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Water Sensitivity of Asphalt-Aggregate Mixes: Test Selection

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Abstract

The research presented in this report was conducted to identify the important factors influencing the water sensitivity of asphalt paving mixtures, and to develop a test method to evaluate water sensitivity of asphalt concrete mixtures for mix design. The test method was to be performance related. A review of current procedures revealed that no single method was suitable for evaluation and related to field performance.

Based on a hypothesis that air voids in the mixture may be the major source and cause of water damage (i.e., if a water-sensitive mixture has very few air voids, minimal water damage can occur because moisture cannot penetrate the mixture, and if the mixture has many voids, water drains out, also minimizing damage), a test system was developed to evaluate the major factors that influence water sensitivity. The Environmental Conditioning System (ECS) was used to develop a test procedure that includes specimen preparation; measurement of permeability using air, water, or both; vacuum wetting (partial saturation); cycling at various temperatures; and continuous repeated loading while monitoring resilient modulus after each conditioning cycle. Results using four core mixtures (two aggregates and two asphalts) indicated that the ECS can distinguish different materials and their relative water susceptibility. A tentative test procedure is recommended.

Companion reports by Scholz, Terrel, Aljoaib, and Bea (1994) and by Allen and Terrel (1994) illustrate the use of the test on a wider range of materials and demonstrate the validity of the test method through studies on actual field projects.

Executive Summary

Environmental factors such as temperature, air, and water can have a profound effect on the durability of asphalt concrete mixtures. In mild climates where good-quality aggregates and asphalt cement are available, the major contribution to deterioration may be traffic loading. The resultant distress manifests as fatigue cracking, rutting, and raveling. When a more severe climate is coupled with poor materials and heavy traffic, however, premature failure may result.

Although many factors contribute to early failures in asphalt concrete pavements, moisture[1] is a key element in the deterioration of the asphalt mixture. There are three mechanisms by which moisture can degrade the integrity of an asphalt concrete matrix: (1) loss of cohesion (strength) and stiffness of the asphalt film that may be due to several mechanisms; (2) failure of the adhesion (bond) between the aggregate and asphalt (often called *stripping*), and (3) degradation or fracture of the aggregate, particularly when the mixture is subjected to freezing.

The development of tests to determine the water sensitivity of asphalt concrete mixtures began in the 1930s (Terrel and Shute 1989). Since then, numerous tests have been developed in an attempt to identify asphalt concrete mixtures susceptible to water damage. Current test procedures have attempted to simulate the strength loss (defined as damage) that can occur in the pavement so that asphalt mixtures that suffer premature distress from the presence of moisture or water can be identified before construction. However, none of the test procedures has emerged as acceptable over a wide range of conditions or materials, and none were performance related.

This subtask had two objectives: (1) to define water sensitivity of asphalt concrete mixtures with respect to performance, including fatigue, rutting, and thermal cracking, and (2) to develop laboratory testing procedures that will predict field performance. This report deals primarily with the second objective and also addresses the hypothesis that much of the water damage in pavements is caused by water in the void system. It is proposed that most of the water problems occur when void content is in the range usually used in construction, about 5 to 12 percent. Thus, the term *pessimum voids* is used to indicate that range, which is the opposite of optimum.

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[1]The terms *moisture* and *water* are often used interchangeably, but there appears to be a difference between the actions of moisture vapor and liquid water in distress mechanisms such as stripping.

To evaluate the hypothesis and the numerous variables affecting water sensitivity, the Environmental Conditioning System (ECS) was designed and fabricated. The ECS consists of three subsystems: (1) fluid conditioning, in which the specimen is subjected to predetermined levels of water, air, or vapor, and permeability is measured; (2) an environmental chamber that controls the temperature and humidity and encloses the entire loading frame; and (3) the loading system that determines resilient modulus at various times during environmental cycling and also provides continuous repeated loading as needed.

The ECS has been used to evaluate four core materials from the Materials Reference Library and also to investigate the relative importance of variables thought to be significant. Many details of specimen preparation and testing procedures were evaluated during a "shakedown" of the ECS. As minor variables were resolved, a procedure emerged that appears to be reasonable and suitable. An experiment design for the four core mixtures was developed, and the overall experiment design included three ranges of voids (less than 5 percent, low; 5 to 12 percent, pessimum; greater than 12 percent, high). Six-hour cycles of wet-hot (60°C [140°F]) and wet-freeze (-18°C [-0.4°F]) are the principle conditioning variables, while resilient modulus is monitored before and between cycling at 25°C (77°F).

A conventional testing procedure (AASHTO T 283) was also used on the core mixtures to provide a baseline for comparison. The results suggest that the ECS has better repeatability and requires fewer specimens. In addition, the temperature cycling and repeated loading used in the ECS provides a better means for predicting long-term performance.

Results presented in this report show that the ECS is capable of discerning the relative differences in performance, such as resilient modulus. Three hot cycles and one freeze cycle appear to be enough to determine the projected relative performance when comparing different aggregates, asphalts, void levels, loading, etc. Based on these results, a preliminary recommendation for further validation testing has been made and also a procedure for water conditioning specimens before testing in fatigue, rutting, and thermal cracking.

Two companion reports that demonstrate the validity of the ECS procedure through studies using a wider range of materials and actual field projects are "Water Sensitivity: Binder Validation," Scholz, R. L. Terrel, A. Aljoaib, and J. Bea (1994) and "Laboratory Aging of Asphalt-Aggregate Mixtures: Field Validation, " by W.L. Allen and R.L. Terrel, (1994).

1

Introduction

Environmental factors such as temperature, air, and water can have a profound effect on the durability of asphalt concrete mixtures. In mild climates where good-quality aggregates and asphalt cement are available, the major contribution to deterioration may be traffic loading, and the resultant distress manifests as fatigue cracking, rutting, and raveling. But when a more severe climate is coupled with poor materials and traffic, premature failure may result.

Although many factors contribute to the degradation of asphalt concrete pavements, moisture[2] is a key element in the deterioration of the asphalt mixture. There are three mechanisms by which moisture can degrade the integrity of an asphalt concrete matrix: (1) loss of cohesion (strength) and stiffness of the asphalt film that may be due to several mechanisms; (2) failure of the adhesion (bond) between the aggregate and asphalt, and (3) degradation or fracture of individual aggregate particles when subjected to freezing. When the aggregate tends to have a preference for absorbing water, the asphalt is "stripped" away. Stripping leads to premature pavement distress and ultimately to failure of the pavement.

The development of tests to determine the water sensitivity of asphalt concrete mixtures began in the 1930s (Terrel and Shute 1989). Since then numerous tests have been developed in an attempt to identify asphalt concrete mixtures susceptible to water damage. Current test procedures have attempted to simulate the strength loss or other damage that can occur in the pavement so that asphalt mixtures that suffer premature distress from moisture can be identified before construction. An asphalt mixture is identified as being sensitive to moisture if the laboratory specimens fail a moisture sensitivity test. The implication of the failure is that the particular combination of asphalt, aggregate, and antistripping additive (if used) would fail before reaching its anticipated design life because of water-related degradation mechanisms. However, no currently used test is able to predict performance.

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[2]The terms *moisture* and *water* are often used interchangeably, but there appears to be a difference between the actions of moisture vapor and liquid water in distress mechanisms such as stripping.

The major difficulty in developing a test procedure has been to simulate the field conditions to which the asphalt-aggregate mixtures are exposed. Environmental conditions, traffic, and time are the factors that must be accounted for in developing test procedures to simulate field conditions. Environmental considerations include water from precipitation or groundwater sources, temperature fluctuations (including freeze-thaw conditions), and aging of the asphalt. The effect of traffic or moving wheel loads could also be considered as an external influence of the environment. Variability in construction procedures at the time an asphalt-aggregate mixture is placed can also influence its performance in the pavement. Since most test procedures are currently used at the mixture-design stage of a project, this variability adds to the difficulty in predicting field performance. Current test procedures measure the loss of strength and stiffness, both cohesive and adhesive, of an asphalt mixture caused by water effects. The conditioning processes associated with current test methods are attempts to simulate field exposure but accelerate strength loss. Testing the cohesive or adhesive properties that would identify a moisture-susceptible mixture follows the conditioning process. Table 1.1 summarizes factors that should be considered in evaluating water sensitivity (Terrel and Shute 1989).

A moisture sensitivity (or susceptibility) test has a *conditioning* phase and an *evaluation* phase. The conditioning phases vary, but all attempt to simulate the deterioration of the asphalt concrete in the field. The two general methods of evaluating conditioned specimens are a visual evaluation and a physical test. In the visual evaluation, the retained asphalt coating is examined following the conditioning process. Typically, physical testing includes strength or modulus testing, in which a ratio is computed by dividing the result from the conditioned specimen by the result from an unconditioned specimen. If the ratio is less than a specified value, the mixture is determined to be moisture susceptible.

The subject of this report is a part of the Strategic Highway Research Program (SHRP) that addressed the relationship between asphalt binder properties and the performance of asphalt concrete mixtures. The specific charge for this task was (1) to define water sensitivity of asphalt concrete mixtures with respect to performance, including fatigue, rutting, and thermal cracking, and (2) to develop laboratory testing procedures that will predict field performance.

The scope of this report includes a brief summary of the philosophy and accompanying hypothesis on the nature and effect of water on asphalt paving mixtures. Following this is the development of these methods, proposed protocols, and preliminary test results, along with preliminary recommendations.

1.1 Background

1.1.1 Test Procedures and Moisture Sensitivity

Numerous methods have been developed to determine whether an asphalt concrete mixture is sensitive to moisture and therefore prone to early water damage. In general, the tests can be divided into two categories:

Table 1.1. Factors influencing response of mixtures to water sensitivity (Terrel and Shute 1989)

Variable	Factor
Existing condition	• Compaction method • Voids • Permeability • Environment • Time • Water content
Materials	• Asphalt • Aggregate • Modifiers or additives
Conditioning	• Curing • Dry versus wet • Soaking • Vacuum saturation • Freeze-thaw • Repeated loading • Drying
Other	• Traffic • Environmental history • Age

1. Tests that coat "standard" aggregate with an asphalt cement with or without an additive. The loose, uncompacted mixture is immersed in water (which is either held at room temperature or boiled). The amount of stripping is estimated by a visual assessment.

2. Tests that use compacted specimens—either laboratory compacted or cores from existing pavement structures. These specimens are conditioned in some manner to simulate in-service conditions of the pavement structure. The specimens are generally evaluated by the ratios of conditioned to unconditioned results from a stiffness or strength test (e.g., diametral resilient modulus test, diametral tensile strength test).

Terms such as *reasonable*, *good*, and *fair* are often used to describe how well the results of a test correlate with actual field performance. Stuart (1986) and Parker and Wilson (1986) found that for the tests they evaluated, a single pass/fail criterion could not be established that would enable the results of the tests to correctly indicate whether the asphalt mixtures tested were moisture sensitive. These results are characteristic of all test methods currently used to assess asphalt concrete mixtures for moisture sensitivity.

From a review of the literature, the following tests have received the most attention and cover the variety of methods used to evaluate moisture sensitivity, and therefore were selected for review:

1. NCHRP 246, Indirect tensile test and/or modulus test with Lottman conditioning (Lottman 1982).

2. NCHRP 274, Indirect tensile test with Tunnicliff and Root (1984) conditioning.

3. AASHTO T 283, which combines features of both NCHRP 246 and 274.

4. Boiling water tests (ASTM D 3625).

5. Immersion-compression tests (AASHTO T 165, ASTM D 1075).

6. Freeze-thaw pedestal test (Kennedy et al. 1982).

7. Static immersion test (AASHTO T 182, ASTM D 1664).

8. Conditioning with stability test (AASHTO T 245).

Although not covered in detail in this report, it is apparent from the literature review and survey of current practice that a variety of test methods have been employed to assess the following:

1. The potential for moisture sensitivity in asphalt concrete mixtures.

2. The benefits offered by antistripping agents to prevent moisture-induced damage to asphalt concrete mixtures.

3. The prediction of performance, which so far has not been achieved.

Conditioning can be accomplished by several methods. Table 1.1 shows a list of factors or criteria that should be considered when evaluating procedures. A summary of the methods evaluated was documented in an earlier report (Terrel and Shute 1989). So far, no single test has proven to be superior, as is evident from the number and variety of tests currently being used. From the data and experience to date, it appears that no test has yet been established that is highly accurate in predicting moisture-susceptible mixtures and estimating the life of the pavement.

1.1.2 Philosophy of Water-Damage Mitigation

The design of asphalt paving mixtures is a multistep process of selecting asphalt and aggregate materials and proportioning them to provide an appropriate compromise among several variables that affect the mixtures' behavior. Consideration of external factors such as traffic loading and climate is part of the design process. Performance factors that are of concern in any design include at least the following goals:

1. To maximize the fatigue life.

2. To minimize the potential for rutting.

3. To minimize the effect of low temperature or thermal cycling on cracking.

4. To minimize or control the amount and rate of age hardening.

5. To reduce the effect of water.

In many instances, water or moisture vapor in the pavement can reduce the performance life by affecting any of the factors listed above. The effect of stripping or loss of adhesion is readily apparent because the integrity of the mixture is disrupted. The loss of cohesion is often less obvious but can cause a major loss of stiffness or strength. The introduction of air or moisture into the void system accelerates age hardening, thus further reducing pavement life. The following discussion is aimed at the evaluation of water sensitivity and mitigation of damage or loss of performance resulting from water in mixtures.

1.2 Hypothesis for Water-Damage Mitigation

The effect of water on asphalt concrete mixtures has been difficult to assess because of the many variables involved. One variable that affects the results of current methods of evaluation is the air void content of the mixture. The very existence of these voids, as well as their characteristics, can play a major role in performance. Contemporary thinking would have us believe that voids are necessary or at least unavoidable. Voids in the mineral aggregate are designed to be filled to a point less than full of asphalt cement to allow for traffic compaction. But if one could design and build the pavement properly, allowing for compaction by traffic would be unnecessary. In the laboratory, mixtures are designed at, say, 4 percent voids, but actual field compaction may result in as much as 8 to 10 percent voids. These voids provide the major access for water into the pavement mixture.

Existing mixture design methods and construction practices for asphalt concrete tend to create an air void system that may be a major cause of moisture-related damage. A major effect of air voids is illustrated in Figure 1.1. If mixtures of asphalt concrete are prepared and conditioned by some process such as water saturation followed by freezing and thawing, the retained strength or modulus is typically somewhat lower than that of the original dry mixture. However, this effect tends to be tempered by the voids in the mixture, particularly access to the voids by water. If the mixtures shown in Figure 1.1 were designed for a range of voids by adjusting the aggregate size and gradation and the asphalt content, a range of permeability would result. Mixtures with minimal voids that are not interconnected; would be essentially impermeable. When air voids increased beyond some critical value, they would become larger and interconnected; thus water could flow freely through the mixture. Between these two extremes of impermeable and open or free-draining mixtures is where most asphalt pavements are constructed. The voids tend to range from small to large, with a range of permeability depending on their interconnection.

The curve in Figure 1.1 indicates that the worst behavior in the presence of water occurs in the range at which most conventional mixtures are compacted. Thus, the term *pessimum voids* can be used to describe a void system that is the opposite of optimum. Pessimum voids can actually represent a concept of quantity (amount of voids in the mixture) and quality (size, distribution, and interconnection) as they affect the behavior and performance of pavements.

Intuitively, one could describe the three regions in Figure 1.1 as follows:

1. Impermeable or low-void mixtures are made with high asphalt content or are mastics. To offset the instability expected from high binder content, aggregate gradation is modified (with crushed sand or large stone), and an improved binder containing polymers or fibers can be used.

2. The midrange or pessimum voids region is represented by conventional dense-graded asphalt concrete as used in the United States.

3. Free-draining or open-graded mixtures are designed as surface friction courses or draining base courses. With the use of polymer-modified asphalt, these mixtures can be designed with higher binder content (thicker films) to remain open and stable under traffic.

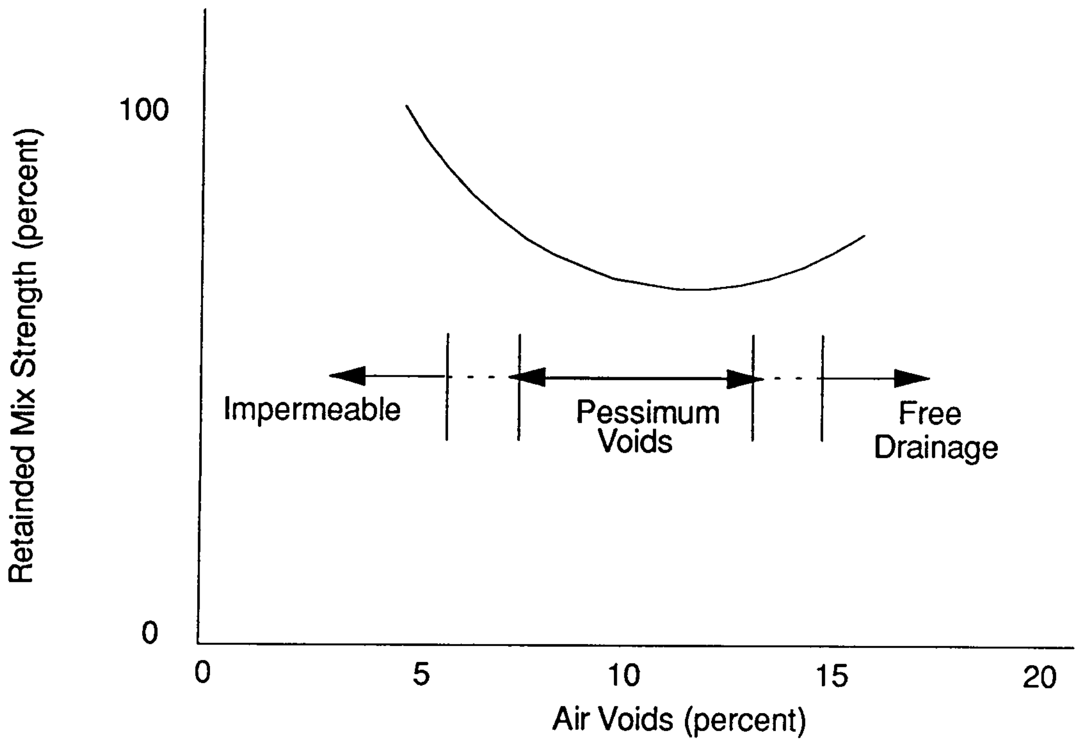

Figure 1.1. Relationship between strength of mixtures and air void content

The European community has recognized the advantages of mixtures that fall outside the pessimum-voids region, as described in an investigation of stone-mastic asphalt and porous asphalt (*Die Asphaltstrasse* June 1989). The stone-mastic mixtures have high stability combined with very good durability and have low void content (3 to 4 percent) and increased performance life (20 to 40 percent) compared with conventional dense-graded mixtures. Porous asphalt is used to improve safety and reduce noise and spray from tires. With the use of polymer-modified asphalt, durability is increased and performance life is increased from 7 to more than 12 years (Shute et al. 1989).

1.2.1 Theory for Water-Sensitivity Behavior

As indicated earlier, water appears to affect asphalt concrete mixtures through three major mechanisms: (1) loss of adhesion between asphalt binder and aggregate surface, (2) loss of cohesion through a gross softening of the bitumen or weakening of asphalt concrete mixtures, and (3) degradation of aggregate upon freezing.

Voids in the asphalt concrete are the most obvious route for water to enter the compacted mixture. Once a pavement is constructed, most water and air ingress is through these relatively large voids. Other voids or forms of porosity may also affect water sensitivity. For example, aggregate particles have varying sizes and amounts of both surface and interior voids. Water trapped in the aggregate voids because of incomplete drying plays a role in coating during construction and during early service life. Also, there is some indication that asphalt cements may themselves absorb water or allow water to pass through films at the aggregate surface. The complexity of the water-void system requires a careful and detailed evaluation to better understand its significance.

Although continued study of water sensitivity will likely result in improved understanding and performance, the starting point or state of the art is a good beginning.

