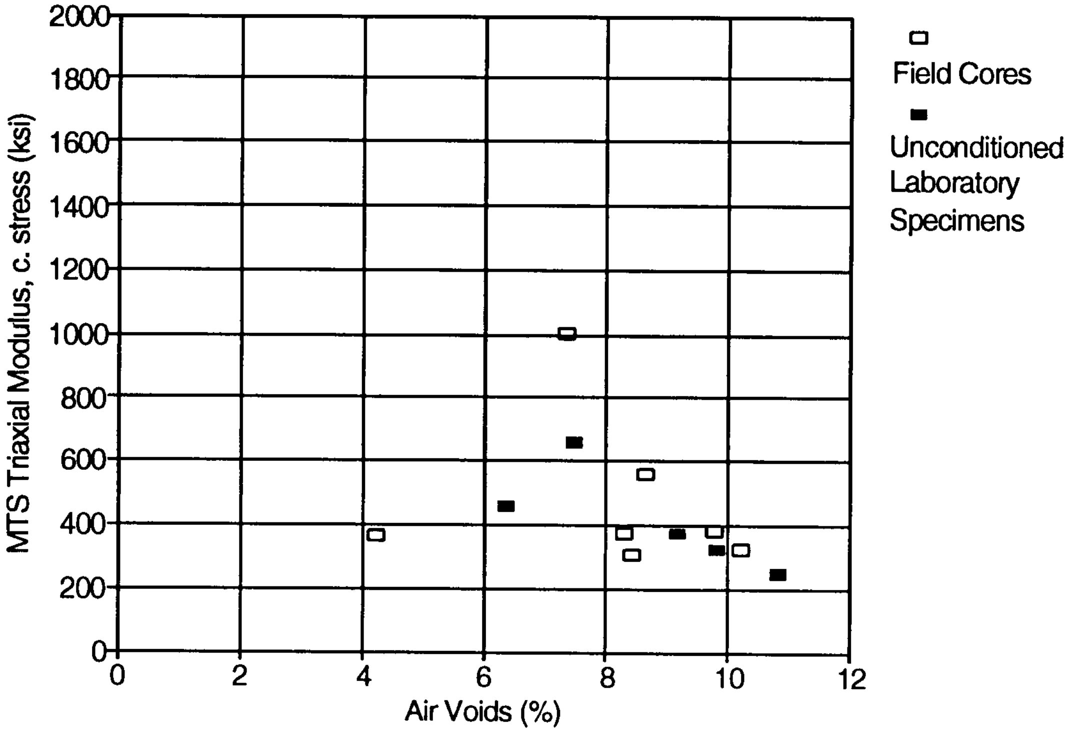


Figure 3.42. GAA field cores, triaxial modulus data (tested at 40 psi (275 kPa))

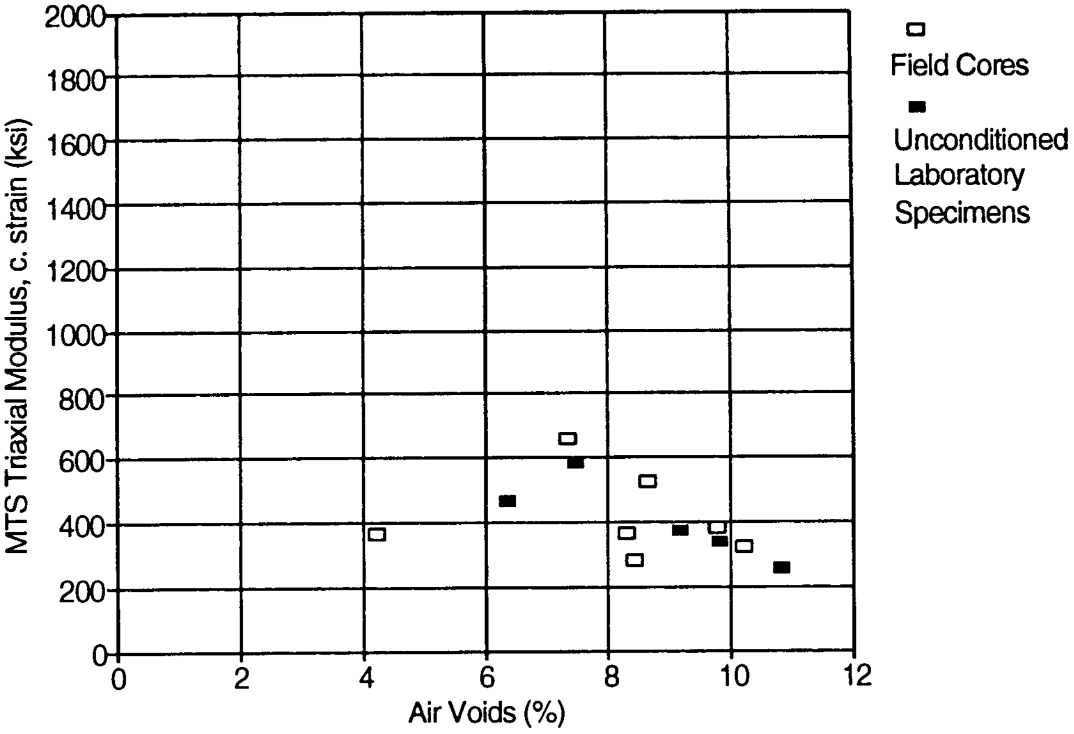


Figure 3.43. GAA field cores, triaxial modulus data (tested at 100 μ-strain)

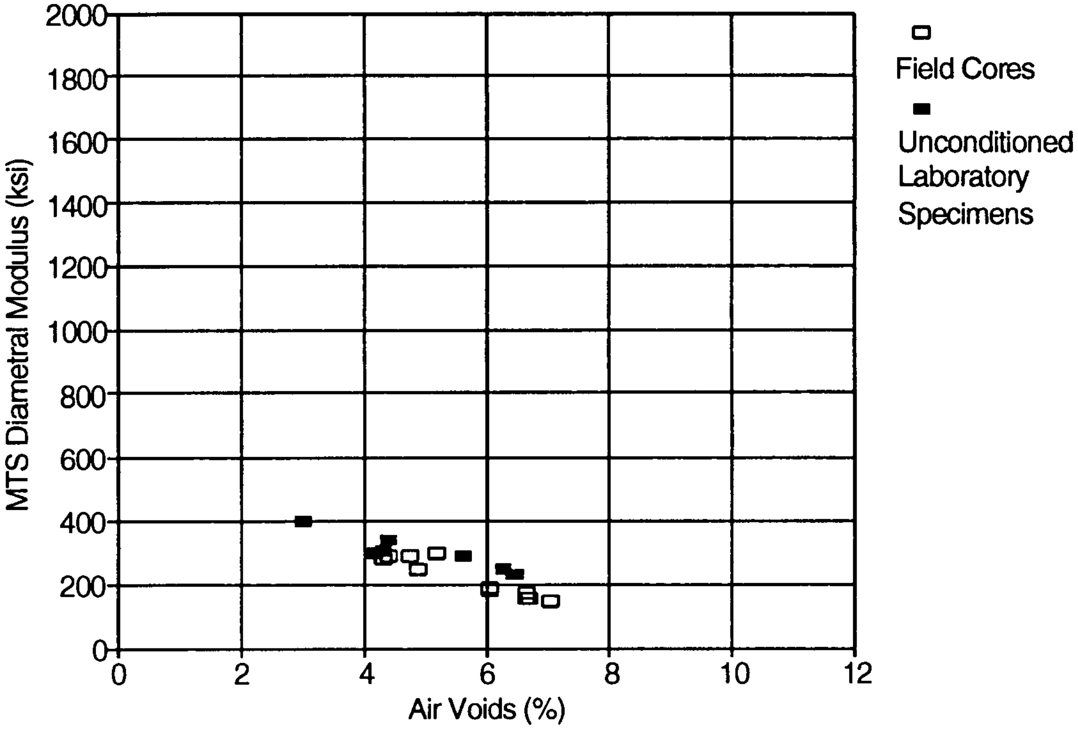


Figure 3.44. MN5 field cores, diametral modulus data

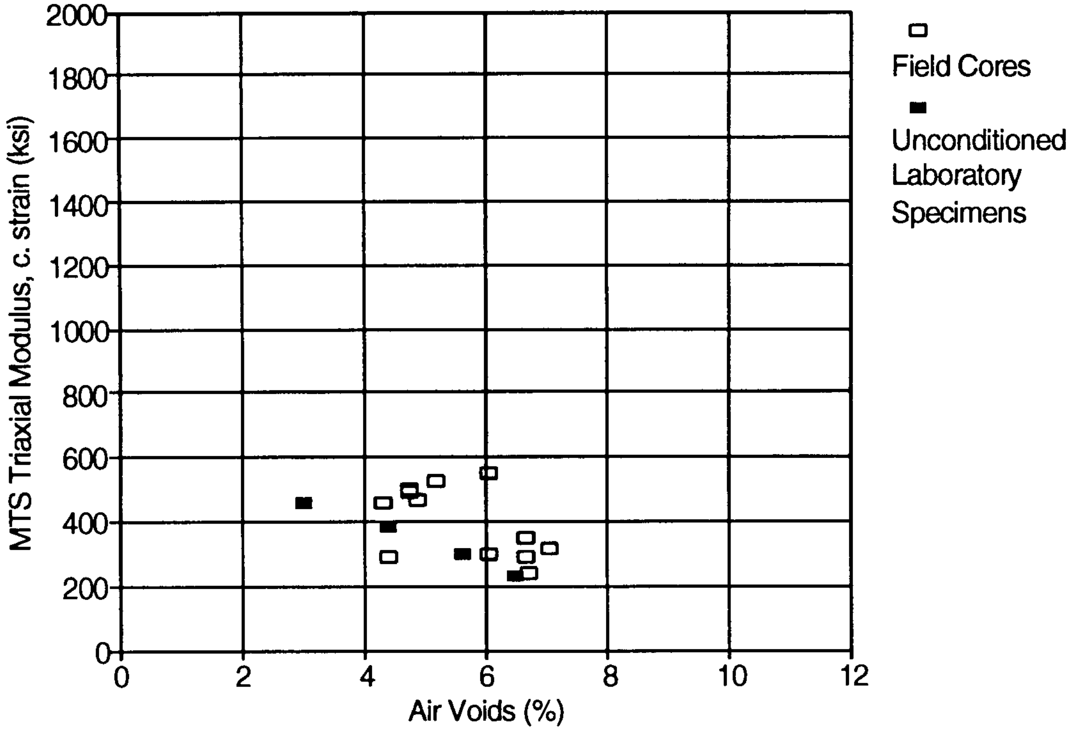


Figure 3.45. MN5 field cores, triaxial modulus data (tested at 100 μ-strain)

