SHRP-A-402

Water Sensitivity: Binder Validation

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Abstract

This study was part of the Strategic Highway Research Program (SHRP) A-003A contract undertaken as an interim evaluation of the hypotheses concerning the influence of binder properties on the moisture susceptibility of asphalt-aggregate mixes.

Thirty-two mixes using eight asphalts and four aggregates from the Materials Reference Library (MRL) were used to fabricate roller-compacted slabs from which specimens were sawed or cored. These mixes were tested by four procedures: (1) Environmental Conditioning System (ECS), (2) Oregon State University (OSU) Wheel Tracker, (3) SWK Pavement Engineering/University of Nottingham (SWK/UN) Wheel Tracker, and (4) Net Adsorption Test (NAT).

Because the water-conditioning and testing procedures were different, it was not appropriate to make direct comparisons of results or to use the results for ranking materials. The ECS was the only test to compare dry- to wet-conditioned mixes, while the two wheel trackers tested only wet-conditioned mixes. The NAT was not directly comparable because it considers only adhesion. The two rutting tests provided results that were similar to the A-002A hypothesis, but did not confirm the ECS results. It was concluded that, for water-sensitivity, asphalts or aggregates could not be ranked alone but that combinations or pairs were more appropriate because of strong interactions.

Executive Summary

The original proposal by the Strategic Highway Research Program (SHRP) A-003A contractor included a major task to evaluate the water-sensitivity of asphalt paving mixes. The testing included a laboratory phase to develop procedures and criteria followed by a field evaluation phase to confirm the performance of various projects that were predicted by laboratory testing. During the development phase SHRP staff became concerned that data may not be sufficient or that time-in-service of the field projects may not be adequate. Therefore, an extended program was developed to provide interim data based on accelerated tests.

The extended test program included evaluation of rutting, thermal and fatigue cracking, aging, and water-sensitivity. Its aim was to perform so-called torture tests that induce damage or failure in a short time period by simulating loading and environmental conditioning that would occur on the in-service pavement. For water-sensitivity evaluation, an accelerated rutting test using the Oregon State University (OSU) wheel tracker (Laboratoires des Ponts et Chausées [LCPC] rutting tester) was selected as the primary method. However, tests on the same mixes were also conducted using the wheel-rutting tester at SWK Pavement Engineering/University of Nottingham (UK) and the Environmental Conditioning System (ECS) developed at OSU. Each test procedure results in a different failure mechanism, but all tests can be used to evaluate the water-sensitivity of asphalt-aggregate mixes.

The primary purpose of this portion of the SHRP A-003A program was to validate the hypothesis and preliminary results of asphalt ranking developed by the SHRP A-002A contractor. Validation of the hypothesis of the SHRP A-003B contractor was also considered. SHRP A-002A researchers originally suggested a hypothesis of expected performance of mixes that is based on asphalt binder properties. They proposed a ranking of the SHRP Materials Reference Library (MRL) asphalts (and to some extent, aggregates) for rutting, aging, fatigue, and water-sensitivity. SHRP A-003B researchers hypothesized an explanation of the chemical relationship between asphalt, aggregate, and water to define asphalt-aggregate interactions that are either resistive or sensitive to water, and they developed a Net Adsorption Test (NAT). They proposed rankings of the water-sensitivity of the SHRP MRL aggregates based on adsorption and desorption of asphaltic model components on aggregates, the net adsorption of asphalts on aggregates, and the percentage change of adsorption and desorption of selected asphalt models and asphalts on selected aggregates pretreated with organosilane compounds.

This report covers the testing, analysis of data, and ranking of the MRL materials based on the ECS, OSU wheel-tracking, and SWK/UN wheel-tracking test results. The ranking of the MRL materials is compared with that proposed by the A-002A and A-003B contractors. Also, the NAT, which was performed at University of Nevada-Reno, was used to further compare the materials used in the testing program.

An eight-asphalt by four-aggregate (8 × 4) matrix was designed with tests repeated on eight of the mixes. The set of 40 tests (32 mixes plus 8 repeats) was designed to identify the water-sensitivity of the mixes using either rutting (OSU and SWK/UN wheel-tracking) or reduction in the ECS modulus. The test program provided information to rank the relative performance of the eight asphalts and four aggregates, thus enabling a comparison of results provided by the A-002A, A-003A, and A-003B contractors.

Specimens were prepared using a procedure developed at OSU. Batches of each mixture were heated in ovens and mixed in a converted concrete mixer. Asphalt concrete slabs approximately 75 cm square by 50 mm thick were prepared using a small tandem wheel roller and a specially constructed mold. After cooling, specimens were sawed and cored from the slab for the various tests.

Cores from the slabs were tested in the ECS using the three-hot and one-freeze cycle and continuous repeated loading procedures. The ratio of dry and water-conditioned resilient modulus (ECS-M_R) was used to compare the mix.

Small slabs or beams, which were conditioned in a special chamber similar to that used for the ECS, were sawed from the slabs for testing in the OSU wheel tracker. Tests were conducted only on conditioned specimens, so the test results were for relative rutting resistance for each mix; i.e., there was no ratio between wet and dry. Comparisons were made after 10,000 wheel passes.

Beams were also sawed and shipped to SWK/UN for testing in a wheel tracker. This device was used to test specimens that were water-conditioned by a combination of soaking and freezing. Wheel-tracking continued on each specimen until it failed or until about 500,000 wheel passes were attained.

The results and conclusions of this study can be summarized as follows:

1) Performance ranking of materials by asphalt type or aggregate type alone was not feasible for the ECS test results because of the significant interaction between asphalt and aggregate. In general, aggregate RC and RJ were the worst performers or most water sensitive; aggregate RH was the intermediate performer; and RD was the best performer or most water resistant.

2) Statistical analysis of ECS test data showed that the test is sensitive to aggregate and asphalt type and can discriminate between moisture-sensitive and moisture-resistant mixes.

3) The OSU wheel-tracking test results indicated that the RJ aggregate was a relatively good performer, the RC aggregate was a poor performer, and the RD and RH aggregates were intermediate performers in terms of rut resistance.

4) The SWK/UN wheel-tracking test results indicated that the RC and RD aggregates were good performers (with practically no difference between the two), the RH aggregate was an intermediate performer, and the RJ aggregate was a poor performer. The significant differences between the results of the two test methods may possibly be attributed to the significant differences in testing methods, test apparatus, specimen size, or specimen environment during testing. However, the results of the SWK/UN wheel-tracking test generally validate the predictions proposed by the NAT (A-003B) but those of the OSU wheel-tracking test do not. Thus, the OSU wheel-tracking test may not be appropriate for evaluating the water-sensitivity of aggregate types unless a wet/dry ratio can be evaluated.

5) Asphalt performance ranking of both wheel-tracking tests showed good correlation with aged asphalt viscosity data. The Size Exclusion Chromatography (SEC)-tan delta test proposed by A-002A appears to predict adequately the rutting potential of asphalt types as evidenced by close agreement with the asphalt rankings from the OSU wheel-tracking and SWK/UN wheel-tracking tests. It is interesting to note that near perfect agreement exists between A-002A predictions and SWK/UN results.

6) Predictions of the water-sensitivity of the binder as proposed by the A-002A Fourier transform infrared (FTIR) test and the A-003B NAT showed little or no correlation to wheel-tracking tests on the mix. Since very good to excellent correlation exists between the wheel-tracking tests and the A-002A predictions for permanent deformation, it appears that the FTIR test and the NAT are poor indicators of the moisture sensitivity of the binder.

Further observation of the results of the tests may be helpful in interpreting them. The range of mixes (32 combinations) was not as wide as might be expected because the mix designs (aggregate gradation, asphalt content) in the laboratory phase were the same, in contrast to those in the field validation phase, which included a much greater variety of mix types. Only the ECS test program measured water-sensitivity, i.e., comparison of wet-conditioned to original dry mixes. The OSU and SWK/UN wheel trackers tested water-conditioned specimens, but the results were not compared to dry test results; thus, the tests only compared similarly conditioned mixes. The NAT is an indicator of potential for adhesion (stripping) only and does not consider the cohesion-loss aspect of water damage. In the final analysis, conclusions must be drawn only after careful consideration of the variables.

The results of ECS testing showed that the ECS can distinguish between good and poor performing mixes with respect to moisture-damage. The results of this test program are not sufficient to establish limits for specifications. The results of the 32 mixes tested in this program were in a relatively narrow range. The testing program included only MRL materials with no direct link to field performance. Therefore, the consideration of specifications will be deferred until completion of field validation testing.

1

Introduction

1.1 Background

The original proposal by the Strategic Highway Research Program (SHRP) A-003A contractor included a major task to evaluate the water-sensitivity of asphalt paving mixes. The testing included a laboratory phase to develop procedures and criteria, followed by a field evaluation phase to confirm the performance of various projects that were predicted by laboratory testing. During the laboratory phase, SHRP staff became concerned that data may not be sufficient or that time-in-service of the field projects may not be adequate. Therefore, an extended program was developed to provide interim data based on accelerated tests. The extended test program included the evaluation of rutting, thermal cracking, aging, and fatigue and water-sensitivity over a range of asphalt and aggregate types. Its aim was to use so-called torture tests that induce damage or failure in a short time period, by simulating loading and environmental conditioning that would occur on the in-service pavement.

For water-sensitivity, an accelerated rutting test using the LCPC rutting tester (OSU wheel tracker) was selected as the primary method of evaluation. However, tests on the same mixes were also conducted using the wheel-rutting tester at SWK Pavement Engineering/University of Nottingham (UK) (SWK/UN wheel tracker) and the Environmental Conditioning System (ECS) developed at OSU. Each test procedure results in a different failure mechanism, but all tests can be used to evaluate the water-sensitivity of asphalt-aggregate mixes.

1.2 Purpose

The primary purpose of this portion of the SHRP A-003A program was to validate the hypothesis and preliminary results of asphalt ranking developed by the SHRP A-002A contractor. Validation of the hypothesis of the SHRP A-003B contractor (Auburn University) was also given consideration. The SHRP A-002A researchers originally presented a hypothesis of expected performance of mixes based on asphalt binder properties. They proposed a tentative ranking of the SHRP Materials Reference Library (MRL) asphalts (and to some extent, aggregates) for rutting, aging, thermal cracking, fatigue, and water-sensitivity. However, based upon later work the hypothesis and rankings were rescinded. SHRP A-003B researchers have hypothesized an explanation of the chemical relationship among asphalt, aggregate, and water to describe and define asphalt-aggregate interactions that are either resistive or sensitive to water. They have proposed rankings of the water-sensitivity of the SHRP MRL aggregates based on adsorption and desorption of asphaltic model components on aggregates, the net adsorption of asphalts on aggregates, and the percentage change of adsorption and desorption of selected asphalt models and asphalts on selected aggregates pretreated with organosilane compounds.

This report covers the testing, analysis of data, and performance ranking of the MRL materials based on the ECS and the OSU and SWK/UN wheel-tracking test results. The ranking of the MRL materials is compared with that proposed by the A-002A and A-003B contractors.

2

Hypotheses of A-002A and A-003B

Since the primary purpose of the Strategic Highway Research Program (SHRP) A-003A work was the validation of the A-002A and A-003B hypotheses for water-sensitivity, this chapter presents reviews of both the A-002A hypothesis prepared in March, 1991 (Robertson 1991) and the A-003B hypothesis (Curtis et al. 1993).

2.1 A-002A

The SHRP A-002A contractor (Western Research Institute) was commissioned to develop predictions for asphalt-aggregate-mixture performance based on the properties of the binder. Mix-performance measures included fatigue, permanent deformation (rutting), aging, thermal cracking, and water-sensitivity (in terms of loss of adhesion). Only the predictions for water-sensitivity and permanent deformation are considered in this report; permanent deformation predictions are included since the A-003A water studies used rutting tests as part of the validation effort.

The ranking of asphalts for permanent deformation are shown in Table 2.1 (Robertson 1991). This ranking is based on preparative Size Exclusion Chromatography (SEC) fraction I to SEC fraction II ratios that show a strong correlation with viscoelastic properties of the binder as shown in Figure 2.1. Note that this ranking is based on asphalts that have not experienced long-term aging. The SEC fraction I is the weight of the nonfluorescent components in the asphalt whereas the SEC Fraction II is the weight of the fluorescent components. The nonfluorescent components assemble into an elastic matrix while the fluorescent components form the dispersing phase for the matrix. This dispersing phase does not appear to self-assemble at moderate to high temperatures and therefore is primarily composed of a viscous material. The SEC fraction I to SEC fraction II ratio provides a measure of the total of the system.

Table 2.1. Rank of High Temperature Permanent Deformation by SEC-Tan Delta[a]

Asphalt Type	Resistance
AAM-1	Excellent
AAK-1	"
AAE	"
AAS-1	Very Good
AAH-1	"
AAD-1	"
AAB-1	"
AAW-1	"
AAJ	"
AAA-1	Good
AAN	"
AAX	Fair
AAF-1	"
AAC-1	"
AAZ	Poor
AAV	"
AAG-1	Little or No Resistance
ABD	"

[a] After Robertson 1991.

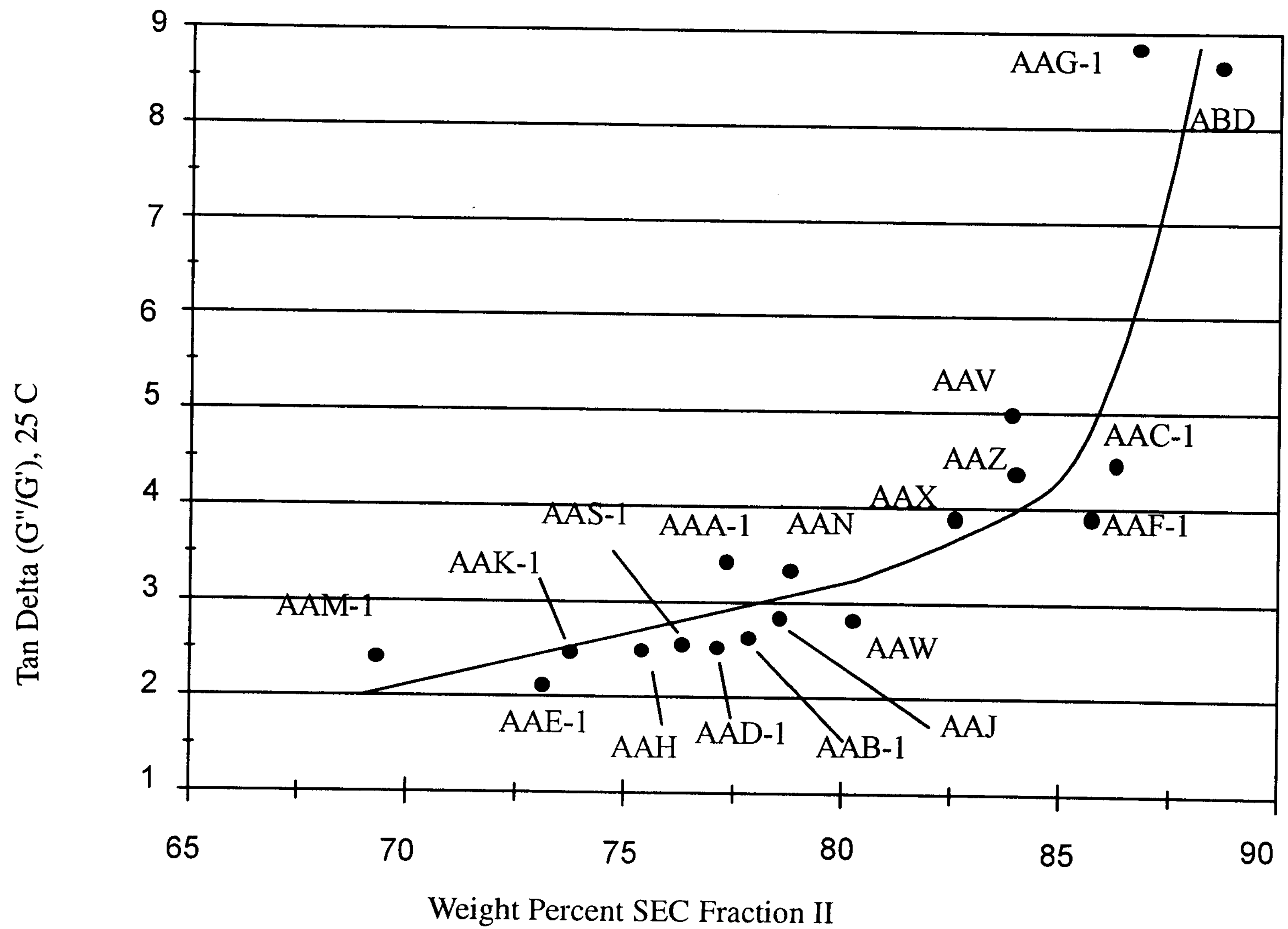

Fig. 2.1. Relationship between weight percent SEC fraction II and tan delta for SHRP asphalts (after Robertson 1991)

Several studies have demonstrated that loss of adhesion via moisture-damage is primarily associated with the aggregate (Curtis et al. 1991; Robertson 1991). The A-002A contractor feels that classification of the moisture-damage susceptibility from the chemistry of the binder alone is probably a minor effect at best (Robertson 1991). However, A-002A formulated the classification shown in Table 2.2, which is based on the carbonyl content (with emphasis on the free acid content) as determined by FTIR. Note that aging affects the asphalts differently.

2.2 A-003B

The SHRP A-003B contractor (Auburn University) was charged with describing and defining asphalt-aggregate interactions that are resistive or sensitive to water. This effort examined three specific areas: (1) evaluation of the specific chemistry of asphalt adsorption onto aggregate using model species that are representative of polar functional group types present in asphalts; (2) evaluation of the compatibility of various asphalt-aggregate pairs and their respective sensitivity to water; and (3) determination of the effect that aggregates treated with saline compounds of differing chemistries have on asphalt-aggregate interactions and water-sensitivity (Curtis et al. 1991).

The A-003B contractor concluded that the adsorptive behavior of asphalt and asphalt model components on aggregates is highly specific and particularly influenced by the aggregate surface chemistry; the chemistry of the asphalt binder has less influence. Tests on aggregates pretreated with saline compounds led to the same conclusion. Experiments evaluating adsorption and aqueous desorption of asphalt model components on aggregates conclusively showed that polar compounds had different affinities for adsorption for different aggregates. The amount and ease by which the polar compounds were removed from the aggregate surface in the presence of water was found to be dependent on the aggregate chemistry as well as the pH and heat history of the particular system.

Net adsorption tests (NATs) were used to investigate the compatibility and water-sensitivity of asphalt-aggregate pairs and clearly showed that the adsorption behavior of asphalt on aggregate was controlled by the aggregate chemistry. The A-003B researchers found that substantial differences in adsorption and aqueous desorption behavior existed among aggregates but that small and generally insignificant differences existed among asphalts; that is, the differences in adsorption and desorption behavior of one particular asphalt in combination with various aggregates were far in excess of those of one particular aggregate in combination with various asphalts. Table 2.3 shows the net adsorption data obtained by the A-003B contractor during the development of the NAT procedure. The initial amount of asphalt adsorbed before introduction of water gives an indication of the affinity a particular asphalt has for a given aggregate. The net adsorption, or the amount remaining on the surface of the aggregate after aqueous desorption, is an indication of the moisture sensitivity of the asphalt-aggregate pair (Curtis et al. 1991). The results of the NAT (i.e., ranking of

Table 2.2. Rank of Moisture-damage Resistance by Infrared of Functional Group Analysis[a]

New Material		Aged Material	
Asphalt	**Resistance**	**Asphalt**	**Resistance**
AAF-1 AAB-1 AAM-1 AAA-1	Good (No order established)	AAB-1 AAM-1 AAC-1 AAF-1	Good (in order as shown)
AAD-1 AAK-1	Intermediate-Good	AAD-1	Intermediate-Good
AAG-1	Fair-Poor		
ABD	Poor	AAG-1 ABD	Poor

[a] After Robertson 1991.

Table 2.3. Initial and Net Adsorption of Asphalt on Aggregate[a]

Aggregate	Asphalt								
	AAD-1			AAK-1			AAM-1		
	Initial Adsorption	Net Adsorption	Percentage Desorption	Initial Adsorption	Net Adsorption	Percentage Desorption	Initial Adsorption	Net Adsorption	Percentage Desorption
RA	0.18±0.03	0.07	61.5	0.25±0.04	0.18	28.7	0.20±0.18	0.001	99.5
RB	0.85±0.04	0.68	19.1	0.89±0.11	0.73	18.1	0.77±0.03	0.60	22.6
RC	1.9[b]	1.5	20.0	1.7	1.3	25	1.4	1.2	22
RD	0.73±0.06	0.60	18.5	0.73±0.02	0.59	18.9	0.69±0.09	0.50	30.4
RE	0.98±0.05	0.69	29.7	1.01±0.06	0.61	39.0	0.85±0.02	0.45	47.1
RF	0.90±0.04	0.61	32.2	0.85±0.06	0.52	43.7	0.83±0.05	0.44	47.2
RG	0.70±0.02	0.58	17.8	0.60±0.09	0.42	31.0	0.59±0.02	0.34	42.0
RH	1.3[b]	1.0	25	1.22	0.94	23	1.2	0.91	24
RJ	0.31±0.03	0.12	60.3	0.34±0.06	0.19	44.0	0.42±0.63	0.21	50.0
RK	1.7[b]	1.4	17	1.56	1.26	19	1.4	1.2	17
RL	1.4[b]	1.0	28	1.4	0.99	30	1.2	0.83	28

[a] After Curtis et al. 1991.
[b] Obtained from isotherm data.

aggregates via net adsorption) are used herein to compare the results of the A-002A and A-003A contractors.

Tests evaluate the effect that saline-treated aggregate has on the asphalt-aggregate interaction and water-sensitivity showed enhanced adsorption and retention of asphalt model compounds and asphalts in specific cases and no change or decreased adsorption and increased water-sensitivity in others. Pretreatment of the aggregate surface (i.e., modification of the surface chemistry) created an asphalt chemistry that was more specific in both its adsorption and desorption behavior than that created by untreated aggregate.

The NAT was used by the A-003B contractors on only a few of the Materials Reference Library (MRL) aggregate-asphalt combinations. Late in the research program, the A-003A contractors determined that additional NAT results would be beneficial. Accordingly, a subcontract to the University of Nevada-Reno was initiated to test the 32 combinations (eight asphalts × four aggregates) used in the validation experiment. The results of the NAT test are addressed later.

3

Experiment Design

The experiment design developed for the Strategic Highway Research Program (SHRP) A-003A task D.2.e work is shown in Table 3.1. The table shows the coding scheme of each mix. The first two digits are the aggregate code (i.e., RC and RJ codes are 00 and 11, respectively); the last three digits are the asphalt code (i.e., AAA-1 and AAG-1 codes are 000 and 101, respectively). Originally only eight mixes were chosen to be replicated; however, all the 32 mixes were actually replicated. The Environmental Conditioning System (ECS) validation phase was divided into two tasks: 1) Laboratory validation, using the ECS, and 2) Field validation, using two wheel-tracking systems Laboratories des Ponts et Chausées (LCPC) and SWK Pavement Engineering (SWK).

As indicated, an eight-asphalt by four-aggregate (8 × 4) matrix was designed for this work with tests repeated on eight of the mixes. (Duplication of tests in the ECS and Oregon State University (OSU) wheel-tracking programs exceeded that which was designed as discussed in further detail in Chapter 4.) The set of 40 tests (32 mixes plus eight repeats) was primarily designed to identify the water-sensitivity of the mixes using either rutting (OSU and SWK/UN wheel-tracking) or reduction in modulus (ECS) as the objective function. The test program provided information to rank the relative performance of the eight asphalts and four aggregates, thus enabling a comparison of results provided by the A-002A, A-003A, and A-003B contractors. The following sections provide details regarding the experiment design including the variables considered, the materials employed, the specimen preparation procedure, and the test procedures used to carry out the work.

3.1 Variables Considered

The testing program consisted of eight asphalt types and four aggregate types. The ECS test program variables considered for this phase of the SHRP project are shown in Table 3.2 and discussed below:

Table 3.1. Experiment Design for Validation of Binder Specifications—Water-Sensitivity

Mix Number	Mix Code	MRL Aggregate	MRL Asphalt	Required Replicate
1	00000	RC	AAA-1	RC & AAA-1
2	10000		AAB-1	
3	01000		AAC-1	
4	11000		AAD-1	
5	00100		AAF-1	
6	10100		AAG-1	
7	01100		AAK-1	RC & AAK-1
8	11100		AAM-1	
9	00010	RD	AAA-1	
10	10010		AAB-1	
11	01010		AAC-1	
12	11010		AAD-1	RD & AAD-1
13	00110		AAF-1	
14	10110		AAG-1	RD & AAG-1
15	01110		AAK-1	
16	11110		AAM-1	
17	00001	RH	AAA-1	
18	10001		AAB-1	
19	01001		AAC-1	
20	11001		AAD-1	RH & AAD-1
21	00101		AAF-1	
22	10101		AAG-1	RH & AAG-1
23	01101		AAK-1	
24	11101		AAM-1	
25	00011	RJ	AAA-1	RJ & AAA-1
26	10011		AAB-1	
27	01011		AAC-1	
28	11011		AAD-1	
29	00111		AAF-1	
30	10111		AAG-1	
31	01111		AAK-1	RJ & AAK-1
32	11111		AAM-1	

Table 3.2. Experiment Design of Water-Sensitivity Testing Program

Controlled Variable	Level of Treatment					Number of Levels
	1		2		3	
Asphalt type						
• Grade	2	Low	2	Medium	High	8
• Content				Optimum		1
Aggregate type						
• Stripping potential		Low	2	Medium	High	4
• Gradation				Medium		1
Compaction						
• Air voids (%)					8±1	1
Testing compaction factors						
• Test temperature	3 Hot Cycles (60°C) + Freeze Cycle (-18°C)					1
• Load					Repeated	1
• Time					6 hr	1
					Total	**32**

Complete factorial	32
Replicate	32
Total number of samples	64

Response variables:

· Initial ECS modulus
· Initial air-permeability
· ECS-M_R after each cycle
· Water-permeability after each cycle
· Visual evaluation, percentage of retained asphalt coating on the aggregate

1) Specimen density (air-voids), mix asphalt content, and gradation of the aggregate were all held as constant as possible.

2) Permeability was used as a measure of the moisture-damage susceptibility. Air-void's range of 8 ± 1 percent was used to control the permeability.