1.2.2 Theories of Adhesion

Shute et al. (1989) have provided a good overview of previous research and current thinking on adhesion. Four theories of adhesion have been developed around the following factors that appear to affect adhesion:

1. Surface tension of the asphalt cement and aggregate.
2. Chemical composition of the asphalt and aggregate.
3. Asphalt viscosity.
4. Surface texture of the aggregate.
5. Aggregate porosity.

6. Aggregate cleanliness.

7. Aggregate moisture content and temperature at the time of mixing with asphalt cement.

No single theory seems to completely explain adhesion; it is most likely that two or more mechanisms occur simultaneously in any one mixture to cause loss of adhesion. In summary, the four theories of adhesion are as follows:

Mechanical adhesion relies on several aggregate properties, including surface texture, porosity or absorption, surface coatings, surface area, and particle size. In general, a rough, porous surface appears to provide the strongest interlock between aggregate and asphalt. Some absorption of asphalt into surface voids provides a mechanical interlock as well as additional surface area.

Chemical reaction is recognized as a possible mechanism for adhesion between asphalt cement and aggregate surfaces. Many researchers have noted that better adhesion may be achieved with basic aggregates than with acidic aggregates. However, very acceptable mixtures have been produced with all types of aggregates. More recent SHRP work (Auburn University, Contract A-003B) has concentrated on the chemical interactions at the aggregate-asphalt interface (Curtis et al. 1991), and it was found that adhesion is specific to individual asphalt-aggregate combinations.

Surface energy theory is used in an attempt to explain the relative wettability of aggregate surfaces by asphalt and water. Water is a better wetting agent than asphalt because it has a lower viscosity and lower surface tension. When asphalt coats aggregate, a change of energy termed *adhesion tension* occurs that is related to the mutual affinity of asphalt cement and aggregates.

Molecular orientation theory suggests that molecules of asphalt align themselves with unsatisfied electric charges on the aggregate surface. Only some molecules in asphalt are dipolar, but water is entirely dipolar, and this difference may help explain the preference of aggregate surfaces for water rather than asphalt.

All these mechanisms may occur to some extent in any asphalt-aggregate system. As part of a study on microwave effects, Al-Ohaly and Terrel (1989) have summarized the various mechanisms as shown in Figure 1.2. Aside from the suggested microwave heating effects, several improvements can be visualized: mechanical interlock, molecular orientation, and polarization.

Research has shown that adhesion can be improved through the use of various commercial liquid antistripping additives as well as lime. In the SHRP research, studies of fundamental behavior of asphalt-aggregate interaction were to be aimed at better understanding and control of the mechanisms leading to stripping; this work was part of SHRP Contract A-002B.

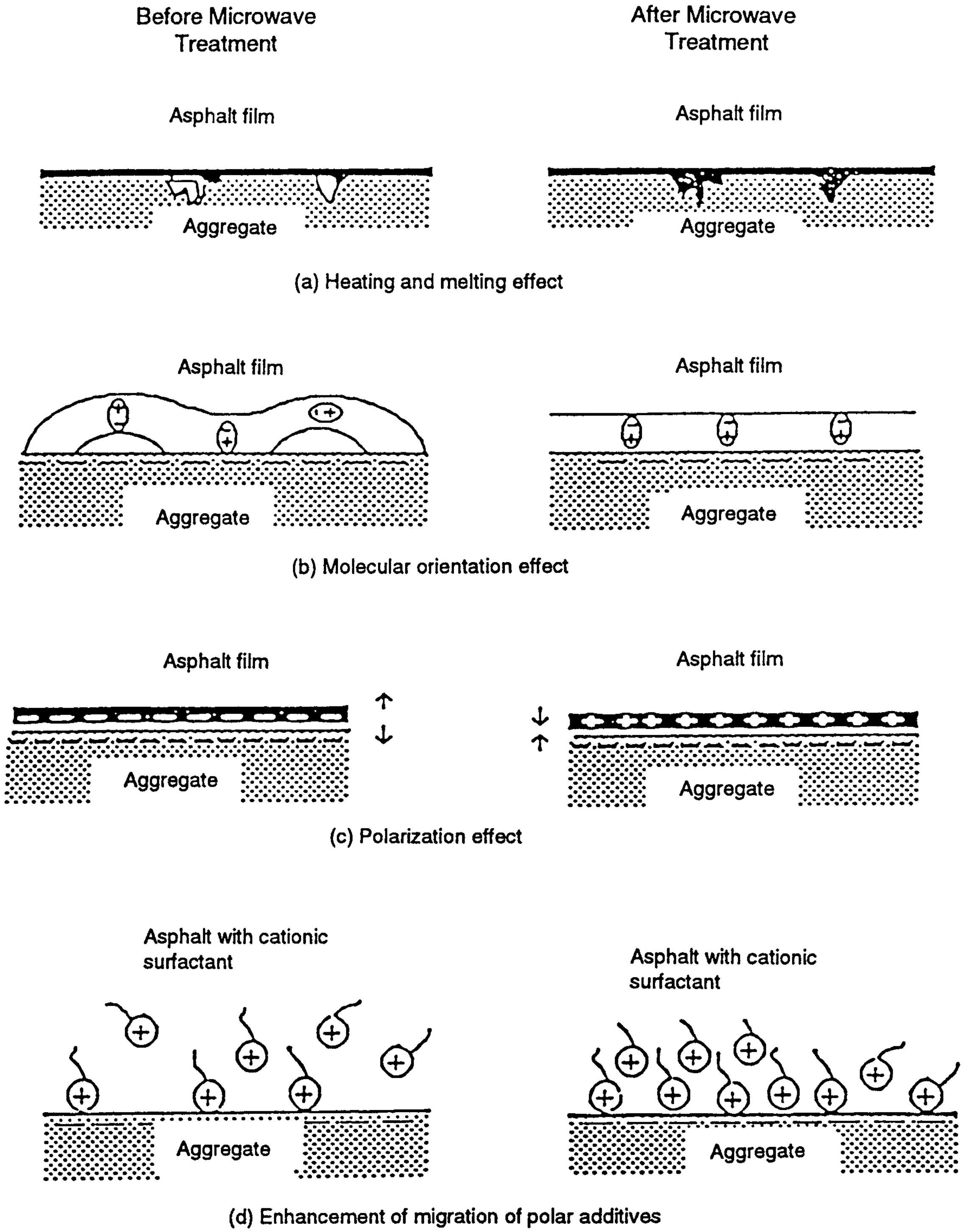

Figure 1.2. Mechanisms of adhesion improvement with microwave energy treatment (Al-Ohaly and Terrel, 1989)

1.2.3 Theories of Cohesion

In compacted asphalt concrete, cohesion might be described as the overall integrity of the material when subjected to load or stress. Assuming that adhesion between aggregate and asphalt is adequate, cohesive forces will develop in the asphalt film or matrix. Generally, cohesive resistance or strength might be measured in the stability test, resilient modulus test, or tensile strength test. The cohesion values are influenced by factors such as viscosity of the asphalt-filler system. Water can affect cohesion in several ways—for example through intrusion into the asphalt binder film or through saturation and even expansion of the void system (swelling). Although the effects of stripping may also occur in the presence of water, a mechanical test such as repeated-load resilient modulus tends to measure gross effects, and the mechanisms of adhesion and cohesion cannot be distinguished separately.

On a smaller scale, in the asphalt film surrounding aggregate particles, cohesion can be considered the deformation or resistance to deformation under load that occurs at some distance from the aggregate surface—beyond the influence of mechanical interlock and molecular orientation. An example of the effect of water on cohesion (i.e., resilient modulus) is shown in Figure 1.3. This early work by Schmidt and Graf (1972) illustrates that a mixture will lose about 50 percent of its modulus upon saturation with water. The loss may continue with time, but at a slower rate while it remains wet. Upon drying, the modulus was completely restored, and a further repetition of wetting and drying resulted in the same behavior. During the conditioning process, which lasted more than 6 months, there appeared to be a slight overall stiffening, probably caused by age hardening of the asphalt cement. Such observations provide a better understanding of the effects of water on mixture performance.

1.3 Research Objectives

Keeping in mind the twofold goal of this SHRP research (Task C.5), this task was focused on relating the effect of water sensitivity to mixture performance (i.e., fatigue and rutting) and the development of a test procedure for evaluating water sensitivity. The program had the following five phases:

- C.5.a. Evaluation of current technology.
- C.5.b. Development of testing techniques and equipment.
- C.5.c. Laboratory implementation of new technique.
- C.5.d. Field validation of new technique.
- C.5.e. Final report (including development of new specifications).

The first phase resulted in a state-of-the-practice summary report (Terrel and Shute 1989). This final report and the second phase focused on the development of a testing or evaluation procedure.

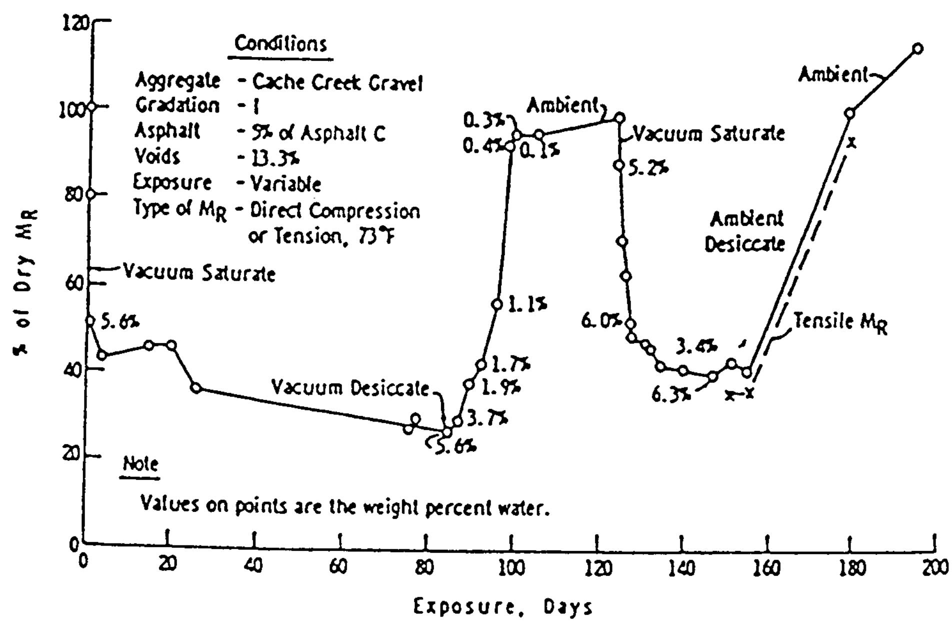

Figure 1.3. Effect of changes in moisture conditioning on resilient modulus of asphalt concrete (Schmidt and Graf 1972)

A materials evaluation procedure for routine use might take several different forms, but the one initially envisioned for this project comprised the following three separate steps:

1. Testing and screening potential materials—both aggregates and asphalt binders—to eliminate candidates with properties that make them unusable, such as a high tendency toward stripping.

2. Mixing aggregates and asphalt together and testing the loose mixtures for adhesion, particularly stripping.

3. Testing compacted mixtures to evaluate their sensitivity to water and their potential for successful performance in pavements.

Figure 1.4 is a diagram showing these steps in the right-hand margin, and more details of the procedure are outlined in the figure. With this type of overall process as a goal, the SHRP team has researched the details of methodology and criteria.

Fundamental properties of asphalt and aggregates are a major concern and have been investigated by several research agencies (step 1). For example, chemical and physical tests of asphalts were developed that attempt to relate their properties to the performance of paving mixtures. Details such as the effect of voids and water on aging, the chemical nature of various phases of the asphalt-aggregate bond, and surface characteristics of the aggregate, such as electrochemical charge, were evaluated for possible inclusion in the overall procedure.

Practical coating and adhesion tests for loose (uncompacted) combinations of aggregate and asphalt were the goal of step 2. These tests were an important screening step for identifying stripping potential before embarking on the more time-consuming final step 3.

Step 3 is the heart of mixture evaluation for water sensitivity. Its goal was not only to evaluate water sensitivity in some rational or comparative manner, but also to translate that information into other performance parameters (i.e., fatigue, rutting, thermal cracking, and aging). An early focus will be a recommended water-conditioning process for mixtures being tested in fatigue or rutting, for example. Finally, after the verification process, a refined procedure was recommended for implementation by SHRP and other agencies.

The generalized procedure in Figure 1.4 was developed as a possible scheme. During the early years of the SHRP research, the preselected SHRP materials were evaluated. These included a stockpile of more than 30 asphalt sources and 11 aggregate sources. Basic information was compiled on these materials for use by the various researchers. Any recommended test procedure should be suitable for the full range of materials to be encountered, so preliminary testing on materials selected for their known extremes of water sensitivity were first evaluated for core information on which to base further development.

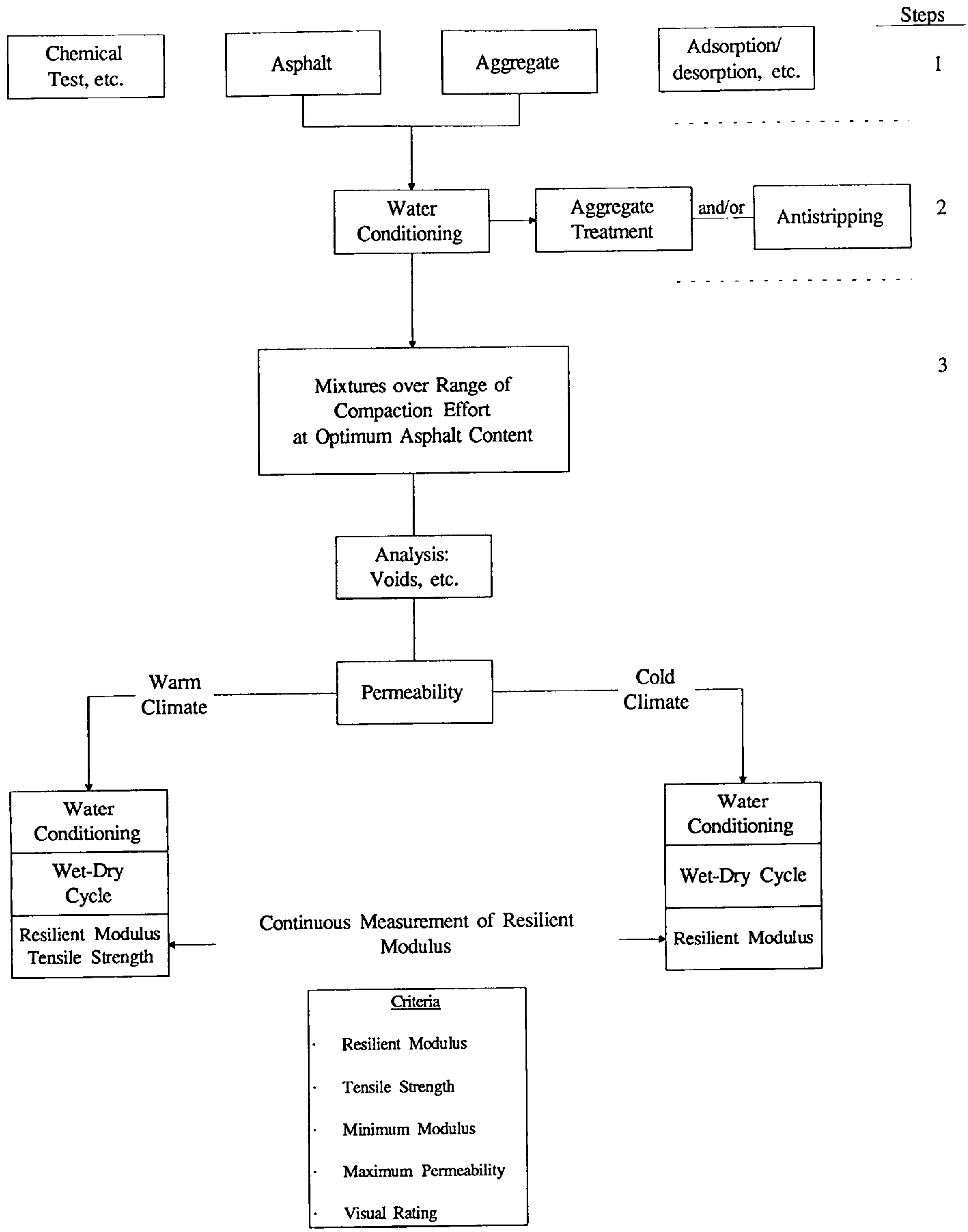

Figure 1.4. Possible improved test procedure for water sensitivity (Terrel and Shute 1989)

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Experiment Design

This study is aimed at determining the factors that most influence the water sensitivity of asphalt paving mixtures. A logical approach is to study the fundamental properties of asphalt and aggregate, as shown in Table 1.1, and develop a series of tests that would rate or screen various combinations for probability of successful performance. The basic factors that influence compacted mixtures, such as permeability, time, rate of wetting or saturation, and aging, would then be evaluated for a range of mixtures. Since the permeability (or air void content) is a major factor, it is used as a controlled variable in the experiment plan to characterize the response of an asphalt concrete specimen to changes in water-conditioning factors such as time, rate of wetting, and temperature cycling. Eventually, a water-conditioning and testing procedure would be recommended for testing by various user agencies before final standardization.

The water-sensitivity task (Task C.5) of SHRP research comprised five phases. A summary of each phase is discussed in the following sections:

Phase C.5.a: Evaluation of current technology. The objective of this phase was to provide a literature review and evaluation of existing test methods and to select the most widely used method to compare with the new technique. The literature review and evaluation of existing test methods was accomplished in 1989 by preparing a state-of-the-practice report, which has been published by SHRP as a stand-alone document, "Summary Report on Water Sensitivity" (Terrel and Shute 1989). AASHTO T 283 was selected as a benchmark and was conducted on the same asphalt-aggregate combinations used for Environmental Conditioning System testing (Phase C.5.b). The comparison between the current practice and the new technique was discussed in this report.

Phase C.5.b: Development of testing techniques and equipment. The evaluation of current test methods indicated that a better method was needed, so the Environmental Conditioning System (ECS) was developed at Oregon State University (OSU) as a test system and used to develop a testing technique. The ECS and related peripheral equipment, such as the permeability measurement device, were developed and refined through several ministudies. The main experiment was conducted by using the ECS to develop a test procedure. This report includes the details of the ECS and testing procedures. Also, the ECS test results were evaluated in conjunction with data from other SHRP contract activities, which improved the reliability of the new equipment and test procedures.

Phase C.5.c: Laboratory implementation of new technique. An expanded series of tests including more materials was conducted to verify the recommended testing procedures. Eight asphalts and four aggregates from the SHRP Materials Reference Library (MRL) were used to prepare specimens to be tested by the ECS. Some specimens were prepared by the wheel-tracking compactor and the others by the kneading compactor (Scholz et al. 1992).

Phase C.5.d: Field Validation of New Technique. This task involved two approaches: (1) validation in mixtures of the ranking of the numerous asphalt binders as determined by SHRP researchers using only binder tests, and (2) validation of behavior and failure concepts using field sites representing of a wide range of materials and climates. The first validation process included 32 asphalt and aggregate combinations from MRL. The mixtures were compacted into slabs by rolling-wheel compaction. From each slab, two test specimens were cut for use in wheel-tracking tests at OSU, and several cores were taken as specimens for the ECS. The wheel-tracking test involves conditioning analogous to that of the ECS and then testing the specimen under repeated passes of a pneumatic tire, with measurements of developing rut depths taken throughout the test.

The second process included 12 field sites from both the United States and Canada. The sites cover four different climate regions. Original asphalts, aggregates, and admixtures were obtained from each site, and core samples were drilled in 1991. The cores were tested for resilient modulus both diametrally and triaxially and were examined visually for stripping. A manual distress survey of each site was also performed to determine whether the site showed visible signs of water damage (Allen and Terrel 1992).

From the original materials, large slabs were fabricated with the rolling-wheel compactor. From these large slabs, specimens for the wheel-tracking device were cut, and cores for the ECS will be drilled. Companion cores were made with the kneading compactor for testing in the ECS. Some of these specimens were tested with the wheel-tracking device and others with the ECS to see whether conditioning could reproduce samples with resilient modulus and visual stripping characteristics similar to those of the cores taken from the field sites.

Phase C.5.e: Final report

The details of phase C.5.c are covered in this report. Conditioning variables and the experiment plan are discussed in the following sections. In addition, a summary final report (Monismith et al. 1993) includes the information from all phases of Task C.5.