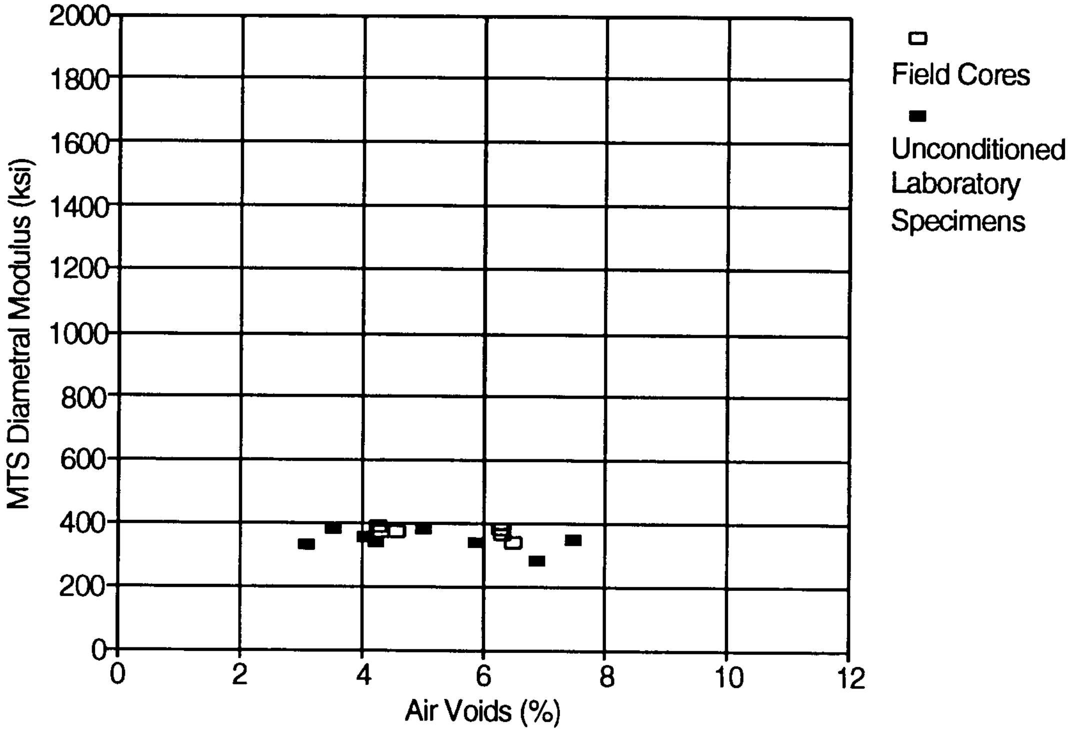


Figure 3.46. MS5 field cores, diametral modulus data

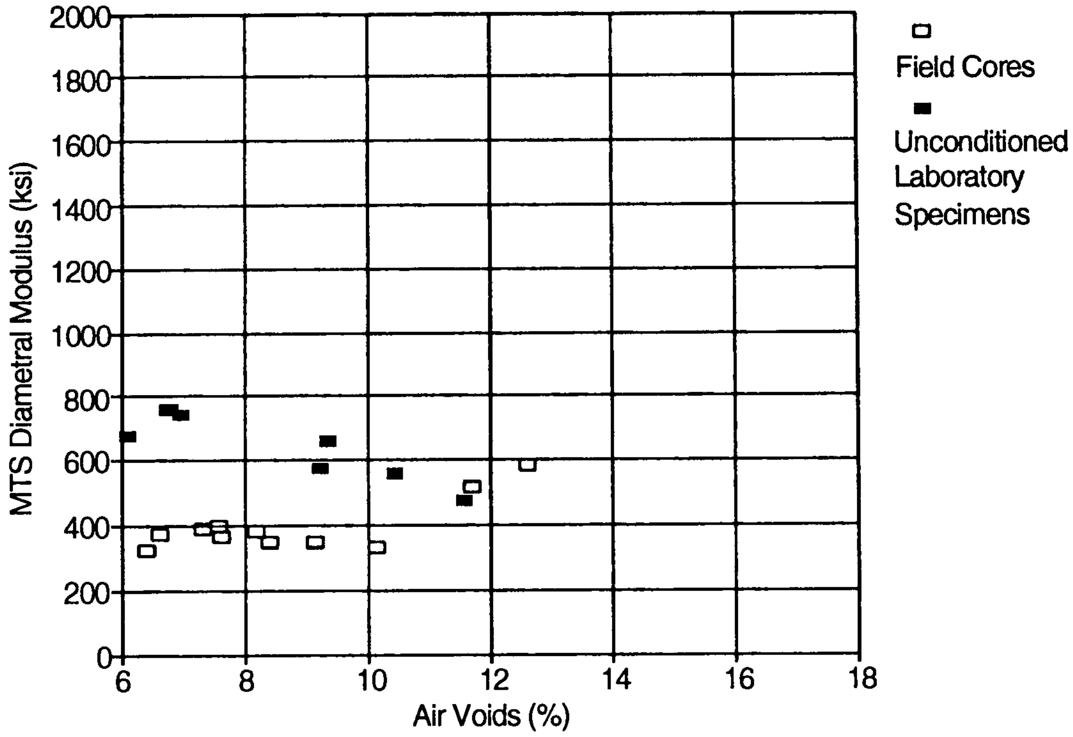


Figure 3.47. OR1 field cores, diametral modulus data

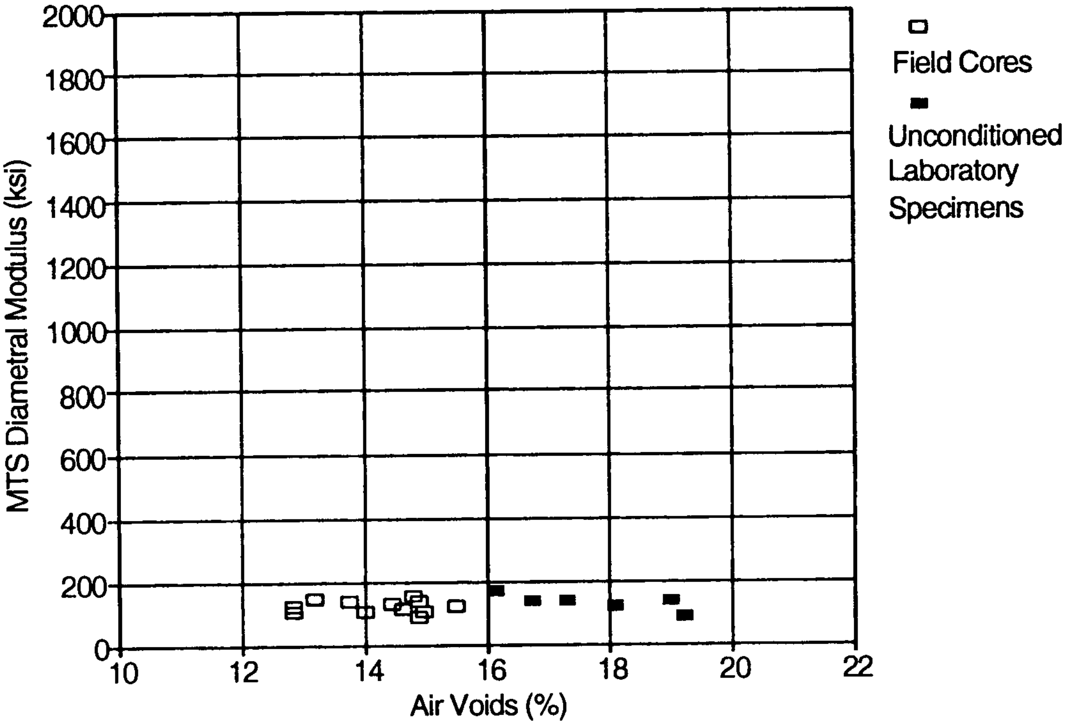


Figure 3.48. OR2 field cores, diametral modulus data

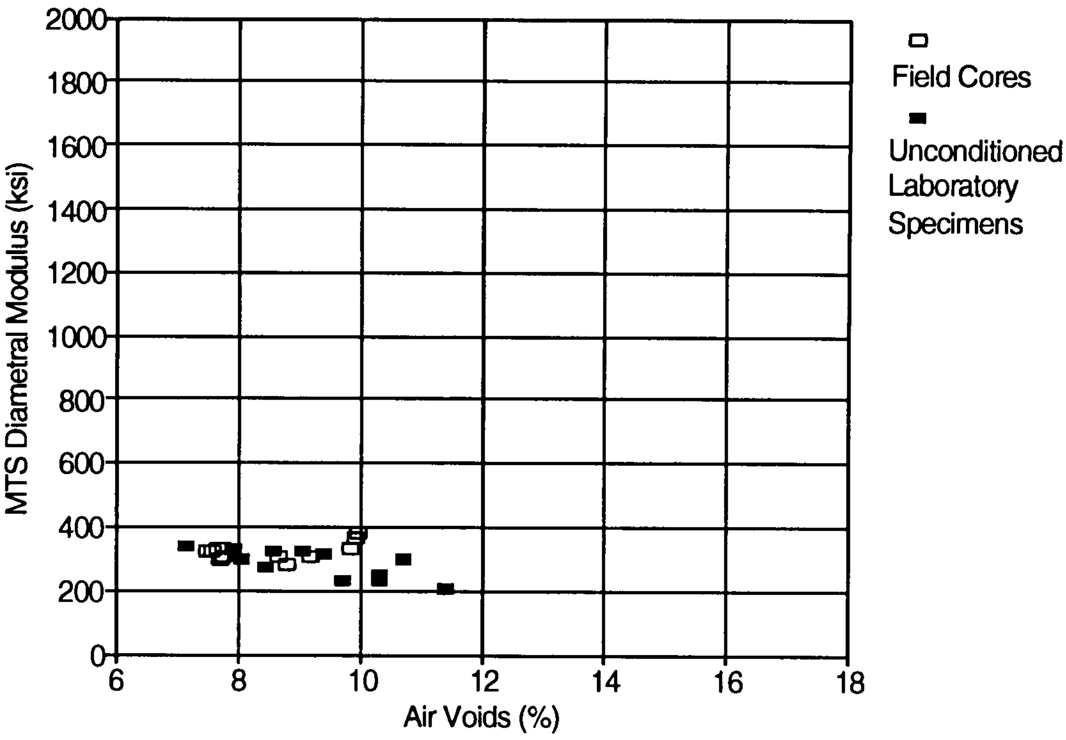


Figure 3.49. WA1 field cores, diametral modulus data

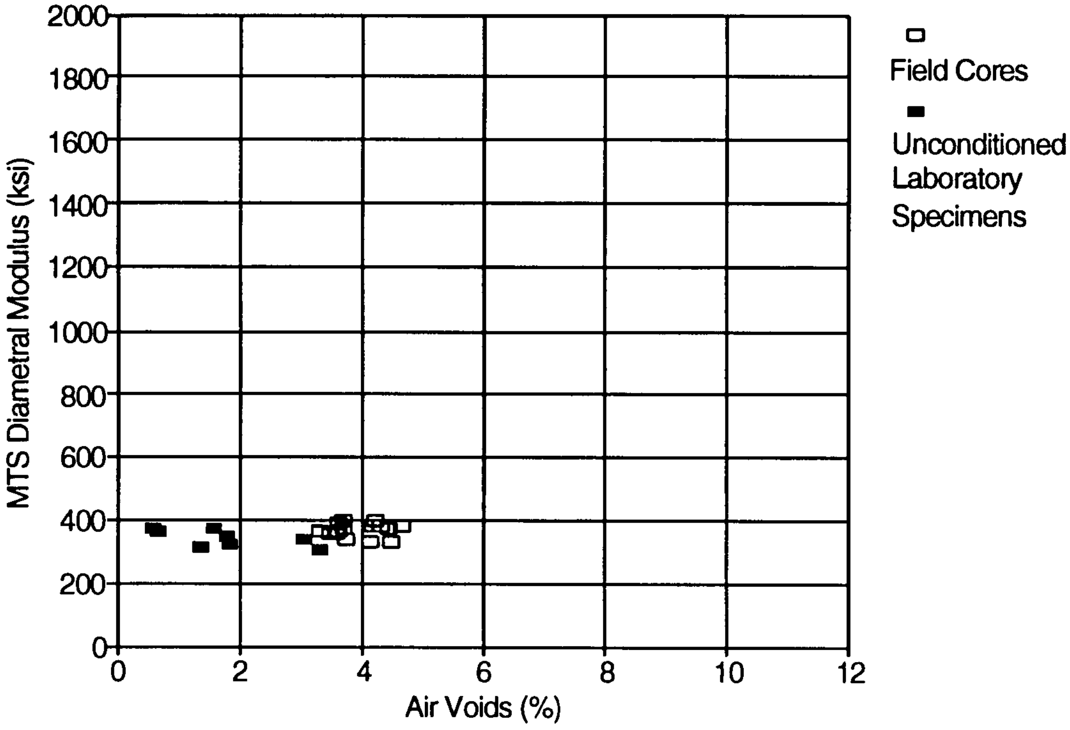


Figure 3.50. WIA field cores, diametral modulus data

Table 3.12. Visual stripping evaluation of field cores

Specimen	Visual Stripping (%)[1]	Comments
AB5F01B	10	
AB5F12	10	
AZ5F03	10	Fines not stripped as in laboratory specimens
AZ5F09	10	
CABF02	5	
CABF10	5	
CADF06	0	
CADF07	5	
CAGF01	20	Very similar to laboratory specimens
CAGF12	20	
GAAF02B	0	Very black
GAAF06A	5	
MN5F06	5	
MN5F21	5	
MS5F02	5	Much darker than laboratory specimens
MS5F03	5	
OR1F06	0	
OR1F09	5	
OR2F05	10	
OR2F12	10	
WA1F01	5	
WA1F07	5	
WIAF01	5	Asphalt duller than laboratory specimens
WIAF13	5	

[1] Evaluated according to Figure 2.20, Visual stripping rating chart.

4

Discussion and Analysis of Results

This chapter presents a discussion and analysis of the results obtained from the field validation effort for water sensitivity. Included is a description of the statistical analysis undertaken on the data from the Environmental Conditioning System (ECS), Oregon State University (OSU) wheel tracker, Elf Asphalt wheel tracker, and field cores. The analysis includes ranking of the performance of the mixtures relative to each other in each test format, development of statistical models for predicting performance of mixtures in each test format, and a comparison of the performance of the mixtures by test procedure. Discussion of general relationships of weather and traffic to the pavement performance are also included.

Analysis of the data obtained during this effort included several goals. First, a ranking of mixture performance for each test procedure was produced. This ranking was based on simple models that related the test performance criteria (i.e., ECS modulus ratio, rut depth, and field core modulus ratio) to mixture type only. This allowed for comparison of the ranking from each test procedure. Second, statistical models were developed to determine the importance of such factors as mixture type, air voids, and air and water permeability on the performance of a mixture in the ECS. Comparison of the effect of test procedures on the performance of the mixtures was made by comparing the rankings generated, using each set of test data. Finally, a model of the modulus ratios developed from ECS and field core data was used to determine the severity of the test procedures relative to one another.

This analysis is designed to demonstrate that the ECS test can discriminate among 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 ECS in a mix design system.

ECS Test Results

ECS Modulus Data

The analysis of the ECS test results employed a General Linear Model (GLM) procedure as provided by the SAS software package (SAS Institute Inc. 1988) to rank the mean ECS modulus ratios (the dependent variable) for each mixture. The performance ranking of the mixtures used the T groupings for the mean ECS modulus ratio generated in the GLM procedure, using the least-significant-difference (LSD) approach. Four rankings were produced: (1) a ranking of the ECS modulus ratio for each cycle of the ECS procedure, for the entire data set; (2) a ranking of the ECS modulus ratio for each cycle of the ECS procedure, for the mixtures from environments with freeze designations; (3) a ranking of the ECS modulus ratio for each cycle of the ECS procedure, for mixtures from environments with no-freeze designations; and (4) an overall ranking using the final ECS modulus ratio obtained for each mixture. For mixtures that came 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 ranking using the final ECS modulus ratio is directly analogous to the performance of the mixture in its particular environmental zone.

The initial rankings for the purposes of comparison among the test procedures used asphalt mixture type (MIX) type, as a class variable. Tables 4.1 through 4.4 show rankings of mixture performance in the ECS with the ECS modulus ratio modeled on mixture type only. The four cases discussed above are shown. For mixtures MS5 and WIA, only specimens that survived the ECS procedure without excessive deformation were used in the analysis, which includes three MS5 specimens and five WIA specimens.

The mixtures tested demonstrated two typical responses. Mixtures seem to either experience most of their damage during the first cycle of ECS conditioning and then maintain a fairly constant modulus ratio, or continue to decrease in modulus through later ECS cycles, demonstrating continuing water damage. Figures 3.1 through 3.12 illustrate that several of the mixtures experience a high percentage of the reduction in ECS modulus ratio in the first cycle of the test. Table 4.5 indicates that eight of the mixtures tested experienced over 50 percent of their reduction in modulus in the first cycle. This result indicates that these mixtures 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 cycle 1 and cycle 3 is also different for each mixture. Table 4.6 indicates the mean values of slope for the ECS modulus curve between cycle 1 and cycle 3 for the mixtures tested. These data are presented graphically in figure 4.1a and 4.1b. The slope is defined as

$$Slope = \frac{(Cycle\ 3\ ECS\ Modulus\ Ratio\ -\ Cycle\ 1\ ECS\ Modulus\ Ratio)}{(3-1)} \qquad (4.1)$$

Table 4.1. Ranking of mixtures for the ECS test procedure, T intervals and groupings, 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	0.952	A	GAA	0.932	A
2	OR2	0.903	A	OR2	0.916	A, B
3	OR1	0.877	A, B	OR1	0.873	A, B
4	AB5	0.875	A, B	WA1	0.865	A, B
5	WA1	0.859	A, B	AB5	0.813	B, C
6	MN5	0.776	B, C	WIA	0.714	C, D
7	WIA	0.748	C, D	AZ5	0.708	C, D
8	AZ5	0.742	C, D	MN5	0.707	C, D
9	CAB	0.698	C, D	CAB	0.674	D
10	MS5	0.690	C, D	MS5	0.667	D
11	CAD	0.647	D	CAD	0.630	D
12	CAG	0.505	E	CAG	0.447	E

	Cycle 3			Cycle 4		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.937	A	OR2	0.916	A
2	OR2	0.904	A	WA1	0.900	A
3	OR1	0.871	A, B	WIA	0.768	A
4	WA1	0.838	A, B, C	AB5	0.758	B
5	AB5	0.775	C, D, E	CAB	0.554	B
6	AZ5	0.720	C, D, E	MN5	0.541	C
7	WIA	0.694	D, E, F	CAD	0.457	C
8	CAB	0.654	D, E, F	[2]		
9	MN5	0.651	D, E, F			
10	MS5	0.623	E, F			
11	CAD	0.589	F			
12	CAG	0.423	G			

[1] Groupings with the same letter designation include means that are not significantly different.

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

Table 4.2. Ranking of mixtures for the ECS test procedure, T intervals and groupings, freeze data

	Cycle 1			Cycle 2		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping[1]	Mixture	Mean ECS Modulus Ratio	T Grouping
1	OR2	0.903	A	OR2	0.916	A
2	AB5	0.875	A, B	WA1	0.865	A
3	WA1	0.859	A, B	AB5	0.813	A, B
4	MN5	0.776	B, C	WIA	0.714	B, C
5	WIA	0.748	C, D	MN5	0.707	B, C
6	CAB	0.698	C, D	CAB	0.674	C
7	CAD	0.647	D	CAD	0.630	C

	Cycle 3			Cycle 4		
Rank	Mixture	Mean ECS Modulus Ratio	T Grouping	Mixture	Mean ECS Modulus Ratio	T Grouping
1	OR2	0.904	A	OR2	0.916	A
2	WA1	0.838	A	WA1	0.900	A
3	AB5	0.775	A, B	WIA	0.768	A
4	WIA	0.649	B, C	AB5	0.758	B
5	CAB	0.654	B, C	CAB	0.554	B
6	MN5	0.651	B, C	MN5	0.541	C
7	CAD	0.589	C	CAD	0.457	C

[1] Groupings with the same letter designation include means that are not significantly different.

Table 4.3. Ranking of mixtures for the ECS test procedure, T intervals and groupings, 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	0.952	A	GAA	0.932	A
2	OR1	0.877	A	OR1	0.873	A
3	AZ5	0.742	B	AZ5	0.708	B
4	MS5	0.690	B	MS5	0.667	B
5	CAG	0.505	C	CAG	0.447	C

Rank	Cycle 3		
	Mixture	Mean ECS Modulus Ratio	T Grouping
1	GAA	0.937	A
2	OR1	0.871	A
3	AZ5	0.720	B
4	MS5	0.623	B
5	CAG	0.422	C

[1] Groupings with the same letter designation include means that are not significantly different.

Table 4.4. Ranking of mixtures for the ECS test procedure, T intervals and groupings, final ECS modulus ratio, regardless of environmental zone

Rank	Mixture	Mean Ratio	T Grouping[1]
1	GAA	0.937	A
2	OR2	0.916	A
3	WA1	0.900	A
4	OR1	0.871	A, B
5	WIA	0.768	B, C
6	AB5	0.758	B, C
7	AZ5	0.720	C, D
8	MS5	0.623	D, E
9	CAB	0.554	E, F
10	MN5	0.541	E, F
11	CAD	0.457	F, G
12	CAG	0.422	G

[1] Groupings with the same letter designation include means that are not significantly different.

Table 4.5. 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	0.875	0.758	52
AZ5	0.742	0.720	92
CAB	0.698	0.554	68
CAD	0.647	0.457	65
CAG	0.505	0.423	86
GAA	0.952	0.937	76
MN5	0.776	0.541	49
MS5	0.690	0.623	82
OR1	0.877	0.871	95
OR2	0.903	0.916	115
WA1	0.869	0.900	131
WIA	0.748	0.768	109

Table 4.6. 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

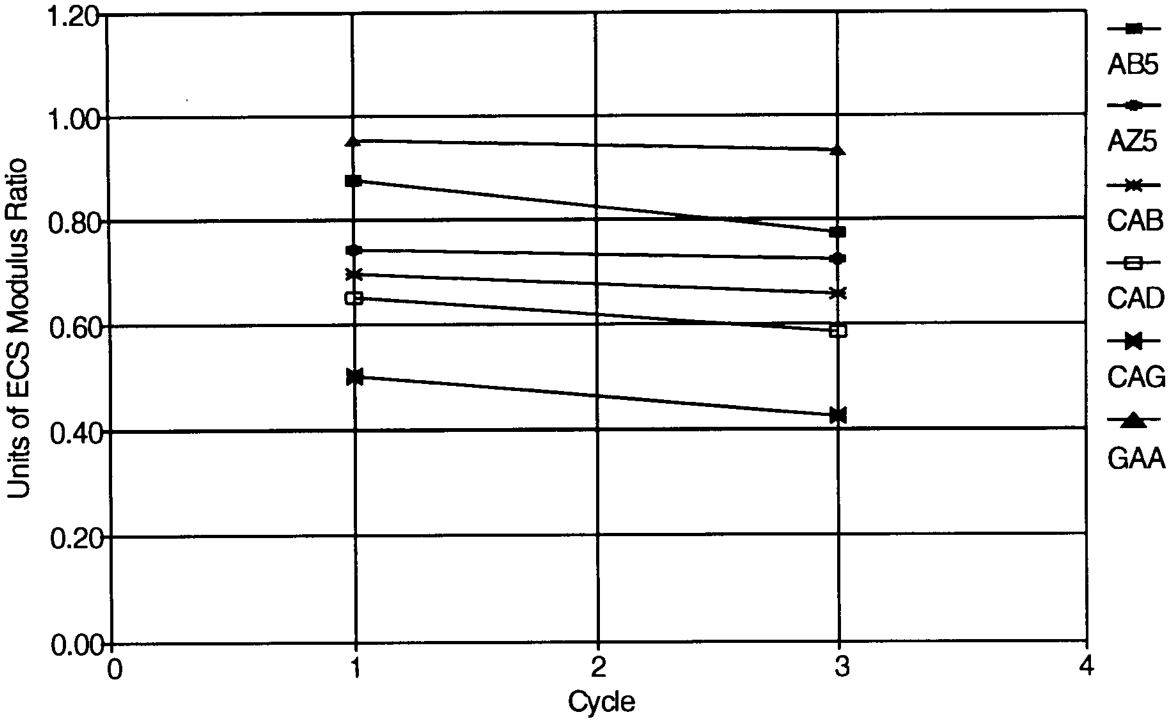


Figure 4.1a. Slope of mean ECS modulus ratio curves between cycle 1 and cycle 3

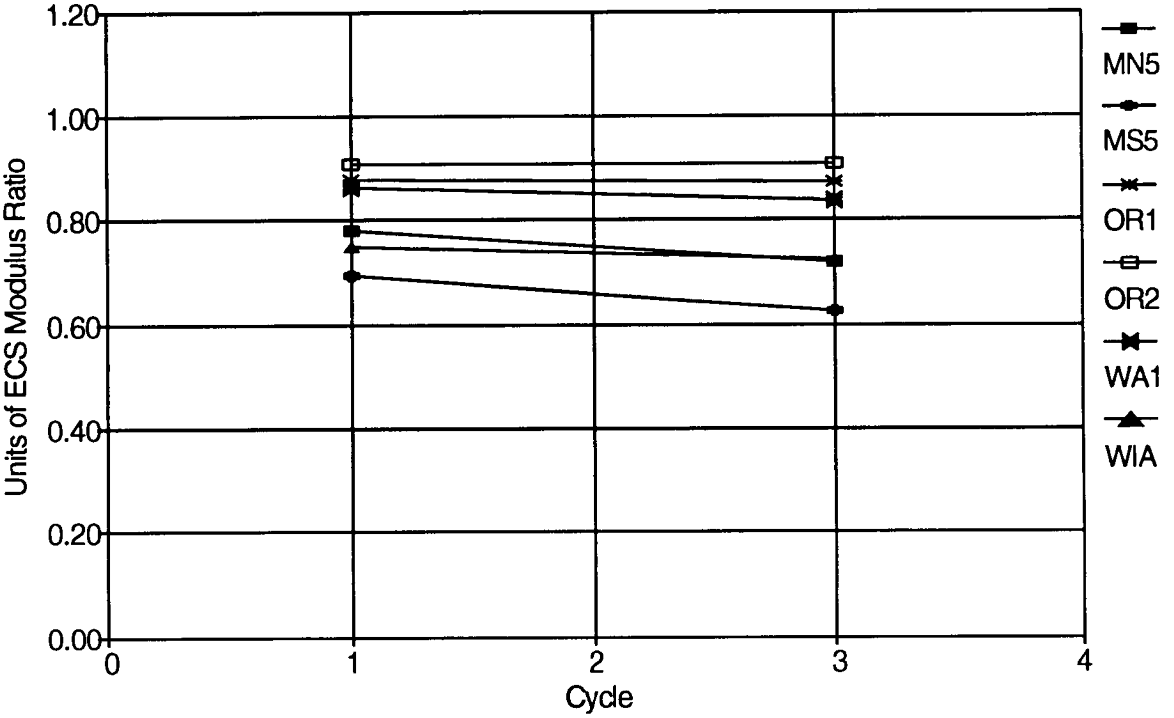


Figure 4.1b. Slope of mean ECS modulus ratio curves between cycle 1 and cycle 3

It is believed that the slope is an indicator of the rate of damage to the specimen as it undergoes the ECS test procedure. Figure 4.2 shows graphically the change in ECS modulus ratio between cycle 1 and cycle 3. The slopes of the modulus curves between cycle 1 and cycle 3 indicate that several of the mixtures experience a reduction in modulus ratio between cycle 1 and cycle 3 of 0.100 or greater (AB5, CAG, and MN5). These mixtures experienced a continual rate of damage and would probably continue to accumulate damage if subjected to further conditioning. The mixtures that 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 4.3.

The model developed using only mixture type as a variable to describe the ECS modulus ratio is reported in table 4.7. The values of the probability of $F > F_0$ (0.0001) 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.

Additional analyses were performed to investigate a more comprehensive set of variables, including percent air voids, air permeability (APERM), initial water permeability (WPERM), and initial ECS modulus. MIX, APERM and WPERM were presented as class variables in the model. Since both APERM and WPERM measurements resulted in specimens with reported “zero” permeability values, or permeabilities lower than the capabilities of the test equipment, these values were divided into four ranges, as shown in table 4.8. 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 analyses 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 that contained only the variable MIX. If the inclusion of a variable resulted in significant values of the probability of $F > F_0$ (< 0.05), then the variable was considered significant. The variable was then added to the model, and possible interactions of that variable were considered. Table 4.9 indicates the results of this study.

Table 4.9 indicates that the most significant variable after considering MIX is the INTM modulus of the mixture. None of the other variables have significant probabilities of $F > F_0$ when combined with MIX alone to constitute a model. The third variable that can be added to the model is the AVOID level of the mixture. When added to a model already containing MIX and INTM, AVOID has a significant value for the probability of $F > F_0$. From the analysis, no other variables, or interactions, add significance to the model, so no other should be included. Therefore, the APERM and WPERM of the unconditioned specimen do not have a statistically significant effect on the final ECS modulus ratio for the mixture.

Tables 4.10 and 4.11 show the full statistical analysis for the two models mentioned above: MIX, 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 values for the probability of $F > F_0$ indicate that throughout the ECS test procedure, the INTM of the mixture continues to be significant in the prediction of the ECS modulus ratio.

The increasing value of the probability of $F > F_0$ for AVOID after each ECS cycle indicates that as the ECS procedure continues, the initial value of AVOID is no longer as significant in predicting the ECS modulus ratio. This is logical if you consider that as the specimen is undergoing the ECS procedure, the AVOID level is being changed by mechanical changes in the specimen. The specimen is deforming under repeated loading during hot cycles, and the flow of water within the specimen may be causing binder migration, also changing the AVOID structure. As the test progresses, the initial AVOID level no longer reflects the true AVOID structure of the specimen.

Analysis of the data set indicates the relative importance of the INTM of a specimen to its performance in the ECS test procedure, which suggests that further discussion of the INTM parameter is warranted.