3) Temperatures that were applied during conditioning were hot (60°C [140°F]) for the first three cycles and freeze (-18°C [-0.4°F]) for the fourth cycle. The resilient modulus (ECS-M_R)[1] test was conducted at 25°C (77°F) after each cycle.

4) Repeated loading was applied during the first three hot cycles, and static loading during the freeze cycle.

5) The specimen was preconditioned or saturated with distilled water at 50.8 cm (20 in.) Hg of vacuum for 30 minutes.

6) The duration of each cycle was 6 hours, and each test had three hot cycles and one freeze cycle.

Response variables:

1) ECS-M_R was measured after each conditioning cycle.

2) Permeability was measured after each conditioning cycle to monitor the change in moisture-damage susceptibility.

3) Visual estimation of the percentage of retained asphalt coating on the aggregate was observed at end of test.

Full factorial experiment design was used (Table 3.2). The order of sample preparation was randomized independently for each replicate, and the specimens were selected and tested randomly.

For OSU and SWK/UN wheel-tracking test programs, the variables considered in the experiment design included asphalt and aggregate type. Specimen density (air-voids), mix asphalt content, gradation of the aggregate, and test specimen conditioning were all held as constant as possible: specimen air-voids' contents here held constant at 8±1 percent; the mix-asphalt contents were based on the content established by the Hveem Method and are given in Table 3.3; the aggregate was of medium gradation (see Table 3.3); and each test

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[1]The resilient modulus obtained in the ECS is termed the ECS-M_R to distinguish it from the traditional diametral and triaxial resilient moduli as well as from the dynamic modulus. The ECS-M_R is a triaxial resilient modulus with zero confining stress (i.e., $\sigma_2 = \sigma_3 = 0$) conducted on a 102 mm (4 in.) diameter by 102 mm (≈4 in.) tall asphalt-aggregate mixture test specimen (Terrel and Al-Swailmi 1992).

Table 3.3. Job-Mix Formula for the Validation Study

Sieve Size	Percent Passing			
	RC	RD	RH	RJ
1 in.	100	100	100	100
3/4 in.	95	95	95	95
1/2 in.	80	80	80	80
3/8 in.	68	68	68	68
#4	48	48	48	48
#8	35	35	35	35
#16	25	25	25	25
#30	17	17	17	17
#50	12	12	12	12
#100	8	8	8	8
#200	5.5	5.5	5.5	5.5
Asphalt content by weight of aggregate, %	6.25	4.5	5.2	5.0
Asphalt content by total weight of mix, %	5.9	4.3	4.9	4.8

program employed a conditioning procedure that remained the same for all specimens tested (each method is described in further detail below).

3.2 Materials

The materials used in this study included eight asphalts and four aggregates from the SHRP Materials Reference Library (MRL). The following paragraphs provide details of these materials.

3.2.1 Aggregates and Their Properties

Two limestones (RC and RD) and two siliceous aggregates (RH and RJ) were used for this research effort. Table 3.4 summarizes the properties of the aggregates available at the time this report was written. Note that the RC limestone aggregate had high water absorption and centrifuge kerosene equivalent (CKE) values compared with the other aggregates. RD aggregate showed very low absorption values. In addition, the RC aggregate had a low bulk specific gravity compared with that of the other aggregates (the gravimetric data for the RH aggregate were unavailable). In the soundness test, RC aggregate exhibited high values of percentage loss of fine and coarse fraction compared with the other aggregates.

3.2.2 Asphalts and Their Properties

Eight asphalts from differing sources (crudes) and having differing grades were used in this research effort. The MRL codes for these asphalts are AAA-1, AAB-1, AAC-1, AAD-1, AAF-1, AAG-1, AAK-1, and AAM-1. Table 3.5 summarizes the properties of these asphalts. Note the wide range of asphalt viscosities as determined by the traditional viscosity and penetration tests. These data show that the AAC-1 asphalt is the softest and the AAK-1 asphalt is the hardest of the asphalts, based on original asphalt viscosity at 60°C (140°F).

3.3 Specimen Preparation

Specimen preparation for this research effort was accomplished by means of rolling wheel compaction. Table 3.6 gives a brief description of the procedure.

Table 3.4. Aggregate Characteristics

MRL Code	RC	RD	RH	RJ
Major element oxide				
SiO2	5.58 (11.79)	16.68 (14.84)	75.91	75.4 (63.98)
TiO2	0.06 (0.18)	0.13 (0.21)	0.46	0.15 (0.41)
Al203	1.18 (1.46)	3.31 (1.95)	10.68	12.88 (14.6)
Fe203	0.76 (0.89)	1.2 (0.96)	4.83	2.01 (4.54)
CaO	48.92 (35.04)	38.8 (33.71)	1.84	1.73 (6.09)
MgO	2.35 (11.76)	3.47 (11.43)	2.28	0.39 (1.52)
Na2O	0.17 (0.21)	0.12 (0.08)	2.76	3.4 (1.67)
K2O	0.18 (0.51)	1.56 (2)	0.74	3.31 (3.31)
Sulfur Trioxide	(0.48)	(0.34)		(0.1)
Phosphorus pentoxide	(<0.01)	(<0.01)		(0.11)
Manganic oxide	(0.03)	(0.02)		(0.13)
LOI	40.62 (37.64)	33.96 (34.45)	2.41	1.13 (3.54)
Composition %	Limestone, 100	Limestone, 53.3 Limestone, 26.8 Arenaceous Limestone, 19.7	Micaceous Sandstone, 71.3 Misc., 11.2 Granite, 10.9 Chert, 6.6	Sandstone, 47.4 Granite, 28.4 Misc., 23.7 Basalt, 0.4
Porosity (ASTM D-4404)				
Average pore diameter (m$\times10^{-6}$)	(0.0611)	(0.0111)		(0.0151)
Total pore area (m^2/g)	(2.548)	(1.465)		(1.888)
Mercury porosimetry data				
Pore size A	Pore vol., cc/g	Pore vol., cc/g	Pore vol., cc/g	Pore vol., cc/g
>300	0.0099	0.0013	0.0128	0.0026
500-3000	0.1085	0.0301	0.0905	0.0071
<500	0.0045	0.0003	0.0023	0.0002
Total volume	0.12	0.03	0.11	0.01
pH	9.7	9.8	8.6	9.6
Los Angeles abrasion (AASHTO T-96)				
Wear %	(39.1)	(23.4)		(29.5)
Water Absorption (AASHTO T-84, T-85)				
Absorption %	(3.7)	(0.3)		(0.7)
Specific gravity (AASHTO T-84, T-85)				
Bulk	(2.536)	(2.704)	(2.550)	(2.625)
Saturated surface dry	(2.595)	(2.717)		(2.646)
Apparent	(2.682)	(2.739)	(2.741)	(2.68)

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Table 3.4. Aggregate Characteristics (continued)

MRL Code	RC	RD	RH	RJ
BET Surface area, m²/g	2.9	.72	2.74	1.32
Rootare-Prenzlow	.84	0.14	0.53	0.05
Surface area (m²/g)	7.9 (4.8)	23.5 (18.1)	92.1	96.2 (99.2)
Acid insolubles (%)	8.1 (2.4)	5.1 (1.9)	9.7	6.3 (4.1)
Water insolubles (%)	-6.1@pH9.82	-13.6@pH9.87	-20.5@pH8.27	-27.5@pH9.45
Zeta potential	(-23.8)	(-20.3)		(-49)
CKE (AASHTO T-270)				
Uncorrected (%)	(8.5)	(3.8)		(1.8)
Oil retained (%)	(3.9)	(2.7)		(2.6)
Flakiness index (%) (Asphalt Institute)	(22.6)	(34.7)		(9.6)
Sand equivalent (%) (AASHTO T-176)	(32)	(69)		(60)
Magnesium soundness (AASHTO T-104)				
Loss (%): Fine fraction	(6.32)	(1.52)		(1.29)
Loss (%): Coarse fraction	(0.51)	(0.04)		(0.16)
Polish value (ASTM D-3319)				
BPN before polish	(42)	(38)		(41)
BPN after polish	(31)	(28)		(22)

Data from University of Kentucky; data in parentheses from Southwestern Lab, Inc., Texas.

Table 3.5. Asphalt characteristics

MRL Code	AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
Grade	**150/200**	**AC-10**	**AC-8**	**AR-4000**	**AC-20**	**AR-4000**	**AC-30**	**AC-20**
Crude	**Lloyd-Minister**	**WY Sour**	**Red Water**	**CA**	**WTX Sour**	**CA Valley**	**Boscan**	**WTX Inter**
Original asphalt viscosity								
140°F, poise	864	1029	419	1055	1872	1862	3256	1992
275°F, cSt	283	289	179	309	327	243	562	569
Penetration, 0.1 mm								
(77°F, 100g, 5s)	160	98	133	135	55	53	70	64
(39.2°F, 100g, 5s)	15	6	7	9	0	2	2	4
Ductility, cm								
(39.2°F, 1 cm/min)	150+	40.1	137	150+	7.6	0	27.8	4.6
Softening point (R&B) °F	112	118	109	118	122	120	121	125
Component analysis, %								
Asphaltenes (n-heptane)	18.3	18.2	11	23	14.1	5.8	21.1	3.9
Asphaltenes (iso-octane)	3.4	2	3.1	3.4	3.1	3.3	2.8	
Polar aromatics	37.3	38.3	37.4	41.3	38.3	51.2	41.8	50.3
Napthene aromatics	31.8	33.4	37.1	25.1	37.7	32.5	30	41.9
Saturates	10.6	8.6	12.9	8.6	9.6	8.5	5.1	1.9

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Table 3.5. Asphalt characteristics (continued)

MRL Code	AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
Grade	**150/200**	**AC-10**	**AC-8**	**AR-4000**	**AC-20**	**AR-4000**	**AC-30**	**AC-20**
Crude	**Lloyd-minister**	**WY Sour**	**Red Water**	**CA**	**WTX Sour**	**CA Valley**	**Boscan**	**WTX Inter**
IEC separations (wt%)								
Strong acid*	6.4	15	7.5	11	15.4	18.1	3.7	4.7
SA	2790	2390		2500	1170	1080	2780	3040
Mol. Wt, VPO, toluene	11			15			15	9
Amphoterics*	6.4	9.2	7.4	7.8	6.1	12	8	10.4
Strong base	8.7	8.6	8.3	7.8	9.8	11.4	8.6	10
Weak acid	5	6.5	7.2	5.5	8.5	9.1	7.5	9.1
Weak base	59.6	56.9	68.2	51.7	56.7	50.4	52.5	53.4
Neutral				60		67.6	61.6	65
Neutrals plus acids**				25.7		18.5	24.3	18.5
Amphoterics**				9.3		12	9.9	14.3
Bases**								
Viscosity, Poise, 77°F	355	1553	3100	197	4795	2605	463	11910
SEC fraction, MW								
VPO, toluene								
I	11000	9200	7380	7000	8690	7900	10000	4600
SEC I, TFAAT aged	11500	9800	8400	13900	10100	7800	13000	5700
II								
Fraction II (wt%)	78.2	78.3	85.8	76.6	85.6	87.1	74.1	69.5
Visc. w/SEC fraction I removed (77°F, poise)	5064	13675	86020	3366	53350	623800	11240	263500
Visc. of whole asphalt, 77°F, Poise 10E-3	275.4	1125	945.4	405.7	3078	3540	1077	1123

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Table 3.5. Asphalt characteristics (continued)

MRL Code	AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
Grade	150/200	AC-10	AC-8	AR-4000	AC-20	AR-4000	AC-30	AC-20
Crude	Lloyd-minister	WY Sour	Red Water	CA	WTX Sour	CA Valley	Boscan	WTX Inter
Elemental analysis								
C (%)	83.9	82.3	86.5	81.6	84.5	85.6	83.7	86.8
H (%)	10	10.6	11.3	10.8	10.4	10.5	10.2	11.2
O (%)	0.6	0.8	0.9	0.9	1.1	1.1	0.8	0.5
Nitrogen (%)	0.5	0.54	0.66	0.77	0.55	1.1	0.7	0.55
Sulfur (%)	5.5	4.7	1.9	6.9	3.4	1.3	6.4	1.2
Vanadium, ppm	174	220	146	310	87	37	1480	58
Nickel, ppm	86	56	63	145	35	95	142	36
Fe, ppm	<1	16		13	100	48	24	255
Aromatic C (%)	28.1	31.9	24.7	23.7	32.8	28.3	31.9	24.7
Aromatic H (%)	7.68	7.12	6.41	6.81	8.66	7.27	6.83	6.51
Molecular weight. (toluene)	790	840	870	700	840	710	860	1300
Aged asphalt (Thin-film oven test)								
Mass Change %	-0.3115	-0.0362	-0.259	-0.8102	-0.092	-0.1799	-0.548	-0.0516
Viscosity								
140°F, poise	1901	2380	1014	3420	4579	3253	9708	3947
275°F, cSt	393	393	239	511	472	304	930	744
Viscosity Ratio (140°F)	2.2	2.31	2.42	3.24	2.45	1.75	2.98	1.98

*calculated
**new method

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Table 3.5. Asphalt characteristics (continued).

MRL Code	AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
Grade	150/200	AC-10	AC-8	AR-4000	AC-20	AR-4000	AC-30	AC-20
Crude	Lloyd-minister	WY Sour	Red Water	CA	WTX Sour	CA Valley	Boscan	WTX Inter
Viscoelastic properties	**WRI rheometer, 25°C, 25 mm plates, 3% strain**							
G', dyne/cm^{2}x-E06	1.243	1.47	1.07	1.498	1.066	0.472	1.596	1.701
G" x-E06	3.957	3.942	4.05	3.888	4.125	4.024	3.935	3.928
Viscosity (Poise) x-E06	0.16	0.506	0.572	0.195	2.376	2.318	0.782	1.389
Tan delta (G"/G')	3.183	2.682	3.786	2.596	3.87	8.914	2.466	2.309
G*, dyne/cm^{2}x-E06	4.148	4.207	4.189	4.166	4.26	4.23	4.247	4.28
Specification properties	**PTI rheometer, bending-beam rheometer**							
Td, Tank, °C	-19.3	-11.6	-5.5	-17.1	-7	-3.9	-14.7	1
Td, TFOT, °C	-14.3	-5.3	-3.8	-13.3	-1.4	0.8	-9.3	4.8
Td, PAV, °C	-14.5	-6	3.5	-8.7	5.2	2.7	-9.2	6
R, Tank	1.5	1.76	1.63	1.66	1.6	1.24	1.6	1.93
R, TFOT	1.75	2.06	1.8	1.8	1.77	1.35	1.8	2.21
R, PAV	1.9	2.13	2.1	2.07	2.02	1.44	1.94	2.61
m, (0.1s) (0°C)	0.53	0.42	0.39	0.5	0.32	0.28	0.42	0.29
Limiting Stiffness, 200MPa S(t)@ 2 h, °C	-31	-28	-25	-30	-21	-18	-27	-24
Ultimate strain at failure Strain, -26°C, 2 h, %	3.1	1.7	1.5	2.5	1.2	0.8	1.7	1.5
Viscous Stiffness@20°C log Sv, 0.1 s, Pa	6.77	7.2	7.17	7.07	7.67	7.5	7.58	7.82

Table 3.6. Summary of Specimen Preparation Procedure for SHRP A-003A Validation Study—Water-Sensitivity

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 mix, and the desired percent air-voids. Batch weights ranged between 125 to 132 kg (275 and 290 lb) at an air-void content of 8 ± 1 percent.
2	Prepare the asphalt and aggregate for mixing.
3	Heat the materials to the mixing temperature for the asphalt (170 ± 20 cSt). Mixing temperatures ranged between 137° and 160°C (279° and 320°F).
4	Mix the asphalt and aggregate for 4 minutes in a conventional concrete mixer fitted with infrared propane burners and preheated to the mixing temperature for the asphalt.
5	Age the mix at 135°C (275°F) in a forced-draft oven for 4 hours stirring the mix every hour to represent the amount of aging that occurs in the mixing plant.
6	Assemble and preheat the compaction mold using infrared heat lamps.
7	Place the mix in the compaction mold and level it using a rake while avoiding segregation of the mix.
8	Compact the mix 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 mix. Compaction temperatures (based on 630 ± 20 cSt) ranged between 112° and 133°C (234° and 271°F).
9	Allow the compacted mix to cool to room temperature (≈ 15 hr).
10	Disassemble the mold and remove the slab. Dry cut (saw) beams for the OSU and SWK/UN wheel trackers. Dry cut cores for the ECS.

The specimen preparation process is shown schematically in Figure 3.1. The mixer used consisted of a conventional concrete mixer modified to include infrared propane heaters (see Figure 3.2) to preheat the mixer bowl prior to mixing as well as to reduce heat loss during the mixing process. The preheated and preweighed aggregate is added to the mixer followed by the asphalt. The mix, typically 125 to 132 kg (275 to 290 lb), is mixed in one batch. After mixing, the asphalt-aggregate mix is placed in a forced-draft oven set to 135°C (275°F) and short-term aged for 4 hours to simulate the amount of aging that occurs in a batch or drum-dryer plant. The mix is stirred once each hour to promote uniform aging. At the completion of the aging process, the mix is placed in the mold and compacted to a predetermined density using a small steel wheel compactor with tandem rollers (e.g., a roller for compacting sidewalks and bike paths). The compactor used at OSU (Figure 3.3) weighed approximately 3260 lb (≈1480 kg). The compacted slab (Figure 3.4) was then allowed to cool overnight (15 hr) after which beam specimens were sawn and core specimens were drilled from the slab (Figure 3.5). The beams were sawn and the cores were drilled without water to prevent errors in density and void analysis as well as in initial air-permeability tests. For air-permeability tests and bulk specific gravity the specimen must be dry; water in voids can hinder the air-flow through the specimen, thus giving wrong air-flow numbers and air-permeability results.

3.4 Testing Methods

Each test program (ECS, OSU wheel-tracking, and SWK/UN wheel-tracking) employed specimen conditioning in its test procedure that subjected the specimen to water damage followed by measurement of rutting (OSU and SWK/UN wheel trackers) or reduction in modulus (ECS). This section briefly describes these procedures; detailed test methods are found elsewhere (Al-Joaib 1993).

3.4.1 OSU ECS Test

The test procedure employed in the ECS program consisted of inducing and monitoring water damage to 10-cm (4 in.) diameter by 10-cm (4 in.) high asphalt concrete cores. The procedure is briefly described in Table 3.7. Figure 3.6 shows a schematic of the equipment used in the ECS test program. The system consists of three components:

1) Environmental chamber with controlled temperature and humidity.

2) Fluid conditioning system that is essentially a constant head permeameter with the fluid medium being either water or conditioned air (dry or moist) and a thermocouple controller with four thermocouples installed on the ECS panel to monitor the temperature of