2.1 Variables

The development of tests to determine the water sensitivity of asphalt concrete mixtures began in the 1930s (Terrel and Shute 1989). Since then, interest in the effect of water sensitivity on life and performance of asphalt concrete pavements has increased, and numerous test procedures have been developed in an attempt to understand the phenomenon of adhesion and cohesion between asphalt cement and mineral aggregate.

Test procedures have attempted to simulate the strength loss or other damage that can occur in the pavement so that asphalt mixtures that suffer premature distress from moisture or water can be identified before construction. An asphalt mixture is identified as being sensitive to water if the laboratory specimens fail a moisture sensitivity test. The implication of the failure is that the particular combination of asphalt and aggregate would fail through water- related mechanisms before reaching its anticipated design life. Simulating the field conditions to which the asphalt concrete is exposed has been the most difficult part of all water- sensitivity tests. A water-sensitivity protocol includes two major phases: a conditioning phase and an evaluation phase. The conditioning phases vary, but all attempt to simulate the behavior of the asphalt concrete in the field in the presence of water. The two general methods of evaluating conditioned specimens are visual evaluation and physical testing.

The objective of SHRP in this study is to develop a laboratory conditioning procedure (moisture, temperature, load) to be used for water-sensitivity evaluation during the design process and for conditioning before testing in other modes, such as fatigue, rutting, aging, and thermal cracking.

It is important not only to simulate the pavement conditions in the laboratory, but also to take into consideration the effect of the environment over a long time. In this study, the laboratory tests and their condition factors were selected with great care to represent the realistic conditions of the asphalt pavement in real service. Table 2.1 summarizes the factors influencing response of asphalt concrete to water sensitivity as they were included in this research.

To conduct the research, it was necessary to design an experimental testing program that included all related variables. Figure 2.1 shows a 3×3×3 factorially designed experiment. This testing program was conducted using the ECS. The controlled variables and their treatment levels incorporated in the experiment were as follows:

1. Temperature, with three treatment levels.

    - Hot: 60°C (140°F)
    - Ambient: 25°C (77°F)
    - Freeze: -18°C (-0.4°F)

2. Permeability, with three treatment levels, depending on the air void content.

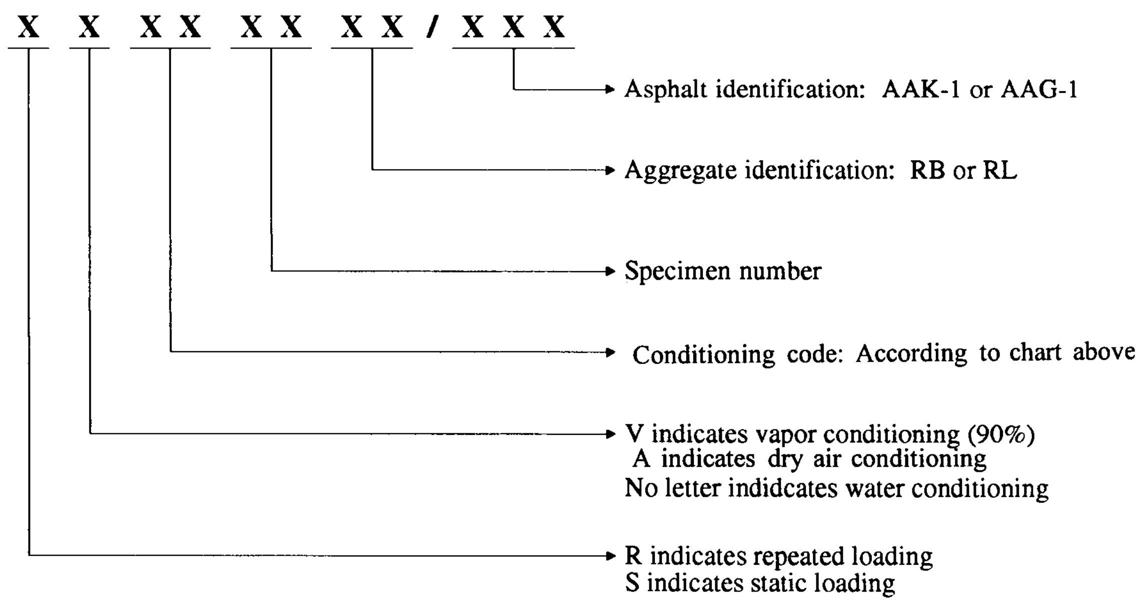
    - Low: percent air voids less than or equal to 6
    - Pessimum: percent air voids greater than 6 but less than 14
    - High: percent air voids greater than or equal to 14

Table 2.1. Factors considered in the experiment plan

Variable	Factor
Existing condition	• Compaction method • Voids • Permeability • Environment • Time • Water content
Materials	• Asphalt • Aggregate
Conditioning	• Dry versus wet • Vacuum saturation • Freeze-thaw • Repeated loading • Drying

		Conditioning Temperature °C								
		Hot (60)			Ambient (25)			Freeze (-18)		
		Water Wet Conditioning								
		Dry	**Moist**	**Wet**	**Dry**	**Moist**	**Wet**	**Dry**	**Moist**	**Wet**
Perm. (%)	Low	LA	LB	LC	LD	LE	LF	LG	LH	LI
	Pessiumum	A	B	C	D	E	F	G	H	I
	High	HA	HB	HC	HD	HE	HF	HG	HH	HI

(a) Environmental Condition System experimental test plan



(b) Specimen identification

Figure 2.1. Experimental test plan and specimen identification

3. Water conditioning, with three treatment levels.

- Dry: No water conditioning
- Moist: Water run through the specimens at 25°C (77°F) under 25.4 cm (10 in.) Hg vacuum for 30 min
- Wet: Water run through the specimen at 25°C (77°F) under 50.8 cm (20 in.) Hg vacuum for 30 min

After most of the preliminary tests and a series of ministudies were completed, a modified test plan was initiated. During the early stages of laboratory testing, it became apparent that it was not necessary to perform all the dry and ambient conditionings (Figure 2.1). The temperatures used for conditioning were limited to the extremes of 60° and -18°C (140° and -0.4°F), with the intermediate 25°C (77°F) used only for limited comparisons. Early testing showed that the dry conditioning provided aging damage, as expected, so only moist and wet were actually used, with the dry range used only to show the boundaries of moisture conditioning. The high air void level was investigated after modifying the test setup to overcome some of the problems associated with conditioning very high air void specimens at high temperatures. The details of the test results of conditioning high air void specimens are discussed in a separate section about proving the pessimum-voids hypothesis. In summary, most of the testing reported under this experiment plan is confined to two permeability levels, hot or freezing temperatures, and moist or wet moistures. Three conditioning cycles were used for the entire experiment, and repeated loading was applied during the hot cycles. No repeated loading was applied during freezing cycles because the pore water was frozen and the load level being used was insufficient to cause deformation of the specimen at this low temperature.

2.1.1 Determination of Saturation Level

A suitable degree of saturation based on AASHTO T 283 and other previous experience was established to be between 55 and 80 percent of the volume of air (Lottman 1978 and 1988). This target window of saturation was achieved by placing the specimen in a vacuum container filled with distilled water and applying a partial vacuum, such as 50.8 cm (20 in.) Hg, for a short time. If the degree of saturation is not within the limits, adjustments could be made by trial and error by changing vacuum level or time of submersion. This saturation method works satisfactorily for asphalt concrete mixtures, 8 ± 1 percent air voids.

The ECS method (as discussed later) attempted to standardize the wetting procedure by controlling water accessibility and vacuum level, rather than controlling water volume and degree of saturation, as in AASHTO T 283. The ECS uses a controlled vacuum for saturation by maintaining the desired vacuum level during the wetting stage according to the experiment plan and a 25.4 cm (10 in.) Hg vacuum level during the conditioning cycles, while some of the current methods, such as AASHTO T 283, use a controlled degree of saturation by maintaining the value between 50 and 80 percent. In the case of similar gradations with one air void level, using the controlled degree of saturation technique is correct. But since the objective of this study is to develop a universal water-conditioning procedure for asphalt mixtures with different air void levels, using the controlled degree of saturation is not considered the best method. This is because of dense mixtures in which 60 percent of the air voids are not connected or inaccessible, and in this case it is not possible to achieve the minimum 50-percent saturation with any high vacuum level. Also, on the other extreme, there are open graded mixtures with air void contents of 25 percent or more, in which almost all the air voids are interconnected and very accessible to water. Soaking these specimens in the water bath without any vacuum or simply dipping them in the water will achieve more than 90-percent saturation.

To illustrate this concept, three sets of specimens with three levels of air voids—4, 8, and 31 percent—were placed in a vacuum container and partially saturated under a 50.8 cm (20 in.) Hg vacuum level for 30 min. Figure 2.2 shows the relationship between degree of saturation and air void level under the same vacuum. This confirms that trying to achieve a target degree of saturation in specimens with certain air void levels may destroy the specimens because of the need for high vacuum, as in the case of 4 percent air voids. In contrast, one may achieve the target degree of saturation before reaching an appropriate accelerated wetting process, as in the case of 31-percent air voids.

In summary, the ECS uses the vacuum controlled water penetration into the mixture as a measure of its relative saturation or wettability rather than a fixed level of saturation.

2.1.2 Other Test Variables

The ECS testing experiment was conducted on the following materials and loading conditions:

1. Two asphalt types.
2. Two aggregate types.
3. Two loading levels.

Originally, specimen height was 6.35 cm (2.5 in.), as in a conventional Marshall briquet. After experience with the ECS, it was observed that measurement of the resilient modulus from 6.35 cm (2.5-in.) specimens had poor repeatability. Thus, a specimen 10 cm (4 in.) in height and 10 cm (4 in.) in diameter was recommended for better repeatability (see chapter 3 for more information on the ECS-M_R). All the results from short specimens are included in appendix A for general information, but they were not used in the analysis and development of conclusions. The test results of 10-cm (4-in.) specimens are included in chapter 3.

The effectiveness of each controlled variable, as shown in Table 2.1, was determined from the values of response variables. Response variables are as follows:

1. Resilient modulus change (retained or gained resilient modulus), ratio from original value.

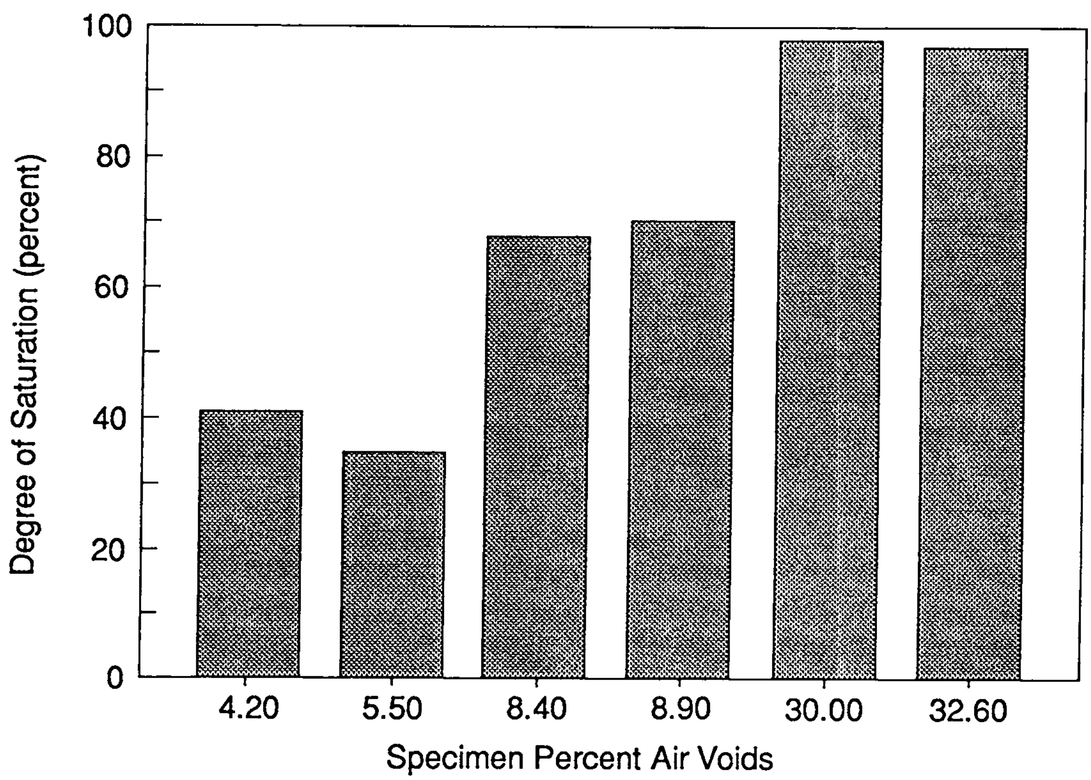


Figure 2.2. Relationship between degree of saturation and percent air voids

2. Permeability change (retained or gained permeability), ratio from original value.

3. Visual evaluation: The percentage of retained asphalt coating on the aggregate for conditioned specimens.

Finally, upon completing this phase (C.5.b) of the water-sensitivity task in the SHRP research, the three goals were achieved:

1. Development of the ECS as a conditioning and testing device.

2. Recommendation of wet conditioning procedure as a water conditioning before testing in fatigue, rutting, and low-temperature cracking.

3. Recommendation of a new water-conditioning procedure for evaluating water sensitivity as a part of mix design.

2.2 Equipment and Procedures

To test the above hypothesis and evaluate the effect of the indicated variables, the ECS was designed and fabricated to help determine which factors most affect the performance of mixtures in the presence of moisture, as shown in Table 2.1. The test setup permits evaluation of air voids and behavior of mixtures in the following ways:

1. Saturation versus wet (partial saturation).
2. Water versus vapor.
3. Permeability versus air void content.
4. Freezing versus no freezing.
5. Volume change effects (i.e., "oversaturation").
6. Effects of time on rate of saturation or desaturation.
7. Continuous monitoring using M_R.
8. Dynamic loading versus static loading.
9. Coating and stripping.

The ECS was used to evaluate the above factors in terms of the effectiveness of currently used testing procedures as well as the development of a new testing procedure. In addition, the ECS was used to help validate concepts developed by others involved in SHRP asphalt research. As noted above, the ECS can test a wide range of factors, but it is recognized that all this capability may not be required in the final version of the SHRP ECS test to be used for routine mix design testing.

2.2.1 *Testing System*

The ECS was designed and fabricated to simulate various conditions in an asphalt pavement. Figure 2.3 shows the ECS and its subsystems.

2.2.2 *Fluid-Conditioning Subsystem*

This system was designed to test air and water permeability and provide water, air, and temperature conditioning.

As shown in Figure 2.4, there are two differential pressure gauges connected directly before and after the specimen to measure the pressure gradient. This technique was used to eliminate known problems with leaking and specimen deformation. Although this system is designed essentially as a constant-head permeameter with vacuum, it can also used with back pressure if full saturation is required. The specimen is placed in a load frame, and a vacuum regulator is used to control the desired pressure gradient across the specimen. Transparent plastic tubing with an outside diameter of 0.6 cm (0.25 in.) is used to connect the inflow and outflow lines of the system. A pH meter is connected directly after the specimen to monitor the change in pH during the conditioning process. A thermocouple controller with four channels is connected to the system. One channel is to read flow temperature just before the specimen and the second to read flow temperature just after the specimen. The third channel is installed inside a dummy specimen to monitor the internal temperature of the specimen inside the environmental cabinet, and the fourth channel is connected to the water reservoir to control water flow temperature, which is required to obtain actual water viscosity. Three water flowmeters of different flow capacities are connected to a fluid water conditioning system to provide a wide enough flow range, from 1 to 3,000 cm^3/min (0.002 to 6.4 ft^3/hr) and another three air flowmeters are also connected to the system to read a total range from 100 to 70,000 cm^3/min (0.21 to 148 ft^3/hr).

2.2.3 *Environmental Conditioning Cabinet Subsystem*

The heart of the prototype system is a Despatch Industries[3] 1600 series environmental conditioning cabinet. The environmental chamber can maintain high or low temperatures or humidity levels. The chamber air is circulated by a fan in the conditioning plenum at the rear of the chamber. The conditioned air is discharged into the work space near the top of the chamber, circulated throughout the chamber, and returned at the bottom of the conditioning plenum for recirculation. The chamber set point accuracy is $\pm 0.5°C$ and ± 5-percent relative humidity. A microprocessor-based control (WALLOW series 1500) is installed in the chamber. The control is by ramping, enabling the system to move uniformly

[3]The final or recommended commercial version may by specified by operating characteristics, and not necessarily by brand.