For the 12 mixtures investigated in ECS, the INTM values ranged from 87.4 ksi (602 MPa) for OR2, the open-graded mixture, to 1,969.3 ksi (13,568.5 MPa) for CAB. Figure 4.4 shows the relation between the final ECS modulus ratio and the initial ECS modulus. Figures 4.5a and 4.5b divide the data by mixture type. For several of the mixtures, the INTM does not vary substantially, such as with AB5, GAA and OR2. However, for other mixtures, the range of initial resilient modulus is quite large, such as with CAD with INTM values ranging from 616.8 ksi to 1,709.5 ksi (4,250 MPa to 11,778 MPa).

The INTM of a mixture depends on several factors, such as gradation, aggregate type, aggregate shape, asphalt content and asphalt type, and AVOID. For any particular mixture used in this task, only AVOID was varied within a set of specimens for the given mixture. Figures 4.6a and 4.6b indicate the relation between INTM and AVOID. (The scales of these figures are expanded to accommodate the OR2 open-graded mixture.) This variation indicates that several mixtures experienced significant changes in resilient modulus with changes in AVOID levels, such as CAB and CAD. For others, OR2 and AB5, the resilient modulus is less sensitive to AVOID levels.

Though 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 sensitivity 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 that influences the performance of a mixture in ECS requires additional consideration for the purpose of defining the relative performance between mixtures. A mixture that has an INTM of 1,000 ksi (6,890 MPa) and a final ECS modulus ratio of 0.6 still has a resilient modulus of 600 ksi (4,134 MPa). However, a mixture that has an INTM of 667 ksi (4,596 MPa) has to have a final ECS modulus ratio of only 0.9 to bring it to the same level of resilient modulus, 600 ksi (4,134 MPa).

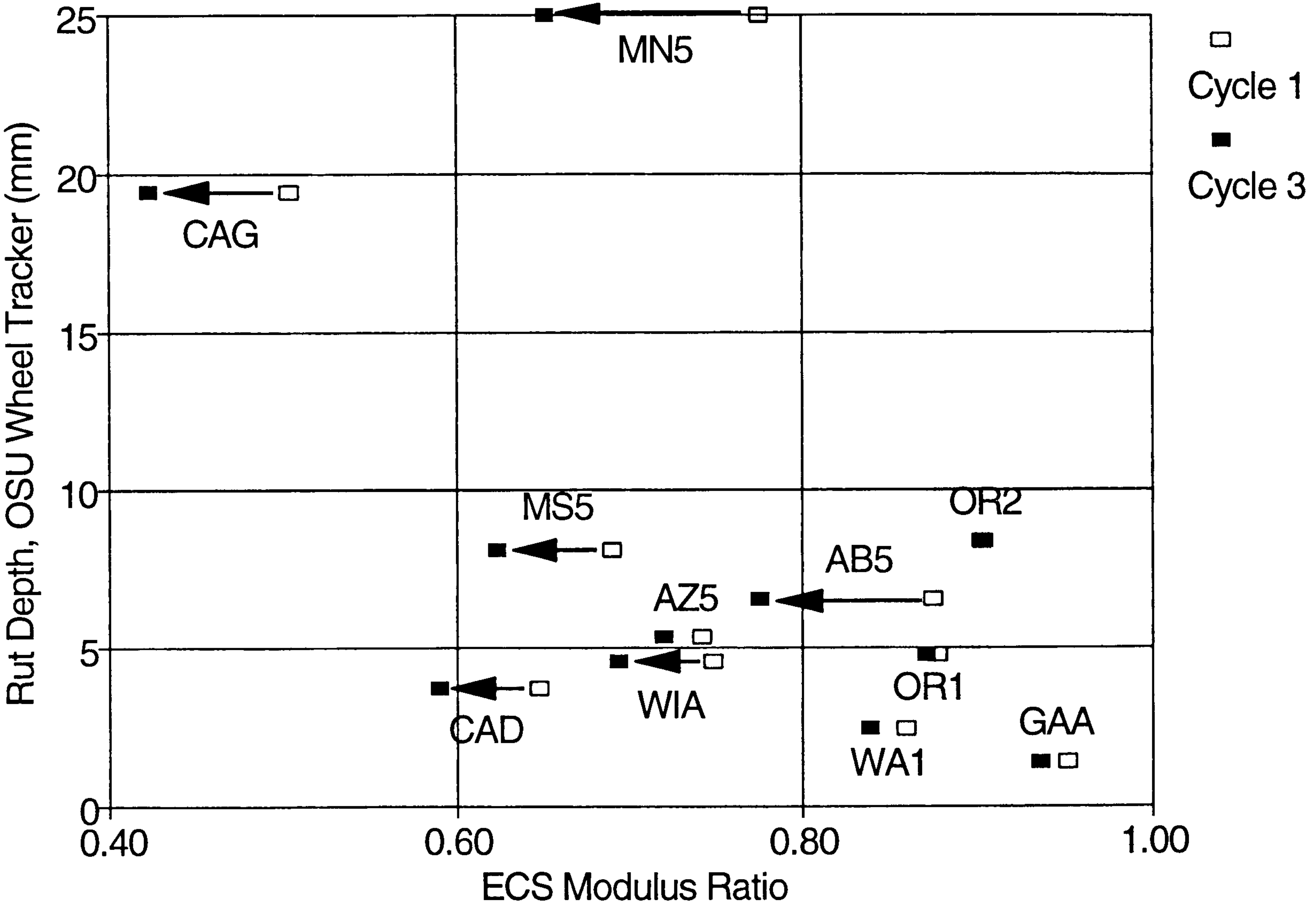


Figure 4.2. Change in ECS modulus ratio between cycle 1 and cycle 3

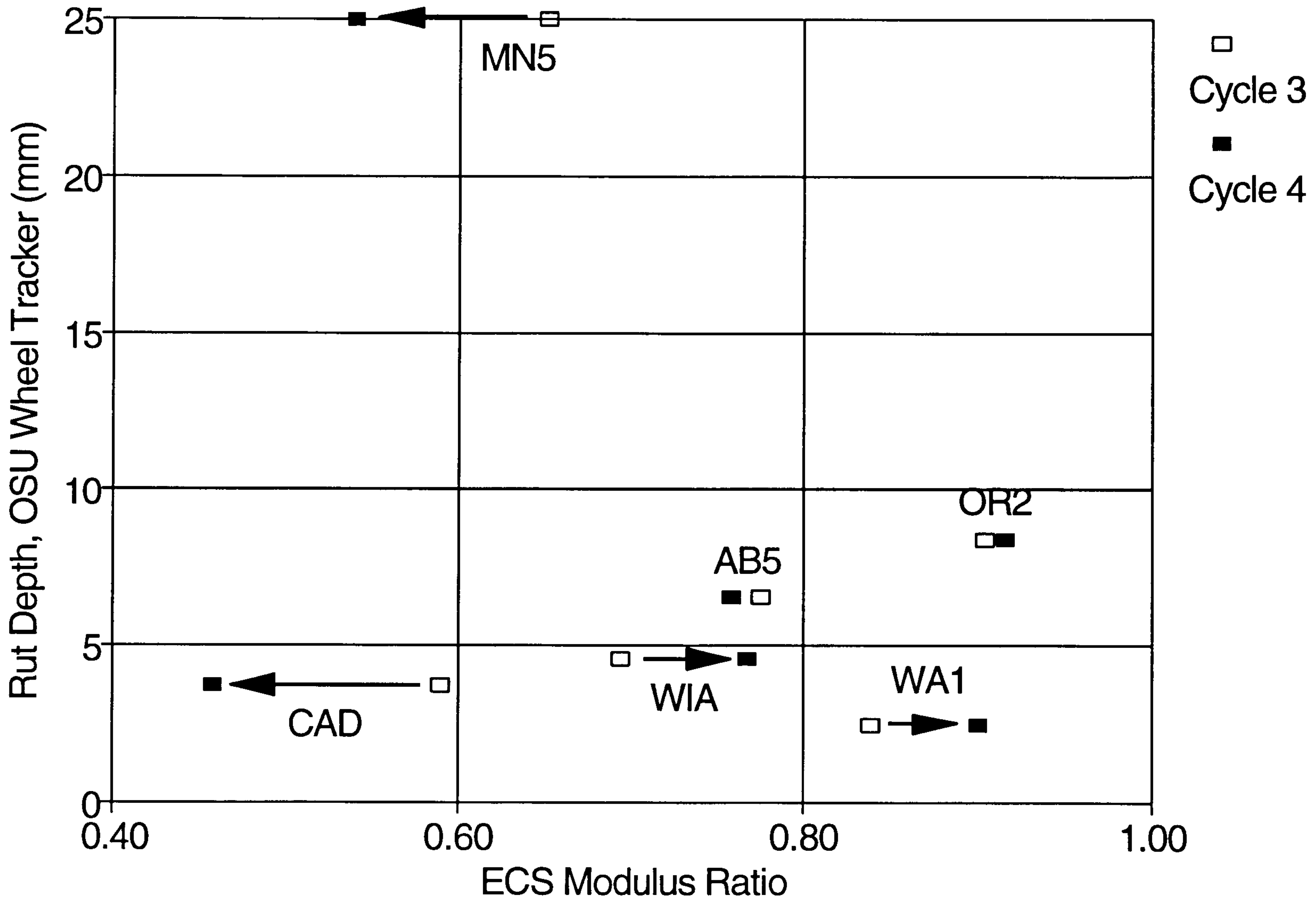


Figure 4.3. Change in ECS modulus ratio between cycle 3 and cycle 4

Table 4.7. GLM analysis of ECS results for 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 = 13.36%, and the ECS modulus ratio mean = 0.781

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.10147487	9.19	0.0001

Cycle = 2
Model: $R^2 = 0.64$, CV = 14.84%, and the ECS modulus ratio mean = 0.755

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.35601930	9.81	0.0001

Cycle = 3
Model: $R^2 = 0.62$, CV = 17.08%, and the ECS modulus ratio mean = 0.733

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.53639193	8.90	0.0001

Cycle = 4
Model: $R^2 = 0.69$, CV = 18.12%, and the ECS modulus ratio mean = 0.706

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	6	1.38321444	14.10	0.0001

Table 4.8. Class variables

Mixture	Levels	Values
MIX	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA
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 4.9. GLM analysis of ECS results, investigation of significance of variable to the model

Variable	Type
MIX	Class
AVOID	Covariate
INTM	Covariate
APERM	Class
WPERM	Class

Source of error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.10147487	9.19	0.0001
MIX	11	1.08011127	9.00	0.0001
AVOID	1	0.00958422	0.88	0.3525
MIX	11	1.021433805	10.92	0.0001
INTM	1	0.15428787	18.14	0.0001
MIX	11	1.06856734	8.99	0.0001
APERM	3	0.03752048	1.16	0.3340
MIX	11	1.10473184	9.86	0.0001
WPERM	3	0.07353670	2.41	0.0765
MIX	11	0.17836491	1.83	0.0742
INTM	1	0.00299512	0.34	0.5637
MIX*INTM	11	.07588992	0.78	0.6596
MIX	11	1.09239167	13.38	0.0001
INTM	1	0.21688027	29.21	0.0001
AVOID	1	0.07219662	9.72	0.0028
MIX	11	0.98883134	10.60	0.0001
INTM	1	0.14343805	16.91	0.0001
APERM	3	0.02667066	1.05	0.3784
MIX	11	1.03808863	11.52	0.0001
INTM	1	0.12392750	15.12	0.0001
WPERM	3	0.04317633	1.76	0.1658
MIX	11	0.13979178	1.94	0.0571
INTM	1	0.23514720	35.91	0.0001
AVOID	1	0.05254372	8.02	0.0067
MIX*AVOID	11	0.12372222	1.72	0.0979
MIX	11	1.04396543	12.78	0.0001
INTM	1	0.18533145	24.97	0.0001
AVOID	1	0.06784111	9.14	0.0038
APERM	3	0.02233515	1.00	0.3984
MIX	11	1.10677529	14.24	0.0001
INTM	1	0.16991928	24.06	0.0001
AVOID	1	0.07148224	10.12	0.0024
WPERM	3	0.04248196	2.00	0.1237

Table 4.10. GLM analysis of ECS results for model I, entire data set

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

Cycle = 1
Model: $R^2 = 0.71$, CV = 11.80%, and the ECS modulus ratio mean = 0.781

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.02143805	10.92	0.0001
INTM	1	0.15438787	18.14	0.0001

Cycle = 2
Model: $R^2 = 0.73$, CV = 12.88%, and the ECS modulus ratio mean = 0.755

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.31219949	13.03	0.0001
INTM	1	0.19907440	21.05	0.0001

Cycle = 3
Model: $R^2 = 0.76$, CV = 13.71%, and the ECS modulus ratio mean = 0.733

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.60139858	14.40	0.0001
INTM	1	0.35085712	34.69	0.0001

Cycle = 4
Model: $R^2 = 0.79$, CV = 15.15%, and the ECS modulus ratio mean = 0.706

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	0.72009792	10.49	0.0001
INTM	1	0.19820338	17.33	0.0001

Table 4.11. GLM analysis of ECS results for model II, entire data set

Variable	Type	Levels	Values
MIX	Class	12	AB5, AZ5, CAB, CAD, CAG, GAA, MN5, MS5, OR1, OR2, WA1, WIA
AVOID	Covariate		
INTM	Covariate		

Cycle = 1

Model: $R^2 = 0.75$, CV = 11.03%, and the ECS modulus ratio mean = 0.781

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.09239167	13.38	0.0001
AVOID	1	0.07217662	9.72	0.0028
INTM	1	0.21688027	29.21	0.0001

Cycle = 2

Model: $R^2 = 0.75$, CV = 12.64%, and the ECS modulus ratio mean = 0.755

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.30335719	13.00	0.0001
AVOID	1	0.02966349	3.25	0.0764
INTM	1	0.22860297	25.08	0.0001

Cycle = 3

Model: $R^2 = 0.76$, CV = 13.64%, and the ECS modulus ratio mean = 0.733

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	1.55353354	14.10	0.0001
AVOID	1	0.01588782	1.59	0.2128
INTM	1	0.35459809	35.41	0.0001

Cycle = 4

Model: $R^2 = 0.80$, CV = 14.80%, and the ECS modulus ratio mean = 0.706

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	11	0.72399953	11.06	0.0001
AVOID	1	0.03048498	2.79	0.1033
INTM	1	0.22807043	20.90	0.0001