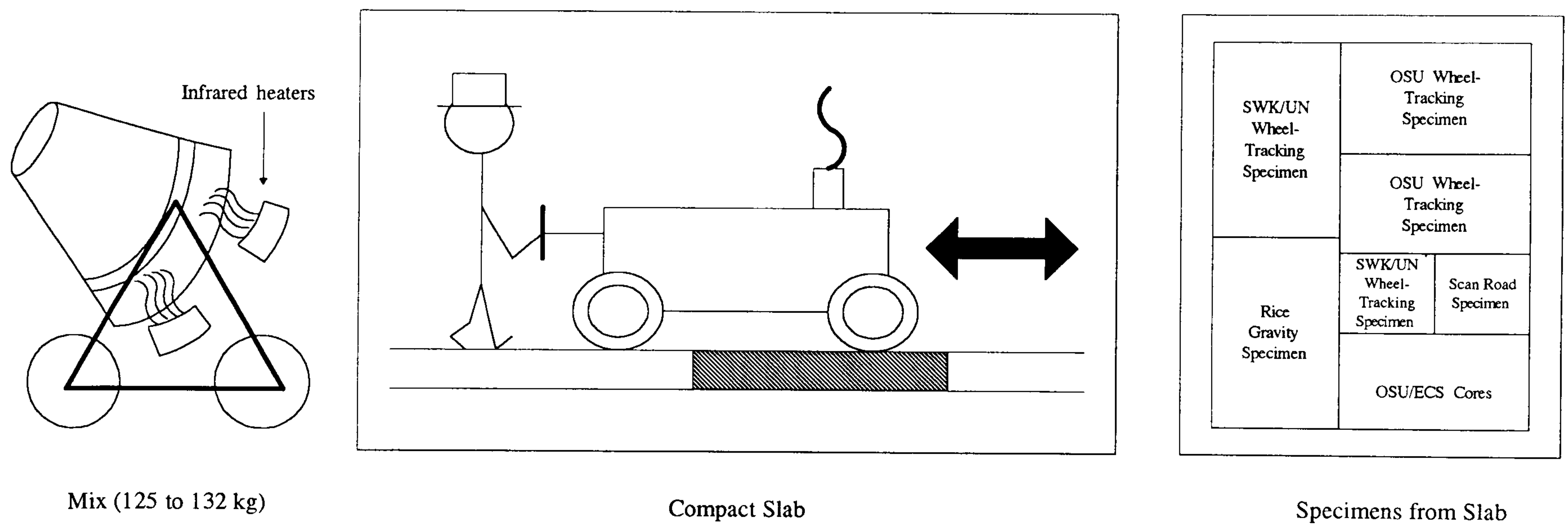

Fig. 3.1. Schematic of the specimen preparation process

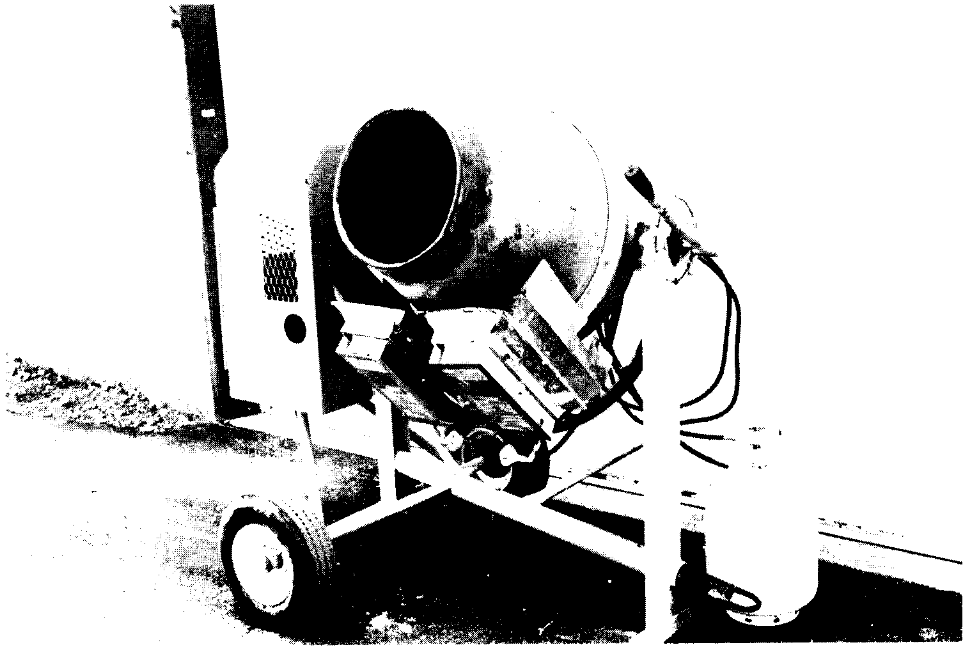

Fig. 3.2. Asphalt-aggregate mixer used at OSU

Fig. 3.3. Rolling wheel compactor used at OSU

Fig. 3.4. The compacted slab

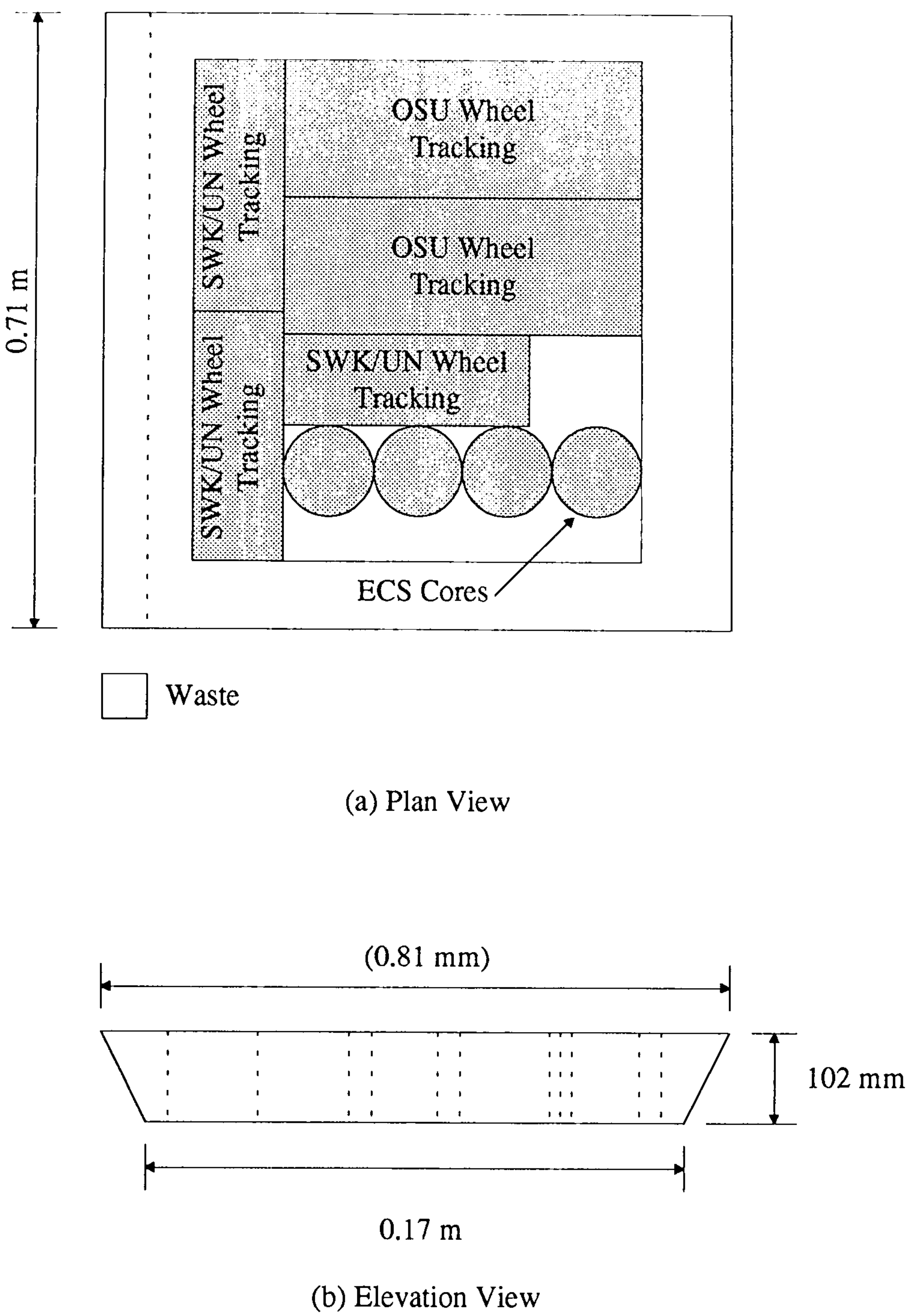

Fig. 3.5. Layout of specimens cut from the slab

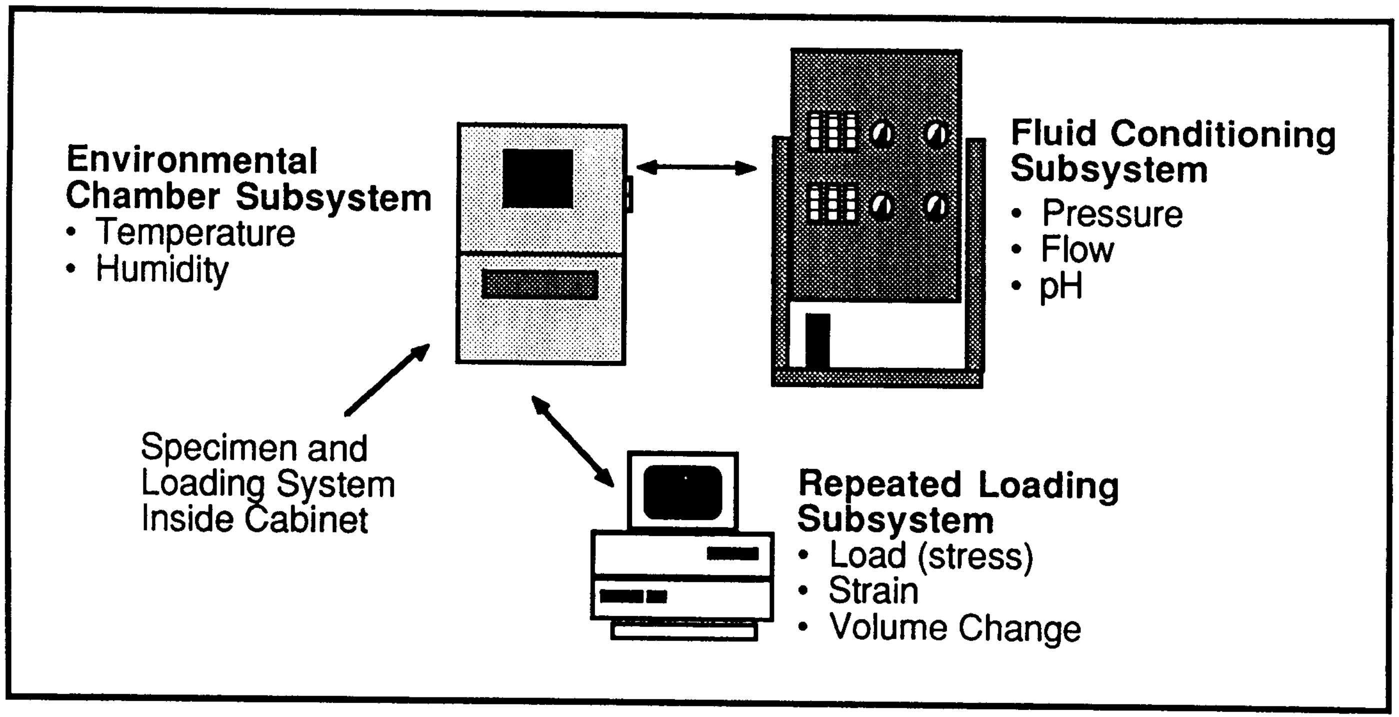

Fig. 3.6. Schematic of the ECS

Table 3.7. Summary of ECS Test Procedure

Step	Description
1	Prepare test specimens as described in Table 3.6. The specimen size is 4 inch (102 mm) diameter by 4 inch (102 mm) height.
2	Determine the geometric and gravimetric quantities of the core.
3	Place a silicone seal around the circumference of the core with a 6 inch membrane and allow the silicone cement to cure overnight ($\approx$24 h).
4	Mount the core specimen in the ECS load frame and determine the air-permeability of the core at various flow levels.
5	Determine the unconditioned (dry) resilient modulus.
6	Apply 20 inch (508 mm) Hg vacuum for 10 minutes.
7	Wet the core by pulling distilled water through the specimen for 30 minutes using a 20 inch (508 mm) Hg vacuum.
8	Determine the unconditioned water-permeability of the core.
9	Heat the wet specimen to 60°C (140°F) for 6 hours and apply axial repeated loading of 18 psi ($\approx$124 kPa). This constitutes a hot cycle.
10	Cool the wet specimen to 25°C (77°F) for 2 hours and measure the water-permeability and resilient modulus.
11	Repeat steps 8 and 9 for two (2) more hot cycles.
12	Cool the wet specimen to -18°C (0°F) for 6 hours. This constitutes a freeze cycle.
13	Heat the specimen to 25°C (77°F) for 2 hours and measure the water-permeability and resilient modulus.
14	Split the specimen and assess the percentage of stripping.
15	Plot water-permeability and resilient modulus ratios (conditioned to unconditioned) versus conditioning cycle.

the water before entering the specimen, after entering the specimen, and inside a dummy specimen in the chamber.

3) Computer-controlled loading and data acquisition system to monitor the axial resilient modulus (ECS-M_R) of the test specimen.

The ECS test is carried out to assess quantitatively the effect water has on the stiffness and permeability of an asphalt-aggregate mix. Prior to testing, gravimetric data (specific gravities) are obtained for the core specimen. The specimen is then encapsulated in a latex membrane with silicone. In the test, the dry (unconditioned) ECS-M_R and air-permeability are determined prior to introduction of water. The specimen is then wetted by flowing distilled water through the specimen under the action of a negative pressure relative to atmospheric pressure (i.e., vacuum) for 30 minutes. Upon completion of the wetting process, the water-permeability of the specimen is determined. The specimen is then subjected to thermal conditioning cycles, consisting of three hot cycles by heating the specimen to 60°C (140°F) and one freeze cycle by cooling the specimen to -18°C (0°F). The duration of each thermal cycle is 6 hours. Between cycles the specimen is brought to 25°C (77°F) and tested to determine the conditioned water-permeability and ECS-M_R, thus monitoring the effect water has on these properties as a function of the type and amount of environmental conditioning.

Important test parameters in the ECS test include the following:

1) All material property testing (modulus and permeability) is conducted at a temperature of 25°C (77°F). Also, only one specimen setup is needed, eliminating errors caused by handling when modulus or permeability test is conducted.

2) The modulus test is a triaxial test with a zero confining pressure (i.e., $\sigma_2 = \sigma_3 = 0$), herein referred to as an axial resilient modulus test. The load (i.e., deviator stress), in the form of a true haversian waveform having a duration of 0.1 s followed by a dwell time of 0.9 s, is targeted to be 40 psi ($\approx$275 kPa). Sufficient conditioning loads with magnitude equal to the target load are applied to the specimen prior to obtaining modulus data to ensure constant plastic deformation at the time data are obtained.

3) The test specimen is loaded automatically by a computer program that uses a closed-loop proportional-derivative (PD) feedback algorithm in conjunction with additional hardware to drive a servovalve-air-piston system and acquire load and deformation data. Such a system helps to minimize user errors.

4) Repeated loading of 18 psi ($\approx$124 kPa) is applied throughout the hot cycles to simulate traffic loading.

3.4.2 OSU Wheel-Tracking Test

The test procedure employed in the OSU wheel-tracking program consisted of inducing water damage to beams of asphalt-aggregate mixes having dimensions of approximately 19 inches long by 6.5 inches wide by 4 inches deep ($\approx$483 mm $\times$ 165 mm $\times$ 102 mm) and monitoring the rut-depth developed in the OSU wheel tracker. Figure 3.7 shows a photograph of the OSU wheel tracker and Figure 3.8 is a schematic of this equipment. The procedure is briefly described in Table 3.8. Note that dry (unconditioned) specimens were not tested since the purpose of the program was to rank the materials (to validate the A-002A predictions), which required that all specimens be tested in the same manner.

The OSU wheel-tracking test, a torture test, is performed to obtain a relative measure of the rutting resistance among asphalt-aggregate mixes after the mixes have been subjected to water-conditioning. Prior to testing, gravimetric data are obtained for the beam specimen followed by subjecting the specimen to water-conditioning. The conditioning procedure employed to induce water damage in the beams used for the OSU wheel-tracking program is essentially the same as that for the ECS test program, except for the following minor differences:

1) The wetting procedure for the wheel-tracking test program employs a slightly higher vacuum level and a significantly longer wetting time than that for the ECS test to achieve the target saturation level of 60 to 80 percent in the larger beam specimens, although a few beams did not reach the this level.

2) The duration of some of the conditioning cycles is longer in the OSU wheel-tracking test procedure than in the ECS test procedure because of scheduling constraints of some of the equipment used for thermal conditioning.

3) The order of conditioning cycles for the wheel-tracking program is slightly different from that of the ECS test program, also because of scheduling constraints of some of the equipment used for thermal conditioning.

Once the beam specimen has undergone water and thermal conditioning, the specimen is wrapped in plastic (e.g., Saran wrap) to prevent moisture loss. The specimen is then placed in a mold for subsequent testing in the OSU wheel tracker. Thin expanded foam sheets are placed between the specimen and the mold walls to prevent movement under the action of the rolling wheel. A Teflon sheet approximately 3 mm (1/8 in.) thick and having the same plan dimensions as the specimen is placed under the specimen to minimize the friction that develops between the specimen and base platen during the test. The mold is then placed in the wheel tracker and brought to the test temperature of 40°C (104°F). The plastic wrap is removed from the top surface of the specimen so as to prevent the plastic from being picked up by the pneumatic tire.

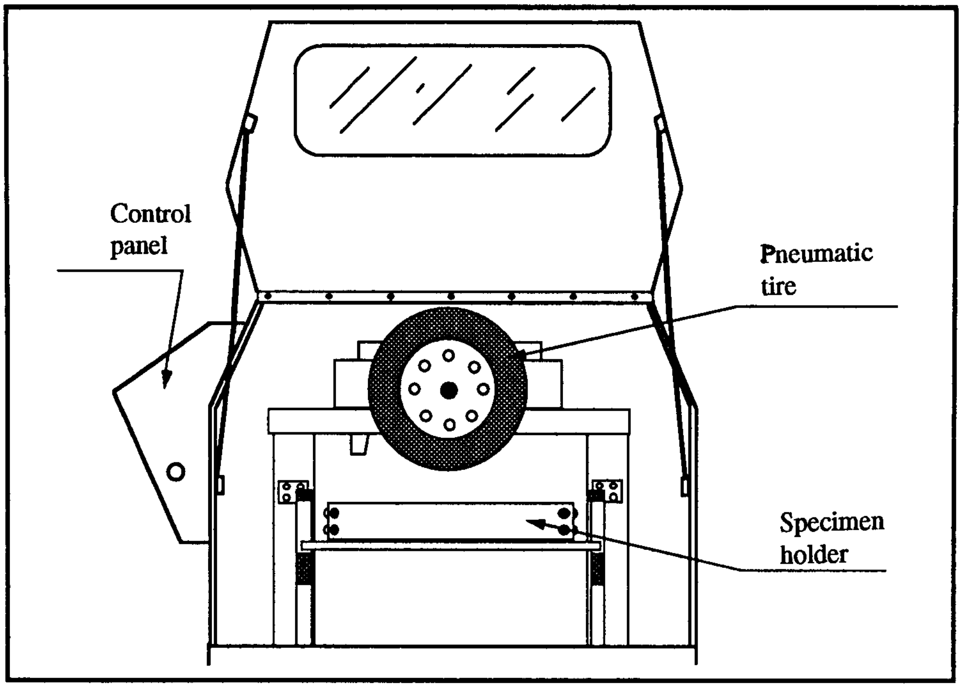

Fig. 3.7. The OSU wheel tracker

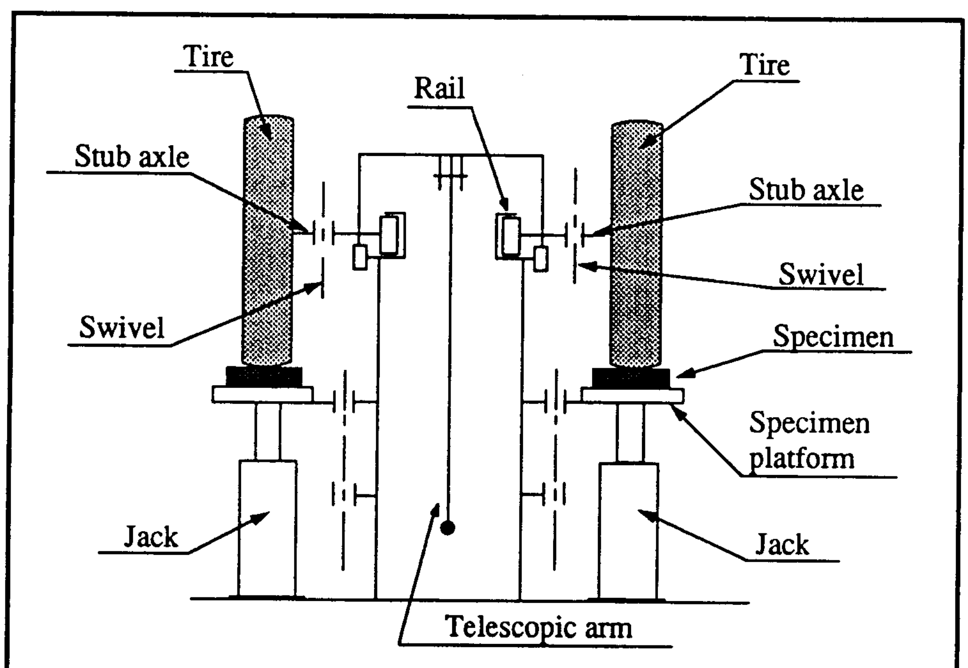

Fig. 3.8. Schematic of the OSU wheel tracker

Table 3.8. Summary of OSU Wheel-Tracking Test Procedure

Step	Description
1	Prepare test specimens as described in Table 3.6.
2	Determine the gravimetric quantities of the beam.
3	Place a circumferential silicone cement seal around the beam at midheight and allow the silicone cement to cure overnight ($\approx$24 hr).
4	Apply 20-inch Hg (508) Hg vacuum for 10 minutes.
5	Wet the beam specimen by pulling distilled water through the specimen under a 23-inch (584 mm) vacuum level for up to 2 hours or until a degree of saturation of at least 60 is obtained.
6	Subject the wet beam specimen to wet thermal conditioning cycles as follows: • Heat the specimen to 60°C (140°F) in a distilled water bath for 6 hours. • Cool the specimen to 25°C (77°F) in a distilled water bath for 10 hours. • Heat the specimen to 60°C (140°F) in a distilled water bath for 6 hours. • Cool the specimen to -20°C (-4°F) in a distilled water bath for 8 hours. • Heat the specimen to 60°C (140°F) in a distilled water bath for 10 hours. • Cool the specimen to 25°C (77°F) in a distilled water bath for 10 hours.
7	Wrap the specimen in plastic (e.g., Saran wrap) to retain moisture in the specimen during the rutting phase.
8	Place the conditioned beam specimen in the rutting tester and heat the specimen to 40°C (104°F).
9	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.
10	Plot rut-depth versus wheel passes.
11	Core the rutted beam specimen along the wheel track to obtain cores for stripping evaluation. Split the cores and assess the percentage of stripping.

After the specimen reaches the test temperature, determined by a thermocouple probe inserted in a hole drilled in the specimen, preconditioning wheel loads of 50 wheel passes at 92 psi ($\approx$635 kPa) are applied to the beam specimen to eliminate the high plastic deformations characteristic of asphalt-aggregate mixes at the onset of loading. After preconditioning, the load is removed and measurements are obtained to establish the base-line specimen surface profile. Figure 3.9 shows the 15 positions in which surface profile measurements are obtained. These measurements are obtained electronically (i.e., via computer), using a displacement transducer specifically designed for these measurements. Note that the measurement positions are concentrated near the center of the specimen along its longitudinal axis to avoid measurement of high plastic deformations that occur in the region where the rolling wheel slows down, stops, and finally reverses direction (i.e., at the ends of the wheel travel).

The wheel load is then reapplied and increased to 100 psi ($\approx$690 kPa). Testing commences by applying up to 10,000 wheel passes or until failure occurs (as established by a sudden and significant increase in plastic deformation). At intervals of 100, 200, 500, 1,000, 2,000, and 5,000 wheel passes, the load is temporarily removed so that surface profile measurements can be obtained. After 10,000 wheel passes (or when loading is terminated because of specimen failure), the final surface profile is determined. From these data the rut-depth is determined as a function of the number of wheel passes.

Important parameters in the OSU wheel-tracking test include the following:

1) Wheel: pressurized pneumatic tire, 40.6 cm (16 in.) diameter by 10.2 cm (4.0 in.) width; smooth tread with 83 mm (3.25 in.) width.

2) Preconditioning load: 50 wheel passes at 92 psi ($\approx$635 kPa) actual contact pressure.

3) Test load: 10,000 wheel passes at 100 psi ($\approx$690 kPa) actual contact pressure (1,600-lb. load with tire tread contact area of 16 in^2).

4) Load frequency: 60 cycles per minute (120 wheel passes per min.).

5) Test specimen temperature: 40°C (104°F).

6) Confinement: base provides reaction to the load; initially unconfined on sides, partially confined as specimen deforms.

7) Environment: conditioned specimen wrapped in plastic (except for the top surface) tested in air at 40°C (104°F).

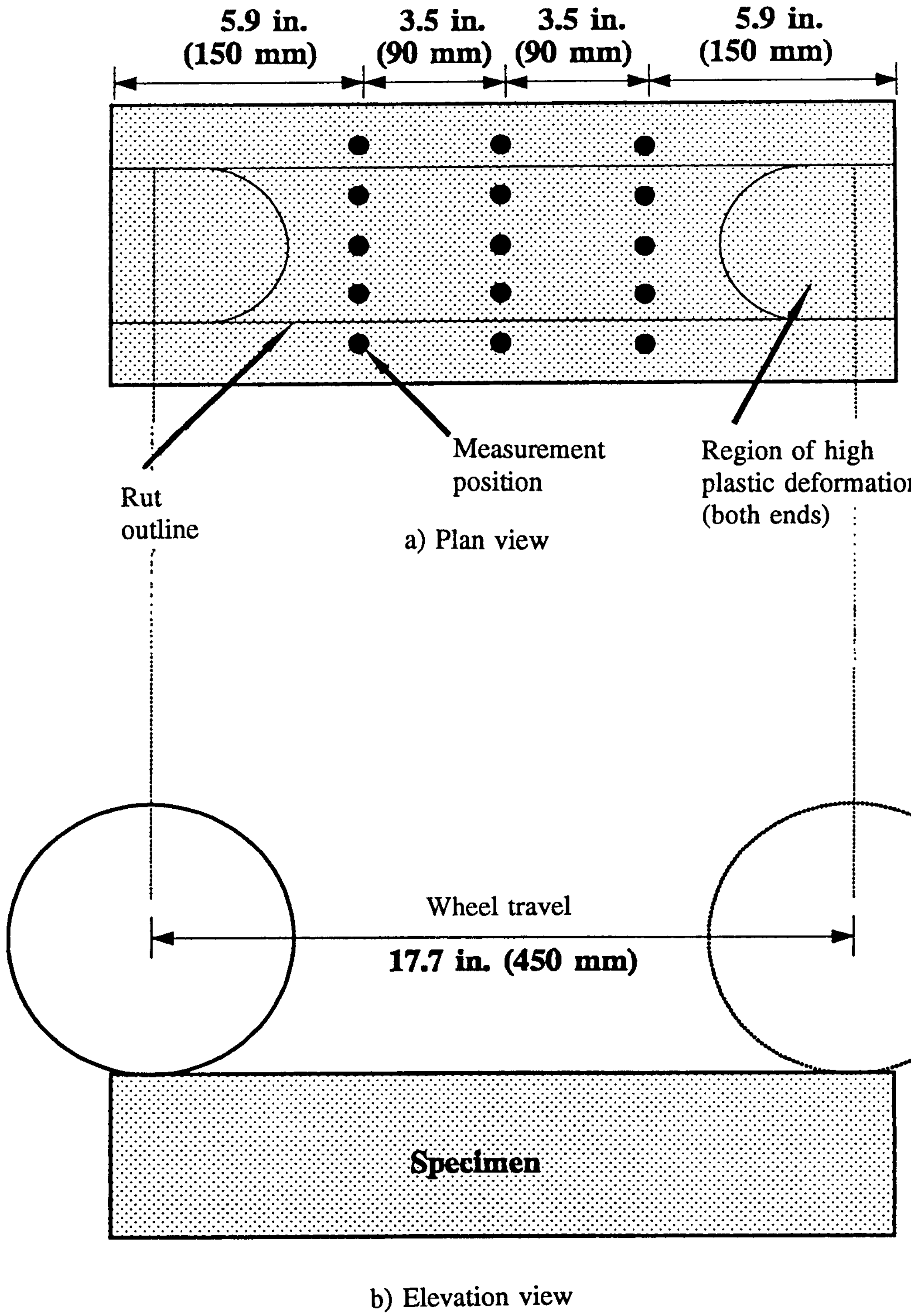

Fig. 3.9. Deformation measurement positions in the OSU wheel tracker

3.4.3 SWK/UN Wheel-Tracking Test

The test procedure employed in the SWK/UN wheel-tracking program consisted of inducing water damage to beams of asphalt-aggregate mixes having dimensions of approximately 12 inches long by 3.5 inches wide by 1 inch deep (305 mm × 90 mm × 25 mm) and monitoring the specimen surface deformation developed in the SWK/UN wheel tracker. Figure 3.10 provides a schematic of this equipment. The SWK/UN wheel-tracking test, also a torture test, is carried out to obtain a relative measure of the rutting resistance among asphalt-aggregate mixes after the mixes have been subjected to water-conditioning. Prior to testing, gravimetric data are obtained for the beam specimen. The specimen is then bonded in the mold for subsequent conditioning and testing (Figure 3.11). The specimen is then subjected to water-conditioning. Note that significant differences exist between the wheel-tracking test conditioning procedures at OSU and SWK/UN (compare Tables 3.8 and 3.9). In particular, note that the duration and number of cycles are quite different. The temperatures for conditioning and testing are the same however.

Once the specimen has been water-conditioned, it is placed in the wheel tracker and brought to the temperature of 40°C (104°F). The specimen is submerged in a water bath during the SWK/UN wheel-tracking test. The specimen is then loaded with the wheel and testing commences. The test continues until failure (as determined by a sudden and significant increase in plastic deformation of the specimen) or, alternately, until seven days of loading (≈500,000 wheel passes) have occurred. Every 20 wheel passes deformation data are obtained that consist of measurements of the vertical position of the wheel via LVDTs and a strip-chart recorder.

Key parameters regarding the SWK/UN wheel-tracking test include the following:

1) Wheel: steel wheel, 20.16 cm (7.9 in.) diameter by 50.4 mm (2 in.) width.

2) Preconditioning load: none.

3) Test load: up to 500,000 wheel passes at 41 pounds (181 N).

4) Load frequency: 25 cycles per minute (50 wheel passes per minute).

5) Test specimen temperature: 40°C (104°F).

6) Confinement: confined on all sides throughout the test; the base provides reaction to the load.

7) Environment: conditioned specimen tested submerged in water at 40°C (104°F).