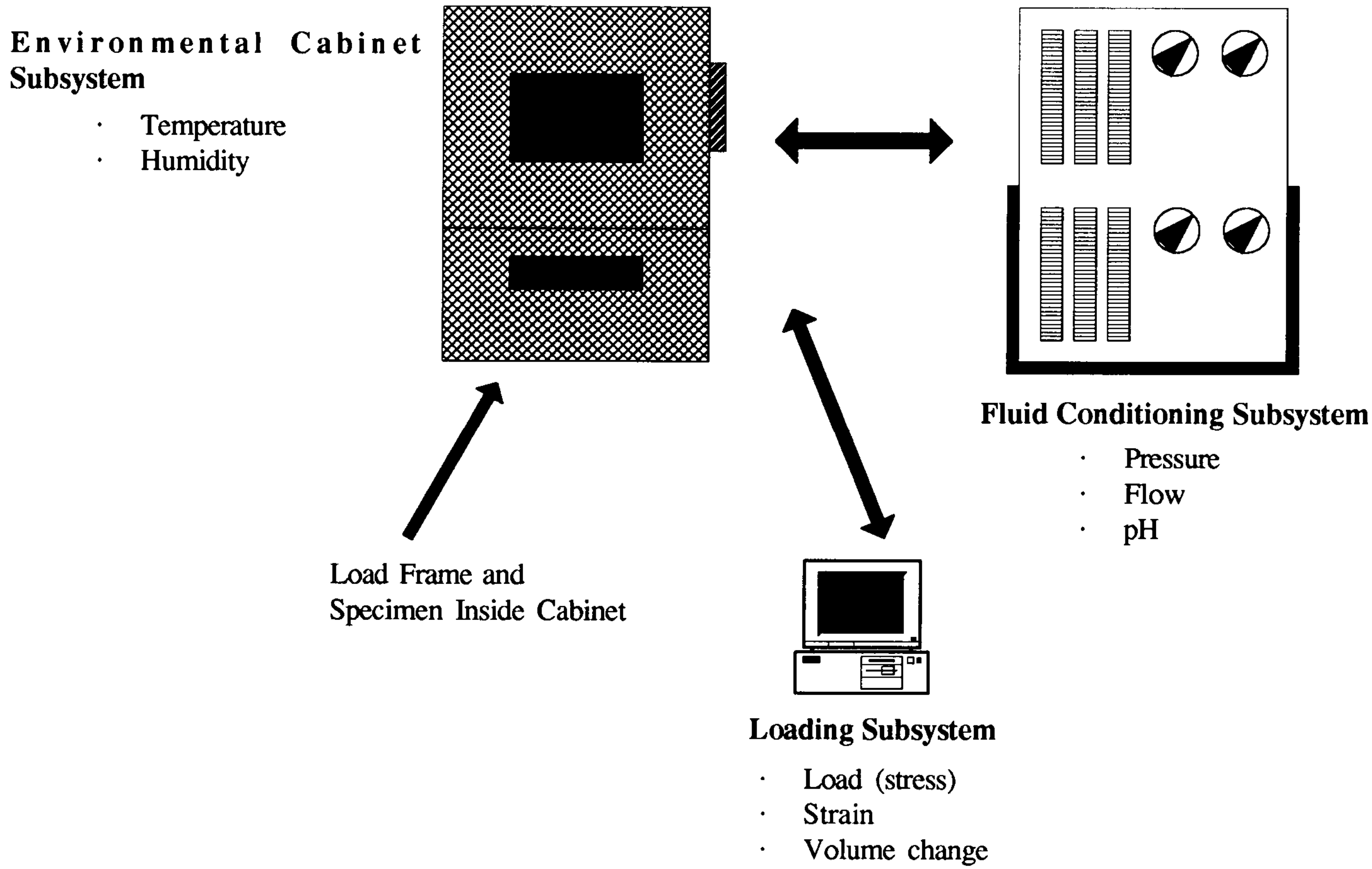


Figure 2.3. Overview of Environmental Conditioning System

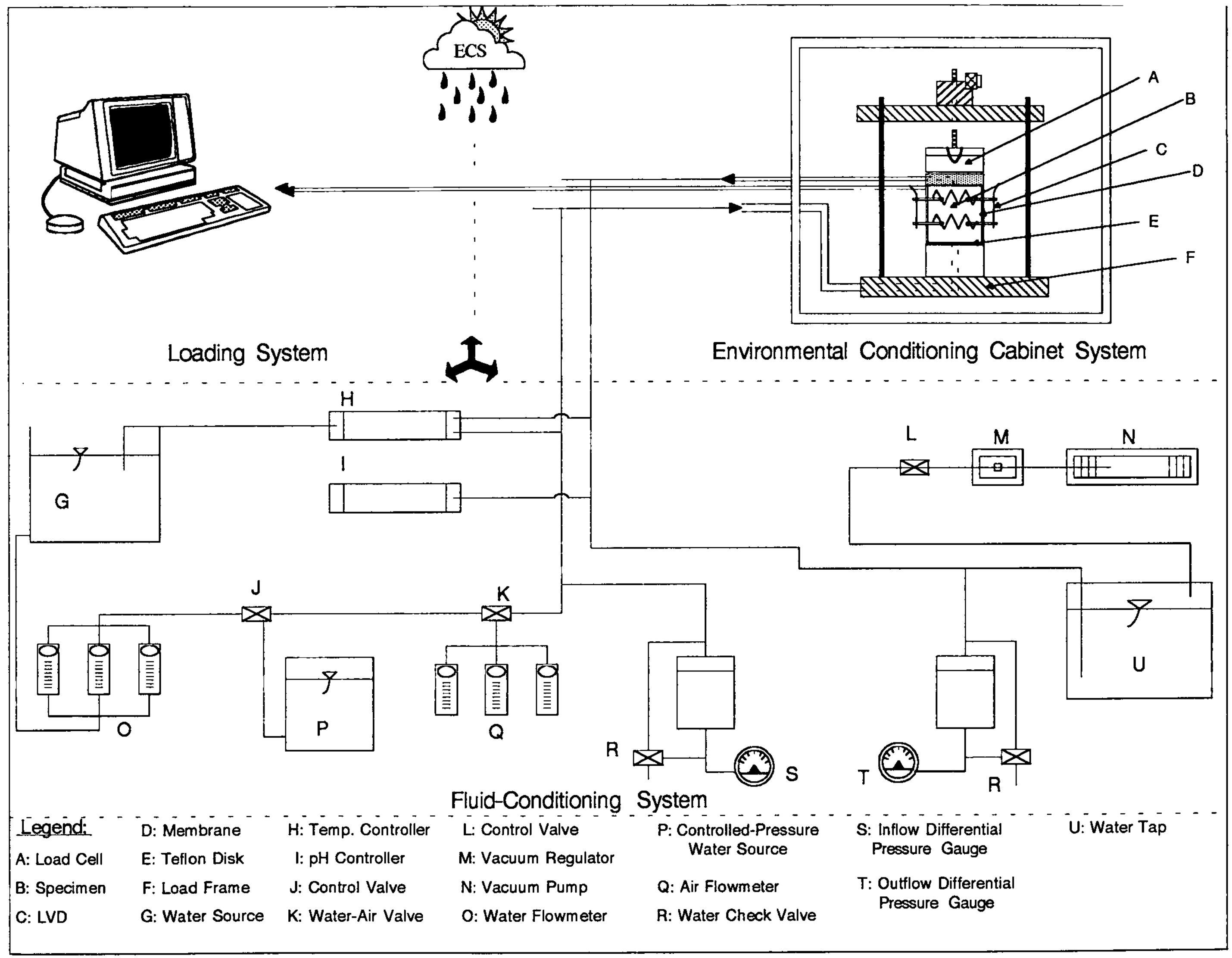


Figure 2.4. Schematic drawing of Environmental Conditioning System

from one value of a process variable to another. Figure 2.5 is an example of programmed profiles for both humidity and temperature.

2.2.4 Loading Subsystem

The repeated loading subsystem is an electropneumatic closed-loop system comprising a personal computer with software and an analog-to-digital/digital-to-analog interface card, a transducer signal-conditioning unit, a servovalve amplifier and power supply, and a load frame. Figure 2.6 shows a schematic of the load frame, which includes a double-acting pneumatic actuator (piston) and servovalve. The servovalve, operated by compressed air and driven by a computer program, drives the piston. Loads are delivered by the piston through its load ram to a load cell mounted on the specimen cap, which rests atop the test specimen. The signals from the load cell and linear variable differential transducers (LVDTs) mounted on the specimen are collected by the computer program and converted to engineering units of stress and strain, allowing the calculation of the resilient modulus. Although the software is capable of delivering a variety of loads and waveforms, tests in the ECS have been conducted almost exclusively using a haversine pulse-load with a pulse load duration of 0.1 s, a pulse-load frequency of 1 Hz, and a pulse-load magnitude of 2.67 kN (600 lb).

2.2.5 Test Procedures

The water-conditioning procedure includes several steps, depending on the mixture and variables being evaluated. Specimen conditioning procedure was conducted in accordance with SHRP M-006. Figure 2.7 summarizes the conditioning variables. Each test procedure has three stages. First, the specimen is evaluated in a dry condition by the dry original resilient modulus and permeability tests. Second is the wetting stage, in which water is run through the specimen for 30 min under the desired vacuum level, either 25.4 or 50.8 cm (10 or 20 in.) Hg. Third is the conditioning stage, which comprises three 6-hour cycles, maintaining a 25.4 cm (10 in.) Hg vacuum and continuous repeated loading on the specimen during the conditioning cycles. For the freeze cycles, there is no repeated loading, but the 25.4 cm (10 in.) Hg vacuum is maintained, which is equivalent to 34 kPa (5 psi). Loading of the conditioning cycles with 25.4 cm (10 in.) Hg vacuum and without a continuous repeated loading is identified as static loading. The steps of the conditioning procedure can be summarized as follows:

1. Mix and compact and a 10 cm (4-in.) in diameter by 10 cm (4 in.) high specimen.

2. Determine physical measurements, density, voids, etc.

3. Determine preconditioned resilient modulus.

4. Apply circumferential silicon seal, and mount specimens in load frame.

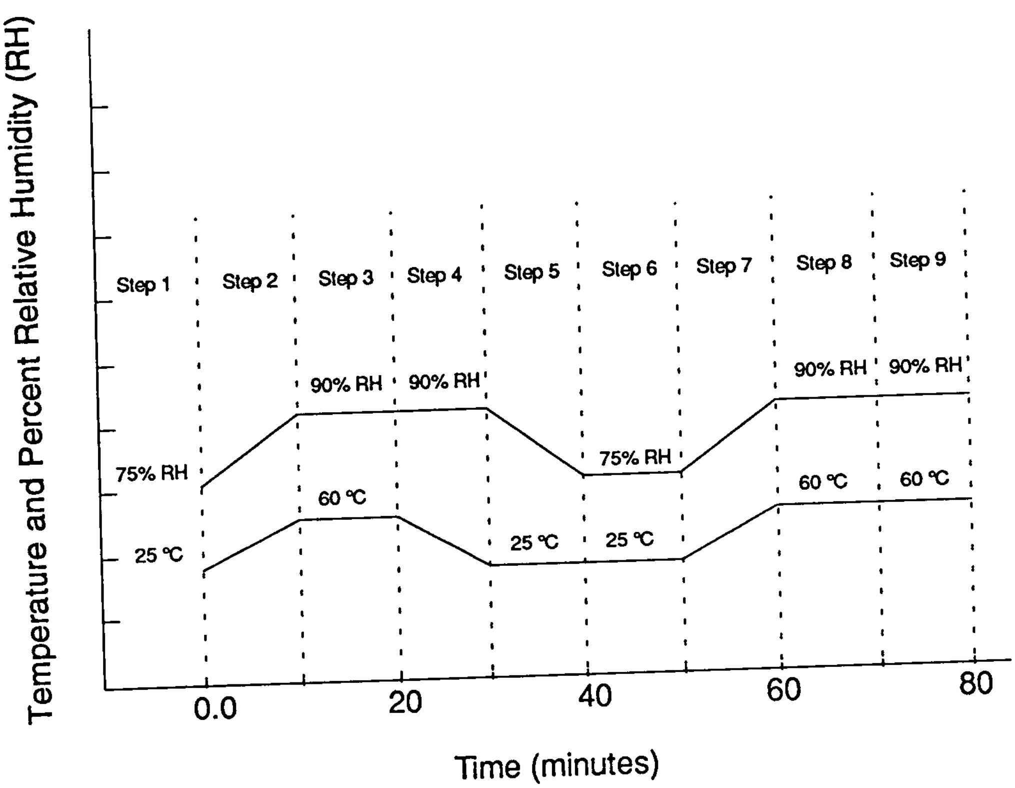


Figure 2.5. Example of controlled environment in the Environmental Conditioning System cabinet

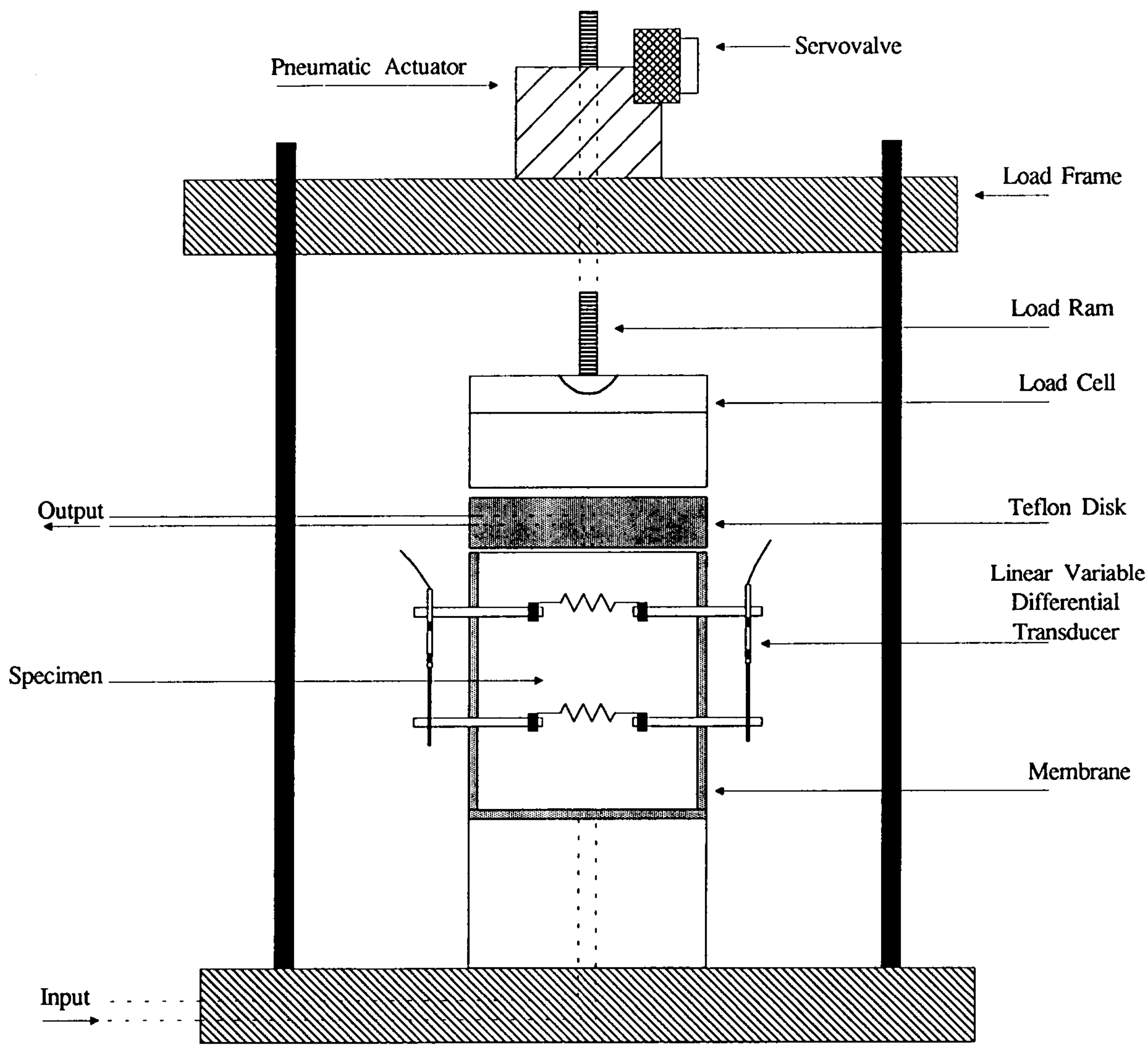


Figure 2.6. Load frame inside environmental cabinet

Conditioning Factor	Conditioning Stage				
	Wetting*	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Vacuum level (in. Hg)	20	10	10	10	10
Repeated loading	No	Yes	Yes	Yes	No
Ambient Temp. (°C)**	25	60	60	60	–18
Duration (hours)	0.5	6	6	6	6

*Wetting the specimen before conditioning cycles.
**Inside the environmental cabinet.

Figure 2.7. Typical conditioning chart

5. Measure air permeability.

6. Mount LVDTs.

7. Wet specimen according to desired procedure and measure water permeability.

8. Begin conditioning cycles according to the desired sequence. Figure 2.7 shows a typical conditioning chart that is used for each test.

9. Measure resilient modulus and water permeability following each cycle at 25°C (77°F).

10. Report stripping rate.

2.3 Materials

The following aggregates and two asphalts were used from MRL at the University of Texas at Austin:

1. Aggregates: Granite, (RB, a nonstripper) and chert gravel, (RL, a stripper).

2. Asphalts: AAG-1 and AAK-1, selected because of their vastly different composition and temperature susceptibility.

From these two asphalts and aggregates, four asphalt-aggregate combinations were used to fabricate mixtures. Table 2.2 shows asphalt content for each mixture, which was compacted using a kneading compactor (ASTM D 1561), according to the state of California mix design method, ASTM D 1560. For each asphalt-aggregate mixture, there are two levels of compaction effort, which were established to achieve the two air void target levels. Table 2.2 also shows the compaction effort used to fabricate each asphalt-aggregate mixture. For the two aggregates RB and RL, the gradation shown in Table 2.3 and plotted in Figure 2.8 was used in this study. It corresponds to a typical dense-graded aggregate with 1.9-cm (0.75-in.) maximum size.

Asphalt from two sources which differed in both composition and temperature susceptibility, and two levels of asphalt content were used. Table 2.4 shows the physical and chemical properties of each asphalt. The types of aggregate differ in stripping potential, as known from their history of moisture sensitivity. Table 2.5 shows the physical and chemical properties of each aggregate.

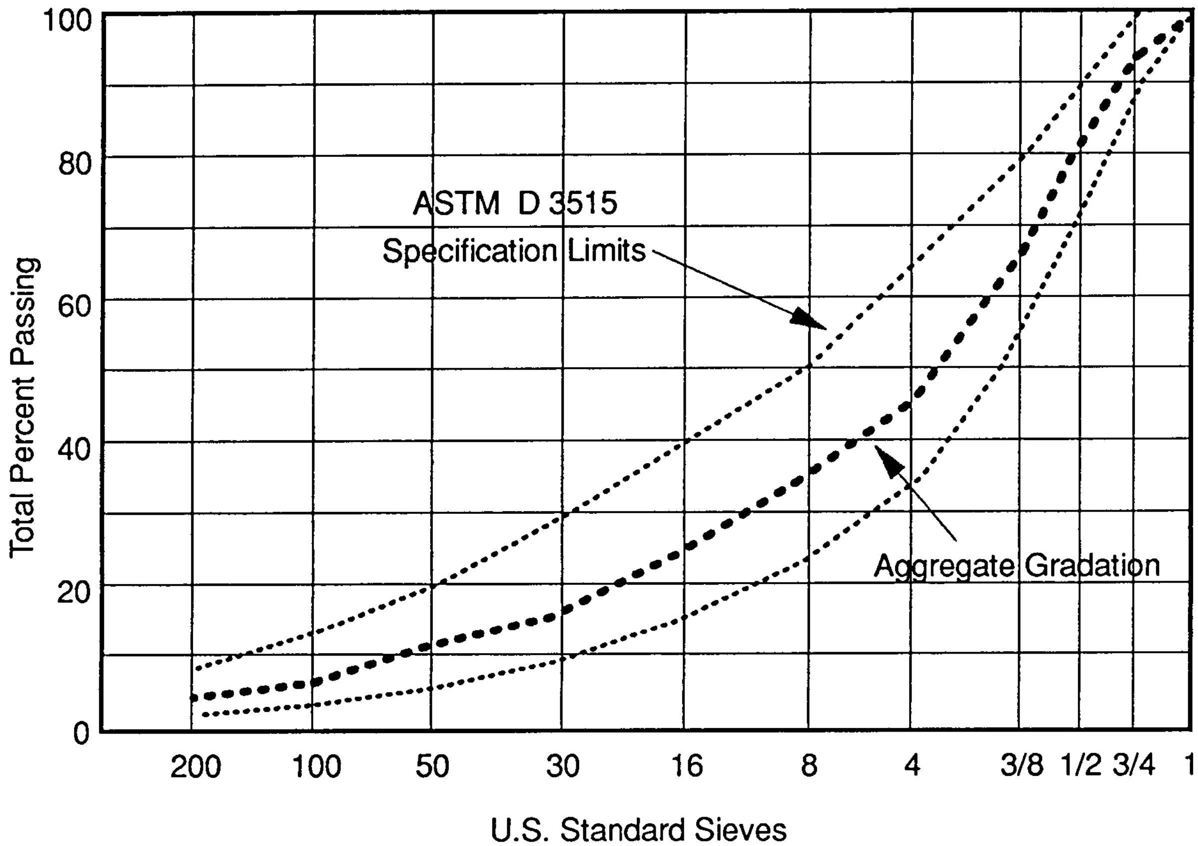
Table 2.2. Mix design results and compaction efforts

Aggregate Type	Asphalt Type	Percent Asphalt by Weight of Aggregate	Compaction Effort on Each Lift	Percent Air Voids Target
RB	AAK-1	5.1	20 blows @ 300 psi and 150 blows @ 450 psi	4
			20 @ 150 and 150 @ 150	8
	AAG-1	4.9	20 @ 300 and 150 @ 450	4
			20 @ 175 and 150 @ 150	8
RL	AAK-1	4.3	20 @ 300 and 150 @ 450	4
			20 @ 150 and 150 @ 150	8
	AAG-1	4.1	20 @ 300 and 150 @ 450	4
			20 @ 150 and 150 @ 150	8

Note: To convert from psi to kPa, multiply by 6.89476.

Table 2.3. RL and RB aggregate gradation used in this study (from Materials Reference Library data, 1990)

Sieve Size	Percent Passing
1 in.	100
3/4 in.	95
1/2 in.	80
3/8 in.	68
#4	48
#8	35
#16	25
#30	17
#50	12
#100	8
#200	5.5



Note:

4 through 200 indicates sieve number;
3/8, 1/2, 3/4 and 1 indicates sieve size in inches.

Figure 2.8. Aggregate gradation

Table 2.4. Physical and chemical properties of asphalt materials (from Materials Reference Library data, 1990)

Property	Asphalt	
	AAK-1	AAG-1
Asphalt grade	AC-30	AR-4000
Crude	Boscan	California Valley
Original asphalt:		
Viscosity at 140°F, poise	3,256	1,862
Viscosity at 275°F, cSt	562	243
Penetration, 0.1 mm (77°F, 100 g, 5 s)	70	53
Ductility, cm (39°F, 1 cm/min)	27.8	0.0
Softening point (R&B),°F	121	120
Aged asphalt:		
Viscosity at 140°F, poise	9,708	3,253
Viscosity at 275°F, cSt	930	304
Mass change, %	-0.5483	-0.1799

Note: To convert from °F to °C, subtract 32 and multiply by 5/9.