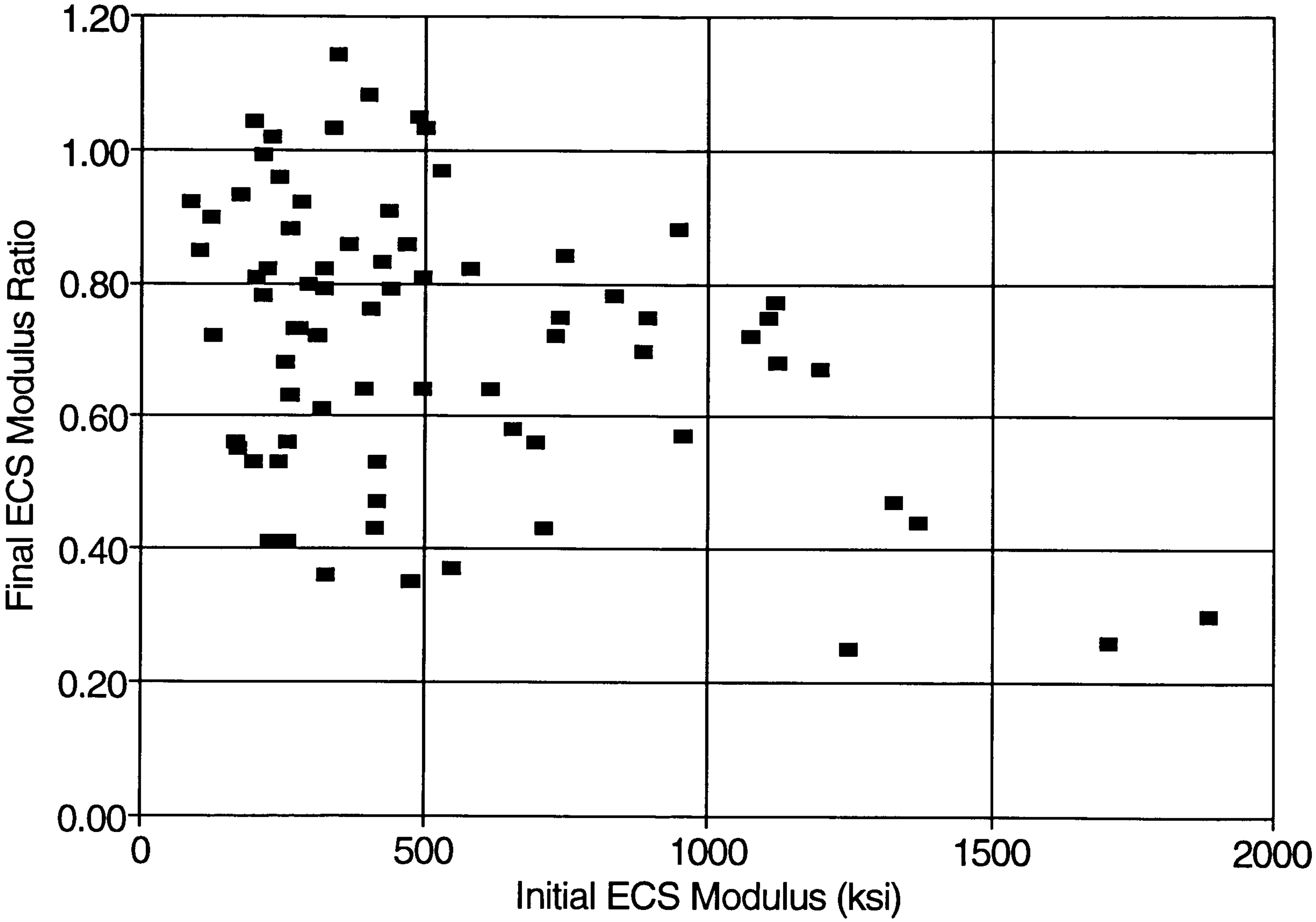


Figure 4.4. Final ECS modulus ratio versus initial ECS modulus

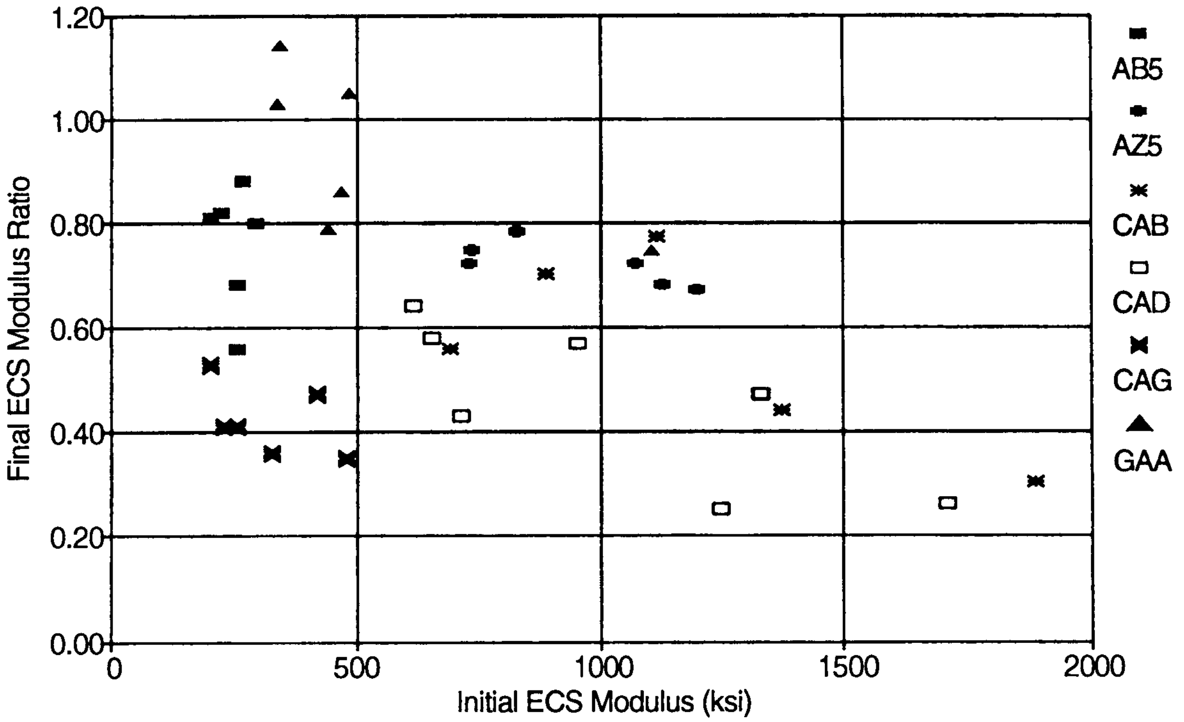


Figure 4.5a. Final ECS modulus ratio versus initial ECS modulus, by mixture

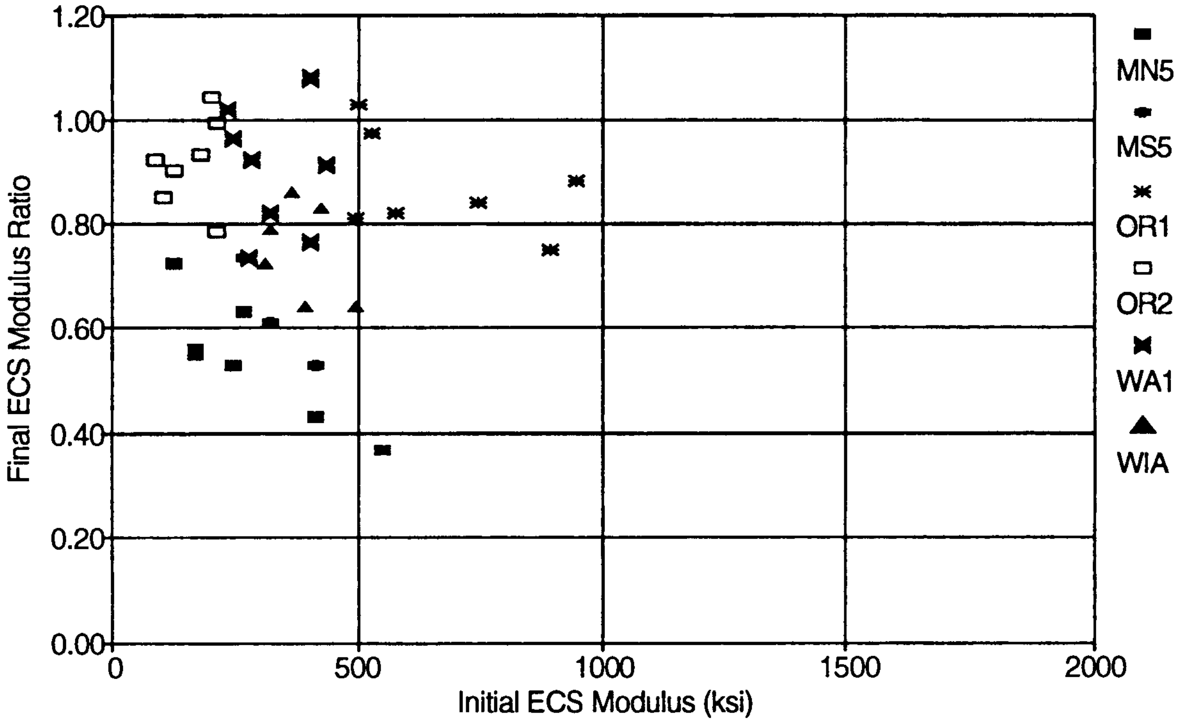


Figure 4.5b. Final ECS modulus ratio versus initial ECS modulus, by mixture

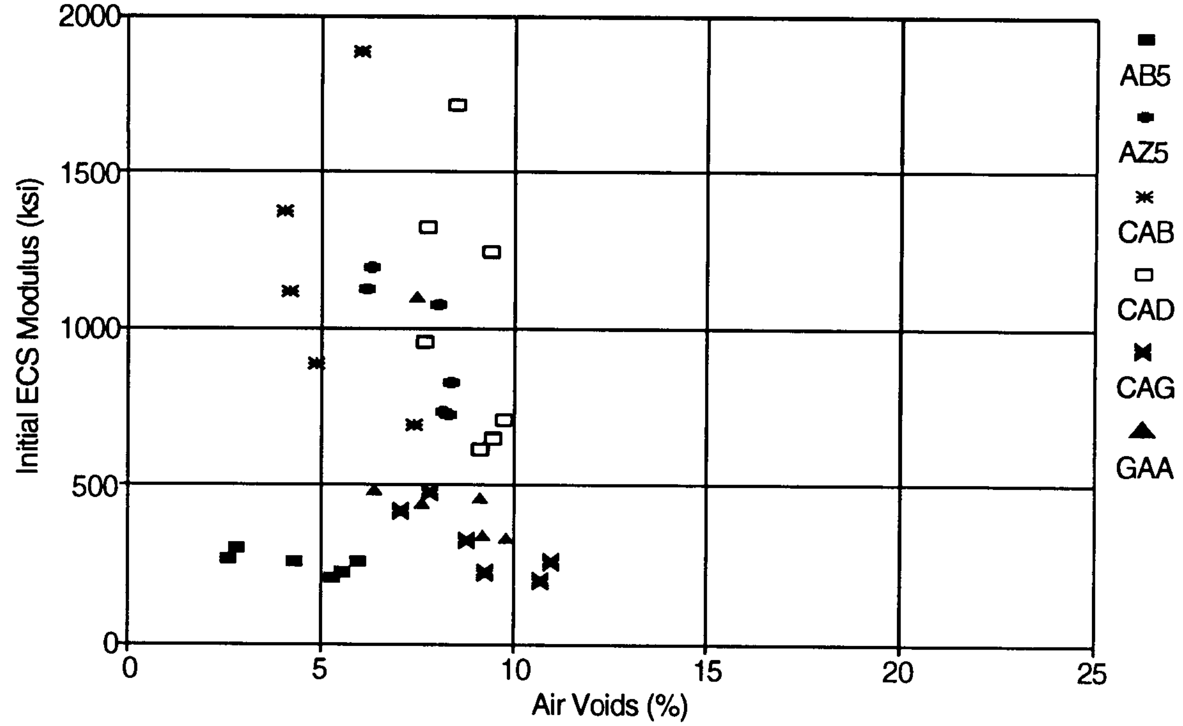


Figure 4.6a. Initial ECS modulus versus air voids, by mixture

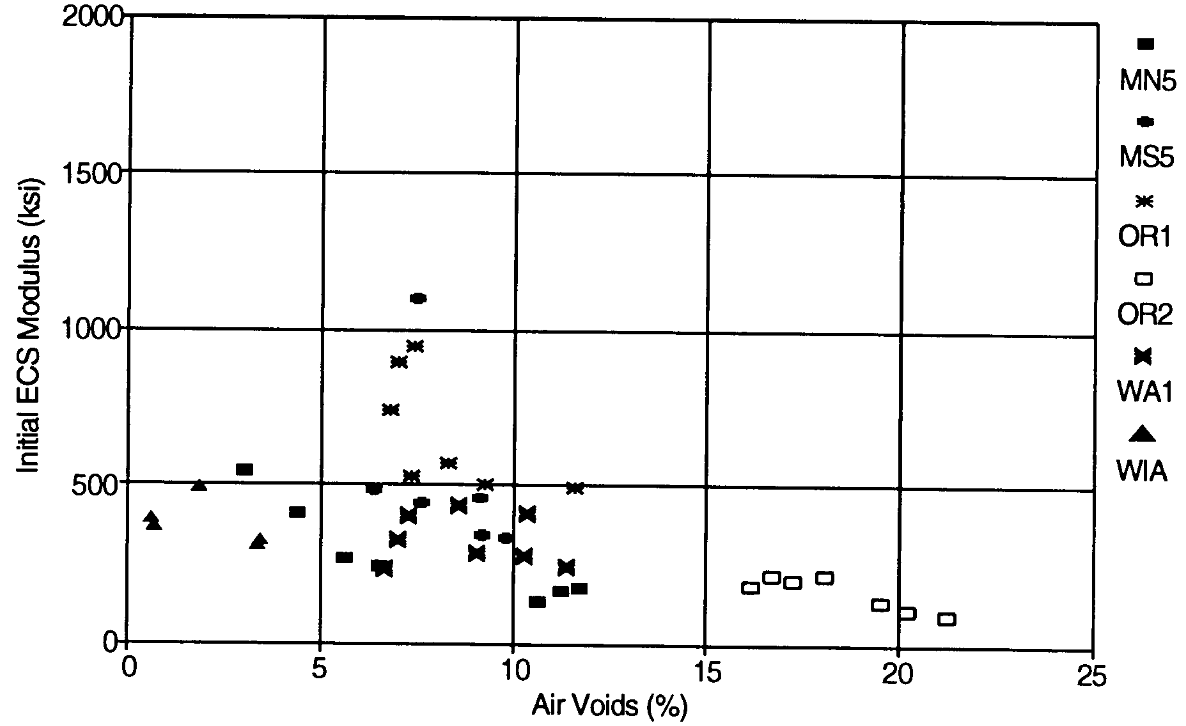


Figure 4.6b. Initial ECS modulus versus air voids, by mixture

In considering the performance of the two mixtures, their relative levels of stiffness — not just the reduction in stiffness as quantified by the resilient modulus ratio — must be considered. Determination of the required level of stiffness for an asphalt-concrete mixture being considered for placement is beyond the scope of the water sensitivity task. 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 value of a modulus to an unacceptable level.

An additional model was run using a class variable (designated as 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 4.12 gives the results of this model. The probability of $F > F_0$ indicates that the environmental zone does not have 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. Subjecting a specimen to the appropriate conditioning for its environmental designation will not influence the performance of the mixture relative to other mixtures tested in conditioning appropriate to their environmental designations. The fact that different grades of asphalt are typically used for freeze and no-freeze environments may also be reflected by these data.

Visual Degree of Stripping and Binder Migration Data

The visual degree of stripping and binder migration were not included in the statistical models run on the ECS data. Visual degree of stripping and binder migration, like ECS modulus ratio, are response variables that change during the ECS test procedure, and it is therefore inappropriate to use them as variables to describe ECS modulus ratio responses. However, some general observations concerning the asphalt stripping and binder migration data can be made.

The visual degree of stripping and the binder migration did not seem to have a correlation with the decrease in modulus as measured by ECS. Several mixtures with low final ECS modulus ratios have higher degrees of stripping (AZ5, CAG, and MS5); however, some mixtures with lower degrees of stripping also have low final ECS modulus ratios (CAB, CAD and WIA). Binder migration shows similar trends. However, within a set of specimens from one mixture, greater binder migration occurs for specimens with lower air void levels.

Permeability Data

After 30 minutes of conditioning, some specimens that are impermeable to air allow water to flow. Additionally, specimens with initial coefficients of permeability for water of less than 1.0E-04 cm/sec. (3.9E-05 in./sec.) typically show an increase in permeability during the first hot cycle with repeated loading. This suggests that the wetting procedure and, even more so, the heating and loading procedure of the first hot cycle with available flow, tend to open the specimen to flow. Several mechanisms may be at work.

Table 4.12. GLM analysis of ECS results for freeze versus no-freeze environmental zone, final ECS modulus ratios

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

Model: $R^2 = 0.0031$, CV = 29.88%, and the ECS modulus ratio mean = 0.715

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of $F > F_0$
ENVR	1	0.01012688	0.22	0.6391

Environmental Zone	Mean ECS Modulus Ratio	T Grouping
Freeze	0.7058	A[1]
No-Freeze	0.7300	A

[1] Means with the same letter T grouping are not significantly different.

During the wetting procedure, the extended time with 20 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 period may be why this break occurs with water flow during the wetting procedure and not during the air flow measurements. In the air permeability test, the air flow is immediately turned off if the specimen is deemed impermeable, so the pressure differential does not last for more than a few minutes.

During the first cycle of loading, specimens with lower coefficients of water permeability may see more breakdown of thin films that separate voids. The repeated loading may cause rearrangement of the asphalt-aggregate matrix and breaking of the asphalt bonds. Also, repeated loading may cause increased pore water pressure within the specimen, especially if water is trapped in pores with only one interconnecting pathway to other pores, or if pathways between pores are small, causing more film damage. During the first cycle, specimens may also be experiencing a loss of adhesion within the asphalt matrix. Several of the specimens that tended to show an increase in permeability during the first cycle were also the specimens in which more binder migration was observed.

Figures 3.15 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 is also seen in figure 3.14. 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 the mixtures that had specimens that displayed binder migration (AB5, AZ5, CAB, CAG, MN5, MS5, OR1, and WA1).

It may be that lower permeability specimens with 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 pressures may tend to break these films and move debonded asphalt particles around until an equilibrium is reached and the pores are connected in such a way as to provide adequate drainage for the structure under the prevailing conditions. In the more permeable mixtures with 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 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 vary this trend.

OSU Wheel Tracker Results

A ranking of the mixtures as they performed in the OSU wheel tracker is presented in table 4.13. This ranking was again produced using the GLM procedure, and the resulting T intervals. The model included only MIX as a class variable. The dependent variable is rut depth, designated by a negative number. A second model including the covariate AVOID was also produced. This model is presented in table 4.14.

When interpreting the results of the OSU wheel tracking tests, it is important to compare the air void levels of the beam specimens with the kneading-compacted specimens tested in ECS and the cores taken from the field. Because of 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 because of adhesion to the drums of the roller. Therefore, MN5 beams had significantly different air voids than intended. Table 4.15 compares the average air void levels of the different specimens.

Table 4.16 presents the mean modulus ratios for the rutted beam specimens. Two methods were used to calculate initial modulus values for these specimens. First, the simple average of the diametral modulus of the unconditioned cores taken from the OSU wheel tracker slab was used. Second, a relation for diametral modulus values for the unconditioned roller-compacted slab cores and air voids was developed using simple linear regression, and the air void level of the rutted core was used to calculate a corresponding initial modulus. Since the rutted cores typically have lower air void levels than the unconditioned companion cores, using either method is prone to error, as it is an extrapolation outside the range of the initial air void data. Additionally, the unconditioned cores do not have a large enough range in air voids to create a good correlation between diametral modulus and air voids.

Cores from several of the mixtures show very high mean modulus ratios. This is believed to be attributable to the configuration of the test beam in the OSU wheel tracker. The beam is confined in such a way as to produce an area of higher density under the wheel path. This densification of the mixture tends to increase the modulus of the mixture, obscuring any reduction in modulus the specimen may have undergone because of water damage to the mixture.

Elf Wheel Tracker Results

Using the rut depth at 5,000 wheel passes, as with the OSU wheel tracking data, the mixtures tested by Elf have performed as shown in table 4.17. It is interesting to note that in all cases in which specimens of the same mixture were tested at two different temperatures, 40°C and 50°C (104°F and 122°F), the specimen tested at the higher temperature experienced higher rut depths, as expected.

Also, according to the Elf criteria, the WIAELF02 specimen did not experience stripping; however, it reached 18 mm of rutting in 3,000 wheel passes. This behavior is similar to that of the mixture in ECS, in which it experienced excessive deformation under repeated loading during the "hot" conditioning cycle.

Table 4.13. Ranking of mixtures for the OSU wheel tracking test procedure[1]

Ranking	200 Passes			5,000 Passes			10,000 Passes		
	Mix	T Grouping[2]	Mean	Mix	T Grouping	Mean	Mix	T Grouping	Mean
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	B, C, D	-4.525	OR1	B, C	-6.692
5	AZ5	A	-0.708	OR1	B, C, D	-4.775	AZ5	C, D	-7.283
6	CAD	A, B	-1.217	AZ5	C, D	-5.383	WIA	D, E	-8.158
7	AB5	A, B	-1.300	AB5	D, E	-6.500	AB5	E	-8.783
8	MS5	A, B	-1.333	MS5	E	-8.108	OR2	F	-10.642
9	CAG	B, C	-2.549	OR2	E	-8.400	MS5	F	-11.092
10	OR2	C	-2.692	CAG	F	-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 that are not significantly different.

Table 4.14. GLM analysis of OSU wheel tracker data

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

Passes = 200

Model: R^2 = 0.87, CV = -45.09%, and the mean rut depth = -1.324

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	10	10.02143661	2.81	0.0676
AVOID	1	1.83446358	5.15	0.0494

Passes = 5,000

Model: R^2 = 0.98, CV = -16.03%, and the mean rut depth = -6.616

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	10	382.0277075	37.73	0.0001
AVOID	1	6.44399000	5.735	0.0436

Passes = 10,000

Model: R^2 = 0.99, CV = -7.24%, and the mean rut depth = -7.137

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of F > F_0
MIX	10	124.3197927	58.20	0.0001
AVOID	1	0.1259595	0.47	0.5143

Table 4.15. 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

Table 4.16. Mean MTS diametral modulus ratios for rutted beam cores

Mixture	Ratio Based on Mean Initial Core Modulus	Ratio Based on Regressed Initial Core Modulus
AB5	0.93	0.80
AZ5	0.89	0.70
CAD	0.47	0.97
CAG	1.43	1.11
GAA	1.02	1.32
MN5	1.88	1.32
MS5	0.86	0.91
OR1	0.76	0.73
OR2	0.66	0.62
WA1	0.83	0.74
WIA	0.88	2.00

Table 4.17. Performance of mixtures in the Elf wheel tracking test

Rank	Specimen	Rut Depth 5,000 Wheel Passes (mm)
1	AZ5ELF01[1]	1.3
2	OR2ELF01	1.4
3	OR1ELF01	2.0
4	OR2ELF02[1]	2.2
5	WIAELF01	3.0
6	AZ5ELF02[1]	4.0
7	OR1ELF02[1]	3.9
8	AB5ELF01[1]	18.2
9	WIAELF02[1]	> 18.0

[1] Specimens tested at 50°C (122°F).

Field Data

Weather Data

Tables 4.18 and 4.19 indicate the variation from the 30-year normals of the precipitation and temperature data for 1991. The 30-year normals perhaps better indicate the climate conditions to be expected over the life of the pavement, rather than any one year of data, because extremes in temperature and precipitation will be averaged from the 30-year data.

It should be kept in mind that even though these sites nominally come from only four environmental zones, the differences in the climate conditions can still be quite significant. For the five sites designated as dry, the 30-year average annual normal precipitation varied from 2.71 in. to 22.35 in. (68.8 mm to 567.7 mm). For the six sites designated as wet, the 30-year average annual normal precipitation varied from 8.57 in. to 58.09 in. (217.7 mm to 1475.5 mm). Variation of precipitation in a given calendar year may be even greater.

Temperature data show similar variation in freeze and no-freeze zones. For sites with freeze designations, the 30-year average monthly normal temperature varies with lows from 2.3°F to 32.1°F (-16.5°C to 0.1°C) and highs from 58.6°F to 70.8°F (14.8°C to 21.6°C). For no-freeze sites, the lows vary from 34.9°F to 54.4°F (1.6 to 12.4°C) and the highs from 67.8°F to 91.3°F (19.9°C to 32.9°C).

It is evident that mixtures in the field are subject to a variety of temperature and water conditions.

Traffic Data

The traffic data obtained for the test sections used in this program were presented in table 3.9. The average daily traffic ranged from a low of approximately 190 to a high of 12,300. The percentage of trucks on these pavements ranged from 10 percent to 25 percent. It is evident that traffic volumes varied substantially among test sections.

Field Core Data

Figures 3.29 through 3.50 indicate that for several of the mixtures, the modulus values measured for the field cores were equal to or greater than the modulus values for new, unconditioned, laboratory-fabricated specimens. For 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 taken has not experienced any decrease in mixture stiffness that would be the result of water damage. However, long-term aging may be causing an increase in stiffness in field mixtures, and the mixtures as constructed in the field may have varied substantially in stiffness from the corresponding laboratory-fabricated specimens.

Table 4.18. Deviation of 1990 from 30-year normal, monthly precipitation[1]

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
AB5[2]	-0.93	+0.24	+0.01	+2.22	-1.84	-0.66	-1.11	+0.30	-0.66	+2.44	-0.44	+0.08	-0.33
AZ5	+0.44	+0.03	-0.69	-0.23	+0.07	-0.03	+0.52	+2.23	+1.00	--[3]	--[3]	-0.57	+1.24
CAB	-2.15	-1.72	-1.43	-0.13	-0.39	-0.76	+1.25	-0.35	-0.13	-1.14	-2.38	-1.86	-11.19
CAD	-2.15	-1.72	-1.43	-0.13	-0.39	-0.76	+1.25	-0.35	-0.13	-1.14	-2.38	-1.86	-11.19
CAG	-0.19	-0.27	-0.21	-0.03	-0.02	+0.07	+0.16	+0.54	+0.22	-0.32	-0.27	-0.42	-0.74
GAA	+2.67	+4.38	+3.68	-1.71	-0.69	-2.72	-2.10	+0.21	+3.51	-2.65	+2.78	2.78	+10.08
MN5	-0.28	+0.10	+0.44	-0.39	-2.32	+0.94	-1.83	-2.38	-1.55	-0.86	-0.60	--[3]	-7.71
MS5	+4.41	+1.05	-0.62	-0.96	+1.25	+0.29	-2.67	-2.07	+0.03	-1.78	-1.09	+6.49	+5.25
OR1	+6.95 +4.46	+2.41 +1.35	-3.58 -2.04	-0.04 -0.53	-0.65 +0.71	+0.70 -0.21	-0.10 -0.26	+0.43 -0.47	-1.98 -1.63	+3.31 +4.53	+0.04 -0.72	-4.67 -3.94	+2.82 +1.18
OR2	+0.34	-0.60	+0.26	-0.15	+0.37	-0.65	--[3]	--[3]	--[3]	--[3]	-0.68	-0.75	-3.81
WA1[4]													
WIA	+0.29	-0.34	+1.09	+0.05	+1.38	+4.76	-1.66	+0.24	-1.45	+0.11	-0.44	+0.76	+4.79

[1] Values of precipitation in inches.