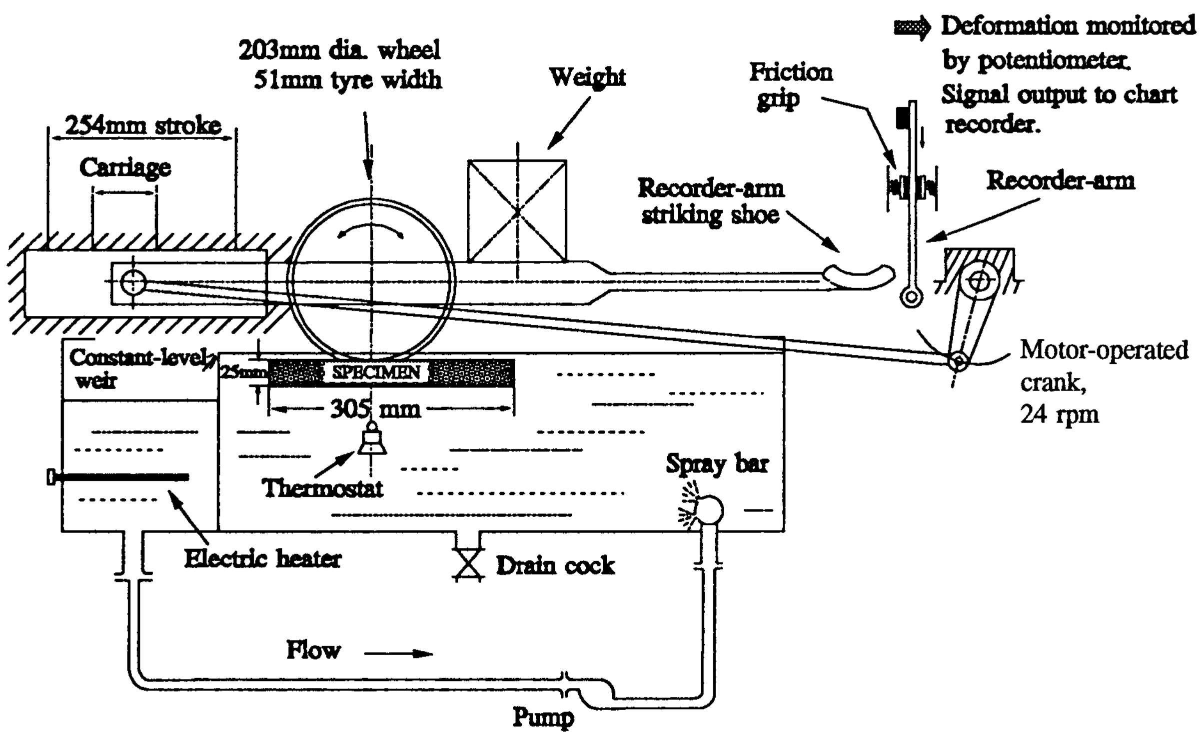

Fig. 3.10. Schematic of the SWK/UN wheel tracker

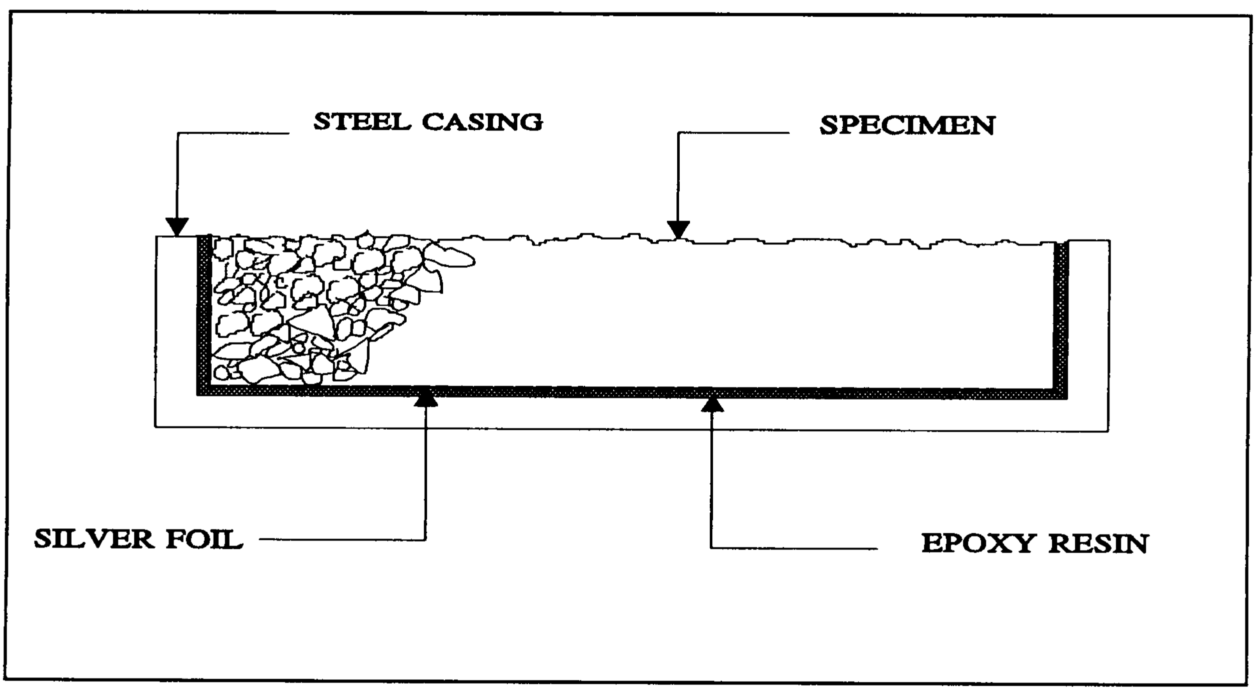

Fig. 3.11. Schematic of test specimen fixed into the mold of SWK/UN wheel tracker

Table 3.9. Summary of SWK/UN Wheel-Tracking Procedure

Step	Description
1	Prepare specimens (at OSU) as described in Table 3.6. Ship to the University of Nottingham.
2	Saw the specimen to size and determine gravimetric quantities for the beam specimen.
3	Condition the beam specimen as follows: • Soak specimen in water at 140°F (60°C) for 120 hours. • Freeze specimen in air at -20°C (-4°F) for 24 hours. • Soak specimen in water at 60°C (140°F) for 24 hours. • Soak specimen in water at 40°C (104°F) for 2 hours.
5	Perform the SWK/UN wheel-tracking test on the conditioned specimen until failure or, alternatively if no failure occurs, after seven days of testing ($\approx$500,000 wheel passes). The specimen is submerged in 40°C (104°F) water during the test. Deformation measurements, as determined by the vertical position of the wheel, are recorded every 20 wheel passes.
6	Report time-to-failure in hours.

4

Results

This chapter presents the results of the validation efforts for water-sensitivity. The results obtained in the Environmental Conditioning Systems (ECS) and Oregon State University (OSU) wheel-tracking programs conducted at OSU as well as those obtained in the SWK Pavement Engineering/University of Nottingham (SWK/UN) wheel-tracking program conducted at the University of Nottingham (UK) are included.

4.1 ECS Test Program

The mixes tested in the ECS program are summarized in Tables 4.1 through 4.4. As indicated, two tests were conducted on each mix, thus exceeding the minimum requirement of eight repeated tests. Tables 4.1 through 4.4 summarize the ECS test program data by aggregate: RC, RD, RH, and RJ, respectively. They include average data for each mix, and all data are included in Appendix A.

The test results for the ECS test program are shown graphically in Figures 4.1 through 4.4. Note that each data point represents the average of two tests and that the line connecting the data points represents the trend in retained resilient modulus (ECS-M_R) ratio as a function of conditioning level (each 6-hour block represents a conditioning cycle with the first three cycles being hot cycles and the last cycle being the freeze cycle); that is, the plots show the ratio of conditioned resilient modulus to unconditioned resilient modulus for several conditioning cycles. Thus, the ECS-M_R ratio provides an indication of the amount of water damage sustained by the test specimen with the dry (and unconditioned) ECS-M_R being the datum.

Figure 4.1 shows the effect of ECS conditioning on all RC mix combinations. The preconditioning stage and first conditioning cycle cause the asphalt to soften and mix to exhibit cohesion loss. Cohesion loss is the first step of water damage, and cohesion loss tends to enhance or accelerate the adhesion-loss mechanism. After the first cycle, mixes

Table 4.1. **Summary of ECS Tests Data for RC Mixes**

Asphalt Type	Air Voids (%)	Cycle No.	ECS MR (ksi)	Retained MR Ratio	Water Perm. E-3 cm/s	Retained Perm. Ratio	Stripping Rate (%)
AAA-1	8.7	0	190.0	1.00	4.41	1.00	
	8.7	1	184.0	0.97	3.58	0.81	
	8.7	2	180.0	0.95	2.89	0.66	
	8.7	3	172.5	0.91	2.87	0.65	
	8.7	4	162.5	0.86	2.56	0.58	15.0
AAB-1	9.4	0	252.5	1.00	4.68	1.00	
	9.4	1	245.5	0.97	3.53	0.76	
	9.4	2	228.0	0.90	2.78	0.59	
	9.4	3	226.0	0.90	2.76	0.59	
	9.4	4	206.5	0.82	2.46	0.53	15.0
AAC-1	9.0	0	305.0	1.00	4.96	1.00	
	9.0	1	262.5	0.86	3.69	0.74	
	9.0	2	255.0	0.84	3.20	0.65	
	9.0	3	251.5	0.82	2.71	0.55	
	9.0	4	228.5	0.75	2.28	0.46	20.0
AAD-1	9.0	0	238.0	1.00	1.88	1.00	
	9.0	1	202.0	0.85	2.03	1.08	
	9.0	2	192.5	0.81	1.87	0.99	
	9.0	3	186.0	0.78	1.71	0.91	
	9.0	4	181.0	0.76	1.64	0.87	10.0
AAF-1	8.7	0	485.0	1.00	5.83	1.00	
	8.7	1	468.0	0.96	2.53	0.43	
	8.7	2	423.0	0.87	2.14	0.37	
	8.7	3	385.0	0.79	1.81	0.31	
	8.7	4	374.5	0.77	1.63	0.28	20.0
AAG-1	10.3	0	362.5	1.00	8.97	1.00	
	10.3	1	354.0	0.98	4.99	0.56	
	10.3	2	338.5	0.93	4.12	0.46	
	10.3	3	321.5	0.89	3.47	0.39	
	10.3	4	292.0	0.81	2.27	0.25	20.0
AAK-1	9.3	0	265.0	1.00	7.41	1.00	
	9.3	1	238.0	0.90	4.68	0.63	
	9.3	2	235.8	0.89	4.02	0.54	
	9.3	3	231.0	0.87	3.64	0.49	
	9.3	4	217.8	0.82	3.39	0.46	15.0
AAM-1	10.1	0	255.0	1.00	9.60	1.00	
	10.1	1	245.1	0.96	5.91	0.62	
	10.1	2	236.0	0.93	4.91	0.51	
	10.1	3	235.5	0.92	4.18	0.43	
	10.1	4	226.1	0.89	4.02	0.42	10.0

ksi = 6,890 kPa

Table 4.2. **Summary of ECS Tests Data for RD Mixes**

Asphalt Type	Air Voids (%)	Cycle No.	ECS MR (ksi)	Retained MR Ratio	Water Perm. E-3 cm/s	Retained Perm. Ratio	Stripping Rate (%)
AAA-1	8.1	0	187.3	1.00	1.92	1.00	
	8.1	1	183.3	0.98	3.40	1.77	
	8.1	2	179.1	0.96	2.98	1.55	
	8.1	3	176.4	0.94	2.80	1.46	
	8.1	4	174.8	0.93	2.72	1.42	10.0
AAB-1	8.0	0	277.5	1.00	4.81	1.00	
	8.0	1	262.5	0.95	4.69	0.98	
	8.0	2	245.1	0.88	4.13	0.86	
	8.0	3	241.7	0.87	3.96	0.82	
	8.0	4	234.5	0.85	3.56	0.74	5.0
AAC-1	8.6	0	265.0	1.00	9.93	1.00	
	8.6	1	255.0	0.96	7.22	0.73	
	8.6	2	248.5	0.94	6.75	0.68	
	8.6	3	240.2	0.91	6.44	0.65	
	8.6	4	234.8	0.89	6.44	0.65	5.0
AAD-1	9.0	0	206.5	1.00	7.20	1.00	
	9.0	1	201.5	0.98	5.41	0.75	
	9.0	2	182.9	0.89	4.20	0.58	
	9.0	3	174.4	0.84	4.78	0.66	
	9.0	4	174.6	0.85	4.73	0.66	10.0
AAF-1	9.7	0	570.0	1.00	4.38	1.00	
	9.7	1	547.5	0.96	5.80	1.33	
	9.7	2	514.8	0.90	5.52	1.26	
	9.7	3	498.9	0.88	5.21	1.19	
	9.7	4	490.0	0.86	5.04	1.15	10.0
AAG-1	8.2	0	528.0	1.00	1.12	1.00	
	8.2	1	491.7	0.93	2.36	2.10	
	8.2	2	473.5	0.90	2.18	1.94	
	8.2	3	464.9	0.88	2.17	1.93	
	8.2	4	488.1	0.92	2.14	1.91	15.0
AAK-1	8.4	0	290.0	1.00	2.42	1.00	
	8.4	1	274.6	0.95	3.40	1.40	
	8.4	2	271.1	0.93	3.45	1.43	
	8.4	3	170.0	0.93	3.43	1.42	
	8.4	4	276.3	0.95	3.43	1.42	5.0
AAM-1	10.3	0	357.5	1.00	1.45	1.00	
	10.3	1	342.8	0.96	3.06	2.11	
	10.3	2	324.7	0.91	2.55	1.76	
	10.3	3	316.5	0.89	2.79	1.93	
	10.3	4	318.5	0.89	2.81	1.94	5.0

ksi = 6,890 kPa

Table 4.3. Summary of ECS Tests Data for RH Mixes

Asphalt Type	Air Voids (%)	Cycle No.	ECS MR (ksi)	Retained MR Ratio	Water Perm. E-3 cm/s	Retained Perm. Ratio	Stripping Rate (%)
AAA-1	8.0	0	126.5	1.00	5.85	1.00	
	8.0	1	119.2	0.94	4.62	0.79	
	8.0	2	113.7	0.90	4.29	0.73	
	8.0	3	120.3	0.95	3.46	0.59	
	8.0	4	118.7	0.94	3.78	0.65	7.5
AAB-1	8.3	0	230.0	1.00	0.06	1.00	
	8.3	1	226.5	0.98	2.50	45.05	
	8.3	2	208.5	0.91	2.09	37.66	
	8.3	3	212.5	0.92	2.09	37.66	
	8.3	4	208.5	0.91	1.79	32.25	10.0
AAC-1	6.9	0	230.5	1.00	0.00		
	6.9	1	252.0	1.09	0.12	1.00	
	6.9	2	269.5	1.17	0.09	0.74	
	6.9	3	259.5	1.13	0.07	0.60	
	6.9	4	259.5	1.13	0.06	0.55	10.0
AAD-1	7.3	0	201.0	1.00	0.00		
	7.3	1	192.0	0.96	1.43	1.00	
	7.3	2	190.5	0.95	1.88	1.32	
	7.3	3	185.5	0.92	1.44	1.01	
	7.3	4	184.0	0.92	1.61	1.13	7.5
AAF-1	7.3	0	564.5	1.00	0.08	1.00	
	7.3	1	471.7	0.84	1.41	17.58	
	7.3	2	431.3	0.76	1.22	15.19	
	7.3	3	446.7	0.79	1.16	14.44	
	7.3	4	444.0	0.79	1.14	14.25	10.0
AAG-1	6.4	0	625.0	1.00	0.05	1.00	
	6.4	1	566.8	0.91	2.33	46.50	
	6.4	2	555.5	0.89	0.13	2.60	
	6.4	3	553.4	0.89	0.09	1.80	
	6.4	4	551.4	0.88	0.07	1.30	10.0
AAK-1	8.0	0	364.5	1.00	1.68	1.00	
	8.0	1	306.5	0.84	2.65	1.57	
	8.0	2	301.0	0.83	2.69	1.60	
	8.0	3	287.5	0.79	2.22	1.32	
	8.0	4	284.0	0.78	2.02	1.20	15.0
AAM-1	7.0	0	415.0	1.00	0.00		
	7.0	1	346.0	0.83	2.29	1.00	
	7.0	2	322.3	0.78	0.14	0.06	
	7.0	3	332.5	0.80	1.50	0.65	
	7.0	4	327.2	0.79	1.44	0.63	10.0

ksi = 6,890 kPa

Table 4.4. **Summary of ECS Tests Data for RJ Mixes**

Asphalt Type	Air Voids (%)	Cycle No.	ECS MR (ksi)	Retained MR Ratio	Water Perm. E-3 cm/s	Retained Perm. Ratio	Stripping Rate (%)
AAA-1	8.2	0	145.5	1.00	2.09	1.00	
	8.2	1	135.4	0.93	1.26	0.60	
	8.2	2	129.4	0.89	0.94	0.45	
	8.2	3	128.5	0.88	0.34	0.16	
	8.2	4	126.7	0.87	0.08	0.04	7.5
AAB-1	8.4	0	337.5	1.00	4.54	1.00	
	8.4	1	328.8	0.97	1.66	0.37	
	8.4	2	286.2	0.85	0.54	0.12	
	8.4	3	281.7	0.83	0.14	0.03	
	8.4	4	273.1	0.81	0.13	0.03	12.5
AAC-1	7.2	0	300.0	1.00	4.29	1.00	
	7.2	1	241.5	0.81	3.95	0.92	
	7.2	2	219.5	0.73	3.04	0.71	
	7.2	3	212.3	0.71	2.41	0.56	
	7.2	4	209.0	0.70	2.25	0.53	7.5
AAD-1	7.5	0	185.0	1.00	3.74	1.00	
	7.5	1	157.7	0.85	1.86	0.50	
	7.5	2	148.0	0.80	0.31	0.03	
	7.5	3	145.5	0.79	0.11	0.03	
	7.5	4	138.9	0.75	0.08	0.02	10.0
AAF-1	8.5	0	426.3	1.00	1.87	1.00	
	8.5	1	424.0	0.99	0.88	0.47	
	8.5	2	406.4	0.95	0.71	0.38	
	8.5	3	385.2	0.90	0.31	0.17	
	8.5	4	355.0	0.83	0.04	0.02	20.0
AAG-1	8.8	0	352.5	1.00	5.85	1.00	
	8.8	1	302.6	0.86	2.73	0.47	
	8.8	2	264.9	0.75	2.35	0.40	
	8.8	3	236.6	0.67	2.09	0.36	
	8.8	4	240.6	0.68	1.98	0.34	10.0
AAK-1	8.5	0	265.0	1.00	4.22	1.00	
	8.5	1	218.6	0.82	3.71	0.88	
	8.5	2	214.2	0.81	3.34	0.79	
	8.5	3	203.1	0.77	3.19	0.76	
	8.5	4	213.0	0.80	3.37	0.80	5.0
AAM-1	8.6	0	299.0	1.00	2.43	1.00	
	8.6	1	272.8	0.91	2.14	0.88	
	8.6	2	260.7	0.87	2.01	0.83	
	8.6	3	245.9	0.82	1.60	0.66	
	8.6	4	234.1	0.78	0.87	0.36	12.5

ksi = 6,890 kPa

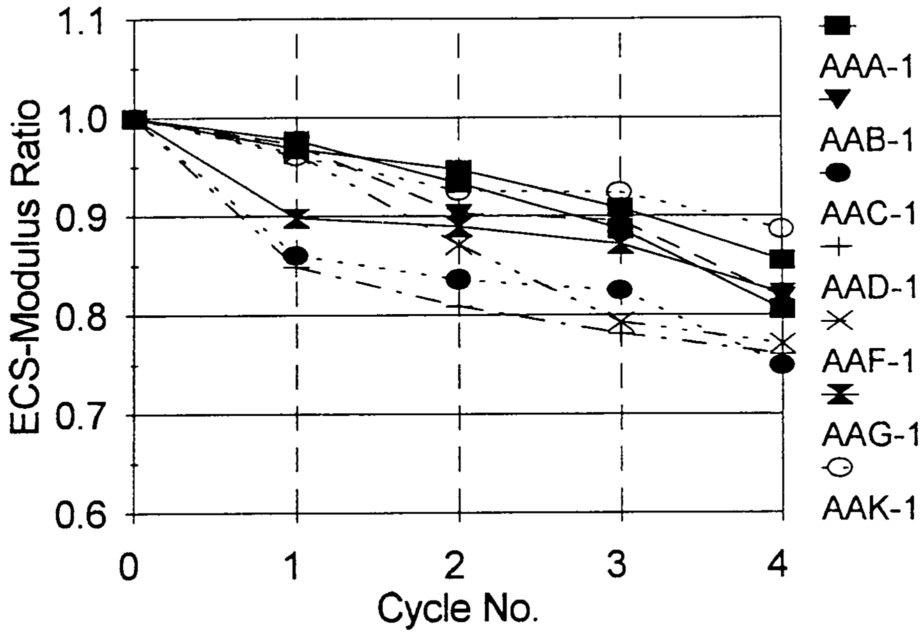

Fig. 4.1. ECS test results for the RC aggregate

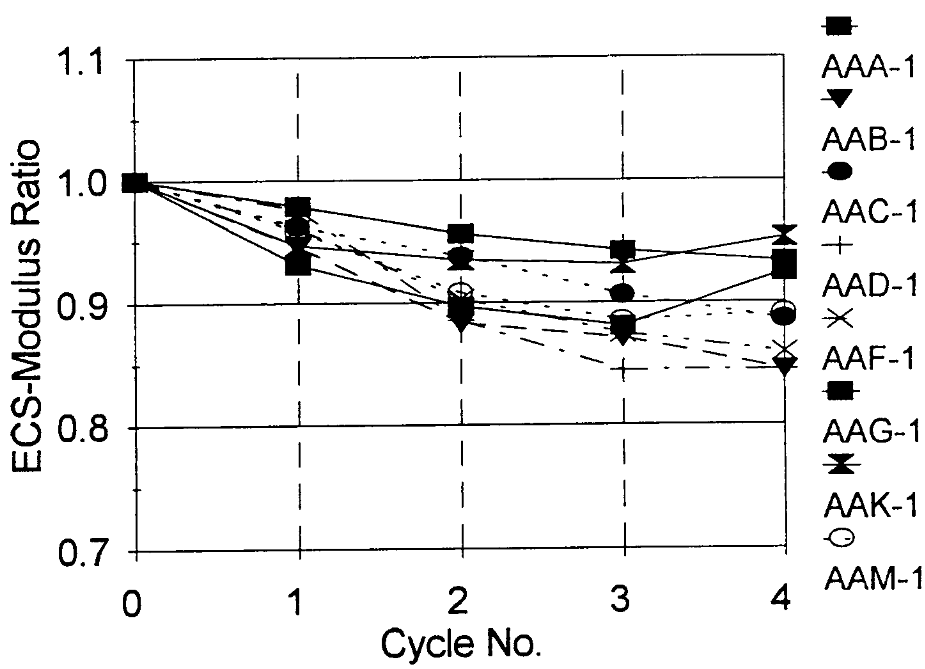

Fig. 4.2. ECS test results for the RD aggregate

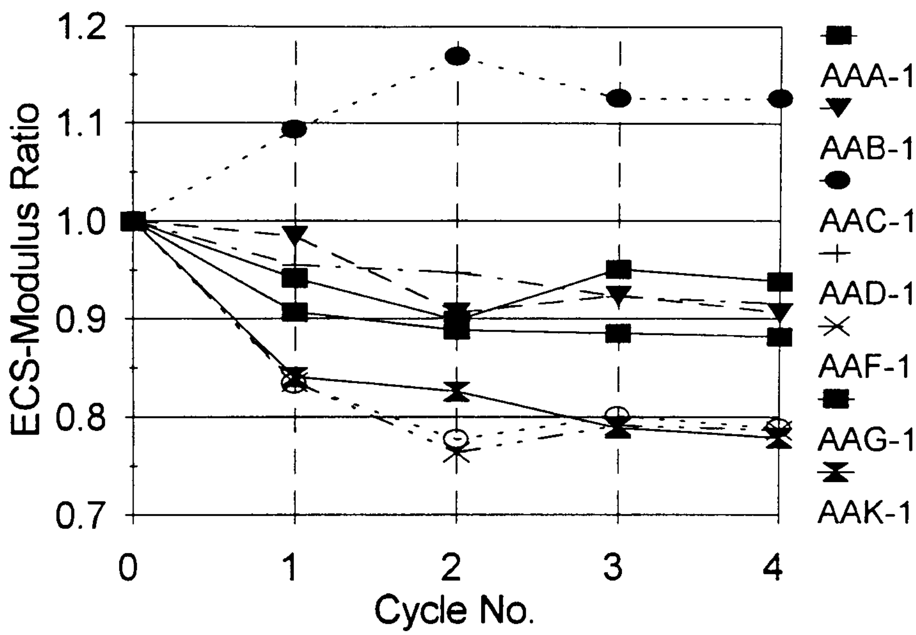

Fig. 4.3. ECS test results for the RH aggregate

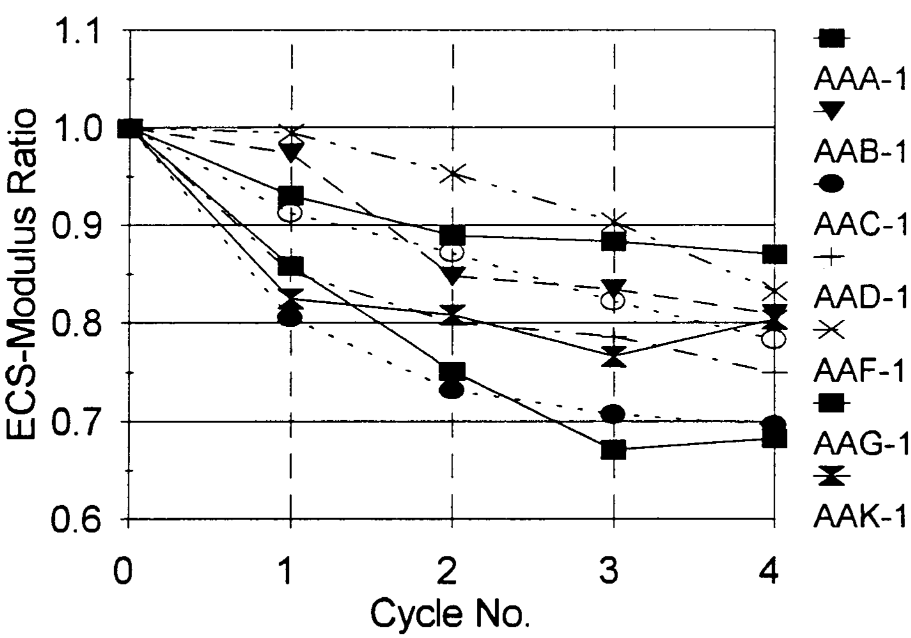

Fig. 4.4. ECS test results for the RJ aggregate

that have good cohesion properties (i.e., do not lose strength after the first cycle) are not affected by successive ECS conditioning cycles (i.e., good cohesion improves adhesion or hinders the adhesion-loss).

Other mixes that are susceptible to cohesion loss tend to lose substantial strength after the first cycle. After the first cycle, mixes that are susceptible to moisture-damage through adhesion-loss tend to continue losing strength with each conditioning cycle. Figure 4.1 shows that after one cycle of ECS conditioning, the different asphalts fall into two groups. Three asphalts (AAK-1, AAD-1, and AAC-1) that are at or below 0.9 ECS-M_R ratio are highly susceptible to moisture-damage and tend to continue to lose strength with each cycle (cohesion loss at first cycle leads to more adhesion-loss). The other asphalts (not affected by the first cycle) tend to exhibit small and gradual loss of strength with each cycle. Mix RC/AAF-1 is an exception to these observations, because some mixes that are not thoroughly wetted (because of low initial permeability) have minimal cohesion loss. However, after first cycle the permeability increases and leads to further moisture-damage.

The crisscrossing of the curves for the different asphalts emphasizes that ECS results are dependent on the asphalt type for any given aggregate. Also, ECS results showed that the behavior of the different mixes change with each cycle (i.e., ranking of mixes changes with each cycle). In the fourth cycle (freeze) all eight mixes lost strength. In the ECS tests poor aggregates tended to disintegrate throughout the freeze cycle—another moisture-damage phenomena. In aggregate processing and sample preparation, RC aggregate disintegrated. Also, RC aggregate is absorptive (i.e., tends to absorb moisture). This absorptive character enhances the disintegration potential when subjected to freeze cycle.

Figure 4.2 shows the ECS conditioning effects on all RD aggregate mixes. RD mixture combinations were less susceptible to ECS conditioning. All mixes showed very slow gradual decrease in strength, i.e., good moisture-damage resistance. The freeze cycle did not have a significant effect on the strength of the mixes, which can be explained by the fact that RD aggregate is nonabsorptive.