Table 2.5. Aggregate properties (from Materials Reference Library data, 1990)

		Aggregate Identification	
		RL	RB
Total aggregate	Apparent specific gravity	2.656	2.821
	Bulk specific gravity	2.634	2.742
	Water absorption %	0.31	1.03
Coarse aggregate	Apparent specific gravity	2.664	2.829
	Bulk specific gravity	2.629	2.735
	Water absorption %	0.50	1.21
Fine aggregate	Apparent specific gravity	2.649	2.815
	Bulk specific gravity	2.639	2.748
	Water absorption %	0.14	0.87
Surface capacity	Experimental %	3.0	2.8
	Corrected %	3.0	2.9
C.K.E.	Experimental %	4.6	4.9
	Corrected %	4.6	5.2
Flakiness index %		17.6	9.6
L.A. abrasion %		59.2	30.0

3

Test Results

3.1 AASHTO T 283

A modified version of AASHTO T 283 (often called modified Lottman) was used for predicting water damage as a basis or benchmark for comparison with the existing procedures and current practice. The conditioning phase includes partial saturation at 50.8 cm (20 in.) Hg vacuum for 30 min, followed by 15 hours freezing at -18°C (-0.4°F), 24 hours at 60°C (140°F), and finally 2 hours at 25°C (77°F) before testing. Evaluation includes measurement of resilient modulus (M_R), tensile strength and their retained ratios.

Data from additional testing also conducted during the AASHTO T 283 procedure will become part of a database. Permeability of each dry specimen was measured using air. For those specimens that would be water conditioned, thickness and any accompanying change in volume (swell or shrinkage) were noted, and volume calculations are shown in Table 3.1. An example of test data for six specimens (three for dry set and another three for wet conditioning) is shown in Table 3.1.

A summary of data for the four asphalt-aggregate combinations is shown in Table 3.2. This summary includes all the test results necessary to evaluate the effect of water damage on the two asphalts (AAK-1 and AAG-1) and the two aggregates (RL and RB). Visual observation for stripping rate was made after the tensile strength test by pulling apart the two halves of the specimen at the crack. Stripping was reported according to a modified visual evaluation rating pattern with six ranges of stripping percentages: 5, 10, 20, 30, 40, and 50 (The method of stripping rate evaluation is explained later).

3.2 Development of Improved Test Methods

The intent of this section is to describe the development and evaluation of the Environmental Conditioning System (ECS). Generally, before embarking on a full-scale test scheme, numerous questions and details need to be evaluated in the development of the testing device. Likewise, before starting the ECS experiment plan (Figure 2.1) at Oregon State University

Table 3.1. Typical data calculations of AASHTO T 283 test results

Aggregate Type: RL
Asphalt Type: AAG-1

Mix Date: 11-21-94
Conditioning Date: 12-16-94

Compaction Effort: 25 blows @ 250 psi and 150 blows at 350 psi
Target Air Voids: 8% ± 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thickness (in.)	G_{mm}	Coeff. of Perm. 10^{-4}cm/s	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{td}), psi	M_R (M_R), ksi	Thickness (in.)	W_W
T141RL/AAG	2.700	2.453	43.20	1,241.4	699.3	1,242.1	2.280	7.0	109.0	210.0		
T142RL/AAG	2.717	2.453	47.68	1,237.5	692.7	1,240.3	2.260	7.7	107.0	203.0		
T143RL/AAG	2.729	2.453	45.62	1,238.9	697.1	1,240.3	2.280	7.2	117.0	213.0		
T144RL/AAG	2.718	2.453		1,236.0	690.9	1,244.0	2.260	7.8			2.7	716.9
T145RL/AAG	2.720	2.453		1,238.7	694.0	1,246.5	2.270	7.6			2.7	720.9
T146RL/AAG	2.690	2.453		1,245.3	699.2	1,249.3	2.260	7.1			2.7	724.6

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Saturation	% Change of Volume	Thickness (in.)	W_W	Wssd	% of Sat.	% Change of Volume	Tens. St. S_{tm}	Tens. St. Rat. (TSR)	Cond. M_R (M_{Rc}), ksi	M_R Ratio (M_RR)	Observed Stripping
1,265.7	69.8	0.440	2.800	720.4	1,279.1	112.20	2.250	59.0	0.530	120.0	0.60	
1,269.0	73.0	0.290	2.800	735.5	1,282.5	114.90	2.290	54.0	0.530	127.0	0.60	
1,272.0	70.7	0.290	2.800	726.8	1,274.6	124.20	1.480	62.0	0.530	138.0	0.60	

Notes:

The first three rows are unconditioned sample data (dry subset). The last three rows are conditioned sample data (wet subset).
Columns 1 to 11 are unsaturated data, columns 12 through 16 are partially saturated, and columns 17 through 26 are fully saturated.
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25°C.
W_{ssd} is the weight of the saturated surface dry sample (blotted and weighed in air).
S_{td} is the tensile strength of the dry sample in psi.
S_{tm} is the tensile strength of the water-conditioned sample in psi.
There are three average colums representing each stage of conditioning for tracking the column change of the specimen.
M_{Rd} is the diametral resilient modulus of the dry specimen in ksi.
M_{Rc} is the diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = M_{Rc}/R_{Rd}), or (25) = (11)/(24).
TSR (Tensile Strength Ratio) = (S_{tm}/S_{td}), or (23) = (22)/(10).
Percent of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100.
Asphalt contents of the samples are at optimum.
Sample IDs indicate (AASHTO T 263) (Sample no.) (Aggregate/Asphalt).
RB = Watsonville granite, RL = Texas chert.
AAK1 = AR-4000. AGG1 = AC-30.

Table 3.2. Summary table of AASHTO T 283 test results

Testing ID	Dry Tensile Strength (TS, psi)	Conditioned Tensile Strength (psi)	Dry M_R (ksi)	Cond. M_R (ksi)	TS Ratio (TSR)	M_R Ratio (MrR)
T,24,RL/AAG	194	181	80	72	0.49	0.40
T,25,RL/AAG	256	107	130	44	0.49	0.40
T,26,RL/AAG	331	120	158	59	0.49	0.40
T,32,RL/AAG	428	146	182	91	0.30	0.40
T,30,RL/AAG	544	147	210	66	0.30	0.40
T,34,RL/AAG	464	168	174	76	0.30	0.40
T,36,RL/AAG	543	316	187	106	0.57	0.63
T,40,RL/AAG	542	325	182	125	0.57	0.63
T,42,RL/AAG	583	366	207	133	0.57	0.63
T,45,RL/AAG	556	414	229	146	0.61	0.47
T,47,RL/AAG	518	217	210	95	0.61	0.47
T,49,RL/AAG	509	236	225	68	0.61	0.47
T,144,RL/AAG	109	59	210	120	0.53	0.60
T,145,RL/AAG	107	54	203	127	0.53	0.60
T,146,RL/AAG	117	62	231	138	0.53	0.60
T,150,RL/AAG	111	46	254	98	0.40	0.38
T,151,RL/AAG	125	52	285	113	0.40	0.38
T,152,RL/AAG	120	46	265	96	0.40	0.38
T,153,RL/AAG	137	50	186	141	0.43	0.69
T,154,RL/AAG	100	52	225	167	0.43	0.69
T,155,RL/AAG	113	50	205	110	0.43	0.69
T,35,RL/AAK	123	72	167	163	0.54	0.74
T,38,RL/AAK	121	60	167	84	0.54	0.74
T,52,RL/AAK	415	371	208	104	0.60	0.82
T,53,RL/AAK	570	283	220	86	0.60	0.82
T,56,RL/AAK	520	386	241	106	0.60	0.82
T,58,RL/AAK	368	311	156	105	0.83	0.62
T,59,RL/AAK	370	295	167	99	0.83	0.62
T,60,RL/AAK	363	277	165	106	0.83	0.62
T,65,RL/AAK	331	223	169	79	0.53	0.53
T,66,RL/AAK	375	194	159	82	0.53	0.53
T,67,RL/AAK	411	217	153	86	0.53	0.53
T,125,RL/AAK	452	408	185	126	0.93	0.68
T,126,RL/AAK	430	394	176	114	0.93	0.68
T,127,RL/AKK	435	343	165	109	0.93	0.68

Table 3.2 (continued). Summary table for AASHTO T 283 test results

Testing ID	Dry Tensile Strength (TS, psi)	Conditioned Tensile Strength (psi)	Dry M_R (ksi)	Cond. M_R (ksi)	TS Ratio (TSR)	M_R Ratio (MrR)
T,164,RL/AAK	145	45	292	82	0.30	0.26
T,165,RL/AAK	153	45	336	80	0.30	0.26
T,166,RL/AKK	145	41	300	83	0.30	0.26
T,80,RB/AAK	352	238	148	99	0.64	0.60
T,81,RB/AAK	402	249	167	97	0.64	0.60
T,83,RB/AAK	365	271	165	105	0.64	0.60
T,87,RB/AAK	369	286	140	106	0.65	0.61
T,88,RB/AAK	380	259	175	93	0.65	0.61
T,92,RB/AAK	463	366	083	130	0.65	0.61
T,102,RB/AAK	389	354	158	122	0.81	0.72
T,103,RB/AAK	412	322	178	115	0.81	0.72
T,104,RB/AAK	422	373	168	135	0.81	0.72
T,187,RB/AAK	161	108	278	361	0.67	1.12
T,188,RB/AAK	170	98	292	322	0.67	1.12
T,189,RB/AAK	148	116	289	277	0.67	1.12
T,193,RB,AAK	134	98	275	286	0.79	0.93
T,194,RB/AAK	113	86	227	225	0.79	0.93
T,195,RB/AAK	114	100	281	215	0.79	0.93
T,96,RB/AAG	477	660	262	136	1.24	0.62
T,97,RB/AAG	478	585	242	171	1.24	0.62
T,98,RB/AAG	526	666	269	167	1.24	0.62
T,109,RB/AAG	435	537	225	187	1.16	0.83
T,111,RB/AAG	506	654	223	223	1.16	0.83
T,113,RB/AAG	520	523	232	147	1.16	0.83
T,117,RB/AAG	494	434	215	137	0.58	0.77
T,118,RB/AAG	498	339	214	116	0.58	0.77
T,120,RB/AAG	503	282	191	101	0.58	0.77
T,204,RB,AAG	165	76	256	148	0.51	0.62
T,205,RB/AAG	111	64	211	154	0.51	0.62
T,206,RB/AAG	162	81	255	144	0.51	0.62
T,210,RB/AAG	131	102	404	158	0.77	0.55
T,211,RB/AAG	143	104	143	204	0.77	0.55
T,212,RB/AAG	137	111	137	225	0.77	0.55

Note: To convert from psi to kPa, multiply by 6.89476.
To convert from ksi to kPa, multiply by 6,894.76.

(OSU), the ECS was subjected to detailed evaluation and refinement to improve its reliability and reproducibility in three aspects: resilient modulus measurement, permeability measurement, and methods of calculating air void content. These are discussed in the following sections.

3.2.1 Resilient Modulus Test

Many test procedures and types of test equipment have been developed and used in several laboratories and agencies to evaluate the structural properties of the asphalt concrete mixtures. The resilient modulus of compacted asphalt mixtures can be obtained by either a repeated-loading triaxial test or repeated loading indirect tensile test (Al-Swailmi et al. 1992). These two test procedures have been standardized by ASTM as "The Standard Test Method for Dynamic Modulus of Asphalt Mixtures" (ASTM D 3497); and "The Standard Method of Indirect Tension Test for Resilient Modulus of Bituminous Mixtures" (ASTM D 4123). Unfortunately, these procedures do not always yield similar results, because of specimen configuration and other factors.

In the ECS, the resilient modulus is defined as the ratio of the applied axial stress to the corresponding recoverable (elastic) axial strain. The vertical stress is applied axially by using an electropneumatic closed-loop testing system. Applied stress is controlled by a load cell placed on top of the specimen. Recoverable axial strain is monitored by linearly variable different transducers (LVDTs). Stresses and strains are recorded and analyzed by the computer and software package. For axial loading, the appropriate specimen height, as recommended in ASTM D 3497, should be at least 20.3 cm (8 in.) for a specimen 10.2 cm (4 in.) in diameter. However, it was not feasible to water condition these tall specimens, because of the long distance for the water to flow under vacuum. As a compromise between the ASTM D 3497 requirement and typical pavement layer thicknesses, a ministudy was conducted to investigate the effect of height-to-diameter (L/D) ratio on resilient modulus. In addition, other ministudies were conducted to investigate details such as the following:

1. Effect of glue type used for strain gauges (strain gauges were later replaced by LVDTs).

2. Repeatability of ECS resilient modulus measurement and necessity of using Teflon disks.

3.2.2 Test Specimen Preparation

One mix, RB/AAK-1, was used for preparing three specimens 10 cm (4 in.) in diameter by 17.8 cm (7 in.) high. After density determinations were completed, a vertical alignment jig was used with capping compound to maintain caps perpendicular to the specimen axis according to the requirements of ASTM C 617, "Standard Practice for Capping Cylindrical Concrete Specimens." After testing the specimens with the full height, 2.54 cm (1.0 in.) was trimmed from each end with a diamond saw. Capping and testing were repeated for the new 12.7-cm (5-in.) specimens. Finally, 3.2 cm (1.25 in.) was trimmed from each end of the 12.7-cm (5-in.) specimens and the resulting 6.35-cm (2.5-in.) specimens were exposed to the same capping and testing procedure. Trimmed specimen densities and air void calculations were monitored for the three heights as shown in Table 3.3.

3.2.3 Test Equipment and Instrumentation

In this ministudy, an MTS electrohydraulic closed-loop system was used for the dynamic compression loading, and stresses were monitored by chart recorder. Recoverable axial strain was measured by the following two techniques:

1. LVDTs attached to the specimen by a pair of clamps that were cemented to the specimen by plates, maintaining a 5.08-cm (2-in.) separation for all specimen heights. Deformations were measured by chart recorder.

2. A pair of strain gauges 2.54 cm (1 in.) long and a strain indicator for recording strains. The test setup is shown in Figure 3.1.

Loading of the specimens was performed using two modes: (1) continuous repeated loading of haversine waveform, and (2) continuous repeated loading of square waveform. A dynamic load of 2,669 N (600 lb) was used after seating the specimen with a 266.9-N (60-lb) static load. The same loading time (0.1 s), and rest period (0.9 s) were used for the two loading modes.

3.2.4 Effect of Height-to-Diameter Ratio on Resilient Modulus

Figures 3.2, 3.3, and 3.4 show the relationship between resilient modulus and specimen thickness for the three similar specimens (three test replications). Moduli of the specimens with 6.35-cm (2.5-in.) thickness were significantly higher than the moduli of the specimens with 12.7- and 17.8-cm (5- and 7-in.) thicknesses. The waveform (haversine or square) and strain measurement device (LVDTs or strain gauges) had no effect on the trend or general relationship, but do affect the magnitude. For the same method of strain measurement and load level, the M_R from the square waveform is higher than the M_R from the haversine wave form, as shown in Figures 3.2, 3.3, and 3.4. Although no detailed analysis was made, observation indicates that square waves tend to produce more impact on the specimen, and that strain gauges measure less deformation than LVDTs. Both factors result in higher modulus values.

For the same waveform, strain gauges detect less strain, which resulted in a higher M_R than with the LVDTs. Strain gauges may not indicate the total strain as the LVDTs do, because large stones located behind the strain gauges may not transmit the total strain. In contrast, LVDTs with total slippage controlled measure the cumulative strain between two points, which may be more realistic. In addition, during the ECS testing program it was noticed that the strain gauges mounted on specimens with high air void levels (such as 10 percent)

Table 3.3. Density and air void calculations for the three specimen thicknesses

Specimen ID	Original Thickness (17.8 cm [7 in.])		After first cut (12.7 cm [5 in.])		After second cut (6.35 cm [2.5 in.])	
	Bulk Specific Gravity	Percent Air Voids	Bulk Specific Gravity	Percent Air Voids	Bulk Specific Gravity	Percent Air Voids
RB/AAK1-1	2.245	8.5	2.255	8.1	2.248	8.4
RB/AAK1-2	2.255	8.1	2.241	8.7	2.218	9.6
RB/AAK1-3	2.255	8.1	2.245	8.5	2.238	8.8

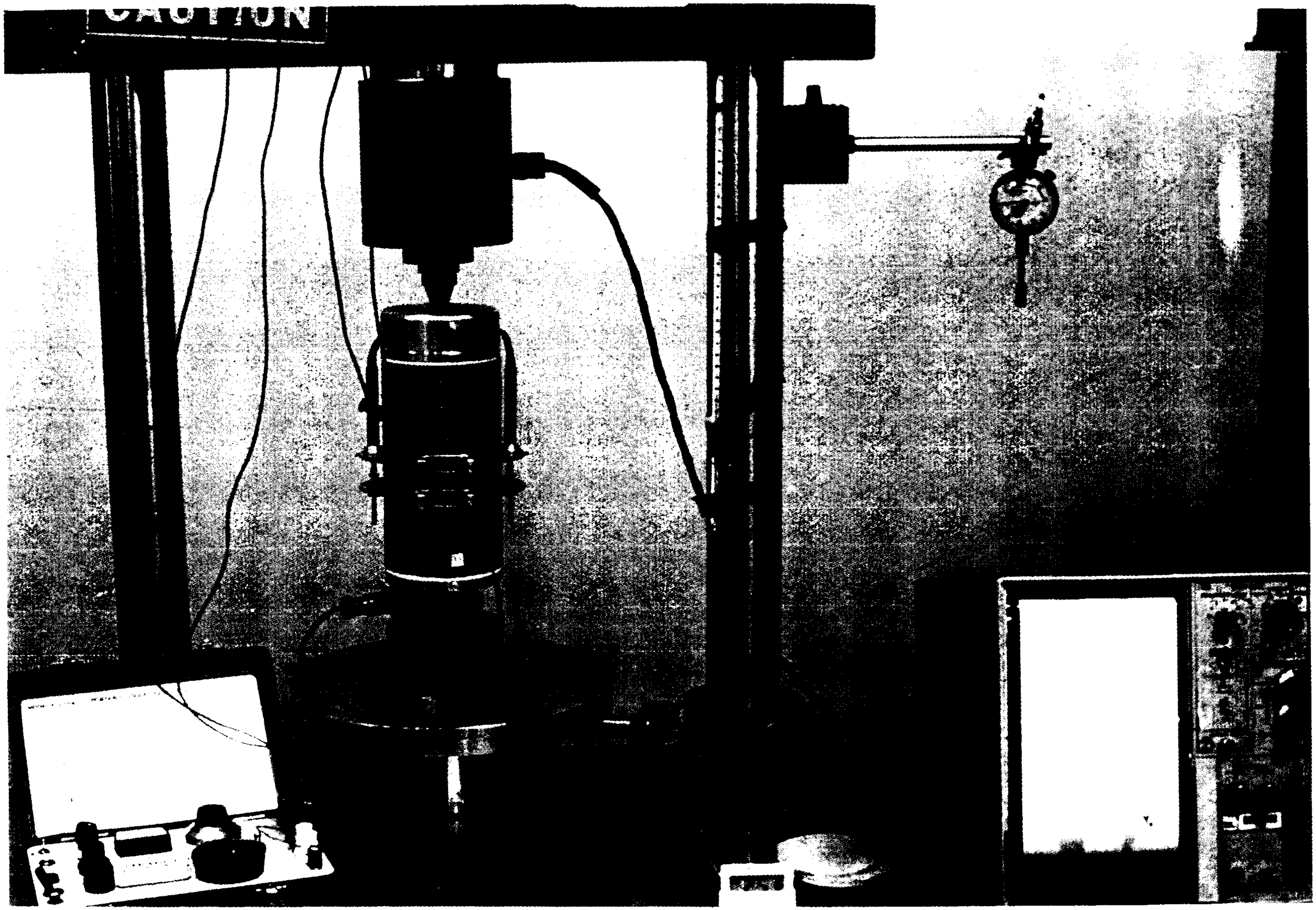


Figure 3.1. Overview of the test setup

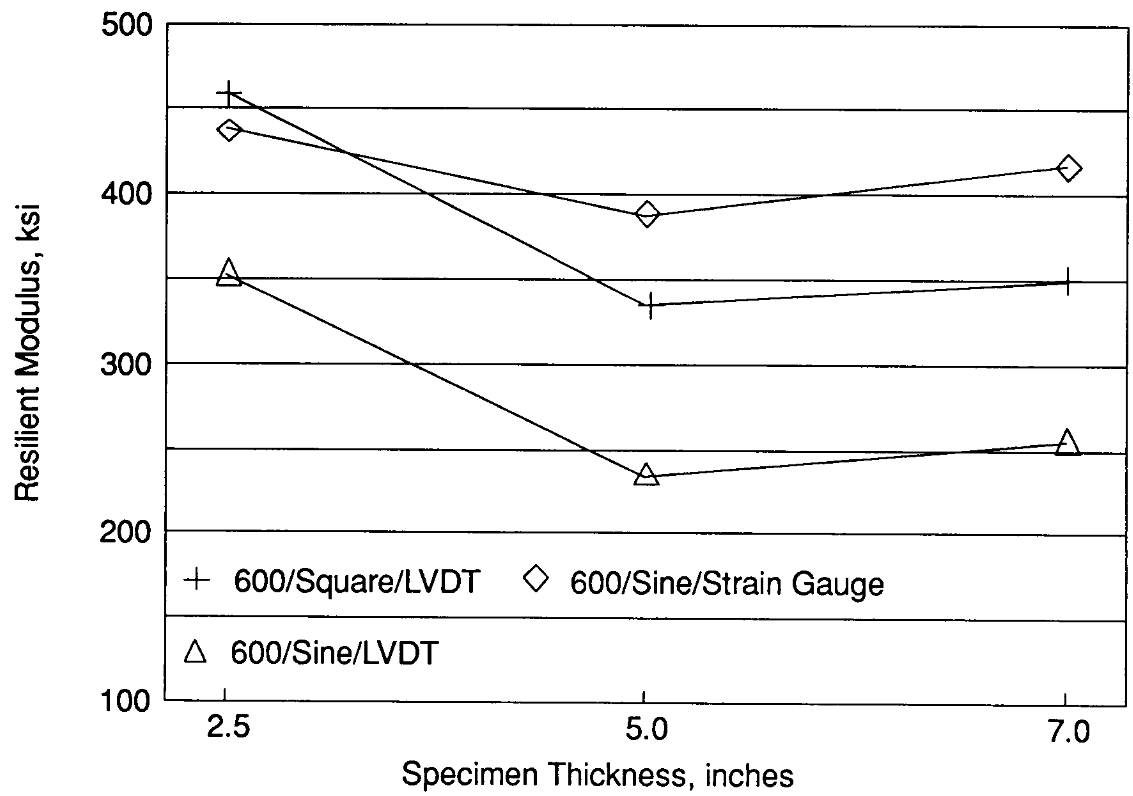


Figure 3.2. Relationship between resilient modulus and specimen thickness for three testing conditions—specimen RB/AAK-1-1