[2] 1991 data.

[3] Data missing from official weather information source document.

[4] 30-year normal data unavailable for this site.

Table 4.19. Deviation of 1990 from 30-year normal, monthly temperature[1]

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
AB5[2]	-0.9	+14.9	-2.7	+2.9	+13.5	-0.9	-0.3	+3.9	+2.5	-4.2	0.0	+6.9
AZ5	-0.3	-2.8	+2.2	+3.6	+0.1	+3.7	-0.8	-2.4	+1.4	--[3]	--[3]	-2.1
CAB	+1.6	-8.9	+2.4	+5.5	-1.6	-1.0	+0.8	-0.6	+2.1	+2.3	-2.0	-11.7
CAD	+1.6	-8.9	+2.4	+5.5	-1.6	-1.0	+0.8	-0.6	+2.1	+2.3	-2.0	-11.7
CAG	+0.4	-1.2	+2.8	+3.8	+0.1	+2.9	+1.0	-1.5	+1.9	+1.6	+1.1	-2.0
GAA	+8.4	+8.7	+5.1	-0.8	+1.0	+1.3	+0.3	+1.5	+1.1	+2.2	+2.2	+6.0
MN5	+13.7	+2.1	+3.1	-0.9	-2.5	--[3]	--[3]	--[3]	--[3]	--[3]	--[3]	--[3]
MS5	+7.0	+8.1	+1.9	-1.4	-1.2	+1.9	-0.6	+0.5	+2.2	-1.9	+2.4	+2.7
OR1	+3.8 +3.9	-3.0 -1.7	+2.6 +3.6	+3.3 +4.9	+0.1 -0.1	+0.5 +1.5	+3.3 +4.2	+2.4 +3.3	+2.9 +5.3	+2.1 -0.9	+1.3 +1.2	-5.7 -5.5
OR2	+4.9	-1.1	+2.7	+7.0	-0.6	-0.3	--[3]	--[3]	--[3]	--[3]	+2.6	-5.7
WA1[4]												
WIA	+13.5	+5.5	+5.3	+2.9	-3.6	+1.0	-0.1	+1.3	+4.0	-1.8	+5.4	-0.2

[1] Temperatures in °F.

[2] 1991 data.

[3] Data missing from official weather information source document.

[4] 30-year normal data unavailable for this site.

The general performance indicator for field cores was a ratio of the MTS diametral modulus of the field core 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.

For field cores nominally 4 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 ECS. An initial unconditioned MTS triaxial modulus value for the unconditioned field cores was calculated in the same manner as for the unconditioned MTS diametral modulus.

The GLM ranking for the field specimens on the basis of retained MTS diametral modulus ratios is presented in table 4.20. The model again had only MIX as an independent variable. As of 1992, only one field site had 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.

Some of the field mixtures have diametral modulus ratios of >1 (WIA AZ5, MS5, and WA1). This may indicate that the mixture has undergone some degree of long-term aging in the field since its placement. Long-term aging tends to increase the modulus of asphalt mixtures.

Comparison of Test Results

Table 4.21 indicates the performance ranking orders given for the mixtures tested in the three procedures. For ECS, this ranking is based on the final ECS modulus ratio using all 12 mixtures, regardless of environmental zone. This listing would correspond to the rankings given by the OSU wheel tracker, which uses both freeze and no-freeze conditioning, and to the field, which may present either a freeze or no-freeze environment.

ECS and Field Results

A comparison was made of the performance of the mixtures in the ECS test procedure with their performance under field conditions. Field cores tall enough to allow for MTS triaxial modulus testing were directly compared with ECS specimens by using the laboratory specimen MTS triaxial data to correspond with ECS data 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 placed in layers that did not produce 4-in. (101.6 mm) cores, the correlation between the performance of the field mixtures, as measured by a diametral modulus ratio, and the performance in ECS, as measured by the ECS modulus ratio, was investigated.

Table 4.20. Ranking of mixtures for field cores, based on MTS diametral modulus ratios

Ranking	Mixture	Mean Modulus Ratio	T Grouping[1]
1	WIA	1.192	A
2	AZ5	1.089	B
3	MS5	1.087	B
4	WA1	1.072	B
5	CAG[2]	0.848	C
6	MN5	0.821	C
7	OR1	0.716	D
8	CAB	0.715	D, E
9	CAD	0.680	D, E
10	GAA	0.667	D, E
11	OR2	0.642	E, F
12	AB5	0.573	F

[1] Groupings with the same letter designation include means that are not significantly different.
[2] First set of CAG cores.

Table 4.21. Comparison of ranking of mixtures 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	B
3	WA1	A	CAD	A, B, C	MS5	B
4	OR1	A, B	WIA	B, C, D	WA1	B
5	WIA	B, C	OR1	B, C, D	CAG	C
6	AB5	B, C	AZ5	C, D	MN5	C
7	AZ5	C, D	AB5	D, E	OR1	D
8	MS5	D, E	MS5	E	CAB	D, E
9	CAB	E, F	OR2	E	CAD	D, E
10	MN5	E, F	CAG	F	GAA	D, E
11	CAD	F, G	MN5	Failed	OR2	E, F
12	CAG	G			AB5	F

[1] Groupings with the same letter designation include means that are not significantly different.

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

Table 4.22 shows the results of this comparison. The significant variable according to the probability of $F > F_0$ is TEST. Table 4.23 indicates the values of the mean modulus ratio and standard deviation for each mixture for each test procedure. For five of the six mixtures, ECS gives a lower modulus ratio, indicating that the specimens had been more severely damaged than the field core. For the sixth mixture, ECS and field mean, MTS triaxial modulus ratios are within one standard deviation of each other.

A comparison of the performance of the mixtures in the ECS and in the field can also be seen in figure 4.7. 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 dimetral modulus ratios obtained from the field cores for 8 of the 12 mixtures tested. This indicates that 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 rutting and reflective cracking, and is due to be overlaid. This distress developed over the 1991-1992 winter season, after the field cores had been taken in the summer of 1991. At that time, 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), ECS predicts no high loss in stiffness caused by water damage and, to date, the field specimens reflect this behavior.

As mentioned above, when comparing results of the ECS testing with modulus ratios developed for the field cores, consider the potential for the mixtures in the field to experience long-term aging. The mixtures tested in ECS are subjected to only short-term aging of the loose mixture. In the field, mixtures are experiencing long-term aging, which tends to increase the modulus of the mixture. In the early life of the pavement, before water damage has developed fully, the increase in stiffness caused by aging may overwhelm any decrease in stiffness that is beginning to occur because of water damage. The data from CAG may illustrate this point. In figure 4.7, 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 over the initial year of pavement life.

Figure 4.8 shows the relationship between the visual stripping shown in field cores and that observed in ECS specimens. Typically, specimens from the same mixture appeared very similar for the field cores and the ECS specimens. However, two differences were noted: (1) asphalt in the field cores appeared a much duller, flat black color, while that 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 aging of the asphalt in the field. The lack of migration of asphalt binder in field specimens may be due to their relatively short lifetime in the field.

Table 4.22. GLM analysis of ECS and field core data by test method

Variable	Type	Levels	Values
MIX	Class	6	AB5, AZ5, CAB, CAD, GAA, MN5
TEST	Class	2	ECS, FLD

Model: $R^2 = 0.3139$, CV = 49.57%, and the modulus ratio mean = 0.972

Source of Error	Degree of Freedom	Type III Sum of Squares	F Values	Probability of $F > F_0$
MIX	5	1.27943922	1.10	0.3652
TEST	1	4.51212952	19.43	0.0001
MIX*TEST	5	2.19456568	1.89	0.1039

Table 4.23. GLM 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	0.778	0.136	0.768	0.102
AZ5	0.720	0.041	1.205	0.644
CAB	0.554	0.191	1.043	0.557
CAD	0.457	0.155	1.055	0.713
GAA	0.937	0.158	1.099	0.453
MN5	0.541	0.117	1.533	0.581

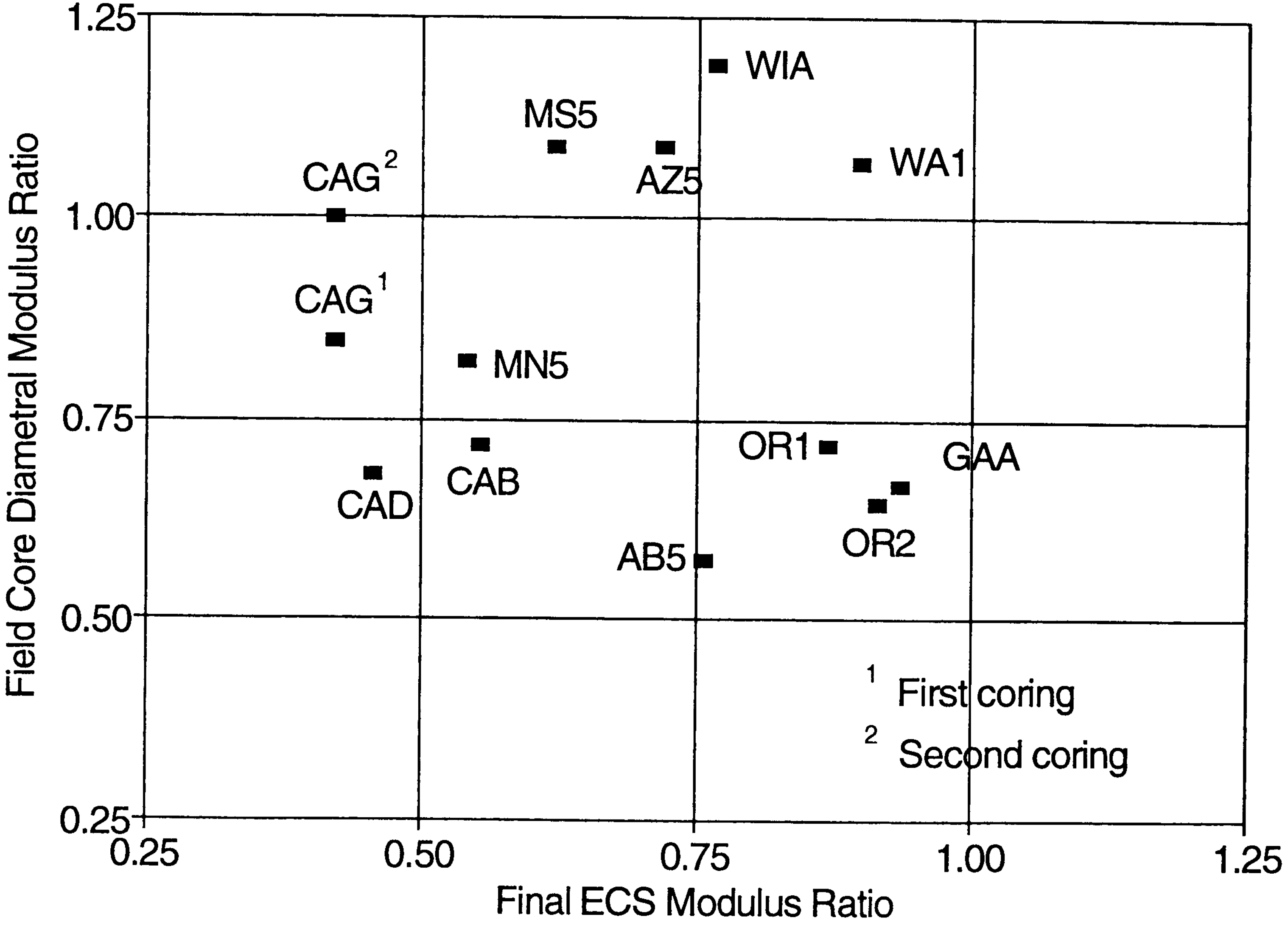


Figure 4.7. Comparison of ECS and field performance

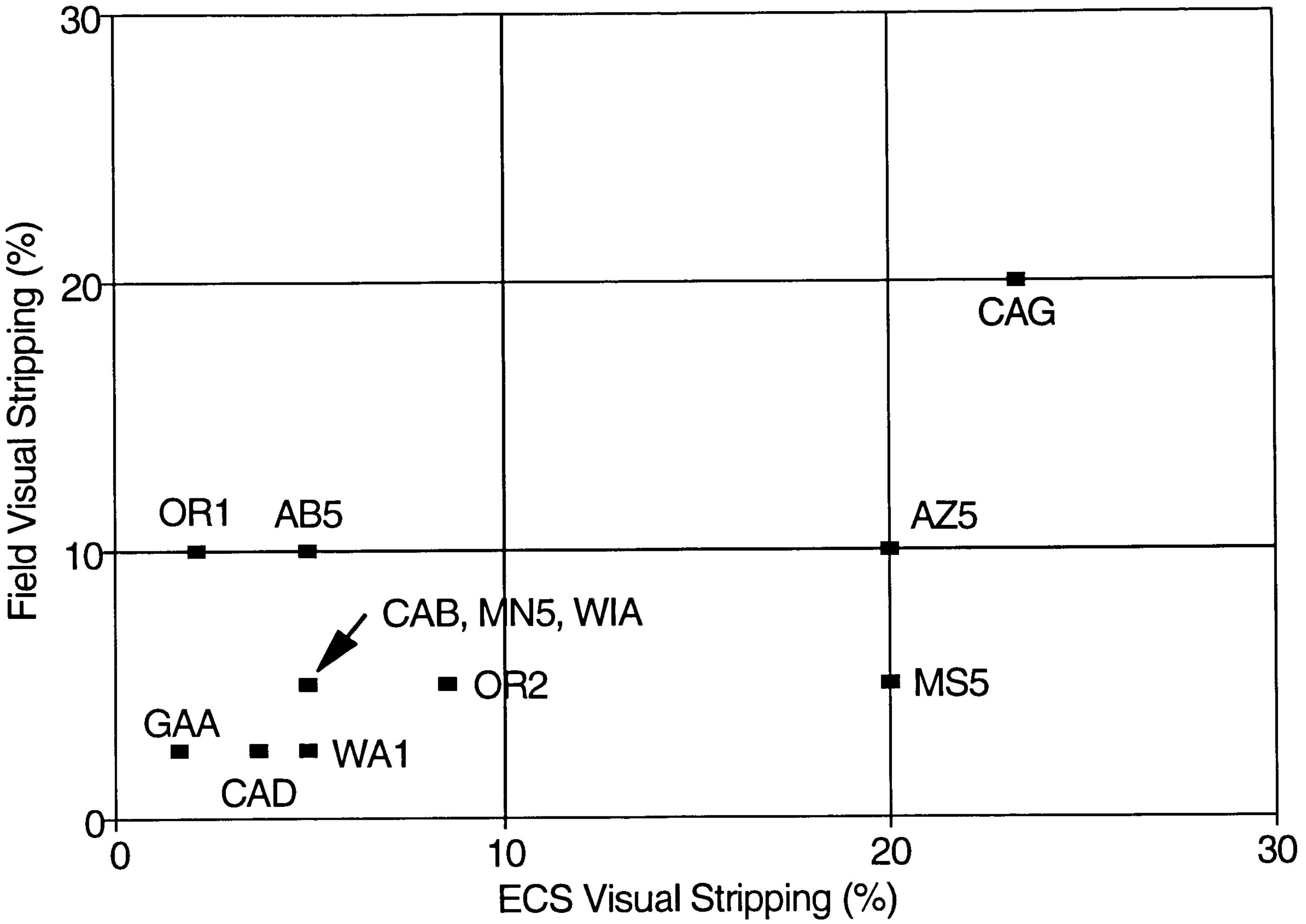


Figure 4.8. Visual stripping, comparison of field and ECS specimens

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

ECS and OSU Wheel Tracker

Figure 4.9 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 4.15. If the data points are removed, for MN5, on the basis of its high air voids, and for OR2, since it is an open-graded mixture, figure 4.10 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 4.10. 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 analogous preparation and water and temperature conditioning. Specimens from the field do not undergo such well-defined or uniform treatment as is evidenced by the weather and traffic data presented previously. 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.

ECS and Elf Wheel Tracker

Figure 4.11 shows the relation between the final ECS modulus ratio and both the OSU wheel tracker and Elf wheel tracker data. The Elf data are similar to those from the OSU wheel tracker and include only those specimens tested at 40°C (109°F). Variation can be attributed to different mixing and saturation techniques.