Figure 4.3 is a plot of all RH mixes and shows a wide spread of data. After one cycle three asphalts lost more than 10 percent of ECS-M_R ratio (AAF-1, AAK-1, and AAM-1). The other five mixes showed ECS-M_R ratio of 0.9 or better. Each group maintained its set of mixes after each cycle, and both groups of asphalts continued to lose strength at very slow rates, which emphasizes that the three asphalt mixes that showed ECS-M_R ratio below 0.9 after one cycle showed cohesion-loss behavior and not much adhesion-loss. The other five asphalt mixes that have ECS-M_R ratio above 0.9 showed little cohesion and adhesion-loss (i.e., high moisture-damage resistance). Through the freeze cycle, constant strength was maintained, i.e., little moisture-damage and aggregate degradation.

Figure 4.4 shows a plot of aggregate RJ results, and the same observations that were made in aggregate RC can be made here. RJ mixes showed significant moisture susceptibility; each continued ECS-M_R loss especially after the first cycle. RJ aggregate proved to be a stripping aggregate (SHRP A-003B). All mix combinations showed gradual decrease in strength after conditioning cycle.

Figure 4.5 is an example of water-permeability plots for RC aggregate. Figure 4.5 shows the change in water-permeability ratio after each conditioning cycle. The water-permeability normally will decrease after each cycle, because repeated loading tends to rearrange and densify the mix. In a few incidences, the water-permeability increased after the first cycle. This was the case with specimens that were impermeable or that had very low initial permeability. Mixes with high air-voids (8 ± 1 percent) developed low permeability because of lack of interconnection within the void structure. However, after one cycle of repeated loading at 60°C (140°F), the voids tended to become better connected and the permeability increased. RC and RJ mix combinations exhibited about the same loss in water-permeability, with average final water-permeability ratios of about 0.5 and 0.4, respectively.

4.2 OSU Wheel-Tracking Program

As previously mentioned, the number of tests included in the OSU wheel-tracking program exceeded that which was required by the experiment design. Table 4.5 summarizes the mixes tested as well as void content data and percent saturation data for each mix. The last column in Table 4.5 shows the percent stripping for as many of the mixes as were available. Percent saturation on most of the mixes was not in the desired range of 60 to 80 percent because of low initial permeability. As indicated, 25 of the 32 mixes were repeated, thus exceeding the minimum requirement of repeating eight of the tests. In retrospect, it probably would have been more informative to test one dry- and one wet-conditioned beam rather than duplicate wet beams in order to provide some measure of water-sensitivity.

The OSU wheel-tracking test results are summarized in Table 4.6. Note that an average value for the rut-depth was used where the mix was replicated (i.e., the results tabulated for replicated mixes is the average of the two tests performed on the mix). Detailed rut-depth data for each mix is provided in Appendix A. Graphic representations of the data presented in Table 4.6 are shown in Figures 4.6 through 4.9. It is clear from these plots that the AAA-1 and AAC-1 asphalt mixes performed worst while the AAK-1 and AAM-1 asphalt mixes performed best with respect to rut resistance.

4.3 SWK/UN Wheel-tracking Program

The test results of the SWK/UN wheel-tracking program are shown in Table 4.7. Note that SWK/UN reported a time-to-failure in hours where failure is defined as a sudden and significant increase in plastic deformation. A pass was reported if the specimen did not

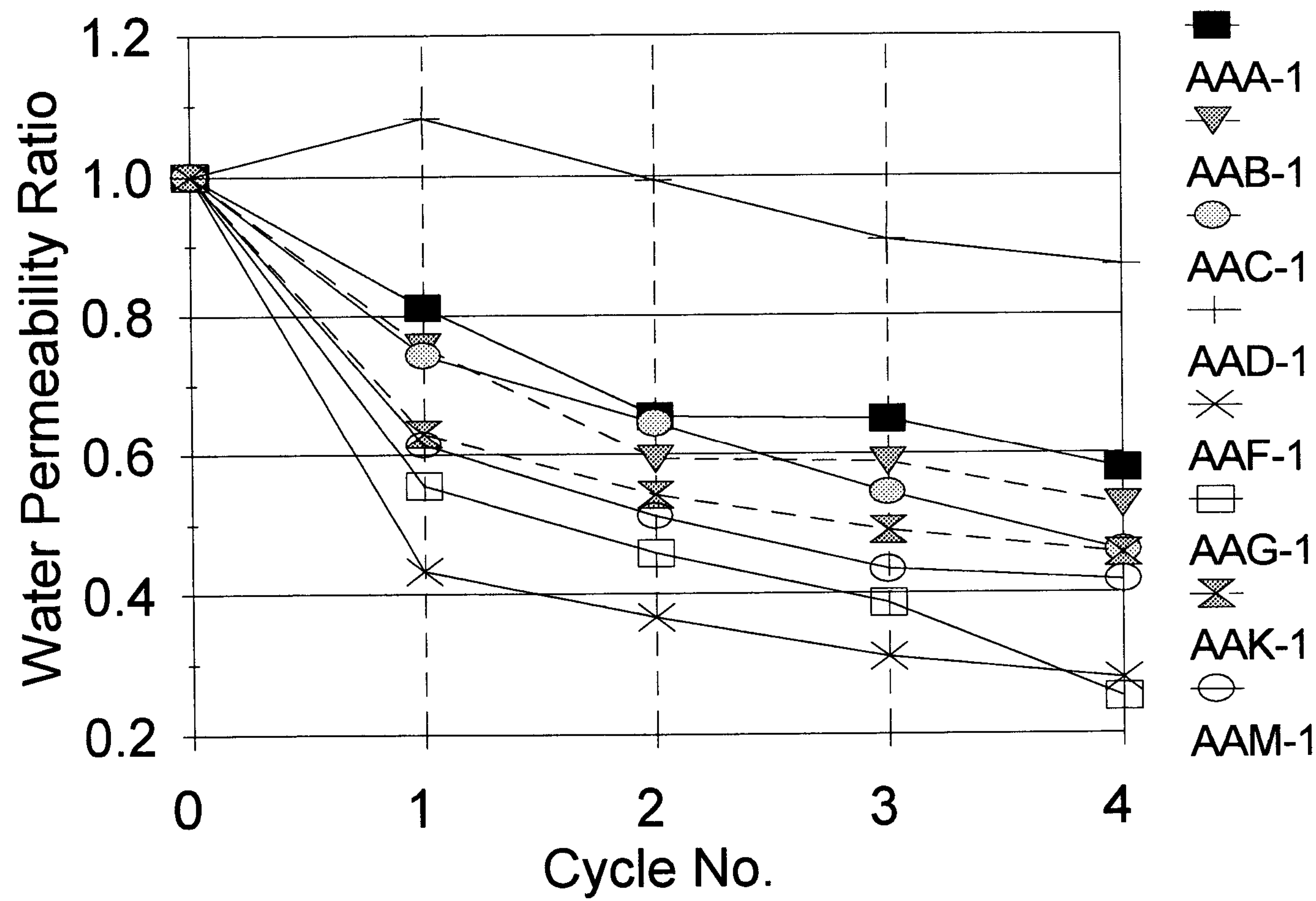

Fig. 4.5. The effect of ECS conditioning on water permeability of RC mixes

Table 4.5. Summary of Mixes Tested in the OSU Wheel-Tracking Program

Mix Number	Aggregate Type	Asphalt Type	Mix Code[a]	Sample ID[b]	Percent Voids	Percent Saturation	Percent Stripping
1	RC	AAA-1	00000	RR0	7.1	33	25.0
1		AAA-1	00000	RR1	7.8	55	40.0
2		AAB-1	10000	RR0	6.9	63	5.0
2		AAB-1	10000	RR1	6.9	73	25.0
3		AAC-1	01000	RR0	7.7	64	N/A[b]
3		AAC-1	01000	RR1	7.8	59	30.0
4		AAD-1	11000	RR0	8.0	65	0.0
4		ADD-1	11000	RR1	7.4	60	30.0
5		AAF-1	00100	RR0	7.6	92	5.0
5		AAF-1	00100	RR1	7.7	66	17.5
6		AAG-1	10100	RR6	7.9	72	0.0
7		AAK-1	01100	RR0	7.8	79	5.0
7		AAK-1	01100	RR1	8.9	61	5.0
8		AAM-1	11100	RR0	7.7	73	0.0
8		AAM-1	11100	RR1	8.0	47	5.0
9	RD	AAA-1	00010	RR2	8.2	52	N/A
9		AAA-1	00010	RR3	8.0	60	5.0
10		AAB-1	10010	RR2	8.7	45	15.0
10		AAB-1	10010	RR3	8.4	52	17.5
11		AAC-1	01010	RR2	8.9	40	5.0
12		AAD-1	11010	RR0	8.4	57	N/A
12		AAD-1	11010	RR1	8.6	56	N/A
13		AAF-1	00110	RR0	9.0	56	N/A
13		AAF-1	00110	RR1	8.6	49	10.0
14		AAG-1	10110	RR2	8.7	61	5.0
14		AAG-1	10110	RR3	8.6	61	0.0
15		AAK-1	01110	RR2	8.1	51	N/A
15		AAK-1	01110	RR3	9.0	63	5.0
16		AAM-1	11110	RR1	8.6	44	N/A

Continued on next page.

Table 4.5. **Summary of Mixes Tested in OSU Wheel-Tracking Program (continued)**

Mix Number	Aggregate Type	Asphalt Type	Mix Code[a]	Sample ID	Percent Voids	Percent Saturation	Percent Stripping
17	RH	AAA-1	00001	RR4	8.2	54	0.0
17		AAA-1	00001	RR5	7.5	63	12.5
18		AAB-1	10001	RR3	8.8	42	10.0
19		AAC-1	01001	RR1	6.9	44	7.5
19		AAC-1	01001	RR3	6.9	32	5.0
20		AAD-1	11001	RR0	7.6	46	15.0
20		AAD-1	11001	RR1	7.8	56	5.0
21		AAF-1	00101	RR0	8.7	40	30.0
21		AAF-1	00101	RR1	8.5	57	0.0
22		AAG-1	10101	RR4	8.7	65	45.0
22		AAG-1	10101	RR5	8.7	61	35.0
23		AAK-1	01101	RR0	8.7	43	7.5
23		AAK-1	01101	RR1	8.8	46	7.5
24		AAM-1	11101	RR0	7.7	71	5.0
24		AAM-1	11101	RR1	7.7	38	2.5
25	RJ	AAA-1	00011	RR2	8.4	53	N/A
25		AAA-1	00011	RR3	8.4	55	N/A
26		AAB-1	10011	RR2	7.7	80	5.0
26		AAB-1	10011	RR3	7.7	55	N/A
27		AAC-1	01011	RR7	9.0	63	25.0
28		AAD-1	11011	RR0	7.2	57	7.5
28		AAD-1	11011	RR1	7.4	66	N/A
29		AAF-1	00111	RR0	8.1	57	N/A
29		AAF-1	00111	RR1	8.0	41	N/A
30		AAG-1	10111	RR4	8.4	53	70.0
31		AAK-1	01111	RR0	7.2	47	N/A
31		AAK-1	01111	RR1	7.1	50	N/A
32		AAM-1	11111	RR3	9.2	54	N/A

[a] The mix code is an accounting system established to distinguish among the 32 asphalt-aggregate combinations (see Table 3.1).

[b] Sample ID is specimen or replicate number.

Table 4.6. Rut-depths for the OSU Wheel-Tracking Program

Wheel Passes	AAA-1	AAB-1	AAC-1	AAD-1	AAF-1	AAG-1	AAK-1	AAM-1
				Rut-depth, mm[a]				
				RC Aggregate				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200	2.38	1.54	2.14	2.19	2.22	1.98	1.30	2.08
500	4.29	2.51	3.65	3.42	3.19	3.00	2.17	3.15
1,000	6.10	3.89	4.99	4.99	4.52	4.09	2.72	4.47
2,000	8.06	5.21	6.88	5.59	6.32	5.06	4.48	5.65
5,000	12.16	7.69	12.29	6.98	8.28	6.65	6.05	7.55
10,000	24.00[b]	10.83	36.00[b]	9.87	10.72	9.82	10.17	9.53
				RD Aggregate				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200	1.03	0.74	1.22	0.77	0.47	0.62	0.39	1.04
500	1.72	1.66	2.47	1.66	1.42	1.52	0.92	1.58
1,000	2.22	2.67	3.12	2.54	2.13	2.43	1.32	2.17
2,000	3.68	3.77	4.35	4.07	3.33	3.99	2.12	3.32
5,000	5.23	5.68	5.91	5.97	4.96	7.08	3.70	4.56
10,000	6.16	6.84	7.16	7.18	6.31	9.47	4.90	5.19
				RH Aggregate				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200	1.05	0.63	1.19	0.78	0.80	1.22	0.47	0.95
500	1.86	1.31	1.72	1.42	1.62	2.26	0.93	1.33
1,000	2.88	1.90	2.63	2.26	1.62	3.06	1.05	1.72
2,000	4.69	3.41	3.71	3.66	3.2	4.22	2.20	2.62
5,000	6.98	5.87	6.40	5.75	5.58	6.09	3.99	4.41
10,000	8.82	7.88	8.68	7.51	7.96	7.70	6.07	6.27
				RJ Aggregate				
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
200	0.65	0.49	0.75	0.65	0.60	1.11	0.46	0.59
500	1.58	1.04	2.18	1.25	1.40	2.43	1.16	0.95
1,000	2.52	1.99	3.16	1.71	1.77	3.14	1.59	1.28
2,000	4.42	3.00	4.43	2.49	2.59	4.36	2.48	1.96
5,000	6.62	3.94	6.91	3.74	4.25	5.81	3.39	2.59
10,000	8.30	4.92	8.79	5.53	6.23	8.65	4.32	2.65

[a] 1 in. = 25.4 mm

[b] Estimated rut-depth.

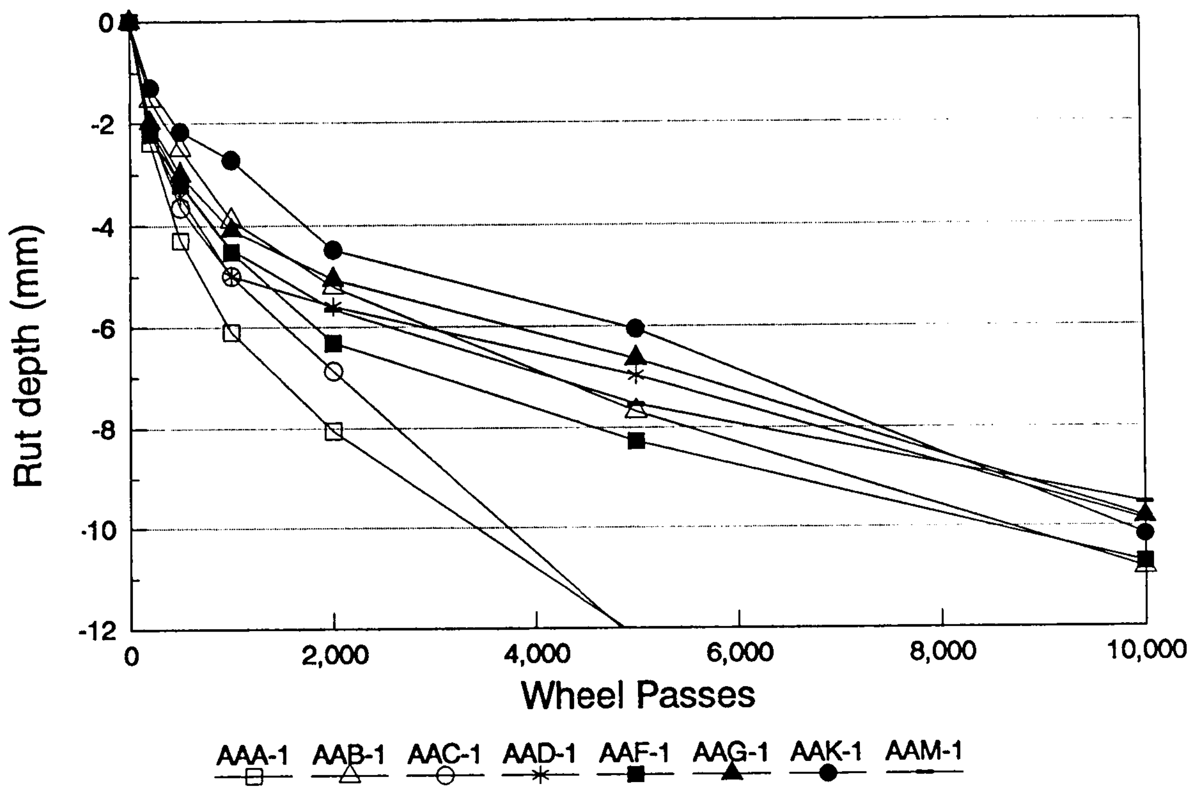

Fig. 4.6. OSU wheel-tracking test results for the RC aggregate

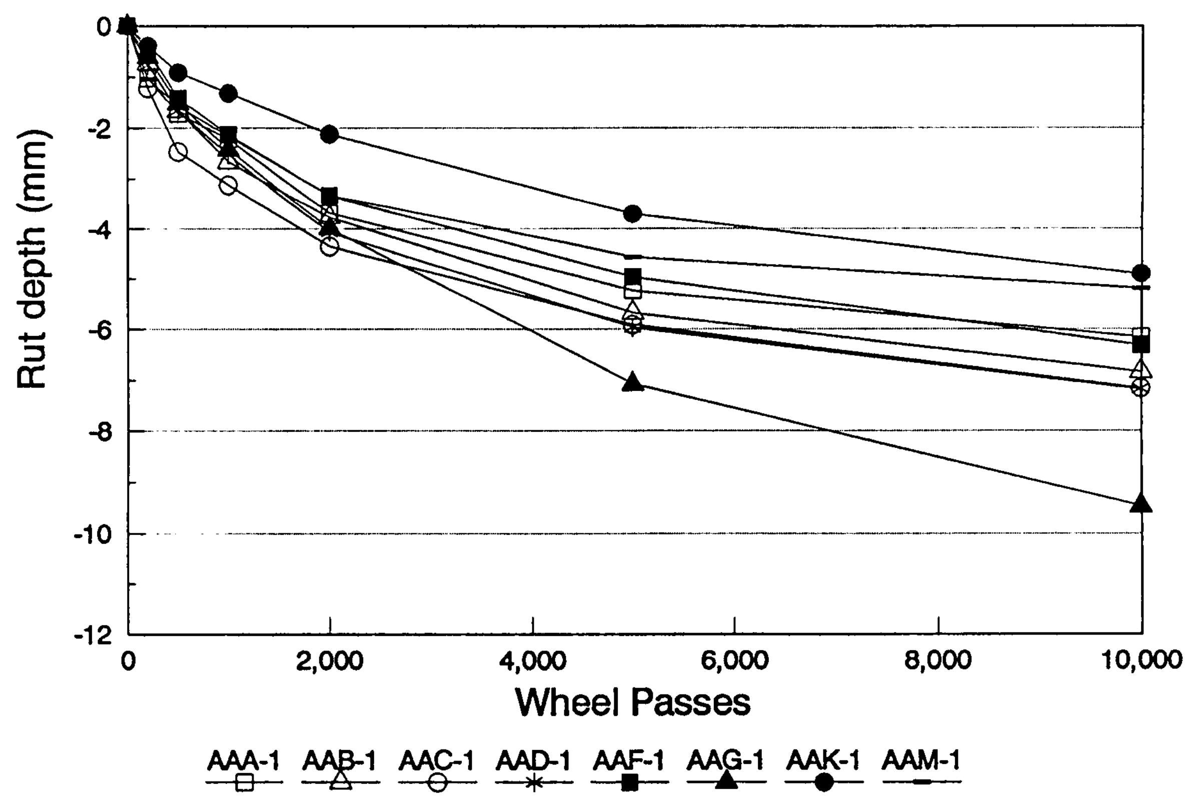

Fig. 4.7. OSU wheel-tracking test results for the RD aggregate

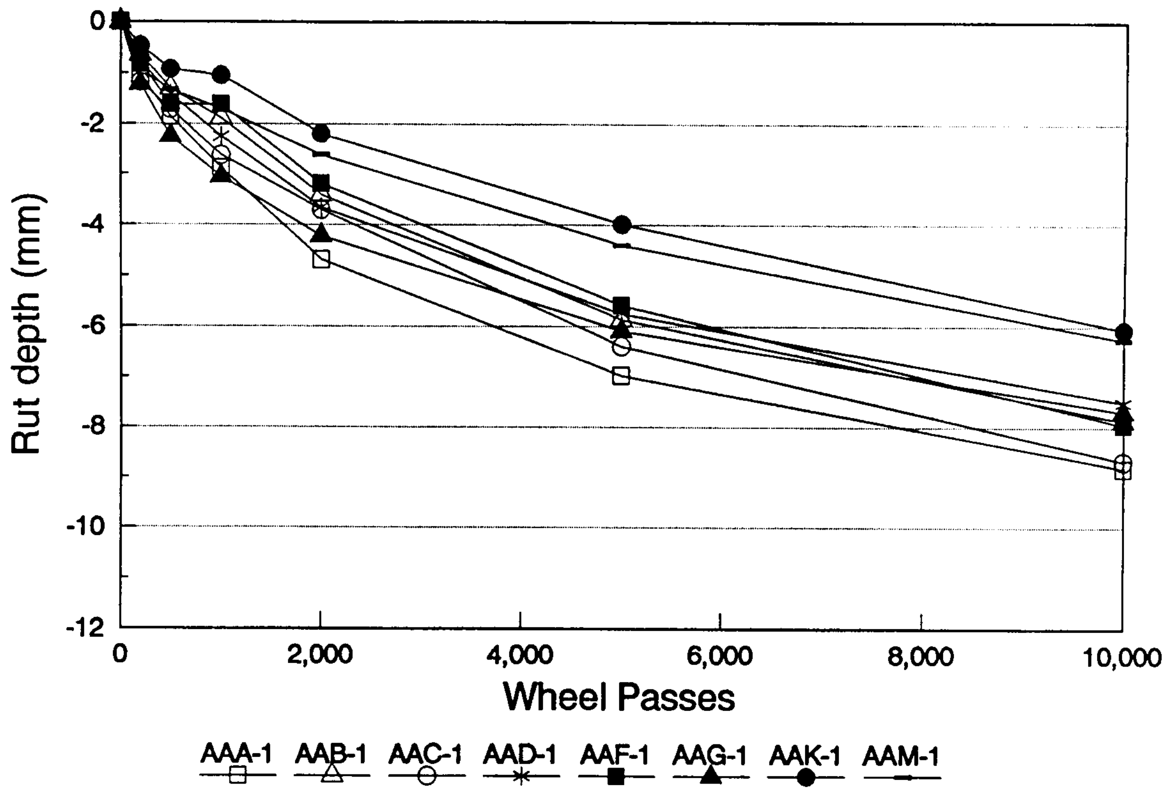

Fig. 4.8. OSU wheel-tracking test results for the RH aggregate

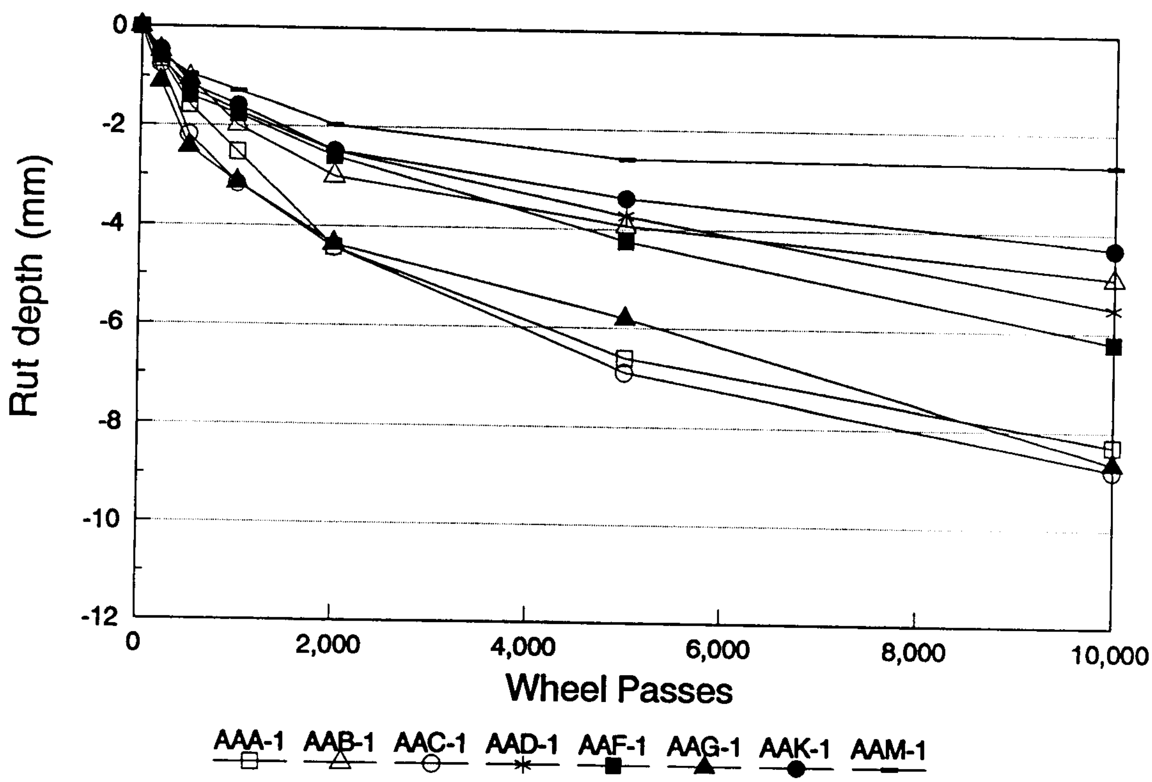

Fig. 4.9. OSU wheel-tracking test results for the RJ aggregate

Table 4.7. SWK/UN Wheel-Tracking Test Results

Mix No.	Aggregate Type	Asphalt Type	Mix Code[a]	Sample ID	Void Content of Beam[b] (%)	Specimen Void Content[c] (%)	Saturation of Test Specimen (%)	Time-to-Failure[d] (hrs.)	Time (hr.) to Deformation (min.) 1	2	3	4	5	6	7	8	9	10
1	RC	AAA-1	00000	RW1	7.0	8.4	64.8	Pass	0.5	64.0	-	-	-	-	-	-	-	-
1		AAA-1	00000	RW0	8.6	11.5	84.7	5	0.5	0.5	1.0	2.0	3.0	4.5	5.5	7.0	8.0	8.5
2		AAB-1	10000	RW1	8.9	12.4	72.9	58	0.5	26.0	56.0	62.0	78.0	87.0	91.0	-	-	-
3		AAC-1	01000	RW0	8.0	11.7	69.0	24	0.5	1.0	3.0	5.5	10.5	16.5	24.0	24.5	25.0	25.5
4		AAD-1	11000	RW0	8.8	11.4	95.8	Pass	0.5	10.0	-	-	-	-	-	-	-	-
5		AAF-1	00100	RW1	9.0	10.9	90.0	165	0.5	3.0	26.0	54.0	70.0	98.0	163.0	164.0	165.0	165.0
6		AAG-1	10100	RW5	9.2	12.8	70.0	10	3.0	8.5	10.0	10.0	10.0	10.0	10.0	10.5	10.5	11.0
7		AAK-1	01100	RW2	8.8	9.2	56.4	Pass	6.0	-	-	-	-	-	-	-	-	-
7		AAK-1	01100	RW3	8.3	9.4	66.0	Pass	2.0	-	-	-	-	-	-	-	-	-
8		AAM-1	11100	RW0	8.9	12.1	75.4	Pass	0.5	13.0	-	-	-	-	-	-	-	-
9	RD	AAA-1	00010	RW1	9.0	8.5	51.9	Pass	20.	-	-	-	-	-	-	-	-	-
9		AAA-1	00010	RW0	6.3	4.3	30.5	Pass	0	-	-	-	-	-	-	-	-	-
10		AAB-1	10010	RW3	9.1	8.9	67.9	Pass	30.	-	-	-	-	-	-	-	-	-
11		AAC-1	01010	RW1	7.0	11.1	65.4	6	0	1.5	1.5	5.5	6.0	6.0	6.5	6.5	7.0	7.5
12		AAD-1	11010	RW0	8.7	8.0	51.4	Pass	1.0	-	-	-	-	-	-	-	-	-
12		AAD-1	11010	RW1	8.7	7.6	54.4	Pass	0.5	30	3.0	-	-	-	-	-	-	-
13		AAF-1	00110	RW1	8.9	8.2	42.4	Pass	-	-	-	-	-	-	-	-	-	-
14		AAG-1	10110	RW1	7.0	6.0	73.3	Pass	0.5	-	-	-	-	-	-	-	-	-
14		AAG-1	10110	RW0	7.0	5.8	42.9	Pass	-	6.0	6.0	-	-	-	-	-	-	-
15		AAK-1	01110	RW3	8.9	8.4	55.5	Pass	13.	-	-	-	-	-	-	-	-	-
15		AAK-1	01110	RW1	6.4	7.6	35.7	Pass	0	-	-	-	-	-	-	-	-	-
16		AAM-1	11110	RW0	9.0	10.2	49.4	Pass	0.5	6.0	6.0	-	-	-	-	-	-	
									-									
									20.									
									0									
									0.5									