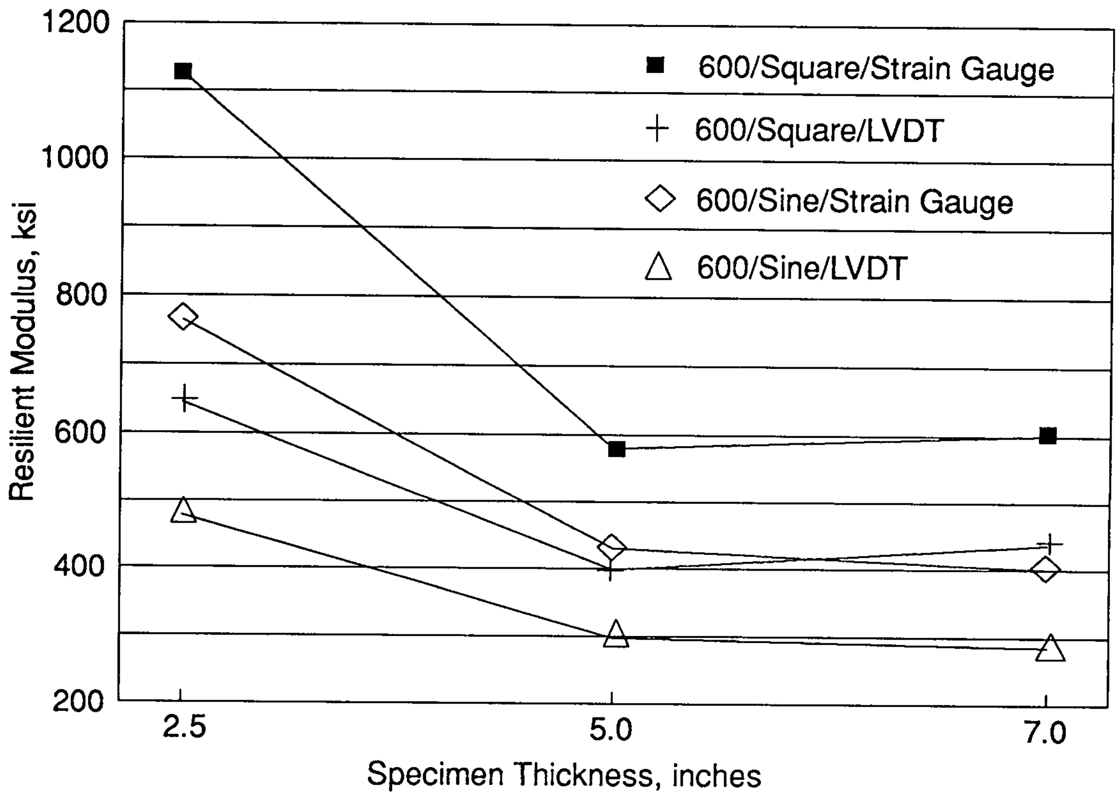


Figure 3.3. Relationship between resilient modulus and specimen thickness for four testing conditions—specimen RB/AAK-1-2

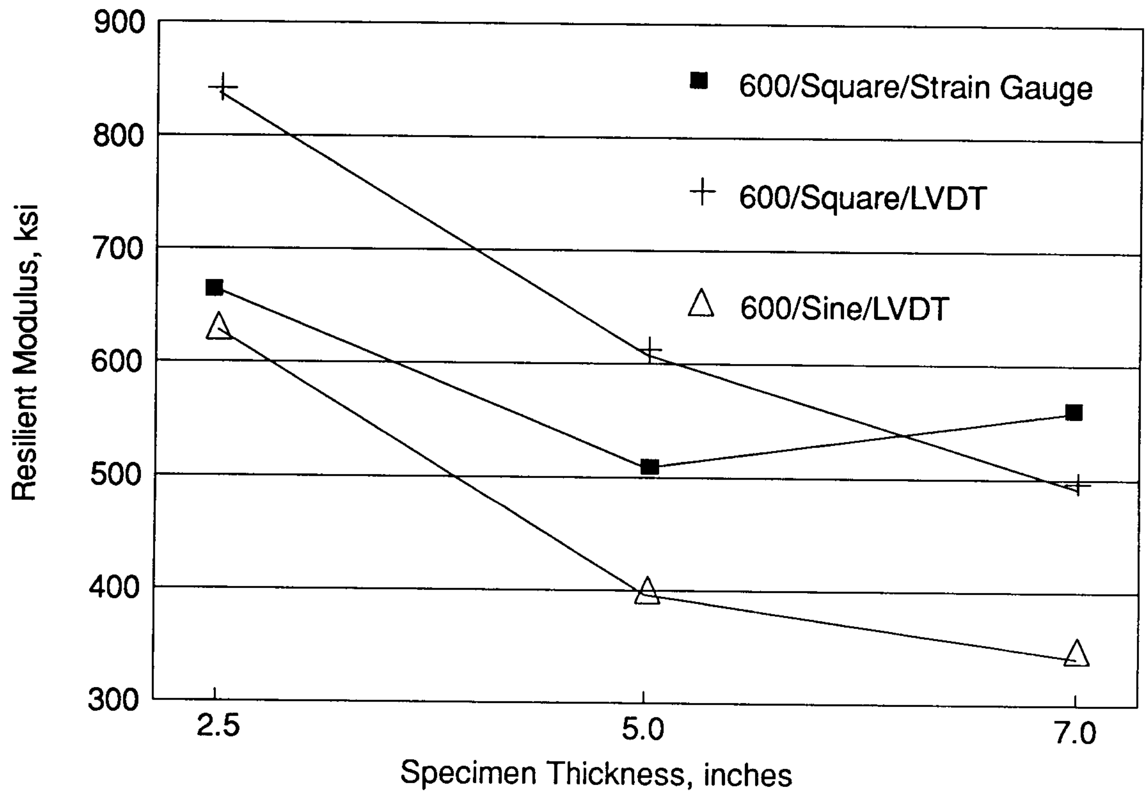


Figure 3.4. Relationship between resilient modulus and specimen thickness for three testing conditions—specimen RB/AAK-1-3

experienced major wrinkles under the effect of repeated loading during hot water conditioning. The deformed strain gauges were most likely caused by large total deformation resulting from compaction or densification. Because of such deficiencies associated with the strain gauges and because of their high cost, a decision was made to switch to LVDTs after a significant part of the ECS testing program was completed using strain gauges. (Note that all validation testing was done using LVDTs.)

Finally, from the above investigation it was concluded that the specimen thickness has considerable effect on resilient modulus value, and the specimen closest in thickness to 20 cm (8 in.) (L/D = 2.0) gives the closest to true resilient modulus. For the ECS, it is sufficient to monitor relative change in resilient modulus during water conditioning, which indicates the real M_R change. This concept of relative M_R using a 10-cm (4-in.) specimen has been used as a compromise for a 20-cm (8-in.) specimen; 10-cm (4-in.) specimens are easier to produce and are more representative of actual pavement lift thicknesses. Thus, a 10-cm (4-in.) specimen was recommended and is used for the ECS testing.

Since the resilient modulus value from the ECS is not the true or familiar M_R, the term ECS-M_R will be used in this report for values determined from 10-cm (4-in.) specimens by a uniaxial test. There are, therefore, two important differences between the ECS-M_R and the dynamic modulus defined in ASTM D 3497: (1) The height of the specimen is 10 cm (4 in.) rather than of 20 cm (8 in.), and (2) the specimen is encapsulated in a rubber membrane throughout the test. A correlation factor between the ECS-M_R and the diametral M_R has not been investigated using a statistical analysis for test results from a wide range of materials but may be included in a following report. In addition to ECS-M_R, a diametral M_R is measured for each specimen before the ECS procedure, to be used for reporting the initial specimen stiffness. All values of M_R in this report stand for ECS-M_R unless otherwise noted.

3.2.5 Effect of Strain Gauge Glue Type

Six strain gauges—X_1, X_2, X_3, Y_1, Y_2, and Y_3—were bonded on a plastic specimen 19.1 cm (7.5 in.) high and 10 cm (4 in.) in diameter. The strain gauges were divided into two groups, and each group was mounted at midheight and opposite to the other group: (1) X_1, X_2, and X_3 were bonded on side X; and (2) Y_1, Y_2, and Y_3 were bonded on side Y. Three different glue types were used for bonding the strain gauges as follows:

1. X_1 and Y_1: 2.5-cm (1-in.) strain gauge with Super Glue.
2. X_2 and Y_2: 2.5-cm (1-in.) strain gauge with Ca-200 LS.
3. X_3 and Y_3: 2.5-cm (1-in.) strain gauge with Testors airplane glue.

Specimens were subjected to dynamic repeated loading by using the MTS, and strains were monitored with a strain indicator. Figure 3.5 shows resilient modulus results from each strain gauge. The difference among glue types is not significant. The M_R on side X was higher than that on side Y because of eccentricity, but this discrepancy was later corrected.

As a result of this experiment, Super Glue was selected for future strain gauge applications because of its very short curing time.

3.2.6 Repeatability of ECS-M_R and Effect of Teflon Disks

Six specimens were used to investigate the repeatability of the ECS-M_R, and the effect of friction between the specimen and the top cap and bottom base. It was suggested that Teflon disks help reduce the friction between the specimen and the top cap and bottom base. The following specimens were used in the study:

1. 54TB and 62TB: Asphalt concrete specimen 10 cm (4 in.) in diameter by 6.35 cm (2.5 in.) high.
2. 1PLAS and 2PLAS: Plastic specimen 10 cm (4 in.) in diameter by 6.35 cm (2.5 in.) high.
3. TG61 and WG77: Asphalt concrete specimen 10 cm (4 in.) in diameter by 10 cm (4 in.) high.

Strain gauges 2.54 cm (1 in.) long were used on specimens 6.35 cm (2.5 in.) high, and 5.08-cm (2-in.) strain gauges were used on the 10-cm (4-in.) specimens. The ECS was used to conduct resilient modulus tests. Two types of 0.33 cm (0.125 in.) thick Teflon disks were used: solid and perforated. Table 3.4 shows test results of tests performed on each specimen, with Teflon disks used as follows:

1. No disks: No disks used.
2. One disk: One solid disk top and bottom.
3. Perf. disk: One perforated disk top and bottom.
4. Two disks: Two solid disks top and bottom.
5. One disk: One solid disk top and bottom.
6. Diff. or: One solid disk top and bottom with different orientation by rotating the specimen 180° around its vertical axis.

The one-disk setting was tested twice to show the repeatability of ECS-M_R for the test setting that represents the ECS testing program standard. Figure 3.6 shows the plots of ECS-M_R for all test settings from each specimen. For all six specimens, the repeatability the of one-disk setting is very high. Teflon disks and test orientation do not affect the results for the plastic specimen because of the frictionless surfaces and high uniformity of this material. Teflon disks and test orientation did have a significant effect on ECS-M_R of 6.35-cm (2.5-in.) asphalt concrete specimens 54TB and 62TB. The effect of Teflon disks and test orientation on ECS-M_R from 10-cm (4-in.) asphalt concrete specimens is not significant.

It was necessary to use perforated spacers between the specimen and top cap and base plate to collect any stripped asphalt that may stick to the bottom of the top cap during the water-conditioning process and thus change its behavior.

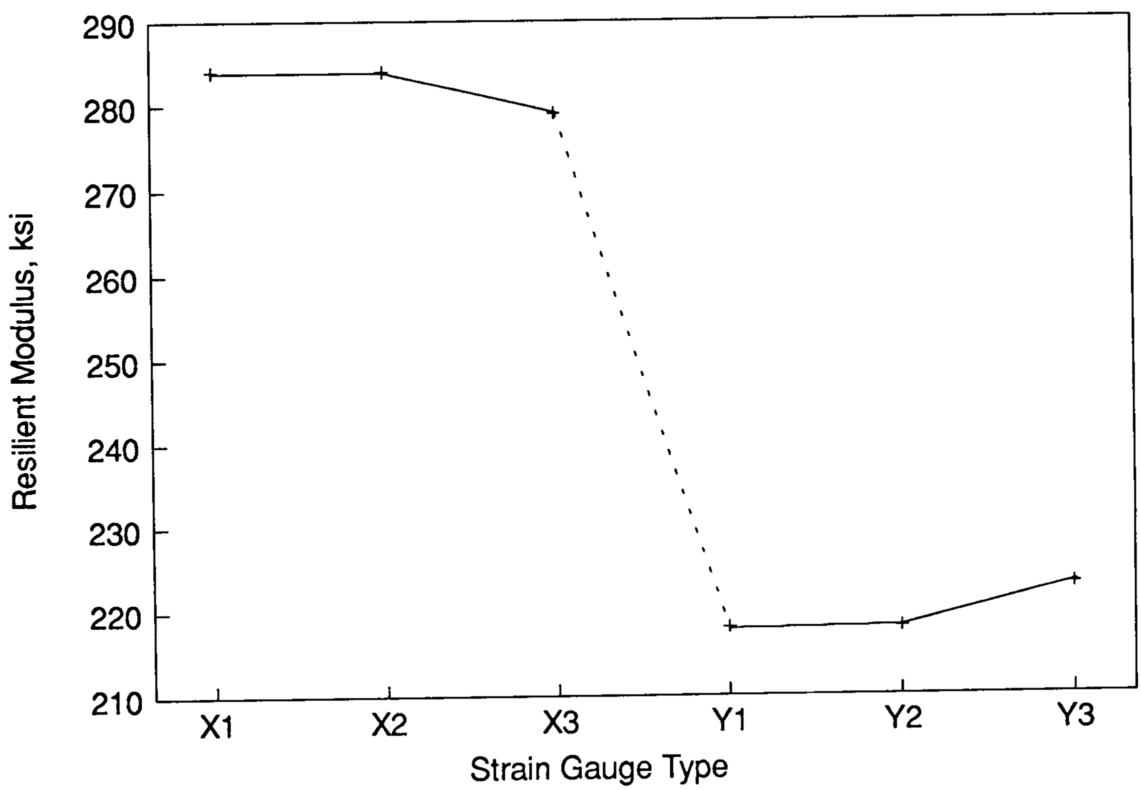


Figure 3.5. Effect of strain gauge mounting glue on M_R

Table 3.4. Resilient modulus (ECS-M_R) for different test conditions

Specimen ID	Resilient Modulus (ECS-M_R), ksi					
	54TB	62TB	1PLAS	2PLAS	TG61	WG77
No disks	646	546	154	137	918	904
One disk	406	433	152	138	882	900
Perf. disk	342	367	135	141	950	928
Two disks	351	381	151	138	818	879
One disk	384	387	144	136	858	890
Diff. or.	449	443	140	126	832	878

Note: To convert from ksi to kPa, multiply by 6,89476.

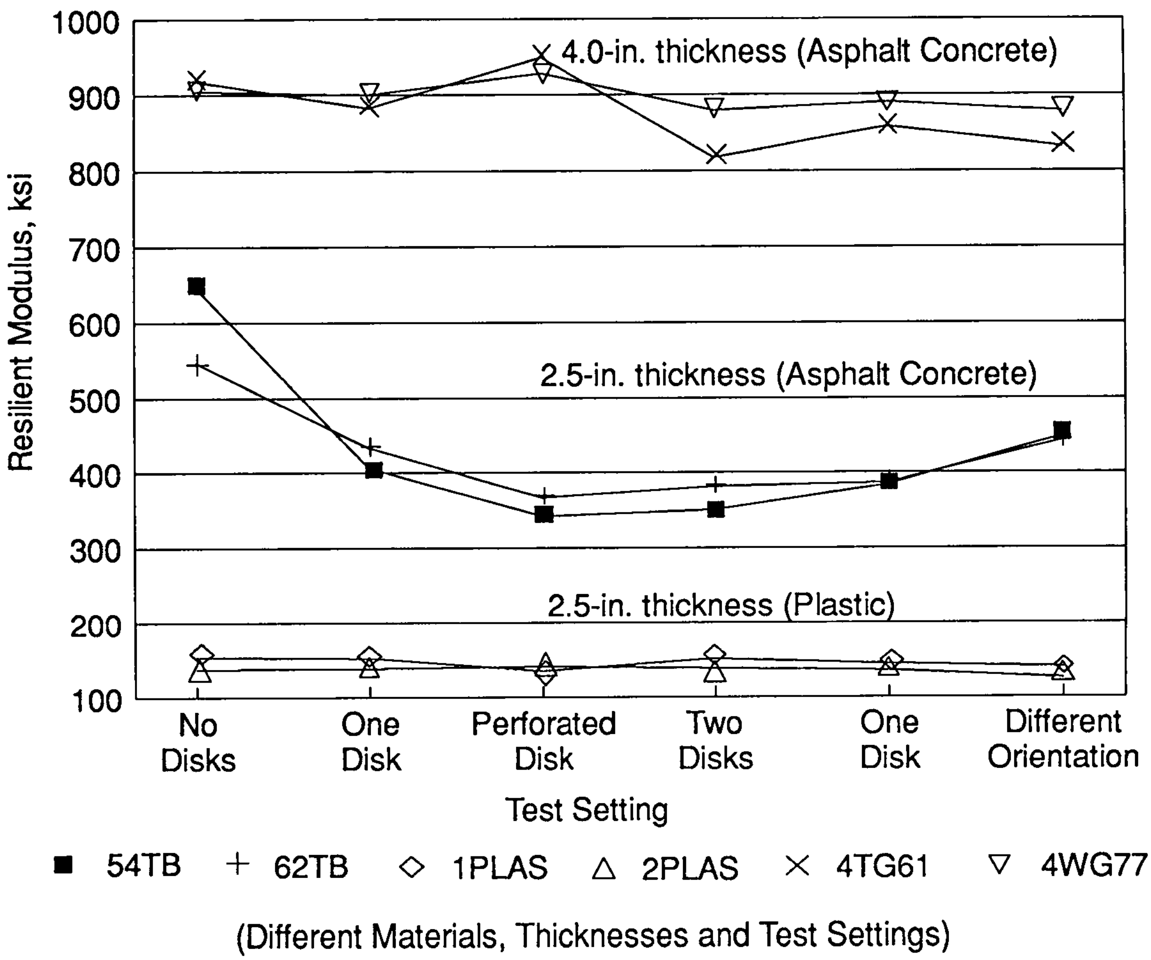


Figure 3.6. Variability of ECS-M_R for different test conditions

Using perforated Teflon disks at top and bottom is recommended for the ECS testing program. Perforation pattern, hole diameter, and groove pattern for base and top cap are shown in Figure 3.7.