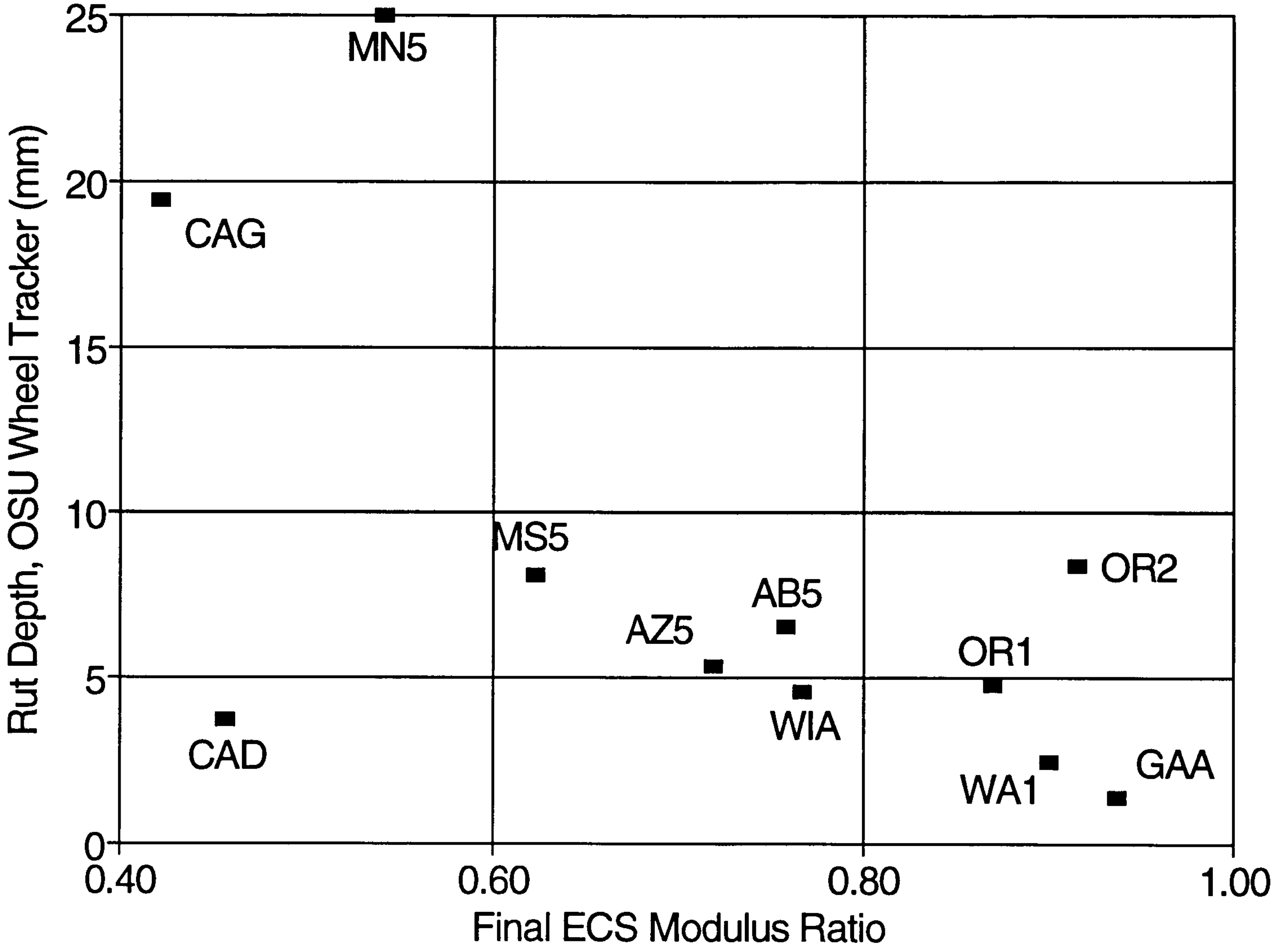


Figure 4.9. Comparison of ECS and OSU wheel tracker performance

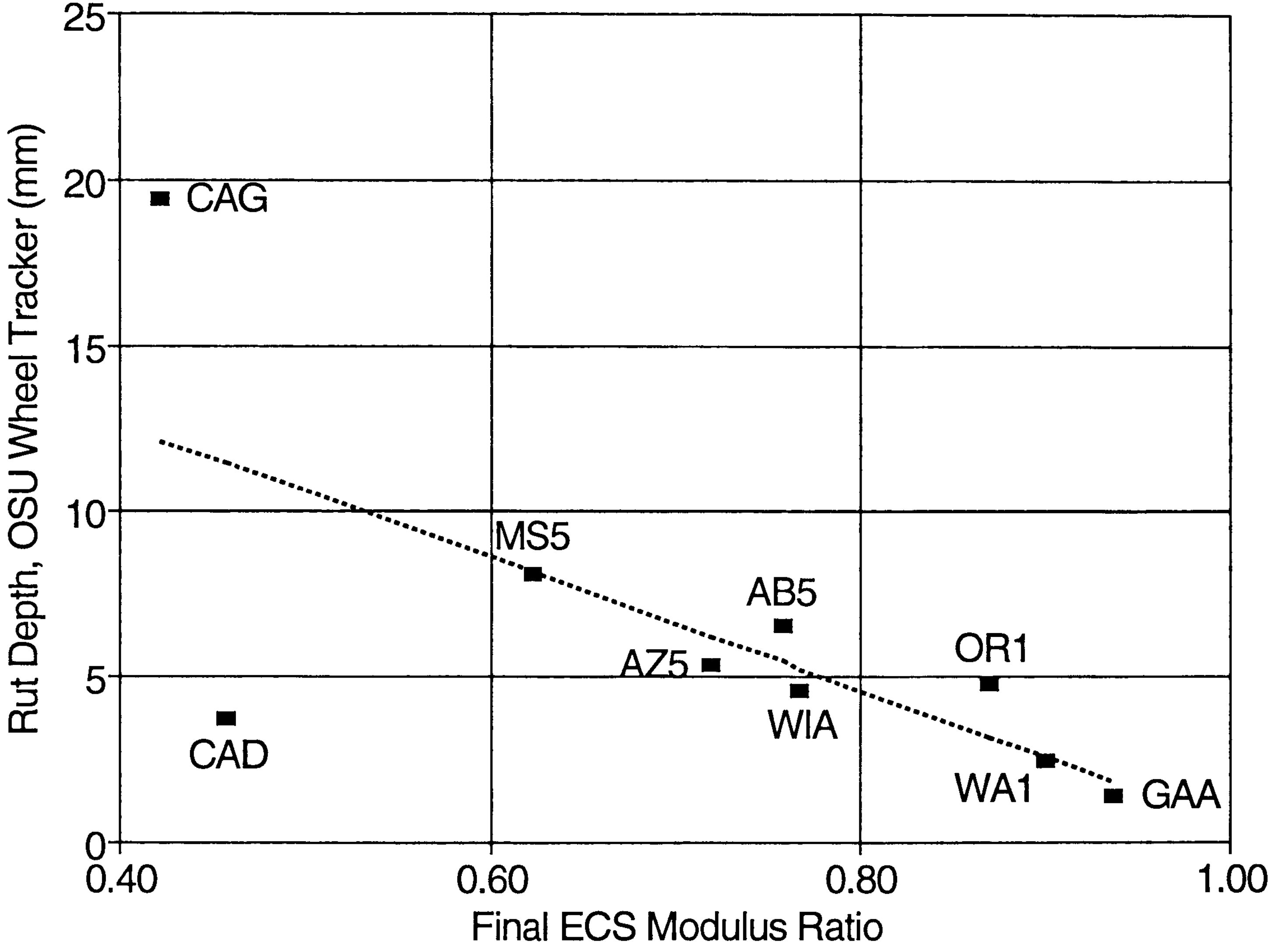


Figure 4.10. Comparison of ECS and OSU wheel tracker performance, MN5 and OR2 removed

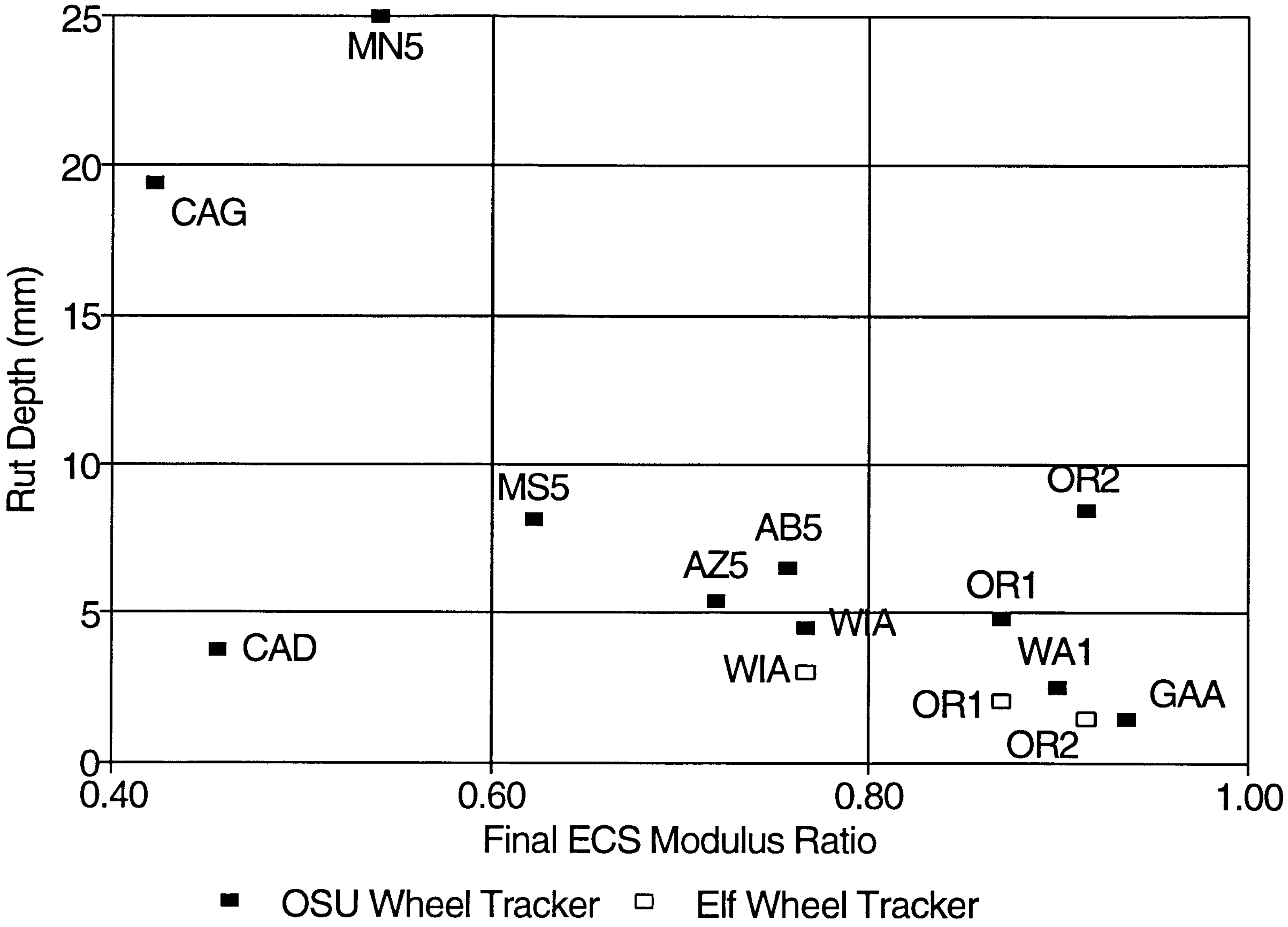


Figure 4.11. Wheel tracker performance versus ECS performance

Significance of Findings

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

ECS results

1. 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).

2. Some mixtures may experience an increase in modulus ratio after the fourth, or freeze, cycle.

3. 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.

4. Of the variables considered (mixture type [MIX], air voids [AVOID], initial modulus [INTM], air permeability [APERM] and water permeability [WPERM]), the first three have the strongest influence on the final ECS modulus ratio of the mixture.

5. There is no statistical difference between the results from mixtures that were subjected to the freezing cycle and those subjected to only three hot conditioning cycles. This indicates that neither procedure — three cycles with no freeze, or four cycles including 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.

OSU wheel tracker results

1. The air void levels between the beam specimens and the corresponding laboratory kneading compactor specimens vary for some mixtures and may result in high rut values (MN5) that are not indicative of the expected performance of the mixture.

2. Anomalous results indicate that several of the mixtures should be retested in this apparatus (CAD, CAG, and MN5).

Elf wheel tracker results

1. The specimens tested at a higher temperature tend to show increased rutting.

Field data

1. Weather data taken from a single observation year may not represent the normal environmental conditions that a pavement will be subjected to throughout its life.

2. Within a given environmental zone, temperature and precipitation values may vary significantly.

3. Traffic volumes will vary substantially, as they did among field projects.

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

Comparison of test procedures

1. ECS and field cores For mixtures with 4-in.-high (101.6 mm) cores, a comparison of triaxial modulus ratios indicates that 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, ECS predicts more damage than has been experienced by the field cores for 8 of the 12 mixtures tested. ECS is predicting damage that has not yet occurred because of the relative youth of the field sections.

3. ECS and field cores The mixtures in the field may 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 that is 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 performance of a mixture in ECS and in the field.

5. ECS and OSU wheel tracker A strong correlation between the performance of mixtures in ECS and the OSU wheel tracker is evident.

6. OSU wheel tracker and Elf wheel tracker Data from the Elf wheel tracker is similar to that of the OSU wheel tracker for those mixtures tested at 40°C (104°F). The relationship between the ECS and Elf data is also very good.

5

Guidelines for Specifications

It is the goal of the A-003A SHRP task to incorporate the findings of the Environmental Conditioning System (ECS) study into usable specifications for one or more levels of mix design procedures. The ECS procedure will investigate the susceptibility asphalt mixtures to water sensitivity and determine if a mixture can be expected to perform well with regard to water damage or if 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, secondary routes; and **level 3**, primary state routes, high-speed and high-volume roads.

Mixture Properties

As designed in the laboratory, mixtures selected in the preliminary volumetric mix design will be subjected to short-term oven aging before compaction into specimens for 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 percent ± 1 percent for levels 1, 2, and 3, and additional specimens at 10 percent ± 1 percent for levels 2 and 3. These air void levels were chosen in accordance with the pessimum voids theory proposed by Terrel and Al-Swailmi (1992). Two specimens will be compacted at each level.

ECS Criteria

Two specimens of a given mixture and of equal air void levels, will be subjected to the ECS procedure using three or four cycles; the fourth, or freeze, cycle is optional for use in environments that 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 that performed well in the ECS, OSU wheel tracker, and the field from those that showed deterioration in the OSU wheel tracker or the field. This result is illustrated in figures 5.1 and 5.2.

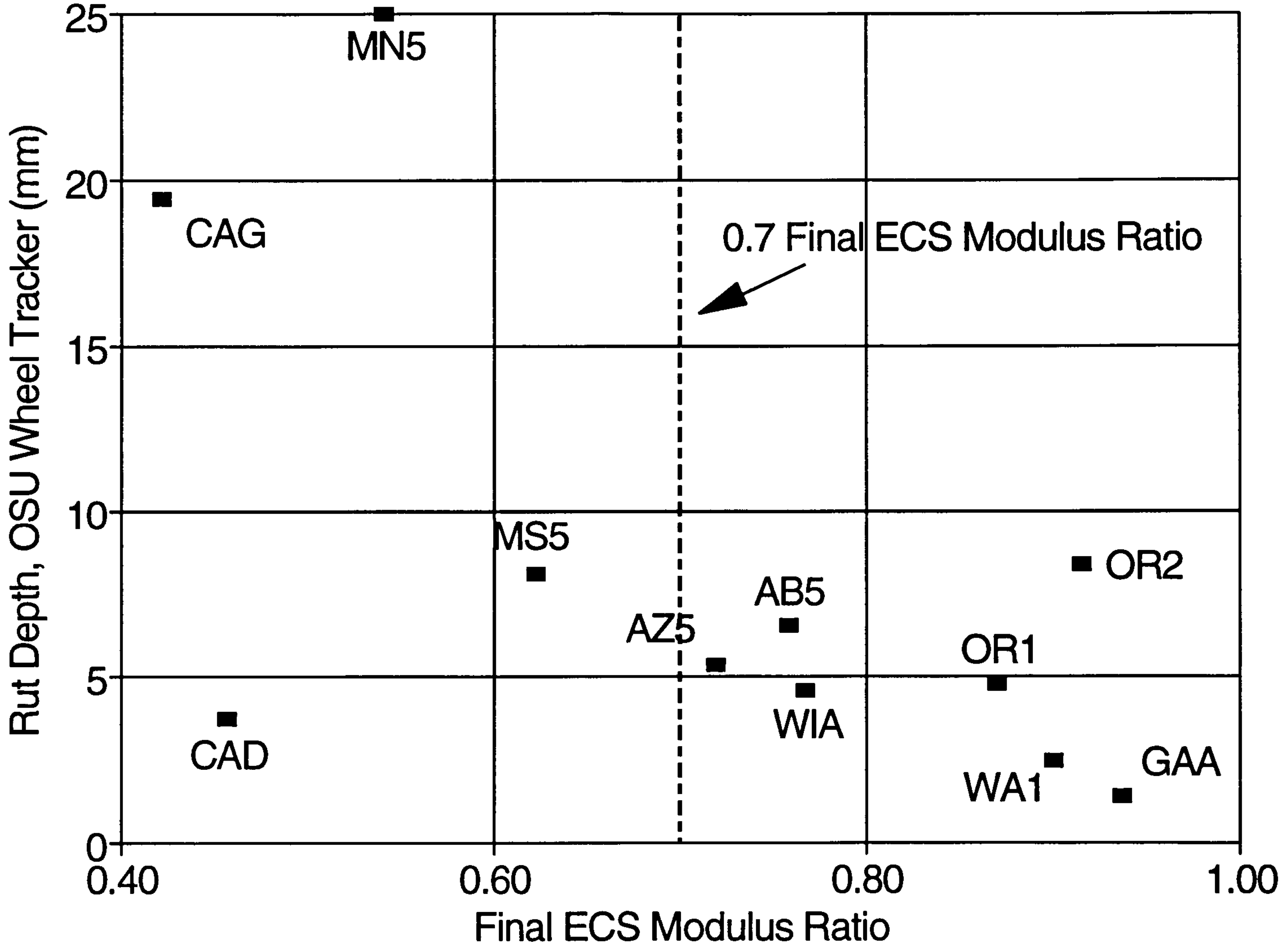


Figure 5.1. Criteria for the performance of mixtures, OSU wheel tracker versus ECS

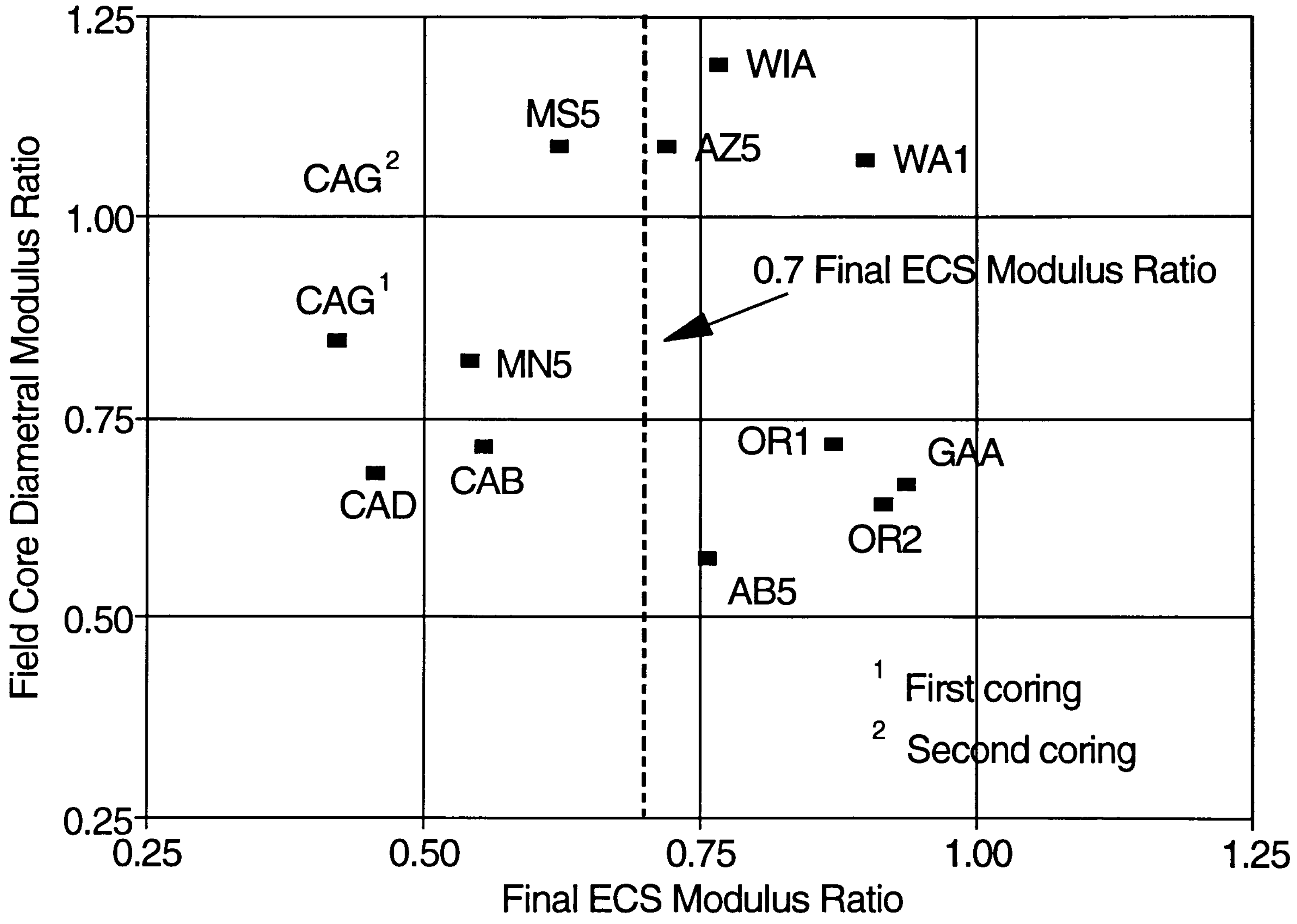


Figure 5.2. Criteria for the performance of mixtures, field versus ECS

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 cycle 1 and cycle 3 (as shown in figure 4.2) moved two of the mixtures tested, MN5 and MS5, from acceptable or questionable to unacceptable. The change in ECS modulus ratio between cycle 3 and cycle 4, as shown in figure 4.3, moved the mixture WIA from unacceptable to acceptable. Therefore, when setting criteria for performance of mixtures in ECS, the mixtures being evaluated should be subjected to the full ECS procedure appropriate for their environmental designation.