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Table 4.7 (continued). SWK/UN Wheel-Tracking Test Results

Mix No.	Aggregate Type	Asphalt Type	Mix Code[a]	Sample ID	Void Content of Beam[b] (%)	Specimen Void Content[c] (%)	Saturation of Test Specimen (%)	Time-to-Failure[d] (hrs.)	Time (hr.) to Deformation (min.) 1	2	3	4	5	6	7	8	9	10
17	RH	AAA-1	00001	RW5	8.0	9.0	77.3	Pass	0.5	24.0	-	-	-	-	-	-	-	-
18		AAB-1	10001	RW5	10.4	12.1	64.2	Pass	4.0	89.0	-	-	-	-	-	-	-	-
19		AAC-1	01001	RW0	7.5	9.2	24.3	54	2.0	47.0	49.5	50.0	51.0	52.0	54.0	55.0	55.5	56.5
20		AAD-1	11011	RW0	7.9	10.8	55.6	56	0.5	49.0	55.0	56.0	56.5	56.5	57.0	57.5	57.5	58.0
20		AAD-1	11001	RW3	9.9	12.4	81.1	14	0.5	5.0	12.5	13.5	13.5	14.0	15.5	15.5	16.0	16.5
21		AAF-1	00101	RW1	8.1	9.8	39.1	13	0.5	11.5	13.0	14.0	14.0	14.0	14.0	14.5	14.5	15.0
22		AAG-1	10101	RW5	7.9	10.6	44.4	90	3.0	55.0	81.0	86.0	86.5	89.0	93.0	94.0	95.0	95.5
22		AAG-1	10101	RW4	9.5	12.3	74.3	26	7.0	21.5	24.0	25.5	26.0	26.0	26.0	26.0-	26.5	27.0
23		AAK-1	01101	RW0	8.4	9.3	92.0	Pass	5.0	-	-	-	-	-	-	-	-	-
24		AAM-1	11101	RW0	7.0	8.1	76.2	Pass	0.5	13.0	-	-	-	-	-		-	-
25	RJ	AAA-1	00011	RW0	9.3	10.6	58.4	10	4.0	7.0	9.0	10.0	10.5	11.0	11.0	11.0	11.0	11.5
25		AAA-1	00011	RW1	7.9	8.3	50.3	20	0.5	4.0	16.0	19.0	20.0	21.0	21.5	21.5	22.0	22.0
26		AAB-1	10011	RW0	11.7	14.0	82.5	3.0	0.5	2.0	3.0	3.0	3.5	3.5	3.5	3.5	4.0	4.0
27		AAC-1	01011	RW0	12.8	9.2	74.3	9.5	0.5	2.0	3.0	4.0	5.5	8.5	8.8	9.0	9.0	9.5
28		AAD-1	11011	RW0	7.1	8.4	41.9	17	3.0	7.5	9.0	9.5	10.5	13.0	13.0	15.0	17.0	17.0
29		AAF-1	00111	RW0	8.0	8.2	38.4	2.0	1.5	2.0	2.5	3.5	5.0	6.0	6.0	6.0	6.5	6.5
30		AAG-1	10111	RW0	9.9	9.7	75.0	6.0	1.5	5.0	6.5	7.0	7.5	9.0	9.5	9.5	9.5	9.5
31		AAK-1	01111	RW3	9.5	11.6	84.4	45	1.0	28.0	36.5	38.5	41.5	44.5	46.0	46.0	47.0	47.5
31		AAK-1	01111	RW1	9.9	11.2	83.0	15	0.5	1.0	4.0	6.0	10.5	15.0	15.0	15.0	15.5	16.0
32		AAM-1	11111	RW0	11.0	11.7	63.6	67	0.5	6.0	57.0	64.5	64.5	67.0	67.0	67.0	67.0	67.0

[a] The mixture code is an accounting system established to distinguish among the 32 asphalt-aggregate combinations (see Table 3.1).
[b] Void content of the beam fabricated at OSU and sent to SWK/UN.
[c] Void content of the test specimen obtained from the beam fabricated at OSU.
[d] Determined by a sudden and significant increase in plastic deformation. A pass is recorded if the specimen does not fail within seven (7) days (approximately 500,000 wheel passes).

experience failure within seven days of testing (approximately 500,000 wheel passes). Void contents of the parent beam and test specimen as well as the percent saturation of the test specimen are also included in Table 4.7. The parent beam is the oversized beam fabricated at OSU and sent to SWK/UN. SWK/UN subsequently cut the beam to the test specimen dimensions. The 10 columns on the right side of the table show the time in hours to attain 1, 2, 3, 4, 5, 6, 7, 8, 9, and 10 mm of deformation.

4.4 University of Nevada (Reno) Net Adsorption Test (UNR/NAT) Program

The NAT results are shown in Table 4.8. The table includes the mean NAT, standard deviation of the test, and coefficient of variations. The amount of asphalt remaining on the aggregate indicates how well the aggregate will withstand water-conditioning; lower NAT values indicate mix that might be water sensitive. Also, the NAT results are shown graphically in Figure 4.10. The NAT shows that aggregate RJ is the most water sensitive and that aggregate RD is the least water sensitive.

Table 4.8. NAT Program

Aggregate	Asphalt	Mean NAT (%)	SD[1]	CV[2]
RC	AAA-1	77.05	1.70	2.18
	AAB-1	76.84	4.00	5.20
	AAC-1	80.79	0.20	0.25
	AAD-1	81.50	0.56	0.70
	AAF-1	77.80	7.47	9.60
	AAG-1	78.86	4.32	5.48
	AAK-1	75.18	2.86	3.80
	AAM-1	71.90	2.21	3.11
RD	AAA-1	74.32	3.30	4.43
	AAB-1	73.97	2.59	3.50
	AAC-1	77.63	2.24	2.89
	AAD-1	81.63	2.49	3.05
	AAF-1	76.99	3.28	4.27
	AAG-1	77.17	2.94	3.81
	AAK-1	81.57	6.66	8.16
	AAM-1	66.52	3.13	4.17
RH	AAA-1	73.29	1.94	2.64
	AAB-1	74.20	3.65	4.91
	AAC-1	74.73	2.74	3.66
	AAD-1	76.33	1.79	2.34
	AAF-1	73.06	3.66	5.00
	AAG-1	55.72	4.86	8.72
	AAK-1	81.48	3.82	4.69
	AAM-1	62.23	0.80	1.29
RJ	AAA-1	70.09	3.24	4.62
	AAB-1	63.78	3.31	5.27
	AAC-1	59.63	3.55	5.96
	AAD-1	63.50	0.61	0.96
	AAF-1	56.01	3.60	6.43
	AAG-1	58.76	8.15	13.87
	AAK-1	61.57	1.72	2.80
	AAM-1	58.90	1.45‘	2.45

[1]Standard deviation
[2]Coefficient of variation

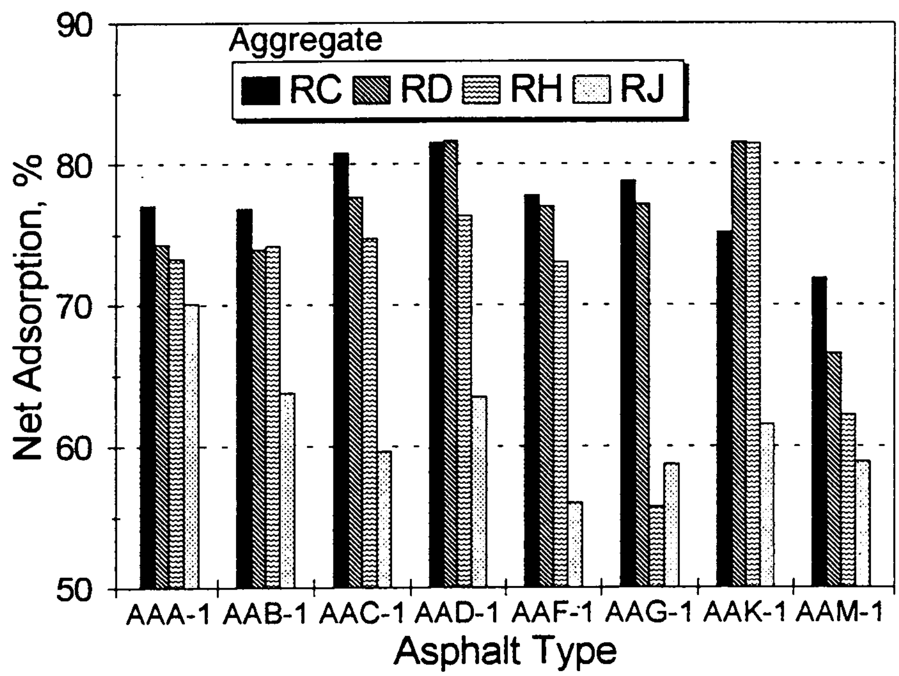

Fig. 4.10. NAT results

5

Analysis of Results

This chapter presents an analysis of the results summarized in Chapter 4. A description of the statistical analyses for the Environmental Conditioning System (ECS), Oregon State University (OSU) wheel-tracking, SWK Pavement Engineering/University of Nottingham (SWK/UN) wheel-tracking, and University of Nevada (Reno) Net Adsorption Test (NAT/UNR) programs as well as the performance rankings of the materials as determined by each program are included. A comparison of the performance rankings for each program with those proposed by the A-002A and A-003B contractors, including a discussion of the results and comparisons is also presented.

5.1 Statistical Analysis

Each test program included 32 asphalt-aggregate mixes according to the experiment design presented in Chapter 3. The set of 40 tests (32 mixes plus 8 repeated tests) was primarily designed to identify the water-sensitivity of the mixes using either rutting (OSU and SWK/UN wheel-tracking) or reduction in modulus (ECS) as the objective function. The ECS test program used full replication (the total of 67 specimens exceeded full replication). The test program provided information to rank the relative performance of the eight asphalts and four aggregates, thus enabling a comparison of results provided by the A-002A, A-003A, and A-003B contractors. The statistical analyses conducted on the results obtained from the ECS, OSU wheel-tracking, and SWK/UN wheel-tracking programs are provided in this section.

5.1.1 ECS Test Results

The analysis of the ECS test results employed a general linear model (GLM) procedure to investigate the significance of the effect of the different variables and their interactions on ECS-M_R ratio (the dependent variable). GLM procedure uses the method of least squares to fit general linear models; i.e., test each variable in a given model to see how significant the variable (or its interaction with other variables) is to the model. Also, GLM can create output data of the dependent variable (ECS-M_R) based on the prescribed model; i.e., the original ECS-M_R data will be changed to show the effects of the different variables in the model. One of the statistical methods available in GLM is analysis of variance for unbalanced data that is utilized in ECS analysis. This method was used because the ECS test program has unbalanced data (29 mixes had two replicates and three mixes had three replicates). GLM procedure is the only statistical method for unbalanced experiments.

The analyses were performed on the results obtained after each of the four conditioning cycles. Table 5.1 shows the variables that were included in the statistical analysis. There are two types of independent variables: classification variables (categorical, qualitative, discrete, or nominal variables) and continuous variables (numeric and not necessarily discrete). In the model statement any variable that was not defined as a classification variable was considered a continuous variable. The aggregate and asphalt type and the time (cycle number) were considered class variables. The other variables were considered independent (or covariant) variables.

The analyses were done using an iterative approach. First, a model was selected in which ECS-M_R ratio was related to all the variables (Table 5.1) and asphalt-aggregate interactions. Then with each iteration, the least significant variables were removed from the model one at a time. Table 5.2 shows the results of each iteration; X in front of the variable means the variable was not significant at 0.05 significance level. The variable that was not significant at 0.05 significance level was eliminated from the model in the next iteration. The final model that best represents the effects of asphalt type, initial modulus, and asphalt-aggregate interactions on ECS-M_R ratio is shown in Table 5.3.

Table 5.3 shows the output of statistical analysis; the class variables, number of levels, and the class values are shown. The analysis was performed by time (cycle number); i.e., for each cycle the model was analyzed (with data for that cycle only). For each cycle, the summary of the statistical analysis is shown in a separate set of data (Table 5.3). Independent variables (aggregate type, asphalt type, initial modulus, and asphalt-aggregate interactions) with degree of freedom, type III sum of squares, F-values, and P-values were given. For each variable, F-values and P-values (based on type III error) can be checked for significance. Type III sum of squares is used to test the significance of each variable because the type III test is invariant to the order of variables in the model, and the test of significance for a variable does not involve the parameters of other variables. At time 6 initial modulus P-value was 0.0433 and below significance level of 0.05, so initial modulus was significant to the model at this cycle. For each cycle (time) the model R^2, coefficient of variation (CV), and ECS-M_R ratio mean are shown. CV gives a relative measure of the variability in the model in percent; i.e., it can be used to compare one model with another. The given model showed low CV and good R^2 values compared with the other models.

Table 5.1. Variables Considered in the Analyses of the ECS Test Results

Variable	Type	Levels
Aggregate type (AGGR)	Class	RC, RD, RM, RJ
Asphalt type (ASPH)	Class	AAA-1, AAB-1, AAC-1, AAD-1, AAF-1, AAG-1, AAK-1, and AAM-1
Time (cycle number)	Class	6, 12, 18, 24 hr (1, 2, 3, 4 cycles)
Percent air-voids (AVOID)	Covariant	8 ± 1.5%
Water-permeability (WK)	Covariant	0.0 ≈ 12.0 E-3 cm/s
Water-permeability ratio (WKR)	Covariant	0.03 ≈ 15.0
Initial air-permeability (AK)	Covariant	0.0 ≈ 20.0 E-5 cm/s
Initial water-permeability (WK0)	Covariant	0.0 ≈ 12.0 E-3 cm/s
Initial Modulus	Covariant	100 ≈ 700 ksi
ECS-M_R Ratio	Dependent	0.6 ≈ 1.1

Table 5.2. An Overview of the ECS Statistical Analyses

Iteration Number 1

Variable	Cycle Number 1	2	3	4	
Aggregate	Y	Y	X	Y	
Asphalt	X	Y	Y	Y	
Air voids	X	X	X	X	↵
Water permeability	X	X	X	X	
Water permeability ratio	X	X	X	X	
Air permeability	X	X	Y	X	
Initial water permeability	X	Y	X	X	
Initial modulus	Y	Y	Y	Y	
Aggregate-asphalt	Y	Y	Y	Y	

Iteration Number 2

Variable	Cycle Number 1	2	3	4	
Aggregate	Y	Y	X	Y	
Asphalt	Y	Y	Y	Y	
Water permeability	Y	X	X	X	
Water permeability ratio	X	X	X	X	↵
Air permeability	X	X	Y	X	
Initial water permeability	X	Y	X	X	
Initial Modulus	Y	Y	Y	Y	
Aggregate-asphalt	Y	Y	Y	Y	

Iteration Number 3

Variable	Cycle Number 1	2	3	4	
Aggregate	Y	Y	X	Y	
Asphalt	Y	Y	Y	Y	
Water permeability	X	X	X	X	↵
Air permeability	X	X	Y	X	
Initial water permeability	X	Y	X	X	
Initial modulus	Y	Y	Y	Y	
Aggregate-asphalt	Y	Y	Y	Y	

Iteration Number 4

Variable	Cycle Number 1	2	3	4	
Aggregate	Y	Y	Y	Y	
Asphalt	Y	Y	Y	Y	
Air permeability	X	X	Y	X	↵
Initial water permeability	Y	Y	X	X	
Initial Modulus	Y	Y	Y	Y	
Aggregate-asphalt	Y	Y	Y	Y	

Iteration Number 5

Variable	Cycle Number 1	2	3	4	
Aggregate	Y	Y	Y	Y	
Asphalt	Y	Y	Y	Y	
Initial water permeability	X	Y	X	X	↵
Initial modulus	Y	Y	Y	Y	
Aggregate-asphalt	Y	Y	Y	Y	

Iteration Number 6

Variable	Cycle Number 1	2	3	4
Aggregate	Y	Y	Y	Y
Asphalt	Y	Y	Y	Y
Initial modulus	Y	Y	Y	Y
Aggregate-aAsphalt	Y	Y	Y	Y

X means the variable was not significant at 0.05 level.

Y means the variable was significant at 0.05 level.

↵ Means eliminate this variable.

Table 5.3. GLM Analysis of the ECS Results for Asphalt and Aggregate Type

Class Variables	Levels	Values
AGGR	4	RC, RD, RH, and RJ
ASPH	8	AAA-1, AAB-1, AAC-1, AAD-1, AAF-1, AAG-1, AAK-1, and AAM-1

Time = 6
Model: R^2 = 0.79, CV = 4.88, ECS-M_R Ratio Mean = 0.93

Source of Error	Degree of Freedom	Type III Sum of Squares	F-Values	Probability of $F > F_{critical}$
AGGR	3	0.03275601	5.35	0.0037
ASPH	7	0.04715846	3.30	0.0079
MR0	1	0.00894455	4.38	0.0433
AGGR-ASPH	21	0.14340240	3.34	0.0007

Time = 12
Model: R^2 = 0.85, CV = 5.22, ECS-M_R Ratio Mean = 0.88

Source of Error	Degree of Freedom	Type III Sum of Squares	F-Values	Probability of $F > F_{critical}$
AGGR	3	0.07121460	11.13	0.0001
ASPH	7	0.04083428	2.73	0.0216
MR0	1	0.02653206	12.44	0.0011
AGGR-ASPH	21	0.25769088	5.75	0.0001

Time = 18
Model: R^2 = 0.81, CV = 6.21, ECS-M_R Ratio Mean = 0.86

Source of Error	Degree of Freedom	Type III Sum of Squares	F-Values	Probability of $F > F_{critical}$
AGGR	3	0.10603905	12.28	0.0001
ASPH	7	0.04310104	2.14	0.0634
MR0	1	0.00825944	2.87	0.0987
AGGR-ASPH	21	0.23901440	3.95	0.0001

Time = 24
Model: R^2 = 0.89, CV = 4.65, ECS-M_R Ratio Mean = 0.84

Source of Error	Degree of Freedom	Type III Sum of Squares	F-Values	Probability of $F > F_{critical}$
AGGR	3	0.15659618	33.88	0.0001
ASPH	7	0.02909552	2.70	0.0231
MR0	1	0.00953970	6.19	0.0175
AGGR*ASPH	21	0.23805089	7.36	0.0001

However, this analysis does not mean that all the variables that were eliminated did not contribute to the results of the ECS. The analysis that was done above (Table 5.2) was performed for each cycle; i.e., for each cycle the model was tested for variable's significance. In another model in which the analysis was done with cycle number (a class variable), initial water-permeability was significant to the model.

Another observation was that initial air-permeability was significant to ECS-M_R ratio at the end of three cycles. This means that initial air-permeability influenced the outcome of ECS test results at the end of three cycles. The most important observation from this analysis is that the asphalt-aggregate interaction is highly significant; i.e., the moisture susceptibility of one aggregate in a mix is dependent on the type of asphalt and vice versa.

5.1.2 OSU Wheel-Tracking Test Results

The analysis of the OSU wheel-tracking test results employed a GLM procedure to investigate the significance that asphalt type, aggregate type, air-voids, stripping rate, and asphalt-aggregate interaction has on the rut-depth developed after 5,000 wheel passes in the OSU wheel tracker. The results of the analysis are provided in Table 5.4. Unlike the analysis of ECS test program results, initial analysis of OSU wheel-tracking test results showed that aggregate-asphalt interaction had no effect on rut-depth developed at 5,000 wheel passes. The analysis showed very high correlation between rutting at 5,000 wheel passes and stripping rate, asphalt type, aggregate type, and percent air-voids, at a 0.05 significance level (95-percent confidence level).

5.1.3 SWK/UN Wheel-Tracking Test Results

The statistical analysis of the SWK/UN wheel-tracking tests utilized a Bayesian survival analysis with time-to-failure distributed as a Weibull random variable. The Weibull model employed a shape factor (C) of 2 (i.e., skewed to the right), a minimum value (A) of zero (A = 0 seemed appropriate since the smallest observed time-to-failure was 2 hours and A must be less than the smallest observation), and a scale parameter (B) as follows:

$$B = e^{-\left[\frac{AV-8}{B_{AV(i)}}\right]} B_{ASPH(j)} B_{AGGR(k)}; \; AV > 8$$

$$B = B_{ASPH*}{}^{(j)} B_{AGGR}{}^{(k)}; \; AV \le 8$$

where:

AV	=	percent air-voids of the test specimen
$B_{AV}(i)$	=	weighting for air-voids with values of 6, 7, 8, 9, or 10

Table 5.4. GLM Analysis of the OSU Wheel-Tracking Test Results

Class	Levels	Values		
AGGR	4	RC, RD, RH, and RJ		
ASPH	8	AAA-1, AAB-1, AAC-1, AAD-1, AAF-1, AAG-1, AAK-1, and AAM-1		
Source of Error	**Degree of Freedom**	**Type III Sum of Squares**	**F-Values**	**Probability of $F > F_{critical}$**
AGGR	3	142.94961295	29.86	0.0001
ASPH	7	70.99560815	6.36	0.0001
AV2*	1	8.79590144	5.51	0.0234
STRIPPING**	1	10.82167482	6.78	0.0125

*AV2 is air-voids of LCPC-rutted core after OSU wheel-tracking test.
**STRIPPING is visual evaluation of broken specimen after OSU wheel-tracking test.

$B_{ASPH}(j)$ = weighting for asphalt type with values of 2, 6, 10, 14, or 18
$B_{AGGR}(k)$ = weighting for aggregate type with values of 2, 6, 10, 14, or 18

As shown, the scale parameter is a multiplicative function of asphalt, aggregate, and air-voids with the contribution from air-voids decreasing exponentially for values greater than 8 percent and having no contribution (i.e., equal to unity) for air-voids less than or equal to 8 percent. It is through the shape parameter (B) that these factors have their effect on the distribution of time-to-failure.

The SWK/UN wheel-tracking data was tested to determine the probability (Pr) of the time-to-failure (T) being less than or equal to some reasonable time value (in this case seven days of testing). The test is mathematically represented as follows:

$$Pr\ [T \leq t^*] = 1 - e^{-\left(\frac{t^* - A}{B}\right)^C}$$

where:

A = the minimum allowed time value (zero in this case)
B = the scale parameter as previously defined
C = the shape factor (2 in this case)
t* = predetermined cutoff time value

The above analysis method allows the ranking of asphalt types and aggregate types and at the same time gives some importance to the air-void content of the test specimen, provided it is greater than 8 percent (i.e., air-void contents greater than 8 percent were considered detrimental to the probability of the specimen surviving beyond seven days with the detriment increasing exponentially with air-void content).

The results of the analysis are shown in Table 5.5. For each asphalt and aggregate, the table lists the probabilities of attaining the scores of 2, 6, 10, 14, and 18 (a range of scores that embraces the whole of the data set) and the expected score for the mix components. The expected score is computed by multiplying the probabilities by their respective scores and summing the values. Higher expected scores indicate a greater probability of obtaining a pass (i.e., not failing after seven days of testing) in the SWK/UN wheel tracker. Thus, as indicated, the AAM-1 and AAK-1 asphalts and the RC and RD aggregates performed best, and the AAC-1 and AAG-1 asphalts and the RJ aggregate performed worst.

Table 5.5. Bayesian Survival Analysis of the SWK/UN Test Results

Mix Component	Probability of Attaining a Score of					Expected Score[a]
	2	6	10	14	18	
Asphalts						
AAA-1	0.0000	0.0225	0.6351	0.2743	0.0681	11.55
AAB-1	0.0000	0.0047	0.3004	0.4293	0.2655	13.82
AAC-1	0.0188	0.9135	0.0606	0.0061	0.0010	6.23
AAD-1	0.0000	0.0000	0.1382	0.4934	0.3683	14.92
AAF-1	0.0000	0.0914	0.5258	0.2806	0.1022	11.57
AAG-1	0.0000	0.7532	0.2252	0.0197	0.0020	7.08
AAK-1	0.0000	0.0000	0.0006	0.1961	0.8032	17.21
AAM-1	0.0000	0.0000	0.0005	0.0143	0.9852	17.94
Aggregates						
RC	0.0000	0.0000	0.0948	0.5035	0.4017	15.23
RD	0.0000	0.0000	0.0526	0.6212	0.3262	15.09
RH	0.0000	0.0006	0.4745	0.3930	0.1318	12.62
RJ	0.9862	0.0138	0.0000	0.0000	0.0000	2.06

[a]Expected score = Σ (Probability)$_i$(score)$_i$; i = 2, 6, 10, 14, 18.