3.2.7 Permeability Measurements

Permeability (K), by definition (Goode and Lufsey 1965), is the volume of fluid Q of unit viscosity μ passing in unit time Δt through a unit cross section A of a porous medium of length L under the influence of a unit pressure gradient ΔP.

$$K = \frac{Q\mu L}{A\Delta P\Delta t}$$

Since permeability K has units of area, without indicating the time of the flow, the coefficient of permeability k was used instead, which has units of length/time. All permeability values in this report stand for coefficient of permeability unless otherwise noted.

It is generally believed that permeability is a better measure of durability than percent air voids because permeability measures fluid accessibility through the asphalt pavement.

Percent air voids may include voids not accessible to water. In the ECS testing program, a relationship was hypothesized between permeability and water damage.

It was necessary to conduct several ministudies to investigate factors related to either the permeability testing technique or the role of permeability in the testing program (expressed by the coefficient of permeability). The topics covered by these ministudies were as follows:

1. Effect of specimen surface flow control on coefficient of permeability.
2. Effect of compaction procedure on specimen surface sealing.
3. Relationship between differential pressure level and coefficient of permeability.
4. Coefficient of permeability as a measure of specimen volume change.
5. Specimen internal coloring indicator.

3.2.8 Effect of Specimen Surface Flow on Coefficient of Permeability

For the air flow to pass only through the specimen during the permeability test, the outer surface of the specimen wall must be sealed. Goode and Lufsey (1965) used paraffin for sealing to prevent leakage between the specimen wall and the membrane. However, this method destroys the specimen for further use by contaminating the asphalt.

Another method is to place the specimen in a cylindrical rubber membrane fastened to a hollow metal cylinder with hose clamps. This method does not totally prevent leakage between the specimen wall and the membrane, especially with coarse mixtures. Another

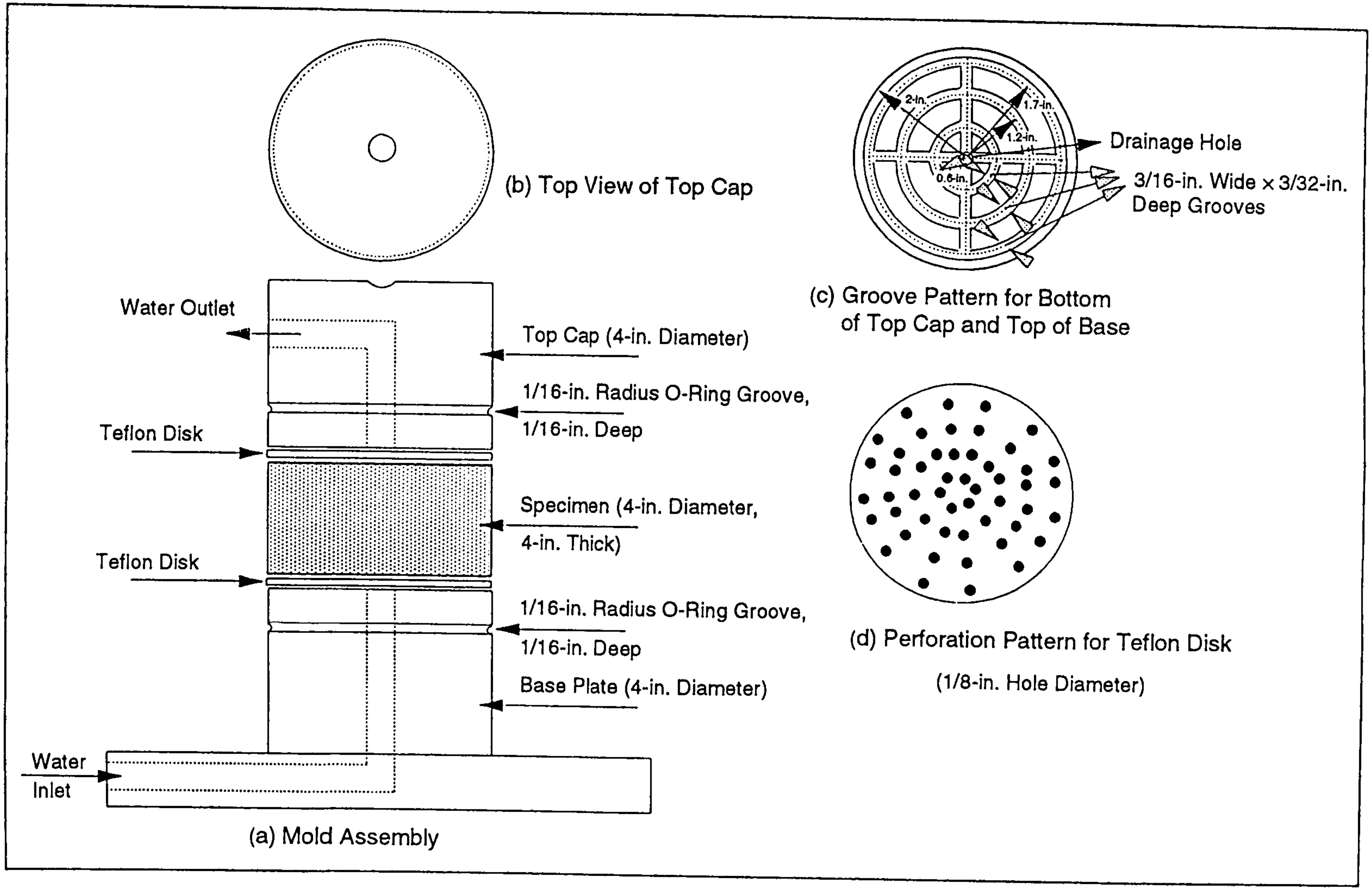


Figure 3.7. Water-conditioning setup for cylindrical specimen

disadvantage of this method is that the air pressure in the membrane may deform the specimen.

Kumar and Goetz (1977b) developed a different technique to prevent leakage. The specimen is placed between two collars (lower collar and upper collar) and coated with silicone rubber sealer all around the specimen and parts of both collars to bind the collars to the specimen. This method prevents leakage along the specimen wall but it is rather involved and time consuming.

In the modified procedure developed at OSU (Al-Swailmi and Terrel 1992), the middle third of the specimen's surface is coated with silicone and then enveloped with a cylindrical rubber membrane 3.81 cm (1.5 in.) high (a wide rubber band, cut from a membrane) to provide a smooth surface. After curing a few hours, the specimen is fitted with a cylindrical rubber membrane long enough to envelop the sample base and sample top cap. This procedure was adopted after investigation of three levels of silicone seals on the surface of the specimen and under the rubber membrane showed that the standard procedure of a single seal at the midpoint was adequate (Figure 3.8).

3.2.9 Effect of Compaction Procedure on Specimen Surface Sealing

From observation, a sealing effect on the end surface specimen during compaction (kneading) was of some concern. Since this effect was expected, several trials were conducted by sawing the specimen ends to obtain a "true" permeability value (expressed by the coefficient of permeability). Both wet sawing and dry sawing were used. Table 3.5 shows a summary of permeability measurements comparing as-molded briquets and briquets with 0.64 cm (0.25 in.) sawed off each end (dry and wet sawing). Dry sawing at ambient temperature showed a 40-percent decrease in permeability compared with as-molded permeability. This unexpected result was due to the high temperature created by the friction between the saw and the aggregate, which melted the asphalt and created another seal by smearing the asphalt binder across the surface. This explanation was confirmed by dry sawing (in a controlled-temperature room) at 0°C (32°F) and applying carbon dioxide to reduce heating during sawing. Cold dry sawing shows higher permeability (Table 3.5) than wet sawing; however, both wet and dry sawing at ambient temperature resulted in lower permeability. From the above comparison, it was concluded that dry sawing is appropriate for the standard ECS specimen preparation, which is used for slab and field specimens.

3.2.10 Relationship Between Differential Pressure Level and Coefficient of Permeability

The permeability test is not only critical to the test parameter setup, but also critical to the test conditions. The following steady-state conditions are required for the permeability test:

1. Continuity of flow with no volume change during a test.
2. Flow with the voids fully saturated.

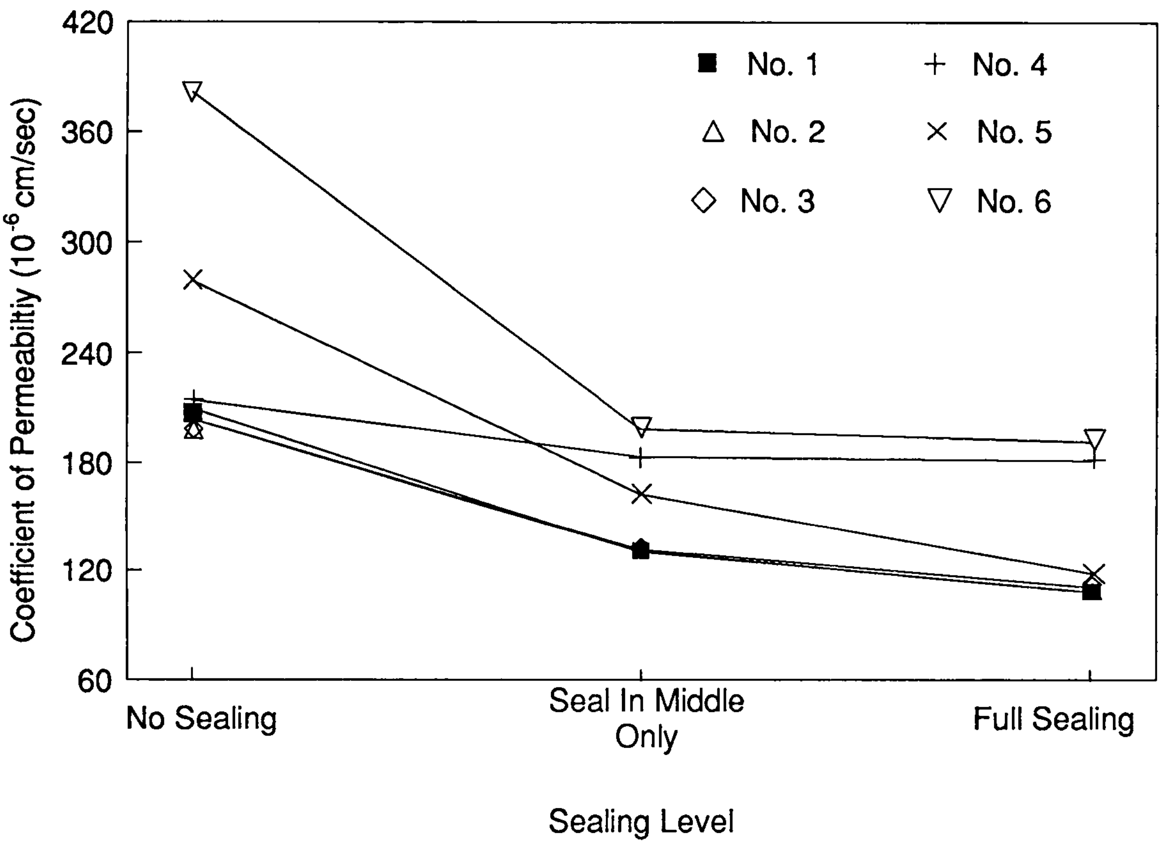


Figure 3.8. Effect of sealing level on permeability

Table 3.5. Summary of coefficient of permeability measurements comparing as-molded briquets and briquets with 0.64 cm (0.25in.) sawed off each end

Specimen No.	Percent Air Voids	Permeability $k_1 \times 10^{-9}$ cm/sec			
		Before Sawing	After Wet Sawing	After Dry Sawing	Average ΔK Xe-9
1	8.3	5.4	--	3.7	
2	8.1	5.1	--	3.5	1.3
3	8.0	3.6	--	3.0	
4	7.7	4.8	3.4	--	
5	7.6	3.3	2.9	--	1.8
6	8.3	3.9	3.8	--	

Note: To convert from cm/s to ft/min, multiply by 1.969.

3. Flow in the steady state with no changes in pressure gradient.

To show that the test was performed in a steady-state condition, at least three air flow readings for three differential pressure readings were required. The rate of air flow Q versus differential pressure ΔP is plotted, and the slope, $Q/\Delta P$, of the straight-line portion of the curve is obtained by linear regression (Kumar 1977). By using the specimen thickness and this slope value, the permeability can easily be calculated. Statistically, the degree of the variation from the straight line can be judged from the R-squared (R^2) value.

The relationship between R^2 and differential pressure level was used in this investigation to indicate the steady-state of the flow. A permeameter (Figure 3.9) was fabricated with three levels of air flowmeters and four levels of differential pressure meters. The differential pressure meters are as follows:

1. Differential pressure meter with a range of 2 cm (0.8 in.) of water and minor division of 0.01 cm (0.004 in.).

2. Differential pressure meter with a range of 5.08 cm (2 in.) of water and minor division of 0.10 cm (0.04 in.).

3. Water manometer with a range of 30 cm (11.8 in.) and minor division of 0.10 cm (0.04 in.).

4. Mercury manometer with a range of 30 cm (11.8 in.) and minor divisions of 0.3 cm (0.1 in.).

An open-graded asphalt concrete specimen was prepared with 20-percent air voids so that a wide range of air flow rates and differential pressures could be used. A total of 61 air flow rates and differential pressure readings were reported for a range of differential pressure from 0.03 to 34.5 cm (0.01 to 13.6 in.) of water and a range of air flow rate from 110 to 18,876 cm^3/min (0.23 to 40 ft^3/hr) (see Table 3.6.)

Figure 3.10 shows a plot of flow rate versus differential pressure, divided into five ranges according to the differential pressure meters, which are indicated by different slopes. The discontinuity in the data (plot) is due to changing either the flow meter or the differential pressure gauge. The coefficient of permeability was calculated for each range and over the entire range as well. Table 3.7 shows permeability (k), slope, and R^2. There is no significant relationship between coefficient of permeability and R^2. For the second and fourth ranges, for example, which both have R^2 equal to 1.0, the coefficients of permeability are significantly different.

It was concluded from this study that indicating the steady state by the slope of the straight-line portion of the curve (flow rate versus differential pressure) with a high R^2, is not the best method. On the other hand, it was found that using the lowest differential pressure possible during the permeability test is the best method for maintaining the steady state, because the lowest differential pressure value is the flattest slope over a wide range of flow rates and differential pressures as shown in Figure 3.10.

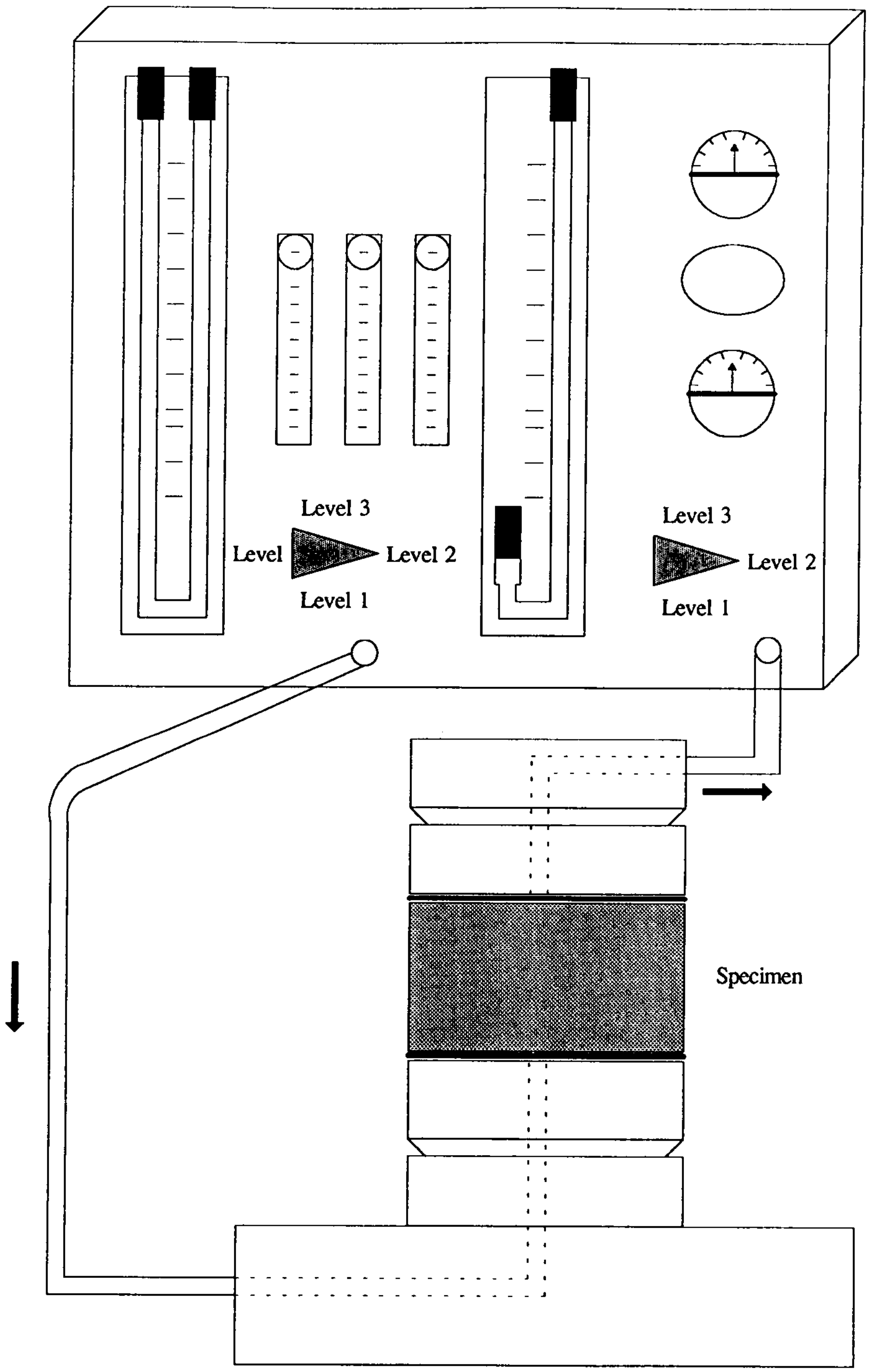


Figure 3.9. Schematic diagram of permeability apparatus

Table 3.6. Rate of air flow versus differential pressure for open-graded asphalt concrete specimen

Pressure, cm H_2O	Pressure, in. H_2O	Air Flow, cm^3/min	Air Flow, ft^3/hr
0.03	0.012	110	0.23
0.04	0.016	130	0.28
0.05	0.020	150	0.32
0.06	0.024	180	0.38
0.07	0.028	200	0.42
0.08	0.031	210	0.45
0.09	0.035	230	0.49
0.10	0.039	260	0.55
0.12	0.047	290	0.61
0.14	0.055	350	0.74
0.16	0.063	390	0.83
0.18	0.071	410	0.87
0.20	0.079	430	0.91
0.22	0.087	460	0.97
0.24	0.094	500	1.06
0.26	0.102	530	1.12
0.28	0.110	550	1.17
0.30	0.118	580	1.23
0.32	0.126	610	1.28
0.34	0.134	660	1.40
0.38	0.150	730	1.55
0.40	0.157	750	1.59
0.42	0.165	790	1.67
0.44	0.173	800	1.70
0.46	0.181	840	1.78