It is recommended that the following procedures be used:

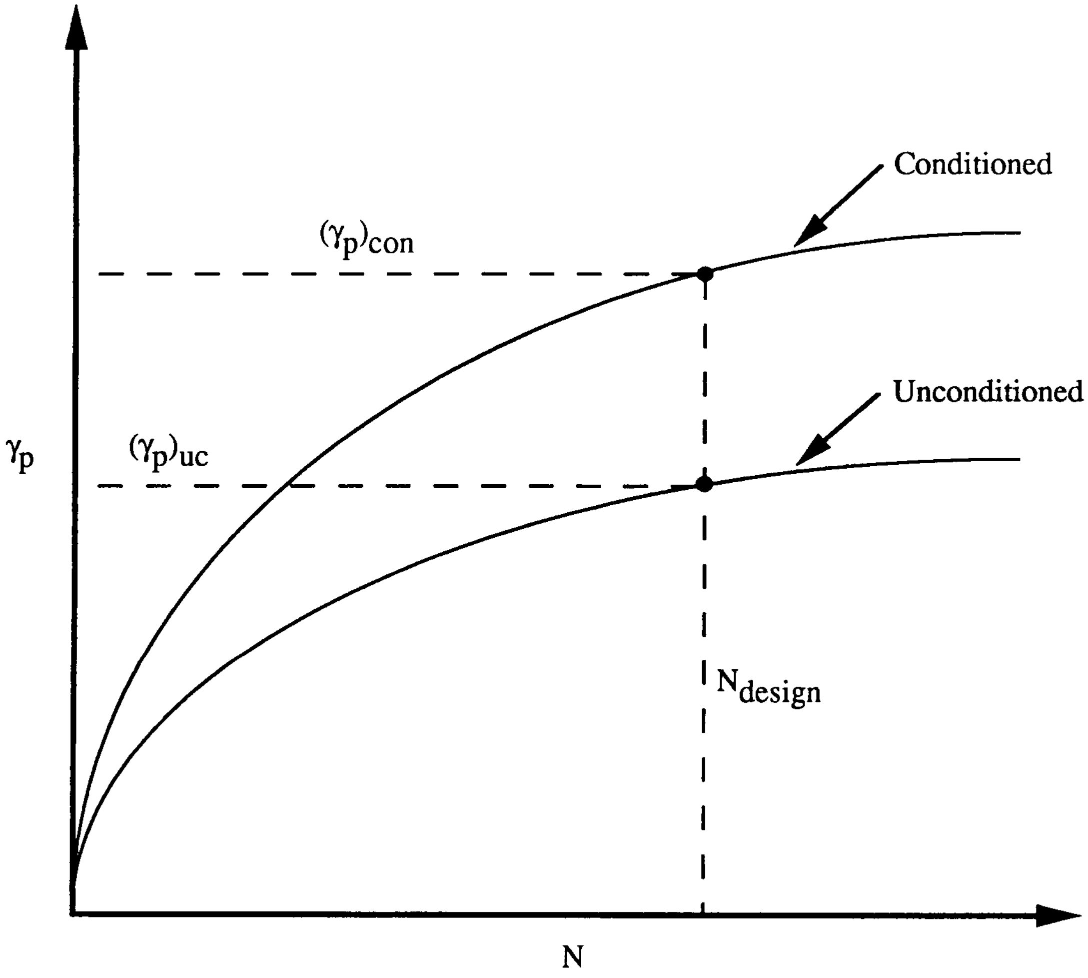
- **Level 1** If the final ECS modulus ratio is < 0.7, the mixture should be treated for moisture susceptibility, and the treated mixture retested in ECS. If the final ECS modulus ratio is < 0.8, the slope of the curve, between cycles 1 and 3, should be investigated. For mixtures with flat slopes, the mixture is expected to perform well and no treatment is recommended. For mixtures with steeper slopes, treatment of the mixture for moisture sensitivity should be considered because these mixtures may experience significant water damage, only at a slower rate than those with final ECS modulus ratios of <0.7.

- **Level 2** For mixture specimens with air void contents of 7 percent ± 1 percent, the criterion is the same as in level 1. For the specimens with air void content of 10 percent ± 1 percent, the mixture should be treated for moisture susceptibility if the final ECS modulus ratio is < 0.6. Again, the slope of the curve between cycle 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. Simple shear tests will be performed on both conditioned and unconditioned ECS test specimens, with a requirement for acceptability of the mixture as shown in figure 5.3. If the mixture does not meet the simple shear criteria, it will be redesigned to improve its performance.

Expected Benefits

Evaluation of 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 effort has failed in the field. This mixture had a final ECS modulus ratio of 0.62 and a slope of -0.0337. Treatment of mixtures that show tendencies for water damage over a longer life, as evidenced by steep modulus ratio curves between the first and third cycles, may also be advisable to extend pavement life even further.



@ N_{design}: $(\gamma_p)_{con}/(\gamma_p)_{uc} \leq 2\text{-}3$

Figure 5.3. Simple shear criteria

6

Conclusions and Recommendations

The work performed during field validation of the Environmental Conditiong System (ECS) test procedure can be considered as an initial database for correlating the performance of mixtures in field, in ECS, and in the OSU wheel tracker. The limited amount of materials available, and length of time that pavements have been in the field indicate that additional time and testing will only better define the role of ECS in modern mix design.

Conclusions

The following conclusions can be drawn from the data collected in the field validation of the ECS test procedure:

1. ECS can discriminate among mixtures that will perform well and those that will perform poorly with regard to water sensitivity of the asphalt mixture.

2. ECS modulus ratio allows for separation of mixtures into performance categories. Typically, mixtures that have final ECS modulus ratios of >0.7 will perform well in the field. Those with lower final ECS ratios should be considered for redesign or treatment with admixtures.

3. The slope of the modulus ratio curve between cycle 1 and cycle 3 is an indicator of the rate of water damage occurring to the specimen. Specimens that have acceptable ECS modulus ratios after three cycles may have slopes that indicate potential water susceptibility problems in the long term.

4. Significant change in the modulus ratio occurs in some mixtures between cycle 1 and cycle 3, moving them from acceptable to unacceptable or questionable in terms of water sensitivity.

5. Of the variables considered (mixture type [MIX], air voids [AVOID], initial modulus [INTM], air permeability [APERM] and water permeability [WPERM]), mixture type, initial modulus and air voids have the strongest influence on the final ECS modulus ratio of the mixture.

6. The mixtures tested 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 migration of the asphalt binder in the specimen is extremely subjective.

8. For new pavements, the increase in resilient modulus as a result 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.

Recommendations

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

1. A strong correlation between ECS performance and number of years of expected field performance has not been made because of 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 data base for 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 mixtures tested in the SHRP A-003A program should have been replicated because of anomalous results from the OSU wheel tracker (CAD, MN5, and CAG). However, there was no opportunity to complete this work because of lack of original aggregates.

3. The procedure for evaluation of visual stripping of mixtures should be improved to remove as much subjectivity as possible. The use of optical scanners to determine the amount of stripping in a mixture is worth investigation.

4. ECS should be used to provide a systematic look at the effects in variations in volumetric mixture proportions, such as gradation and asphalt content, on the performance of mixtures.

5. Inclusion of the ECS equipment and procedure, per the specification guidelines in chapter 5, is recommended for any mix design system proposed.

7

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8

Appendices

Appendix A

Standard Practice for

Preparation of Test Specimens of Bituminous Mixtures by Means of the Elf Rolling Wheel Compactor

This document is the draft of a procedure being used by researchers at Elf Asphalt for preparing specimens for Oregon State University and 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 procedure is finalized. This version represents the state of the procedure as of* ***June 3, 1994****.*

The test procedure 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 preparation of specimens for the Hamburg Wheel Track Test by means of laboratory mixing and rolling wheel compaction.

2. APPLICABLE DOCUMENTS

3. APPARATUS

- **3.1** Linear compactor
- **3.2** Compressed air
- **3.3** Spacer plates for mixture height adjustment
- **3.4** Compactor plates
- **3.5** Mold
- **3.6** Long spatula
- **3.7** Mold release agent
- **3.8** Clovco
- **3.9** Fan
- **3.10** China marker
- **3.11** Aluminum foil
- **3.12** Cake pans
- **3.13** Oven
- **3.12** Electronic balance
- **3.15** Heat shield

4. MATERIAL PREPARATION

4.1 *Aggregate:*

4.1.1 Dry aggregates for 24 hours at 120°C (248°F), cool for 4 hours at 25°C (77°F).

4.1.2 Combine aggregates by the "cold feed" proportions into 12-kg (26.5-lb.) batches.

4.1.3 Fractionate the 12-kg (26.5-lb.) aggregate batches with the Gilson shaker, as follows:

Retained on the 1".
Passing the 1" and retained on the 3/4".
Passing the 3/4" and retained on the 1/2".
Passing the 1/2" and retained on the 3/8".
Passing the 3/8" and retained on the #4.
Passing the #4 and retained on the #8.
Passing the #8 and retained on the #30.
Passing the #30 and retained on the pan.

4.1.4 Accumulate each size in individual containers.

4.1.5 Recombine the aggregates according to the job mix formula. Approximately 10 percent more material than is required by the slab should be mixed. The equation for determining the weight of material for the slab is as follows:

$$Wt = G_{mb} * 832 * t \tag{A.1}$$

where *Wt* = slab wt in g
832 = slab area in cm^2 (129 $in.^2$)
t = slab thickness, normally 3.81 cm to 5.08 cm (1.5 in. to 2.0 in.)

4.2 *Mixing temperature* - Select the mixing temperature according to the bitumen used

Conventional asphalt cements:	temp @ 170 cS
Polymer-modified asphalt cements:	temp @ 350 cS

4.3 *Mixing:*

4.3.1 Heat the recombined aggregate in an oven set 20°C (68°F) higher than the mixing temperature for 4 hours.

4.3.2 Add the bitumen to the heated, recombined aggregates, and mix for 2 minutes at the target temperature ± 5°C (41°F).

4.3.3 Load the mix in a covered metal beaker and place the beaker in an oven set 10°C (50°F) higher than the compaction temperature.

Conventional asphalt cements:	temp @ 280 cS
Polymer-modified asphalt cements:	temp @ 1000 cS

4.3.4 Allow the covered mix to cure in the oven for 4 hours.

4.4 *Compaction:*

4.4.1 Calculate the weight needed for a slab. Use the following formulas:

$$Weight,\ g = Volume,\ cm^3 * Density,\ g/cm^3 \tag{A.2}$$

where *density* = A * h
A = area of slab = 832 cm^2
h = desired height, cm

Normally, two slab heights are used:
1.5 inch = 3.81 cm.
2.0 inch = 5.08 cm.
If the desired density is in pcf, divide by 62.4 before making the weight calculation.

4.4.2 Batch out the amount of mixture needed, based on the weight calculated above, into a cake pan. This mixture is obtained from a sample from the field for evaluation purposes. The mixture can also be obtained from laboratory-mixed specimens for design purposes.

4.4.3 Cover the batched mixture with aluminum foil and place in an oven until the mixture comes to compaction temperature. Place spacer plates in oven.

4.4.4 While the mixture is warming up, prepare the machine for compaction.

4.4.4.1 Place two halves of the mold together and tighten using the knobs.

4.4.4.2 Line the mold on the moving base plate of the machine. This involves positioning the center of the length of the old perpendicular to and in the center of the axis of the steel wheel.

4.4.4.3 Lock the mold in place using the mold lock levers. The mold must be locked tightly to avoid slipping during compaction.

4.4.5 Spray the sides of the mold and bottom of the compactor plates with mold release agent (a lecithin compound). Immediately before compaction, spray the side of the spacer plate in which the mixture will be placed.

4.4.6 Place the spacer plate (sprayed side up) in the mold.

4.4.7 After the mixture has reached compaction temperature, pull out the oven. Remove aluminum foil and carefully place all of the mixture in the mold.

4.4.8 Smooth the mixture in the mold with a long spatula. Rod the corners with the spatula. Build the corners up slightly.

4.4.9 Place the compactor plates on the mixtures, sprayed side down. Make certain the plates are vertical. This task is best accomplished by two people.

4.4.10 Lower the position the compactor arm and place the large pin into the top hole of the connector and through the positioning block of the height adjustment rod.

4.4.11 Turn the switch of the control box to the "on" position. Turn the air inlet valve on the wall to the "on" position. Turn the valve at the foot of the compactor to the "on" position.

4.4.12 Lower the arm with the height adjustment rod until the steel wheel just starts touching the compactor plates. Continue lowering the arm slowly until the plates are even with each other.

4.4.13 Lower the steel wheel with the height adjustment rod one-half turn for every four passes of the specimen (two round trips).

4.4.14 Continue lowering the wheel at this rate until the red lamp is illuminated. After the red light comes on, the adjustment rod will turn one-half turn to its stop block.

4.4.15 Allow 40 additional passes at the final roller wheel height.

4.4.16 Turn the machine's electric power off. Turn the compressed air supply off at the wall-mounted valve. Turn the air valve off at the foot of the machine.

4.4.17 Reverse the direction of the height adjustment rod to raise the steel wheel about 4 inches above the mold. Disconnect the pin that holds the arm to the height adjustment rod.

4.4.18 Manually raise the arm to the upright rest position.

4.4.19 Turn the power back on. Turn the air on at the foot of the machine to bleed the air. The gauge should read "0." Turn air off again. Turn power off.

4.4.20 Raise the mold lock levers and rotate the mold one-eighth circle. Loosen the knobs of the mold halves from the specimen.

4.4.21 Carefully remove the compactor plates from the top of the mixture. Place the plates on the table with the side originally on the mixture facing up.

4.4.22 If the slab is on the spacer plate, remove the compacted slab and spacer plate together. Place on a flat surface, spacer plate down.

4.4.23 Write sample designation on the slab with the china marker.

4.4.24 Carefully turn the slab/spacer plate over, slab side down. Carefully slide the large spatula between the slab and plate until the plate can be freely lifted from the slab. Allow the slab to cool overnight before further handling.

Appendix B

Standard Method of Test for

Hamburg Wheel Track Testing of Compacted Bituminous Mixtures

This document is the draft of a procedure being used by researchers at Elf Asphalt for preparing specimens for Oregon State University and 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 procedure is finalized. This version represents the state of the procedure as of* ***June 3, 1994****.*

The test procedure 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.*

This document is a description of a test method used at the Elf Asphalt Laboratory in Terre Haute, IN. This method is based on current test practices in northern Europe, and at the Elf Bitumen Deutschland Laboratory at Brunsüttel, Germany.

1. SCOPE

1.1 This method describes the testing of compacted bituminous mixtures in a reciprocating rolling wheel device. A special laboratory compactor has been designed to prepare slab specimens. Alternatively, field core samples of large diameter (25 cm) may be tested. This test provides information for the rate of permanent deformation from a moving, concentrated load.

1.2 Additionally, the potential for moisture damage effects is tested because the specimens are submerged in water during loading.

2. APPLICABLE DOCUMENTS

2.1 *Miscellaneous Test Methods:*

Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of the Elf Rolling Wheel Compactor

2.2 ASTM Test Methods:

D 2726 Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens.

3. SUMMARY OF METHOD

3.1 A laboratory-compacted slab of a bituminous mixture or a saw-cut field core sample is tested by a loaded, reciprocating steel wheel. The deformation of the wheel into the mixture is measured. The test temperature is typically 40°C or 50°C and is maintained by a water bath.

3.2 The depth of deformation is plotted as a function of the number of wheel passes. When stripping damage occurs during the test, an abrupt increase in the rate of deformation coincides with the emergence of clean aggregates from the specimen.

4. SIGNIFICANCE AND USE

4.1 This test simulates traffic loading, but with a more concentrated load than what normally occurs in the field. The concentrated loads are necessary to produce measurable deformations within a single day of testing.

4.2 This test has been widely used in northern Germany, and the city of Hamburg includes it for mixture specifications. The specification was developed from an empirical data base of wheel tracking test data and the field rut depth measurements. The specification of 4 mm maximum deformation at 20,000 wheel passes with a 50°C test temperature has been used to identify mixes that will resist permanent deformation and moisture damage with heavy industrial traffic in a maritime environment.

4.3 This test is also used as a research tool by laboratories in Canada, Finland, Norway, the United States, and Sweden. For research work, rankings of permanent deformation potential, moisture damage potential, and temperature susceptibility are possible with this device. Typical experimental factors are bitumen type, aggregate type, and additive amount and type.[1]

4.4 Because the testing of field core samples is possible, the data variations caused by differences between laboratory and field mixing and compaction practices are removed.

5. DEFINITIONS

5.1 *Postcompaction Consolidation* - The depth of impression that rapidly accumulates during the first 1,000 ± passes of the wheel. This deformation is due to the compactive effects of the loaded wheel.

5.2 *Creep Slope* - The inverse rate of deformation expressed in units of wheel passes per millimeter of deformation. This rate is calculated after postcompaction consolidation but before the onset of moisture damage. For example, a creep slope of 2,500 means the specimen is deforming at the rate of 1 mm every 2,500 passes.

5.3 *Stripping Inflection Point* - The number of wheel passes necessary to induce moisture damage to the specimen. After moisture damage begins, the rate of deformation increases rapidly. This number is related to the amount of mechanical energy required to initiate stripping distresses in the sample. The commencement of stripping damage is visually obvious in the test because of the emergence of uncoated aggregate particles, coinciding with an abrupt and sustained increase in the rate of deformation.

5.4 *Stripping Slope* - The inverse rate of deformation measured after the stripping inflection point. Like the creep slope, the stripping slope is expressed in units of passes per millimeter. The stripping slope is measured after the striping inflection point until the end of the test.

5.5 *Slab* - A rectangular compacted bituminous mixture sample intended for testing in the wheel tracking device. Slabs are produced by rolling wheel compactors such as the *compacteur de plaques* of the French Laboratoire Central des Ponts et Chaussées[2]

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[1] For more information, see Arand, Harders, and Herr, "Criteria and Methods for Field-related Evaluation of the Behavior of Asphalts Made with Conventional and Polymer Modified Bitumen at High and Low Temperatures."

[2] This compactor was evaluated along with several other methods in the SHRP A-005 contract.

(LCPC) and the Elf Asphalt Linear Kneading Compactor[3]. Rectangular saw-cut field specimens are also called slabs.

5.6 *Rut Depth* - Describes the impression made in the test specimen by the loaded wheel.

6. APPARATUS

6.1 *Wheel Tracking Machine*[4] - An electrically powered machine capable of moving an 8-in. (203.6-mm) diameter, 1.85-in. (47.0-mm) wide steel wheel over the test specimen. The load on the wheel is 697 N (156 lb.). The wheel will reciprocate over the specimen, with the speed varying sinusoidally. The wheel will make 50 passes over the specimen per minute. The maximum speed of the wheel will be 1.1 ft./sec., and will be reached at the midpoint of the specimen. This configuration results in a 0.1-sec. loading period and a 1.0-sec. relaxation period at the midpoint of the specimen.

6.2 *Temperature Control System* - A water bath capable of controlling the temperature within ± 0.5°C over a range of 25°C to 70°C. This bath shall have a mechanical circulating system to stabilize temperature within the specimen tank.

6.3 *Impression Measurement System* - A linear variable differential transducer device capable of measuring the depth of the impression of the wheel within 0.01 mm over a minimum range of 20 mm. The system shall be mounted to measure the depth of impression at the midpoint of the wheel's path on the specimen. The impression will be measured at least every 100 passes of the wheel. This system must be capable of measuring rut depth without stopping the wheel. This measurement must be referenced to the number of wheel passes.

6.4 *Wheel Pass Counter* - A noncontacting solenoid that counts each wheel pass over the specimen. The signal from this counter will be coupled to the wheel impression measurement, allowing for the rut depth to be expressed as a function of wheel passes.

6.5 *Specimen Mounting System* - A stainless steel tray that can be mounted rigidly to the machine. This mounting must restrict shifting of the specimen to within 0.005 mm during testing. The system will suspend the specimen, allowing for free circulation of the water bath on all sides. The specimen will be mounted with a minimum of 2 cm of free-circulating water on all sides.

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[3] See Bonnot 1988, p.15.

[4] This device is available commercially from Helmut Wind, GmbH, of Hamburg, Germany.

7. TEST SPECIMENS

7.1 *Laboratory-Compacted Slabs* - These will be 260 mm ± 2 mm wide and 320 mm ± 2 mm long. The thickness will be a minimum of twice the nominal maximum aggregate size. These specimens will be compacted on the Elf Asphalt Linear Kneading Compactor or the LCPC *compactuer de plaques*. Slabs thicknesses of 3.8 cm to 10 cm can be used. Typically, slab thickness is at least twice the maximum nominal aggregate size.

7.2 *Cored Field Samples* - These will consist of wet-cut cores taken from pavements. The cores will have a diameter of 24 cm ± 1 cm. The height of the specimen may be adjusted to fit the specimen mounting system by wet saw cutting.

7.3 *Density Measurement* - The bulk specific gravity of the specimen will be measured prior to mounting in the machine by test method ASTM D 2726.

8. SAMPLE PREPARATION

8.1 *Sample Curing* - After compacting the slabs, allow them to cool at normal room temperature for 16 hours. The surface for cooling will be clean and flat.

8.2 *Bulk Specific Gravity* - This will be determined using the ASTM D 2726 method. No modifications to this method are necessary for testing slabs.

8.3 *Plaster Mounting* - To rigidly mount the specimens in the mounting trays, use plaster of paris. The plaster will be mixed with water at a ratio of 60 percent plaster and 40 percent water, to allow for a firm set within 30 minutes. The plaster layer at the bottom of the specimens will not exceed 2 mm. The paster will fill in all sides of the specimen except for the top surface that will be exposed to the wheel.