5.1.4 NAT/UNR Results

The GLM procedure was used to investigate the effect of aggregate type, asphalt type, and asphalt-aggregate interactions on NAT results. The statistical analysis was one iteration, unlike ECS results analysis (see Table 5.6). Analysis showed that the aggregate-asphalt interactions were highly significant at 0.05 significance level. Also, the statistical model used showed high R^2 value. Because aggregate-asphalt type interactions are significant, caution must be exercised in interpreting the ranking of aggregate types and asphalt types (similar to ECS).

5.2 Performance Ranking

In addition to investigating which independent variables influence the dependent variable for each test program, analyses were also performed on the test results with the objective of ranking the materials (asphalts and aggregates) for rutting resistance (OSU and SWK/UN wheel-tracking) and resistance to reduction in modulus (ECS) of moisture-damaged mixes. This section presents the performance rankings of the materials obtained from the analyses of the ECS and the OSU and SWK/UN wheel-tracking test results.

5.2.1 Aggregates

Analysis of the ECS test program results showed the interaction of asphalt type and aggregate type (i.e., ASPH × AGGR) to be significant (Table 5.3). Ranking the ECS results by aggregate type is inappropriate; thus, aggregate ranking presented in Table 5.7 should be interpreted with caution. Ranking of the aggregates based on ECS test results was done per cycle, i.e., for each ECS-M_R ratio after each cycle. These values are not the arithmetic (true) mean of all ECS-M_R ratio values for any given aggregate with the eight asphalts; they are the mean of adjusted ECS-M_R ratio values using least squares mean (M_RR least squares mean) (LSMean) for any given aggregate with the eight asphalts. In the statistical analysis, ECS-M_R ratio LSMean was the expected value of ECS-M_R ratio if the experiment was balanced and all the covariant variables were at their mean.

For comparison purposes, it does not make sense to compare one mix with another if the mixes have different statistically significant variables values. For example, to compare aggregate RD with aggregate RC, each aggregate specimen has to be adjusted to account for the difference in initial modulus (initial modulus is a significant covariant variable) and must be compared at the same cycle number. The analysis of ECS test results showed that, after three cycles of conditioning, aggregates RH and RD were the best (most moisture-resistant), aggregate RC was in the middle, and aggregate RJ was the worst (most moisture-sensitive). After four conditioning cycles, aggregate RD and RH were still the best, and aggregate RC and RJ were the worst. In Chapter 4 it was mentioned that RC aggregate is

Table 5.6. GLM Analysis of the NAT Results for Asphalt and Aggregate Type

Class Variables	Levels	Values
AGGR	4	RC, RD, RH, and RJ
ASPH	8	AAA-1, AAB-1, AAC-1, AAD-1, AAF-1, AAG-1, AAK-1, and AAM-1

Model: R^2 = 0.89, CV = 5.00, NAT mean = 71.57

Source of Error	Degree of Freedom	Type III Sum of Squares	F-Values	Probability of $F > F_{critical}$
AGGR	3	3725.3464	97.21	0.0001

Table 5.7. Performance Ranking of Aggregates Based on ECS Test

Aggregate	$M_R R$ Least Squares Mean	Aggregate	$M_R R$ Least Squares Mean
First Hot Cycle		Second Hot Cycle	
RD	0.952	RD	0.911
RC	0.931	RH	0.897
RH	0.921	RC	0.889
RJ	0.899	RJ	0.840
Third Hot Cycle		Freeze Cycle	
RH	0.897	RD	0.897
RD	0.892	RH	0.889
RC	0.860	RC	0.811
RJ	0.801	RJ	0.783

highly absorptive and tends to disintegrate. The freeze cycle affected aggregate RC (loss in strength) more than all the other aggregates.

Analysis of the OSU wheel-tracking program results showed the interaction of asphalt type and aggregate type (i.e., ASPH × AGGR) to be not significant. Thus in this case, ranking the results by aggregate is appropriate. The performance ranking of aggregates (based on least squares mean) for the OSU wheel-tracking program is summarized in Table 5.8. As indicated, the analysis showed that the RJ aggregate performed best and the RC aggregate performed worst. The performance ranking of aggregates based on SWK/UN wheel-tracking test results is summarized in Table 5.9. The ranking indicates that the RC and RD aggregates were good performers and the RJ aggregate was a poor performer. The NAT program performance ranking of aggregate types in Table 5.10 indicates that aggregates RC and RD performed best (least desorptive) and that aggregate RJ performed worst.

5.2.2 Asphalts

The analysis of results for the ECS test program showed the interaction of asphalt type and aggregate type (i.e., ASPH × AGGR) to be significant. However, ranking the results by asphalt type is inappropriate. The data are shown in Table 5.11. In ranking the asphalt types, LSMean of ECS-M_R ratio was used, similar to the procedure used in aggregate ranking. Asphalts AAA-1, AAC-1, and AAB-1 performed better than the other asphalts in the ECS test; asphalts AAF-1, AAG-1, and AAD-1 showed sensitivity to moisture-damage.

The analysis of results for the OSU wheel-tracking program showed that significance does not exist for the asphalt-aggregate interaction. Thus, a ranking by asphalt type can be accomplished. The performance ranking of asphalts (based on least squares means) for the OSU wheel-tracking program is summarized in Table 5.12. Asphalts AAK-1 and AAM-1 performed best (or lowest rut-depth values) and asphalts AAG-1, AAA-1, and AAC-1 performed worst (or highest rut-depth values). The performance ranking of asphalts based on the SWK/UN wheel-tracking test results is summarized Table 5.13. Based on the SWK/UN wheel-tracking test results, asphalts AAM-1 and AAK-1 ranked highest (least failures) and asphalt AAC-1 and AAG-1 ranked lowest (most test failures). The performance rankings of asphalt types based on NAT results is shown in Table 5.14. Asphalt AAD-1 ranks best (lowest desorption values), and asphalts AAG-1 and AAM-1 ranks worst (highest desorption values).

5.2.3 Mixes

The statistical analysis of the ECS results shows that the asphalt-aggregate interaction is very significant based on 0.05 significance level (i.e., 95-percent confidence). This conclusion rejects any rankings by asphalt type only or aggregate type only. To conclude that aggregate RD performs much better than RJ in moisture susceptibility, a single common asphalt would have to be matched with either of these aggregates. The statistical analysis of OSU wheel-tracker results showed no asphalt-aggregate interactions, so it would be inappropriate to include rankings based on mixes here. Table 5.15 shows ECS ranking based on ECS-M_R ratio after each cycle, and the mixes are ranked from 1 to 32.

Table 5.8. Performance Ranking of Aggregates (OSU Wheel-Tracking Program)

Level	Least Squares Mean	Homogenous Groups	Performance Ranking
RJ	4.456875	A	Good
RD	5.384375	B	Intermediate
RH	5.653125	B	
RC	8.475375	C	Poor

Table 5.9. Performance Ranking of Aggregates (SWK/UN Wheel-Tracking Program)

Level	Least Squares Mean	Homogenous Groups	Performance Ranking
RC	15.23	A	Good
RD	15.09	A	
RH	12.62	B	Intermediate
RJ	2.06	C	Poor

Table 5.10. Performance Ranking of Aggregates (NAT/UNR Test Program)

Level	Least Squares Mean	Homogenous Groups	Performance Ranking
RC	77.49	A	Good
RD	76.05	A	
RH	71.39	B	Intermediate
RJ	61.53	C	Poor

Table 5.11. Performance Ranking of Asphalt Based on ECS Test

Asphalt	M_RR Least Squares Mean	Least Squares Mean Number	Asphalt	M_RR Least Squares Mean	Least Squares Mean Number
Asphalt First Hot Cycle			Second Hot Cycle		
AAB-1	0.968	1	AAC-1	0.924	1
AAA-1	0.956	2	AAA-1	0.922	2
AAC-1	0.934	4	AAB-1	0.895	3
AAF-1	0.926	5	AAG-1	0.874	4
AAG-1	0.923	5	AAM-1	0.867	5
AAD-1	0.910	6	AAF-1	0.865	6
AAM-1	0.910	7	AAK-1	0.865	7
AAK-1	0.880	8	AAD-1	0.861	8
Third Hot Cycle			Freeze Cycle		
AAA-1	0.921	1	AAA-1	0.901	1
AAB-1	0.894	2	AAC-1	0.868	2
AAC-1	0.894	3	AAB-1	0.851	3
AAM-1	0.855	4	AAK-1	0.846	4
AAK-1	0.840	5	AAM-1	0.831	5
AAD-1	0.834	6	AAG-1	0.825	6
AAF-1	0.834	7	AAD-1	0.816	7
AAG-1	0.828	8	AAF-1	0.809	8

Table 5.12. Performance Ranking of Asphalts (OSU Wheel-Tracking Program)

Level	Least Squares Mean	Homogenous Groups[a]	Performance Ranking
AAK-1	4.28125	A	Good
AAM-1	4.77750	AB	Good
AAD-1	5.60875	BC	Intermediate
AAF-1	5.76625	BC	Intermediate
AAB-1	5.79375	BC	Intermediate
AAG-1	6.40500	C	Poor
AAA-1	7.38625	C	Poor
AAC-1	7.87750	C	Poor

[a] Groups with the same letter designation are not significantly different.

Table 5.13. Performance Ranking of Asphalts (SWK/UN Wheel-Tracking Program)

Level	Expected Score	Homogenous Groups	Performance Ranking
AAM-1	17.94	A	Very Good
AAK-1	17.21	A	
AAD-1	14.92	B	Good
AAB-1	13.82	B	
AAF-1	11.57	C	Fair
AAA-1	11.55	C	
AAG-1	7.08	D	Poor
AAC-1	6.23	D	

Table 5.14. Performance Ranking of Asphalts (NAT/UNR Test Program)

Level	Least Squares Mean	Homogenous Groups	Performance Ranking
AAD-1	75.487	A	Good
AAK-1	74.950	A B	Intermediate
AAA-1	73.688	A B	
AAC-1	73.198	A B	
AAB-1	72.199	A B	
AAF-1	70.964	B	
AAG-1	66.759	C	Poor
AAM-1	64.912	C	

Table 5.15. Ranking of 32 Mixes after Each ECS Cycle

Aggregate	Asphalt	ECS M_R Least Squares Mean	Least Squares Mean Number	Aggregate	Asphalt	ECS M_R Least Squares Mean	Least Squares Mean Number
First Hot Cycle				Second Hot Cycle			
RH	AAC-1	1.090	1	RH	AAC-1	1.170	1
RJ	AAF-1	0.993	2	RJ	AAF-1	0.957	2
RH	AAB-1	0.985	3	RD	AAA-1	0.953	3
RD	AAA-1	0.980	4	RH	AAD-1	0.950	4
RD	AAD-1	0.975	5	RC	AAA-1	0.945	5
RC	AAG-1	0.975	6	RD	AAC-1	0.940	6
RC	AAB-1	0.970	7	RC	AAG-1	0.935	7
RC	AAA-1	0.970	8	RD	AAK-1	0.935	8
RD	AAC-1	0.965	9	RC	AAM-1	0.920	9
RJ	AAB-1	0.965	10	RD	AAM-1	0.915	10
RC	AAF-1	0.965	11	RC	AAB-1	0.905	11
RC	AAM-1	0.960	12	RH	AAB-1	0.905	12
RD	AAM-1	0.960	13	RD	AAB-1	0.903	13
RH	AAD-1	0.955	14	RH	AAA-1	0.900	14
RD	AAK-1	0.950	15	RD	AAG-1	0.897	15
RD	AAB-1	0.950	16	RJ	AAA-1	0.890	16
RH	AAA-1	0.940	17	RH	AAG-1	0.890	17
RJ	AAA-1	0.935	18	RD	AAD-1	0.885	18
RD	AAG-1	0.930	19	RC	AAK-1	0.885	19
RJ	AAM-1	0.915	20	RJ	AAM-1	0.875	20
RD	AAF-1	0.907	21	RC	AAF-1	0.870	21
RJ	AAG-1	0.905	22	RJ	AAB-1	0.865	22
RC	AAK-1	0.895	23	RD	AAF-1	0.857	23
RJ	AAG-1	0.880	24	RC	AAC-1	0.840	24
RC	AAC-1	0.865	25	RH	AAK-1	0.830	25
RJ	AAD-1	0.860	26	RC	AAD-1	0.810	26
RC	AAD-1	0.850	27	RJ	AAK-1	0.810	27
RH	AAK-1	0.845	28	RJ	AAD-1	0.800	28
RH	AAF-1	0.840	29	RH	AAF-1	0.775	29
RJ	AAK-1	0.830	30	RJ	AAG-1	0.775	30
RJ	AAC-1	0.815	31	RH	AAM-1	0.757	31
RH	AAM-1	0.807	32	RJ	AAC-1	0.745	32

Continued on next page.

Table 5.15. Ranking of 32 Mixes after Each ECS Cycle (continued)

Aggregate	Asphalt	ECS M_R Least Squares Mean	Least Squares Mean Number	Aggregate	Asphalt	ECS M_R Least Squares Mean	Least Squares Mean Number
Third Hot Cycle				Freeze Cycle			
RH	AAC-1	1.125	1	RH	AAC-1	1.125	1
RH	AAA-1	0.950	2	RD	AAK-1	0.955	2
RD	AAA-1	0.943	3	RH	AAA-1	0.940	3
RD	AAK-1	0.930	4	RD	AAA-1	0.933	4
RH	AAB-1	0.925	5	RD	AAG-1	0.927	5
RC	AAM-1	0.920	6	RH	AAB-1	0.910	6
RH	AAD-1	0.915	7	RH	AAD-1	0.910	7
RD	AAB-1	0.907	8	RD	AAM-1	0.890	8
RC	AAA-1	0.905	9	RD	AAC-1	0.885	9
RD	AAC-1	0.905	10	RC	AAM-1	0.885	10
RJ	AAF-1	0.903	11	RH	AAG-1	0.880	11
RC	AAB-1	0.895	12	RJ	AAA-1	0.870	12
RD	AAM-1	0.895	13	RC	AAA-1	0.860	13
RC	AAG-1	0.885	14	RD	AAB-1	0.860	14
RJ	AAA-1	0.885	15	RD	AAD-1	0.845	15
RH	AAG-1	0.885	16	RC	AAK-1	0.840	16
RD	AAG-1	0.873	17	RJ	AAF-1	0.840	17
RC	AAK-1	0.870	18	RD	AAF-1	0.830	18
RJ	AAB-1	0.850	19	RJ	AAB-1	0.820	19
RD	AAD-1	0.845	20	RC	AAB-1	0.815	20
RD	AAF-1	0.837	21	RC	AAG-1	0.810	21
RC	AAC-1	0.830	22	RJ	AAK-1	0.805	22
RJ	AAM-1	0.825	23	RH	AAF-1	0.795	23
RH	AAF-1	0.800	24	RH	AAK-1	0.785	24
RH	AAK-1	0.795	25	RJ	AAM-1	0.785	25
RC	AAF-1	0.795	26	RC	AAF-1	0.770	26
RJ	AAD-1	0.795	27	RH	AAM-1	0.763	27
RH	AAM-1	0.780	28	RC	AAD-1	0.760	28
RC	AAD-1	0.780	29	RJ	AAD-1	0.750	29
RJ	AAK-1	0.765	30	RC	AAC-1	0.750	30
RJ	AAC-1	0.715	31	RJ	AAC-1	0.710	31
RJ	AAG-1	0.670	32	RJ	AAG-1	0.685	32

The data presented in Table 5.15 are based on LSMean procedure of GLM statistical method, similar to ranking of asphalts and aggregate types. Table 5.15 does not show the breakdown between poor aggregate (moisture-susceptible) and good aggregate (moisture-resistant) or between poor asphalt and good asphalt. The mixes are not grouped by homogenous groups, in which mixes within the same group are not significantly different and each group is ranked. However, it shows the breakdown between moisture-susceptible mixes and moisture-resistant mixes. After each cycle, mixes that tended to be moisture-susceptible progressively lost stiffness, but the mixes that were least susceptible to moisture-damage maintained about the same stiffness. Table 5.15 shows that some mixes that performed well after one cycle did not maintain the same ranking after subsequent cycles. Figure 5.1 shows the ranking of the 32 mixes (based on LSMean of ECS-M_R ratio) after one and three conditioning cycles. The significance of this observation is that one cycle of ECS conditioning is not sufficient and results are unpredictable (ranking of the mixes might not have a good basis). Finally, note that the range of data presented in Table 5.15 is very small; i.e., ECS-M_R ratio of all 32 mixes varies between 1.12 and 0.685.

5.3 Comparison of A-002A and A-003B Results

This section compares A-003A results with A-002A and A-003B (including UNR/NAT test program) results pertaining to moisture sensitivity and permanent deformation. The ranking provided by A-003B covered four aggregates and three asphalts. Since the rankings of NATs performed by both A-003B and UNR were similar and since A-003B had only three asphalts, both NAT rankings were combined. The rankings of aggregates from A-002A, A-003A, and A-003B contractors are summarized in Table 5.16. It is evident that the SWK/UN wheel-tracking results and the A-003B UNR/NAT results are in agreement. However, disparity exists between the OSU wheel-tracking results and those of the other two tests.

The rankings of asphalts from the A-002A, A-003A, and A-003B (including UNR/NAT) contractors are summarized in Table 5.17. As indicated, the SWK/UN wheel-tracking results, the OSU wheel-tracking results, and the A-002A predictions for permanent deformation are in agreement. Thus, it appears that the OSU and SWK/UN wheel-tracking test results do indeed validate the predictions made by the SEC-tan delta tests proposed by A-002A. Figure 5.2 shows the NAT and ECS-M_R results plotted against the ECS rankings. The plot shows that about 16 of the 32 mixes have similar ranking and that the rest are different.

However, very little agreement exists between the wheel-tracking test results and the predictions for the water-sensitivity of the binder made by the A-002A and A-003B contractors and, since both wheel-tracking tests indicate similar rankings that closely match the predicted ranking for permanent deformation, it appears that either the wheel-tracking tests are poor indicators of water-sensitivity of the binder or that the NAT (A-003B) and the FTIR test (A-002A) are not appropriate tests for predicting the water-sensitivity of the binder. It is appropriate to point out that the original performance predictions for water-

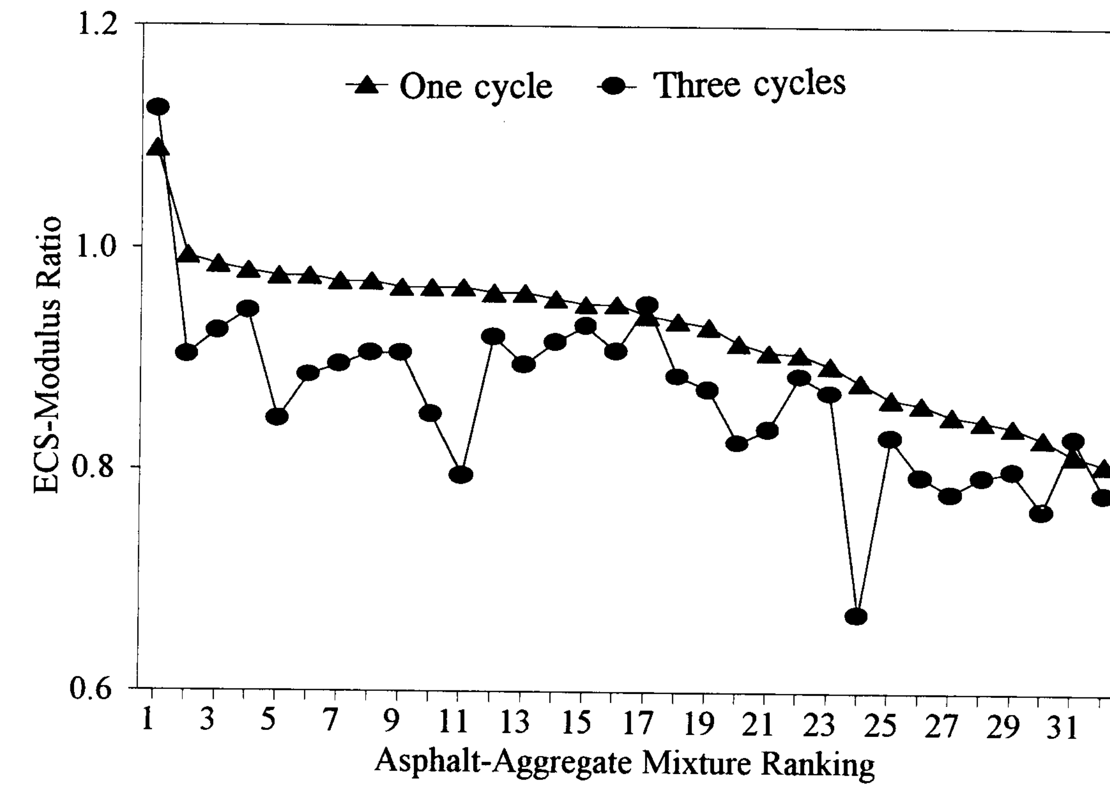

Fig. 5.1. Ranking of 32 mixes after one and three cycles

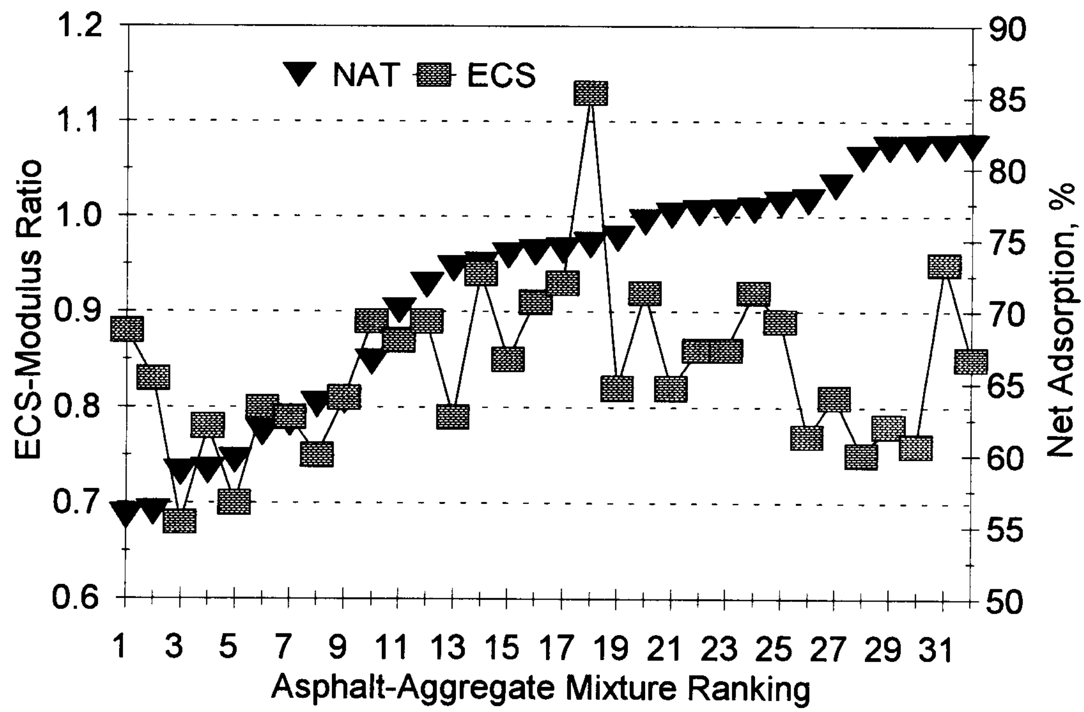

Fig. 5.2. Ranking of 32 mixes by NAT and ECS test

Table 5.16. Summary of Aggregate Rankings

Performance Ranking	Water-sensitivity	Rutting	
	A-003B/UNR (Net adsorption)	A-003A (OSU wheel-tracking)	A-003A (SWK/UN wheel-tracking)
Good	RC, RD	RJ	RC, RD
	RH	RD, RH	RH
Poor	RJ	RC	RJ

Table 5.17. Summary of Asphalt Rankings

Performance Ranking	Water-sensitivity		Permanent Deformation		
	A-002A	A-003B/UNR	A-002A	A-003A (OSU wheel-tracking)	A-003A (SWK/UN wheel-tracking)
Good	AAF-1	AAD-1	AAM-1	AAK-1	AAM-1
	AAB-1	AAK-1	AAK-1	AAM-1	AAK-1
	AAM-1				
	AAA-1	AAA-1	AAD-1	AAD-1	AAD-1
		AAC-1	AAB-1	AAF-1	AAB-1
	AAD-1	AAB-1		AAB-1	
	AAK-1	AAF-1	AAA-1		AAF-1
			AAF-1	AAG-1	AAA-1
	AAG-1	AAG-1	AAC-1	AAA-1	
		AAM-1	AAG-1	AAC-1	AAG-1
Poor					AAC-1

sensitivity proposed by the A-002A contractor were tentative and were later withdrawn; therefore, there is no hypothesis for water-sensitivity prediction by A-002A.

Considering the comparisons of ranking of the materials by different test procedures, keep in mind that the mechanisms leading to varying performance are not the same. The aim of testing reported herein was to measure water-sensitivity, but all the tests did not do so directly. Both the ECS test and NAT evaluated the mix before and after water-conditioning, but the rutting tests of OSU and SWK/UN evaluated the mix only after the wet conditioning. Because of the large specimen size of the beams tested (compared with ECS or NAT specimens), the water-conditioning of the beams may not have been severe enough to induce true water damage. Furthermore, the NAT procedure addressed only the potential for stripping (adhesion) and was not capable of evaluating cohesion loss. The other tests (ECS and OSU and SWK/UN wheel-tracking) included all the mechanisms simultaneously and provided a gross effect without clearly separating the cause of failure in each case.

5.4 Discussion Regarding Specifications

One of the goals of the ECS test development was to establish guidelines for specifications. The appropriate limits for specifications should be based on field performance. The validation testing covered in this report includes only Materials Reference Library (MRL) materials with no direct link to field projects. Therefore, specifications are discussed in the report on field validation (Allen and Terrel 1994), which includes actual pavements, and thus provides an opportunity to compare field and laboratory results.