8.4 *Specimen Mounting* - After the plaster has hardened, bolt the specimen tray to the wheel tracking machine. Introduce water into the machine.

9. TEST PROCEDURE

9.1 *Test Temperature Determination* - For bituminous mixes using binders of viscosity grades AC-10 or softer, or penetration grades of 120/150 or softer, a test temperature of 40°C is suggested. For all harder grades of binder, a test temperature of 50°C is used.

9.2 *Temperature Preconditioning* - Fill the specimen tank with potable water. If the available potable water is suspected to cause testing irregularities because of chemical contamination, fill the tank with distilled water. The heating system will raise the tank containing the specimen from ambient to the required temperature within one hour. After the temperature has stabilized, allow the specimen to condition for 30 minutes ± 5 minutes.

9.3 Lower the wheel onto the specimen, and set the deformation measurement system to begin recording.

9.4 Start the reciprocating motion of the loaded wheel. Count each pass of the wheel over the wheel of the specimen. Zero rut depth is defined after 10 wheel passes, to ensure that the deformation measurement system is properly operating.

9.5 Restart the counting of wheel passes from zero. Record the rut depth after at least every 100 passes. Note the number of passes at which stripped aggregate particles are ejected from the specimens into the water bath. The test is finished after 20,000 passes, or when a 20 mm rut depth is reached.

9.6 At the conclusion of the test, note the type of aggregates that stripped from the specimen and accumulated in the tank.

10. CALCULATIONS

10.1 Plot the rut depth versus the number of wheel passes.

10.2 The creep slope is the inverse of the rate of deformation in the linear region of the deformation curve, after postcompaction effects have ended, and before the onset of stripping. This region is located graphically. The value of the creep slope is the inverse of the coefficient of a linear regression equation, which was calculated from data points in the creep slope region of the deformation curve.

10.3 The postcompaction consolidation is the value of the intercept of creep slope linear regression line with the deformation axis.

10.4 The stripping slope is the inverse of the rate of deformation in the linear region of the deformation curve, after stripping begins and until the end of the test. This region is located graphically, and the value is calculated from the inverse of the coefficient of a linear regression equation from the point in the stripping slope region of the deformation curve.

10.5 The stripping inflection point is calculated from the intersection of the creep slope line and the stripping slope line. The number of passes to this intersection is related to the resistance of the mixture to moisture damage.

11. REPORT

The report will include the following parameters:

11.1 The bulk specific gravity of the test specimen.
11.2 The average temperature during the test to ± 0.5°C.
11.3 The value of the postcompaction consolidation to ± 0.1 mm.
11.4 The value of the creep slope in passes per millimeter., to ± 100 passes per millimeter.
11.5 The value of the number of passes to the stripping inflection point to ± 100 passes.
11.6 The value of the stripping slope in passes per millimeter.

12. PRECISION and BIAS

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

REFERENCES

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2. Button, J.W., Little, D.N., et al., "Correlation of Selected Laboratory Compaction methods with Field Compaction," Texas Transportation Institute, Texas A&M University, College State, Texas, May 1992.

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Appendix C

Table C.1. 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
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	4.77E-05	5	NO
									1	40.9	204.0	200.5	0.89	7.56E-05		
									2	40.8	204.5	200.0	0.89	7.94E-05		
									3	40.9	213.5	191.1	0.85	5.84E-05		
									4	40.0	219.0	183.9	0.82	4.68E-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	7.36E-06	5	NO
									1	44.0	239.5	183.8	0.90	4.37E-05		
									2	44.5	271.5	163.9	0.80	5.05E-05		
									3	44.4	269.0	164.9	0.81	5.18E-05		
									4	44.7	270.0	165.8	0.81	4.53E-05		
AB5KL01	02/23/92	5.40	5.98		164.0		195.0	A	0	34.9	135.5	257.5	1.00	2.07E-07	5	C
									1	38.1	216.5	176.5	0.69	3.59E-05		
									2	36.9	230.0	160.9	0.62	2.87E-05		
									3	37.3	236.5	158.4	0.62	1.70E-05		
									4	37.7	260.0	144.9	0.56	1.56E-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	1.31E-06		
									2	41.4	209.0	197.8	0.77	2.17E-06		
									3	41.3	228.0	181.0	0.71	2.77E-06		
									4	36.1	237.0	173.7	0.68	1.33E-06		
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			
									2	40.7	164.0	248.3	0.84			
									3	40.8	173.5	234.5	0.79			
									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	2.38E-06		
									2	39.5	155.0	254.1	0.96	2.24E-07		
									3	39.8	171.5	231.3	0.87	1.75E-07		
									4	41.5	178.0	232.9	0.88	1.75E-07		
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	1.99E-04	20	NO
									1	40.0	79.1	506.0	0.69	9.52E-05		
									2	39.5	77.1	514.0	0.70	4.58E-05		
									3	39.7	75.7	524.9	0.72	2.39E-05		
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	7.00E-05	20	NO
									1	42.3	79.4	532.7	0.72	1.66E-04		
									2	41.9	78.0	537.3	0.73	1.33E-04		
									3	42.6	77.5	550.3	0.75	5.52E-05		
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	3.81E-05	20	NO
									1	43.1	69.2	622.0	0.75	7.88E-05		
									2	42.8	68.4	626.4	0.75	1.12E-04		
									3	42.2	65.0	649.7	0.78	5.83E-05		
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	5.86E-06	20	NO
									1	36.8	49.1	757.3	0.70	5.08E-05		
									2	36.0	50.9	707.3	0.66	7.85E-05		
									3	37.8	48.8	775.8	0.72	3.87E-05		
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			
									2	40.5	53.0	763.4	0.68	1.35E-06		
									3	41.3	53.6	769.7	0.68			
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	4.79E-05		
									2	43.0	48.9	880.0	0.73	3.13E-05		
									3	42.9	53.1	807.8	0.67	5.77E-06		

Table C.1. ECS test data (continued)

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
CABKL02	04/05/92	5.61	7.41	7.08E-06	601.5	729	755	B	0	41.6	59.8	694.5	1	1.41E-05	5	C
									1	42.2	87.6	481.7	0.69	7.64E-06		
									2	42.1	91.2	462.7	0.67	4.77E-06		
									3	40.6	88.6	458.8	0.66	3.87E-06		
									4	40.4	104	389.1	0.56			
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			
									2	43.5	58.5	742.7	0.84			
									3	43.2	59.2	733.2	0.83			
									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	5.93E-06		
									2	38.7	52.9	731.2	0.39	5.93E-06		
									3	37.9	56.3	673.4	0.36	1.11E-05		
									4	38.9	69.9	557.8	0.30	3.93E-06		
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	1.67E-07		
									2	40.3	47.2	854.3	0.76	1.57E-07		
									3	39.3	41.5	947.8	0.85	1.67E-07		
									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			
									2	39.5	28.1	1405.7	0.71			
									3	39.9	35.8	1116.1	0.57			
									4	40.6	47.2	864.0	0.44			
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	7.55E-05	5	NO
									1	47.1	79.3	596.0	0.48	6.59E-05		
									2	46.9	93.4	502.5	0.40	4.19E-05		
									3	47.2	93.3	473.9	0.38	3.08E-05		
									4	46.4	146.5	317.4	0.25	2.61E-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	3.28E-04	5	NO
									1	42.3	92.7	456.5	0.64	4.78E-05		
									2	42.5	96.6	440.1	0.62	3.42E-05		
									3	42.5	98.0	433.4	0.61	3.29E-05		
									4	41.8	136.5	306.4	0.43	3.36E-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	3.67E-04	5	NO
									1	43.6	84.7	515.0	0.79	1.19E-04		
									2	43.7	86.5	505.0	0.77	1.58E-04		
									3	44.2	94.2	469.5	0.72	9.65E-05		
									4	43.6	114.0	382.2	0.58	7.11E-05		
CADKM04	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	1.69E-04	5	NO
									1	42.9	84.4	508.8	0.82	4.31E-05		
									2	43.0	93.1	462.2	0.75	2.73E-05		
									3	42.9	91.5	468.7	0.76	4.34E-05		
									4	42.1	107.5	392.7	0.64	2.42E-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	8.51E-05	5	NO
									1	39.4	46.4	847.9	0.64	3.63E-05		
									2	40.0	47.6	839.7	0.63	3.30E-05		
									3	40.5	52.0	779.2	0.59	2.89E-05		
									4	40.2	64.5	623.9	0.47	1.93E-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	5.49E-05	5	NO
									1	38.9	46.3	844.5	0.49	1.04E-06		
									2	38.7	56.5	685.1	0.40	4.51E-06		
									3	38.9	68.8	564.6	0.33	9.53E-06		
									4	39.9	89.5	449.0	0.26	4.29E-06		
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	4.07E-05	5	NO
									1	38.7	60.3	643.2	0.67	1.02E-05		
									2	38.5	48.1	802.4	0.84	1.03E-05		
									3	38.7	58.2	693.3	0.73	1.67E-05		
									4	39.2	72.5	540.9	0.57	9.94E-06		

Table C.1. ECS test data (continued)

Specimen D	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
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	3.53E-04	20	NO
									1	41.1	330.0	124.7	0.48	1.11E-04		
									2	40.9	376.0	108.5	0.42	9.91E-05		
									3	40.8	380.0	107.4	0.41	7.36E-05		
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	5.59E-04	20	NO
									1	38.5	305.0	126.3	0.63	2.48E-04		
									2	38.8	343.5	112.7	0.56	2.13E-04		
									3	38.5	364.0	105.5	0.53	1.35E-04		
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	2.43E-04	30	NO
									1	40.0	338.5	117.9	0.52	6.17E-05		
									2	39.4	375.5	105.0	0.46	3.81E-05		
									3	39.5	416.0	94.8	0.41	2.05E-05		
CAGKM04	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	1.19E-04	20	NO
									1	38.5	282.5	136.4	0.42	4.50E-05		
									2	38.6	320.0	120.5	0.37	2.50E-05		
									3	39.8	335.5	118.6	0.36	1.82E-05		
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	2.35E-05	30	A
									1	39.7	203.5	194.8	0.41	2.72E-05		
									2	41.3	229.0	180.2	0.38	1.64E-05		
									3	39.6	236.5	167.3	0.35	1.81E-05		
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	7.88E-06	20	B
									1	40.8	170.5	239.2	0.57	1.38E-05		
									2	40.5	194.5	207.7	0.49	1.19E-05		
									3	39.8	201.0	198.2	0.47	1.04E-05		
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	6.03E-05	0	NO
									1	41.0	106.0	387.3	0.87	4.50E-05		
									2	42.1	122.5	343.5	0.78	3.62E-05		
									3	40.1	115.0	348.8	0.79	4.33E-05		
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	1.34E-03	0	NO
									1	39.7	100.8	394.4	0.84	1.02E-03		
									2	40.0	105.0	381.3	0.82	8.97E-04		
									3	40.3	100.7	399.8	0.86	8.39E-04		
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	1.60E-04	5	NO
									1	39.4	121.0	325.9	0.96	8.44E-05		
									2	39.3	113.5	345.8	1.02	1.02E-04		
									3	39.5	113.5	348.7	1.03	1.05E-04		
GAADM11	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	3.95E-04	0	NO
									1	39.9	97.1	410.3	1.19	2.73E-04		
									2	39.6	101.5	389.7	1.13	2.23E-04		
									3	39.5	101.1	390.4	1.14	1.98E-04		
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	6.46E-05	0	NO
									1	38.8	46.9	827.0	0.75	3.19E-05		
									2	39.5	45.5	868.0	0.79	2.05E-05		
									3	39.0	47.4	823.6	0.75	1.51E-05		
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	2.03E-05	5	NO
									1	39.0	73.0	535.0	1.10	5.56E-05		
									2	39.5	77.2	511.8	1.05	4.28E-05		
									3	39.2	76.3	513.4	1.05	6.24E-05		

Table C.1. ECS test data (continued)

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
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	5.38E-04	5	NO
									1	42.5	329.0	129.1	0.76	4.40E-04		
									2	40.0	324.0	123.5	0.73	2.96E-04		
									3	40.1	320.5	125.1	0.74	2.86E-04		
									4	41.0	430.0	95.1	0.56	2.78E-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	2.26E-04	5	NO
									1	43.4	373.0	116.1	0.90	2.12E-04		
									2	40.9	358.0	114.0	0.88	1.80E-04		
									3	39.9	354.5	112.5	0.87	1.16E-04		
									4	40.9	436.0	93.8	0.72	9.99E-05		
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	6.48E-04	5	NO
									1	40.2	355.0	113.2	0.65	5.66E-04		
									2	40.6	330.5	122.9	0.71	5.06E-04		
									3	40.6	337.0	120.5	0.70	4.45E-04		
									4	41.1	430.0	95.5	0.55	4.13E-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	9.15E-06	5	D
									1	38.9	208.5	186.4	0.76	4.57E-05		
									2	39.0	225.0	172.9	0.70	2.50E-05		
									3	38.2	251.0	152.1	0.62	2.08E-05		
									4	41.0	314.0	130.5	0.53	2.28E-05		
MN5KM05	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	1.49E-06		
									2	38.8	196.5	197.5	0.74			
									3	38.4	210.5	182.5	0.69			
									4	39.6	237.0	166.5	0.63			
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	1.72E-06		
									2	40.3	156.0	258.4	0.63	2.70E-06		
									3	40.9	195.5	209.0	0.51	3.81E-06		
									4	40.9	228.0	179.2	0.43	2.25E-06		
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	1.52E-06		
									2	40.7	133.0	306.2	0.56	1.63E-07		
									3	41.7	175.5	237.9	0.43	7.63E-07		
									4	40.9	199.0	205.4	0.37	1.27E-06		
MS5R804	02/29/92	5.90	7.62		255.50	245.00	236.00	B	0	405.5	150.5	269.5	1.00	4.73E-05	20	NO
									1	41.2	196.5	209.9	0.78	2.96E-04		
									2	41.6	204.0	203.8	0.76	3.50E-04		
									3	41.6	212.5	195.5	0.73	2.91E-04		
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	7.87E-05	20	NO
									1	45.8	215.0	213.2	0.67	1.14E-04		
									2	46.1	235.5	195.4	0.61	1.08E-04		
									3	45.8	236.5	193.6	0.61	9.82E-05		
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	5.09E-05		
									2	39.0	148.0	264.0	0.63	7.21E-05		
									3	38.0	171.0	221.6	0.53	5.13E-05		
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					3.14E-05		
									2					3.66E-05		
									3					3.48E-05		
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							
									2							
									3							

Table C.1. ECS test data (continued)

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
OR1R803	03/11/92	5.20	8.29	3.09E-05	560.0			A	0	44.1	76.6	578.0	1.00	2.28E-04	5	NO
									1	46.3	103.5	444.8	0.77	2.88E-04		
									2	44.8	104.4	430.0	0.74	2.31E-04		
									3	46.5	97.9	474.3	0.82	1.54E-04		
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	1.57E-04	0	NO
									1	40.3	48.1	836.4	0.88	3.56E-04		
									2	40.9	50.7	806.8	0.85	3.14E-04		
									3	40.9	48.8	838.7	0.88	2.58E-04		
OR1R806	03/11/92	5.20	7.33	2.34E-05	519.0			B	0	60.4	79.2	530.2	1.00	4.65E-04	5	NO
									1	42.7	173.4	492.5	0.93	6.08E-04		
									2	42.7	83.9	508.7	0.96	6.19E-04		
									3	42.8	455.7	512.3	0.97	5.69E-04		
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	1.31E-03	5	NO
									1	42.7	99.7	427.7	0.86	7.23E-04		
									2	42.5	98.6	430.9	0.87	6.51E-04		
									3	42.8	106.5	401.3	0.81	7.01E-04		
OR1KM04	03/07/92	5.20	9.21		575.5	519.0	519.0	B	0	41.0	81.5	502.2	1.00	7.48E-04	0	B
									1	41.2	83.8	492.0	0.98	1.18E-04		
									2	41.5	82.6	502.9	1.00	8.69E-05		
									3	41.3	81.9	515.0	1.03	5.01E-05		
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	2.91E-05		
									2	43.0	58.5	733.9	0.82	1.19E-05		
									3	41.0	60.8	674.7	0.75	5.68E-06		
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	1.75E-07		
									2	39.4	60.9	647.8	0.87	9.36E-07		
									3	19.7	63.5	626.0	0.84	1.88E-07		
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	2.06E-03		
									2	38.0	486.5	78.0	0.89	2.56E-04		
									3	37.4	484.5	77.3	0.88	1.74E-03		
									4	37.9	474.0	80.0	0.92	1.70E-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	6.94E-04		
									2	40.2	45.0	89.6	0.87	9.54E-04		
									3	39.5	44.4	89.0	0.86	9.11E-04		
									4	41.4	47.1	87.9	0.85	9.27E-04		
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	5.21E-03	20	NO
									1	39.1	31.3	124.9	1.00	5.19E-03		
									2	39.6	31.7	125.0	1.00	4.81E-03		
									3	41.6	36.4	114.4	0.92	4.12E-03		
									4	40.2	35.6	112.8	0.90	4.99E-03		
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	1.00E-03	5	NO
									1	40.9	215.0	190.0	0.95	7.67E-04		
									2	40.2	192.5	208.5	1.05	6.12E-04		
									3	40.6	197.5	205.1	1.03	8.06E-04		
									4	39.4	190.5	206.6	1.04	8.52E-04		
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	2.58E-03	5	NO
									1	39.5	254.0	155.6	0.87	2.12E-03		
									2	40.4	258.0	156.5	0.88	2.27E-03		
									3	40.0	254.0	157.2	0.88	1.84E-03		
									4	40.1	242.0	165.5	0.93	2.30E-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	2.13E-07	10	NO
									1	39.9	200.0	199.1	0.93	3.04E-04		
									2	40.0	196.5	203.5	0.95	2.06E-03		
									3	39.7	195.0	203.8	0.95	1.69E-04		
									4	39.7	188.5	210.9	0.99	1.74E-04		
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	1.21E-04	5	NO
									1	35.1	214.5	163.6	0.76	3.53E-04		
									2	35.0	211.0	166.1	0.77	3.28E-04		
									3	35.7	203.5	174.9	0.81	2.25E-04		
									4	35.4	210.5	167.9	0.78	2.13E-04		

Table C.1. ECS test data (continued)

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
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	1.02E-04	0	NO
									1	40.2	148.0	270.9	0.84	1.40E-04		
									2	40.9	145.0	281.7	0.87	1.12E-04		
									3	40.9	148.0	276.3	0.86	1.01E-04		
									4	40.7	155.0	263.9	0.82	8.71E-05		
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	7.52E-05	0	NO
									1	38.9	188.0	206.6	0.89	2.32E-04		
									2	39.6	183.5	213.8	0.92	2.21E-04		
									3	39.5	180.0	219.6	0.95	2.36E-04		
									4	40.0	169.5	235.9	1.02	1.90E-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	1.12E-04	5	D
									1	39.3	195.0	201.7	0.83	1.90E-04		
									2	39.0	186.0	209.8	0.86	2.08E-04		
									3	39.2	180.0	217.8	0.90	2.88E-04		
									4	40.0	172.0	233.3	0.96	3.90E-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	7.74E-05		
									2	39.6	162.0	244.2	0.88	7.05E-05		
									3	39.5	208.5	189.4	0.68			
									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	5.00E-05		
									2	40.7	142.0	286.3	0.71	3.56E-05		
									3	40.6	138.0	293.8	0.72	4.58E-05		
									4	40.0	129.5	303.3	0.76	5.45E-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			
									2	41.1	98.0	413.1	1.04			
									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			
									2	39.1	112.0	348.2	0.80			
									3	37.6	132.5	283.3	0.65			
									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			
									2	38.7	163.5	236.8	0.84			
									3	39.4	164.5	238.6	0.84			
									4	40.0	153.5	259.8	0.92			
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	7.52E-06		
									2	49.3	233.5	210.9	0.68	9.47E-06		
									3	50.8	248.5	204.3	0.66	8.26E-06		
									4	50.9	226.5	224.7	0.72	6.45E-06		
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	4.45E-06		
									2	41.9	183.0	229.2	0.71	8.54E-06		
									3	42.1	177.0	238.1	0.74	7.82E-06		
									4	42.0	165.0	254.2	0.79	7.56E-06		
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	1.76E-07		
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			
									2	40.1	131.0	306.3	0.83			
									3	40.5	145.5	277.5	0.76			
									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			
									2	53.8	184.0	293.3	0.69			
									3	56.7	185.5	306.6	0.72	1.53E-07		
									4	53.5	151.5	354.3	0.83	1.62E-07		

Appendix D

Table D.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

Table D.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
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		
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		

Table D.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
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 D.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
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		