6

Conclusions and Recommendations

6.1 Conclusions

The testing results and analysis presented herein warrant the following conclusions:

1) Performance ranking of mixes by asphalt type or aggregate type alone cannot be made for the Environmental Conditioning System (ECS) test results because of the significant interaction between asphalt and aggregate. Water-sensitivity in the ECS is significant for pairs of asphalts and aggregate. The ECS test results show that ECS performance ranking after only one cycle is not sufficient and does not correlate with ranking after three cycles.

2) The Oregon State University (OSU) wheel-tracking test results indicate that the RJ aggregate is a good performer, the RC aggregate a poor performer, and the RD and RH aggregates intermediate performers in terms of rut resistance. The SWK Pavement Engineering/University of Nottingham (SWK/UN) wheel-tracking test results indicate that the RC and RD aggregates are good performers (with practically no difference between the two), the RH aggregate an intermediate performer, and the RJ aggregate a poor performer. The significant differences between the results of the two test methods may possibly be attributed to the significant differences in testing methods, test apparatus, specimen size, and specimen environment during testing. However, the results of the SWK/UN wheel-tracking test generally validate the predictions proposed by the net adsorption test (NAT) (A-003B), but those of the OSU wheel-tracking test do not. Thus, it appears that the OSU wheel-tracking test may not be appropriate for evaluating aggregate type as it pertains to water-sensitivity.

3) The SEC-tan delta test proposed by A-002A adequately predicts the rutting potential of asphalt by type as evidenced by close agreement with the asphalt rankings from the OSU wheel-tracking and SWK/UN wheel-tracking tests. Near perfect agreement exists between A-002A predictions and the SWK/UN results unless both dry and wet-conditioned specimens are included.

4) Predictions of the water-sensitivity of the binder as proposed by the A-002A FTIR test and the A-003B NAT show little or no correlation to wheel-tracking tests on the mixes. Since very good to excellent correlation exists among the wheel-tracking tests and the A-002A predictions for permanent deformation, it appears that the FTIR test and the NAT are poor indicators of the moisture sensitivity of the binder.

6.2 Recommendations

It was evident from the results of this research that some of the test procedures used are not appropriate for evaluating water-sensitivity of mixes. Therefore, recommendations for improving comparisons in future research follow:

1) The ECS should be used to evaluate only specific pairs (i.e., asphalt-aggregate combinations), using at least three conditioning cycles.

2) If water-sensitivity is important in the OSU wheel-tracking tests, both dry and water-conditioned specimens should be tested. This approach will provide a ratio of wet to dry rutting (and possibly other failures) similar to that of the ECS.

3) An improved method of water-conditioning must be developed for the large beam specimens used in the OSU wheel tracker. The method used in this project was slow and cumbersome, and the thoroughness of wetting and/or conditioning was uncertain.

7

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Appendix A

Test Data

Wheel Tracking Data

Asphalt ID	Agg ID	Asphalt Content %	Air Voids %	Sat'n %	Strip %	Rut Depth, mm, at Wheel Passes					
						200	500	1000	2000	5000	10,000
AAA	RC	6.25	7.1	33	25.0	1.79	3.48	4.98	6.48	9.43	18.00
AAA			7.8	55	40.0	2.97	5.11	7.23	9.63	14.88	*
AAB			6.9	63	5.0	1.54	2.36	3.77	4.69	6.89	10.31
AAB			6.9	73	2.5	1.55	2.66	4.02	5.74	8.49	11.35
AAC			7.7	64	*	1.95	3.44	4.61	6.26	12.43	*
AAC			7.8	59	30.0	2.33	3.85	5.37	7.51	12.15	24.00
AAD			8.0	65	0.0	2.35	3.28	5.05	5.42	6.94	9.47
AAD			7.4	60	30.0	2.02	3.55	4.94	5.76	7.01	10.26
AAF			7.6	92	5.0	2.39	3.32	4.51	6.13	8.20	10.80
AAF			7.7	66	17.5	2.06	3.07	4.52	6.50	8.35	10.64
AAG			7.9	72	0.0	1.98	3.00	4.09	5.06	6.65	9.82
AAK			7.8	79	5.0	1.30	1.90	2.19	3.57	4.52	8.45
AAK			8.9	61	5.0	1.30	2.44	3.26	5.39	7.58	11.89
AAM			7.7	73	0.0	1.80	2.93	4.02	5.28	7.05	9.18
AAM			8.0	47	5.0	2.36	3.38	4.93	6.02	8.04	9.88
AAA	RD	4.5	8.2	52	*	0.51	1.26	2.11	3.72	5.35	6.31
AAA			8.0	60	5.0	1.56	2.17	2.33	3.64	5.11	6.00
AAB			8.7	45	15.0	1.07	1.60	2.62	3.79	5.77	6.69
AAB			8.4	52	17.5	0.41	1.72	2.72	3.75	5.58	6.99
AAC			8.9	40	5.0	1.22	2.47	3.12	4.35	5.91	7.16
AAD			8.4	57	*	0.87	1.88	2.82	4.37	6.05	7.20
AAD			8.6	56	*	0.67	1.44	2.25	3.77	5.89	7.16
AAF			9.0	56	*	0.19	1.34	2.00	3.19	4.51	5.72
AAF			8.6	49	10.0	0.75	1.50	2.27	3.46	5.41	6.90
AAG			8.7	61	5.0	0.53	1.32	2.36	3.58	6.61	8.60
AAG			8.6	61	0.0	0.70	1.72	2.50	4.40	7.54	10.35
AAK			8.1	51	*	0.13	0.56	0.87	1.67	3.42	4.82
AAK			9.0	63	5.0	0.65	1.29	1.76	2.57	3.97	4.99
AAM			8.6	44	*	1.04	1.58	2.17	3.32	4.56	5.19

Wheel Tracking Data

Asphalt ID	Agg ID	Asphalt Content %	Air Voids %	Sat'n %	Strip %	Rut Depth, mm, at Wheel Passes					
						200	500	1000	2000	5000	10,000
AAA	RH	5.2	8.2	54	0.0	1.22	1.47	2.15	3.92	5.25	7.12
AAA			7.5	63	12.5	0.92	2.50	3.90	7.11	9.02	10.52
AAB			8.8	42	10.0	0.63	1.31	1.90	3.41	5.87	7.88
AAC			6.9	44	7.5	1.66	2.23	3.43	4.91	8.62	10.98
AAC			6.9	32	5.0	0.72	1.21	1.83	2.50	4.18	6.37
AAD			7.6	46	15.0	0.81	1.50	2.01	3.10	5.08	6.85
AAD			7.8	56	5.0	0.75	1.34	2.51	4.22	6.42	8.17
AAF			8.7	40	30.0	0.64	1.26	1.46	2.59	4.97	7.67
AAF			8.5	57	0.0	0.96	1.98	1.79	3.81	6.19	8.24
AAG			8.7	65	45.0	1.59	2.79	3.60	4.63	6.21	7.52
AAG			8.7	61	35.0	0.85	1.74	2.52	3.81	5.96	7.88
AAK			8.7	43	7.5	0.42	0.89	1.17	2.25	3.29	5.17
AAK			8.8	46	7.5	0.52	0.98	0.92	2.16	4.69	6.97
AAM			7.7	71	5.0	1.29	1.81	2.17	3.08	4.86	6.56
AAM			7.7	38	2.5	0.61	0.86	1.27	2.16	3.97	5.98
AAA	RJ	5	8.4	53	*	0.89	1.52	1.78	2.34	3.43	4.49
AAA			8.4	55	*	0.65	1.58	2.52	4.42	6.62	8.30
AAB			7.7	80	5.0	0.64	1.14	2.21	3.22	3.91	4.43
AAB			7.7	55	*	0.34	0.93	1.78	2.79	3.97	5.41
AAC			9.0	63	25.0	0.75	2.18	3.16	4.43	6.91	8.79
AAD			7.2	57	7.5	0.69	1.31	1.76	2.63	3.84	6.40
AAD			7.4	66	*	0.62	1.20	1.65	2.36	3.64	4.66
AAF			8.1	57	*	0.65	1.50	1.76	2.43	3.90	5.47
AAF			8.0	41	*	0.55	1.31	1.78	2.75	4.60	6.99
AAG			8.4	53	70.0	1.11	2.43	3.14	4.36	5.81	8.65
AAK			7.2	47	*	0.24	1.07	1.46	2.59	3.51	4.32
AAK			7.1	50	*	0.68	1.26	1.71	2.37	3.27	4.32
AAM			9.2	54	*	0.59	0.95	1.28	1.96	2.59	2.65

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAF	RJ	8.4	0	473.0	1.00	Very Low	N/A
			6	470.2	0.99	Very Low	N/A
			12	468.0	0.99	Very Low	N/A
			18	453.1	0.96	Very Low	N/A
			24	403.6	0.85	Very Low	N/A
AAC	RJ	6.4	0	220.0	1.00	3.81	1.00
			6	189.0	0.86	2.91	0.76
			12	174.0	0.79	1.08	0.28
			18	164.5	0.75	0.13	0.04
			24	164.0	0.75	0.10	0.03
AAM	RJ	8.2	0	318.0	1.00	2.13	1.00
			6	278.7	0.88	1.98	0.93
			12	262.8	0.83	1.72	0.81
			18	251.7	0.79	0.96	0.45
			24	242.1	0.76	0.53	0.25
AAK	RJ	8.7	0	255.0	1.00	3.65	1.00
			6	218.2	0.86	3.48	0.95
			12	213.4	0.84	3.54	0.97
			18	204.7	0.80	3.30	0.90
			24	212.6	0.83	3.30	0.90
AAK	RJ	8.2	0	275.0	1.00	4.87	1.00
			6	219.0	0.80	3.93	0.81
			12	215.0	0.78	3.14	0.64
			18	201.5	0.73	3.07	0.63
			24	213.4	0.78	3.44	0.71
AAB	RJ	8.2	0	210.0	1.00	5.04	1.00
			6	197.5	0.94	1.91	0.38
			12	190.3	0.91	0.93	0.18
			18	189.5	0.90	0.10	0.02
			24	177.6	0.85	0.10	0.02
AAD	RJ	7.5	0	215.0	1.00	3.39	1.00
			6	174.4	0.81	2.75	0.81
			12	172.0	0.80	0.12	0.04
			18	160.9	0.75	0.07	0.02
			24	157.7	0.73	0.05	0.02
AAA	RJ	8.3	0	155.0	1.00	2.28	1.00
			6	137.8	0.89	2.42	1.06
			12	136.2	0.88	1.77	0.78
			18	135.0	0.87	0.59	0.26
			24	133.0	0.86	0.11	0.05

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAF	RJ	8.1	0	550.0	1.00	0.08	1.00
			6	547.5	1.00	Very Low	N/A
			12	502.5	0.91	Very Low	N/A
			18	473.9	0.86	Very Low	N/A
			24	438.8	0.80	Very Low	N/A
AAG	RJ	9.4	0	440.0	1.00	7.72	1.00
			6	350.4	0.80	4.73	0.61
			12	298.7	0.68	4.58	0.59
			18	297.9	0.68	4.10	0.53
			24	297.1	0.68	3.89	0.50
AAA	RJ	8.1	0	136.0	1.00	1.89	1.00
			6	133.0	0.98	0.10	0.05
			12	122.6	0.90	0.10	0.05
			18	122.0	0.90	0.09	0.05
			24	120.3	0.88	0.04	0.02
AAA	RD	8.0	0	195.0	1.00	2.20	1.00
			6	190.7	0.98	4.36	1.98
			12	190.7	0.97	3.19	1.45
			18	185.0	0.95	2.92	1.33
			24	180.5	0.93	2.90	1.32
AAC	RD	8.6	0	245.0	1.00	10.53	1.00
			6	240.0	0.98	7.34	0.70
			12	227.0	0.93	7.01	0.67
			18	215.4	0.88	6.92	0.66
			24	214.6	0.88	6.92	0.66
AAD	RD	9.2	0	218.0	1.00	8.57	1.00
			6	216.0	0.99	5.46	0.64
			12	192.0	0.88	3.19	0.37
			18	178.8	0.82	4.36	0.51
			24	178.8	0.82	4.26	0.50
AAA	RD	8.1	0	177.0	1.00	2.89	1.00
			6	175.0	0.99	3.36	1.16
			12	165.2	0.93	3.27	1.13
			18	164.3	0.93	3.27	1.13
			24	165.2	0.93	3.27	1.13
AAD	RD	8.8	0	195.0	1.00	5.82	1.00
			6	187.0	0.96	5.36	0.92
			12	173.7	0.89	5.20	0.89
			18	170.0	0.87	5.20	0.89
			24	170.3	0.87	5.20	0.89

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAG	RD	8.0	0	510.0	1.00	3.24	1.00
			6	440.0	0.86	2.32	0.72
			12	430.0	0.84	1.60	0.49
			18	408.7	0.80	1.55	0.48
			24	466.8	0.92	1.50	0.46
AAB	RD	7.2	0	280.0	1.00	4.08	1.00
			6	259.0	0.93	3.85	0.94
			12	234.2	0.84	2.83	0.69
			18	215.4	0.77	2.83	0.69
			24	214.0	0.76	2.03	0.50
AAG	RD	7.7	0	540.0	1.00	0.05	1.00
			6	530.0	0.98	0.19	3.73
			12	490.5	0.91	0.09	1.82
			18	481.1	0.89	0.09	1.82
			24	502.4	0.93	0.09	1.82
AAF	RD	9.6	0	560.0	1.00	4.99	1.00
			6	545.0	0.97	5.95	1.19
			12	489.6	0.87	5.76	1.15
			18	457.7	0.82	5.33	1.07
			24	450.0	0.80	5.28	1.06
AAG	RJ	8.1	0	265.0	1.00	3.97	1.00
			6	254.8	0.96	0.72	0.18
			12	231.0	0.87	0.12	0.03
			18	175.2	0.66	0.07	0.02
			24	184.0	0.69	0.07	0.02
AAG	RH	6.8	0	640.0	1.00	0.05	1.00
			6	553.5	0.86	2.52	48.46
			12	545.0	0.85	0.13	2.40
			18	540.7	0.84	0.09	1.69
			24	553.5	0.86	0.05	0.88
AAK	RD	8.7	0	293.0	1.00	2.71	1.00
			6	274.2	0.94	3.48	1.28
			12	269.1	0.92	3.58	1.32
			18	281.0	0.96	3.73	1.38
			24	280.0	0.96	3.73	1.38
AAA	RH	7.5	0	135.0	1.00	6.03	1.00
			6	128.0	0.95	4.41	0.73
			12	125.0	0.93	4.41	0.73
			18	130.0	0.96	2.75	0.46
			24	128.0	0.95	3.40	0.56

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAK	RD	8.1	0	287.0	1.00	2.13	1.00
			6	275.0	0.96	3.32	1.56
			12	273.0	0.95	3.32	1.56
			18	258.9	0.90	3.12	1.46
			24	272.5	0.95	3.12	1.46
AAG	RH	5.9	0	610.0	1.00	0.05	1.00
			6	580.0	0.95	2.13	42.60
			12	566.0	0.93	0.13	2.54
			18	566.0	0.93	0.09	1.78
			24	549.2	0.90	0.08	1.68
AAF	RH	7.6	0	454.0	1.00	0.16	1.00
			6	388.3	0.86	2.69	17.13
			12	387.5	0.85	2.26	14.39
			18	383.3	0.84	2.12	13.50
			24	383.0	0.84	2.12	13.50
AAM	RH	7.1	0	430.0	1.00	0.00	N/A
			6	365.0	0.85	4.37	1.00
			12	344.6	0.80	0.12	0.03
			18	374.9	0.87	2.83	0.65
			24	368.3	0.86	2.73	0.62
AAA	RH	8.4	0	118.0	1.00	5.66	1.00
			6	110.3	0.93	4.83	0.85
			12	102.3	0.87	4.16	0.73
			08	110.5	0.94	4.16	0.73
			24	109.4	0.93	4.16	0.73
AAB	RJ	8.5	0	465.0	1.00	4.03	1.00
			6	460.0	0.99	1.41	0.35
			12	382.0	0.82	0.15	0.04
			18	373.8	0.80	0.17	0.04
			24	368.6	0.79	0.15	0.04
AAF	RJ	9.1	0	256.0	1.00	5.54	1.00
			6	254.2	0.99	2.64	0.48
			12	248.6	0.97	2.13	0.38
			18	228.7	0.89	0.93	0.17
			24	222.7	0.87	0.13	0.02
AAB	RD	6.8	0	300.0	1.00	0.00	N/A
			6	283.5	0.95	3.92	1.00
			12	281.8	0.94	2.58	0.66
			18	293.8	0.98	1.98	0.51
			24	268.2	0.89	0.86	0.22

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAM	RD	10.1	0	285.0	1.00	2.70	1.00
			6	283.5	0.99	3.35	1.24
			12	269.4	0.95	2.79	1.03
			18	269.0	0.94	3.16	1.17
			24	247.0	0.87	3.16	1.17
AAA	RD	8.2	0	190.0	1.00	0.67	1.00
			6	184.3	0.97	2.48	3.70
			12	182.0	0.96	2.48	3.70
			18	180.0	0.95	2.20	3.28
			24	178.8	0.94	2.00	2.99
AAM	RC	9.7	0	235.0	1.00	13.18	1.00
			6	223.2	0.95	8.58	0.65
			12	210.0	0.89	7.09	0.54
			18	210.0	0.89	5.94	0.45
			24	204.2	0.87	5.76	0.44
AAK	RC	9.4	0	250.0	1.00	8.93	1.00
			6	215.5	0.86	5.12	0.57
			12	216.0	0.86	4.57	0.51
			18	212.0	0.85	4.48	0.50
			24	209.0	0.84	4.22	0.47
AAM	RJ	9.0	0	280.0	1.00	2.73	1.00
			6	266.9	0.95	2.30	0.84
			12	258.6	0.92	2.30	0.84
			18	240.0	0.86	2.24	0.82
			24	226.0	0.81	1.20	0.44
AAD	RH	7.6	0	172.0	1.00	0.00	N/A
			6	162.0	0.94	0.17	1.00
			12	161.0	0.94	0.17	0.99
			18	152.0	0.88	0.16	0.89
			24	150.0	0.87	0.14	0.81
AAK	RH	8.4	0	248.0	1.00	3.27	1.00
			6	210.0	0.85	3.56	1.09
			12	208.0	0.84	3.39	1.04
			18	202.0	0.81	2.69	0.82
			24	198.0	0.80	2.38	0.73
AAB	RH	7.4	0	250.0	1.00	0.11	1.00
			6	250.0	1.00	2.11	19.01
			12	232.0	0.93	2.11	19.01
			18	232.0	0.93	2.11	19.01
			24	222.0	0.89	1.77	15.95

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAF	RH	6.9	0	675.0	1.00	0.00	N/A
			6	555.0	0.82	0.13	1.00
			12	475.0	0.70	0.17	1.36
			18	510.0	0.76	0.19	1.49
			24	505.0	0.75	0.16	1.29
AAC	RD	8.6	0	285.0	1.00	9.33	1.00
			6	270.0	0.95	7.09	0.76
			12	270.0	0.95	6.48	0.69
			18	265.0	0.93	5.96	0.64
			24	255.0	0.89	5.96	0.64
AAC	RH	7.0	0	230.0	1.00	0.00	N/A
			6	240.0	1.04	0.13	1.00
			12	275.0	1.20	0.11	0.83
			18	260.0	1.13	0.06	0.49
			24	260.0	1.13	0.05	0.42
AAM	RH	6.8	0	400.0	1.00	0.00	N/A
			6	327.0	0.82	0.20	1.00
			12	300.0	0.75	0.16	0.80
			18	299.0	0.75	0.16	0.80
			24	286.0	0.72	0.15	0.77
AAA	RC	8.3	0	220.0	1.00	3.55	1.00
			6	210.0	0.95	2.72	0.77
			12	210.0	0.95	2.26	0.64
			18	199.0	0.90	2.22	0.63
			24	183.0	0.83	2.22	0.63
AAB	RC	9.2	0	255.0	1.00	5.42	1.00
			6	245.0	0.96	4.09	0.75
			12	242.0	0.95	3.44	0.63
			18	239.0	0.94	3.44	0.63
			24	215.0	0.84	3.14	0.58
AAD	RC	9.2	0	230.0	1.00	3.72	1.00
			6	195.0	0.85	3.91	1.05
			12	179.0	0.78	3.60	0.97
			18	178.0	0.77	3.29	0.88
			24	174.0	0.76	3.15	0.85
AAD	RC	8.7	0	246.0	1.00	0.03	1.00
			6	209.0	0.85	0.15	4.93
			12	206.0	0.84	0.13	4.23
			18	194.0	0.79	0.12	3.93
			24	188.0	0.76	0.12	3.83

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAC	RC	9.0	0	335.0	1.00	4.92	1.00
			6	275.0	0.82	4.20	0.85
			12	270.0	0.81	3.63	0.74
			18	270.0	0.81	3.20	0.65
			24	250.0	0.75	2.67	0.54
AAC	RC	9.0	0	275.0	1.00	5.00	1.00
			6	250.0	0.91	3.17	0.63
			12	240.0	0.87	2.77	0.55
			18	233.0	0.85	2.21	0.44
			24	207.0	0.75	1.89	0.38
AAK	RC	9.2	0	280.0	1.00	5.89	1.00
			6	260.5	0.93	4.23	0.72
			12	255.5	0.91	3.47	0.59
			18	250.0	0.89	2.80	0.48
			24	235.0	0.84	2.55	0.43
AAF	RC	8.3	0	490.0	1.00	2.24	1.00
			6	470.0	0.96	0.70	0.31
			12	458.0	0.93	0.11	0.05
			18	385.0	0.79	0.08	0.04
			24	374.0	0.76	0.04	0.02
AAG	RC	10.1	0	410.0	1.00	10.31	1.00
			6	398.0	0.97	5.42	0.53
			12	378.0	0.92	4.36	0.42
			18	373.0	0.91	3.68	0.36
			24	326.0	0.80	2.31	0.22
AAG	RC	10.4	0	315.0	1.00	7.63	1.00
			6	310.0	0.98	4.56	0.60
			12	299.0	0.95	3.87	0.51
			18	270.0	0.86	3.25	0.43
			24	258.0	0.82	2.22	0.29
AAF	RC	9.0	0	481.0	1.00	9.42	1.00
			6	466.0	0.97	4.35	0.46
			12	388.0	0.81	4.16	0.44
			18	385.0	0.80	3.54	0.38
			24	375.0	0.78	3.21	0.34
AAM	RC	10.5	0	275.0	1.00	6.02	1.00
			6	267.0	0.97	3.24	0.54
			12	262.0	0.95	2.73	0.45
			18	261.0	0.95	2.41	0.40
			24	248.0	0.90	2.27	0.38

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAD	RJ	7.5	0	155.0	1.00	4.08	1.00
			6	141.0	0.91	0.97	0.24
			12	124.0	0.80	0.14	0.03
			18	130.0	0.84	0.14	0.03
			24	120.0	0.77	0.10	0.02
AAB	RC	9.5	0	250.0	1.00	3.93	1.00
			6	246.0	0.98	2.97	0.76
			12	214.0	0.86	2.11	0.54
			18	213.0	0.85	2.07	0.53
			24	198.0	0.79	1.78	0.45
AAA	RC	9.0	0	160.0	1.00	5.27	1.00
			6	158.0	0.99	4.44	0.84
			12	150.0	0.94	3.52	0.67
			18	146.0	0.91	3.52	0.67
			24	142.0	0.89	2.89	0.55
AAB	RH	9.1	0	210.0	1.00	0.00	N/A
			6	203.0	0.97	2.89	1.00
			12	185.0	0.88	2.07	0.72
			18	193.0	0.92	2.07	0.72
			24	195.0	0.93	1.81	0.63
AAC	RH	6.8	0	231.0	1.00	0.00	N/A
			6	264.0	1.14	0.10	1.00
			12	264.0	1.14	0.06	0.62
			18	259.0	1.12	0.08	0.77
			24	259.0	1.12	0.07	0.75
AAG	RD	8.8	0	534.0	1.00	0.08	1.00
			6	505.0	0.95	4.57	60.93
			12	500.0	0.94	4.86	64.80
			18	495.0	0.93	4.87	64.93
			24	495.0	0.93	4.83	64.40
AAB	RD	8.8	0	275.0	1.00	5.53	1.00
			6	266.0	0.97	5.53	1.00
			12	256.0	0.93	5.43	0.98
			18	268.0	0.97	5.09	0.92
			24	255.0	0.93	5.09	0.92
AAF	RD	9.7	0	580.0	1.00	3.76	1.00
			6	550.0	0.95	5.65	1.50
			42	540.0	0.93	5.28	1.40
			18	540.0	0.93	5.09	1.35
			24	530.0	0.91	4.79	1.27

ECS Data

Asph Code	Agg Code	Air Voids (%)	Cond Time (hr)	ECS M_r (ksi)	ECS M_r Ratio	Water Perm (E^{-3} cm/s)	Retained Perm Ratio
AAM	RD	10.4	0	430.0	1.00	0.19	1.00
			6	402.0	0.93	2.76	14.76
			12	380.0	0.88	2.31	12.35
			18	364.0	0.85	2.46	13.16
			24	390.0	0.91	2.46	13.16
AAC	RJ	8.0	0	380.0	1.00	4.76	1.00
			6	294.0	0.77	4.99	1.05
			12	265.0	0.70	4.99	1.05
			18	260.0	0.68	4.69	0.99
			24	254.0	0.67	4.40	0.92
AAD	RH	6.9	0	230.0	1.00	0.00	N/A
			6	222.0	0.97	2.68	1.00
			12	220.0	0.96	3.59	1.34
			18	219.0	0.95	2.72	1.01
			24	218.0	0.95	3.07	1.15
AAK	RH	7.6	0	481.0	1.00	0.09	1.00
			6	403.0	0.84	1.73	18.40
			12	394.0	0.82	1.98	21.06
			18	373.0	0.78	1.75	18.62
			24	370.0	0.77	1.65	17.55
AAF	RD	9.9	0	640.0	1.00	5.69	1.00
			6	510.0	0.80	6.16	1.08
			12	494.0	0.77	5.69	1.00
			18	488.0	0.76	5.69	1.00
			24	500.0	0.78	5.69	1.00
AAM	RH	7.7	0	485.0	1.00	2.35	1.00
			6	362.0	0.75	3.54	1.51
			12	350.0	0.72	2.83	1.20
			18	348.0	0.72	2.73	1.16
			24	345.0	0.71	2.59	1.10