Table 3.6 (continued). Rate of air flow versus differential pressure for open-graded asphalt concrete specimen

Pressure, cm H_2O	Pressure, in. H_2O	Air Flow, cm^3/min	Air Flow, ft^3/hr
0.48	0.189	870	1.84
0.50	0.197	900	1.91
0.52	0.205	930	1.97
0.54	0.213	950	2.01
0.60	0.236	944	2.00
0.77	0.303	1,180	2.50
0.99	0.390	1,416	3.00
0.65	0.256	1,652	3.50
0.75	0.295	1,888	4.00
0.95	0.374	2,124	4.50
1.2	0.472	2,360	5.00
1.45	0.571	2,595	5.50
1.65	0.650	2,831	6.00
1.90	0.748	3,067	6.50
2.10	0.827	3,303	7.00
2.35	1.024	3,775	8.00
2.75	1.083	4,011	8.50
3.15	1.240	4,247	9.00
3.55	1.398	4,483	9.50
3.80	1.496	4,719	10.00
3.15	1.240	4,719	10.00
4.25	1.673	5,663	12.00
6.10	2.402	6,607	14.00
7.30	2.874	7,550	16.00
9.20	3.622	8,494	18.00
10.70	4.213	9,438	20.00
12.10	4.764	10,382	22.00

Table 3.6 (continued). Rate of air flow versus differential pressure for open-graded asphalt concrete specimen

Pressure, cm H_2O	Pressure, in. H_2O	Air Flow, cm^3/min	Air Flow, ft^3/hr
14.00	5.512	11,326	24.00
15.90	6.260	12,269	26.00
18.10	7.126	13,213	28.00
20.00	7.874	14,157	30.00
22.30	8.870	15,101	32.00
25.40	10.000	16,045	34.00
28.90	11.378	16,988	36.00
31.40	12.362	17,932	38.00
34.50	13.582	18,876	40.00

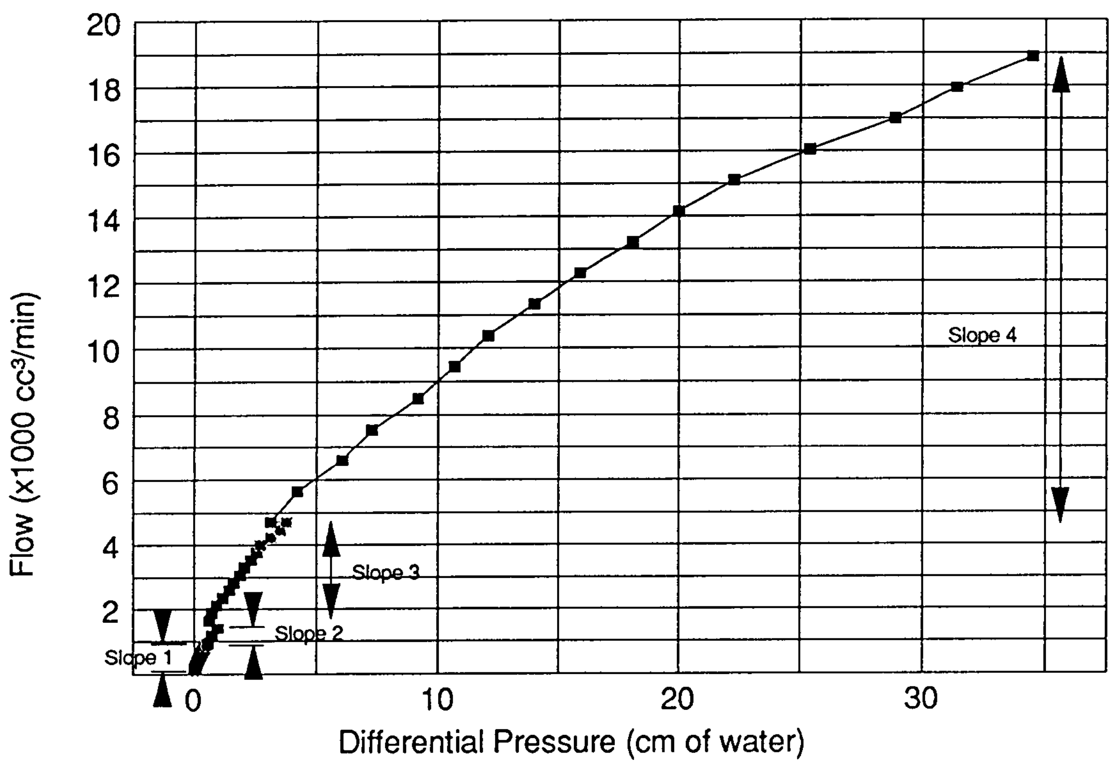


Figure 3.10. Air flow versus differential pressure for open-graded specimen

Table 3.7. R^2 for a range of permeability

	Slope	Coefficient of Permeability, (k), 10^{-6}cm/s	R^2
First range	1,661	7,617	0.99
Second range	116	2,512	1.00
Third range	976	2,129	0.99
Fourth range	785	1,712	1.00
Fifth range	449	977	0.97
Whole range	638	1,394	0.95

3.2.11 Coefficient of Permeability as a Measure of Specimen Volume Change

Volume change of specimen (swell or shrinkage) often occurs during water conditioning and is important in asphalt pavement behavior during the water damage process. Volume change was determined for AASHTO T 283 specimens by reporting specimen bulk specific gravity and saturated surface-dry weight for the three conditioning stages: dry, partially saturated, and water conditioned. Likewise, specimen thickness was measured using ASTM D 3549 for the same three conditioning stages. Logically, any thickness increase should be accompanied by volume increase. In contrast, the results show no significant relation between thickness change and volume change, (Figure 3.11). Therefore, the bulk specific gravity test is not an appropriate method for monitoring specimen volume change during water-conditioning cycles.

In the ECS testing program, specimen volume change was monitored by two methods:

1. Monitoring specimen thickness during water conditioning by an LVDT attached to the top of the specimen and connected to a computer for data acquisition.

2. Monitoring changes in the internal voids volume by determining water permeability at the end of each water-conditioning cycle.

3.2.12 Specimen Internal Coloring Indicator

To investigate water accessibility to the internal air voids of asphalt concrete specimens, dye-treated water was used to wet specimens under the ECS standard vacuum, 50.8 cm (20 in.) Hg. The specimens were then split open diametrally and examined. All interior voids appeared to be dye stained; thus water access was complete. Figure 3.12 shows the setup used to investigate the accessibility of the water through compacted asphalt concrete specimens.

3.2.13 Methods of Air Void Calculations

The determination of the bulk specific gravity of compacted asphalt concrete specimens was accomplished according to ASTM D 1188,"Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens," but replacing paraffin coating by Parafilm wrapping (Del Valle 1985). A comparative study has been conducted for calculating air voids by the regular method—ASTM D 2726, "Test for Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens," based on weight of saturated surface-dry specimen in air—and by method ASTM D 1188. Percent air voids has been calculated by the two methods for each size of specimen from four aggregate-asphalt combinations: RL/AAK-1, RL/AAG-1, RB/AAK-1, and RB/AAG-1. Figure 3.13 shows the comparison of percent air void calculations with and without Parafilm for two of the combinations. There is a significant and consistent difference between the two methods, as might be expected. For this study, both methods were used for ECS testing.

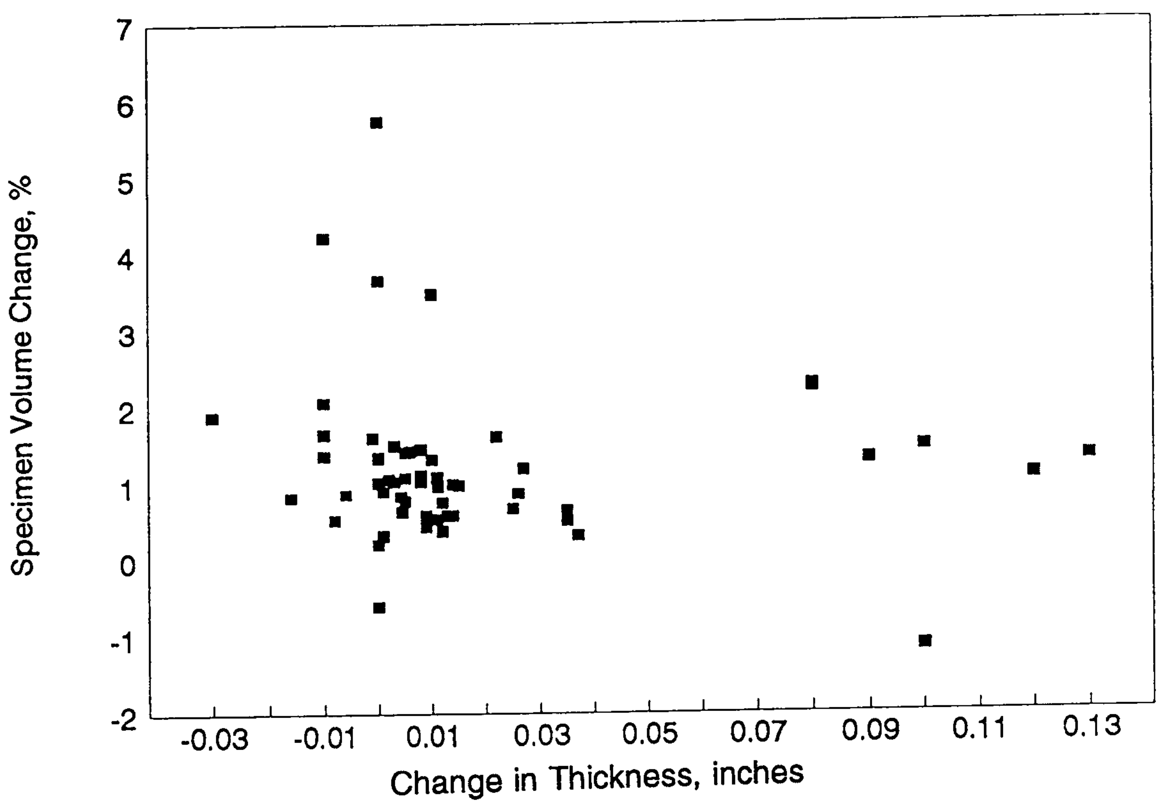


Figure 3.11. Relationship between specimen thickness and volume change

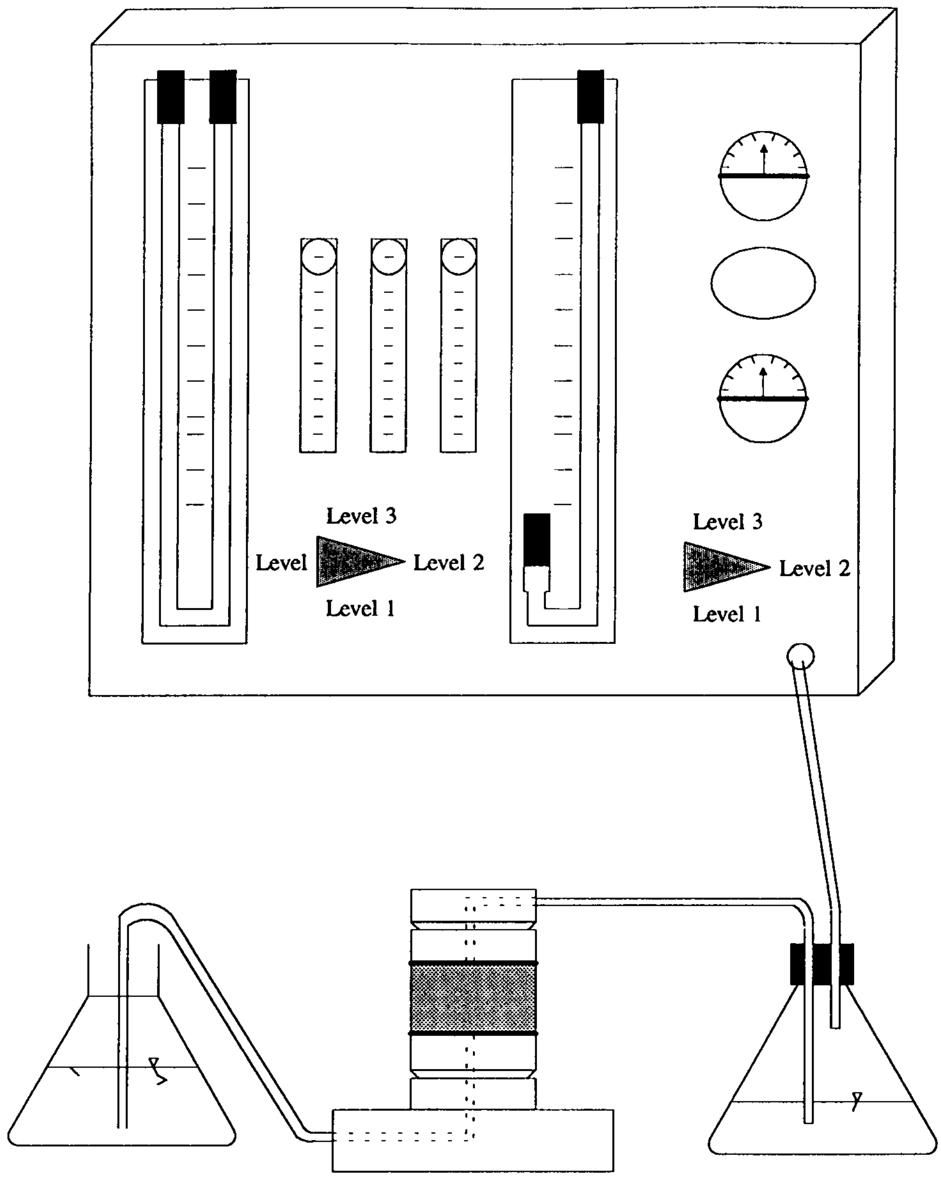


Figure 3.12. Schematic diagram of dye-treatment setup

Aggregate type has considerable effect on the difference because aggregate gradation and aggregate shape influence specimen surface air voids, which are included in the percent air voids in the case with Parafilm and excluded in the case without Parafilm. The percent air void from the RB/AAK-1 mixture with Parafilm is 1.5 points higher than that determined without Parafilm for the same mixture.

As part of the AASHTO T 283 procedure, specimen specific gravity is required for three conditions: dry, partially saturated, and water-conditioned. Wrapping partially saturated and water-conditioned specimens with Parafilm is not practical because under these circumstances the specimens continuously drain water. Therefore, AASHTO T 283 dry specimens were tested by both methods, and partially saturated and water-conditioned specimens were tested only without Parafilm. Specific gravities obtained after wrapping the dry specimen with Parafilm were used for air void reference by the remainder of the SHRP researchers. Degree of saturation and water-conditioning criteria on the AASHTO T 283 test will be based on specific gravities measured without Parafilm and saturated surface-dry weight.

The ECS testing program was based only on specific gravity and percent air voids calculated from ASTM D 1188 with Parafilm wrapping, because this procedure has an advantage over ASTM D 2726 in that the Parafilm keeps the specimen dry. Another advantage is that the Parafilm can be removed easily, and the specimen is not contaminated.

3.3 Environmental Conditioning System (ECS)

The testing program using the ECS was discussed earlier. The experimental plan (Figure 2.1) shows a matrix of the variables being evaluated. Not all of the nine conditioning codes, or cells, for each permeability level were completed for each asphalt-aggregate combination, because of time constraints and because observation showed that not all tests were necessary to obtain the desired results. Specimens 10 cm (4 in.) in diameter and 10 cm (4 in.) high were used for the ECS testing program. Only one combination, RL/AAK, was tested for all the variables, and the remaining three combinations were tested for only the extreme conditions. Figure 3.14 shows the combinations tested for each conditioning code (matrix cell). All the water-conditioning codes shown in Figure 2.1 were performed with repeated loading except the freezing and dry conditioning codes. The testing of open-graded mixtures has been accomplished after modifying the test setup, which is discussed in chapter 4.

Table 3.8 shows all the test results of the development phase of the ECS. During the early stages of ECS testing (early 1990), numerous specimens 10 cm (4 in.) in diameter and 6.35 cm (2.5 in.) high were tested for several conditioning codes. Because a specimen 10 cm (4 in.) high was established for the ECS testing, only results from 10-cm (4-in.) specimens were used in the following analysis sections.

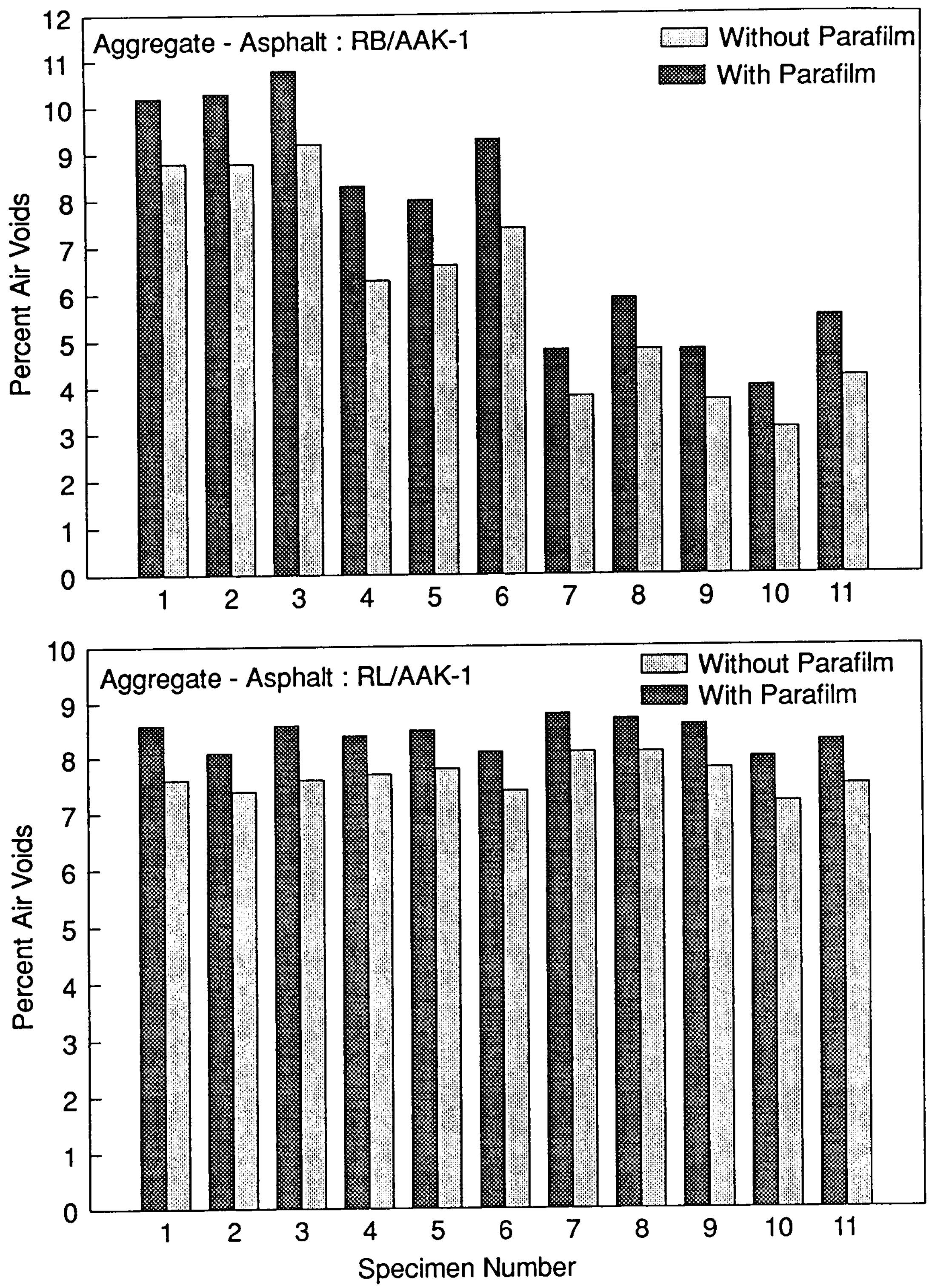


Figure 3.13. Comparison of percent air void calculation with and without Parafilm

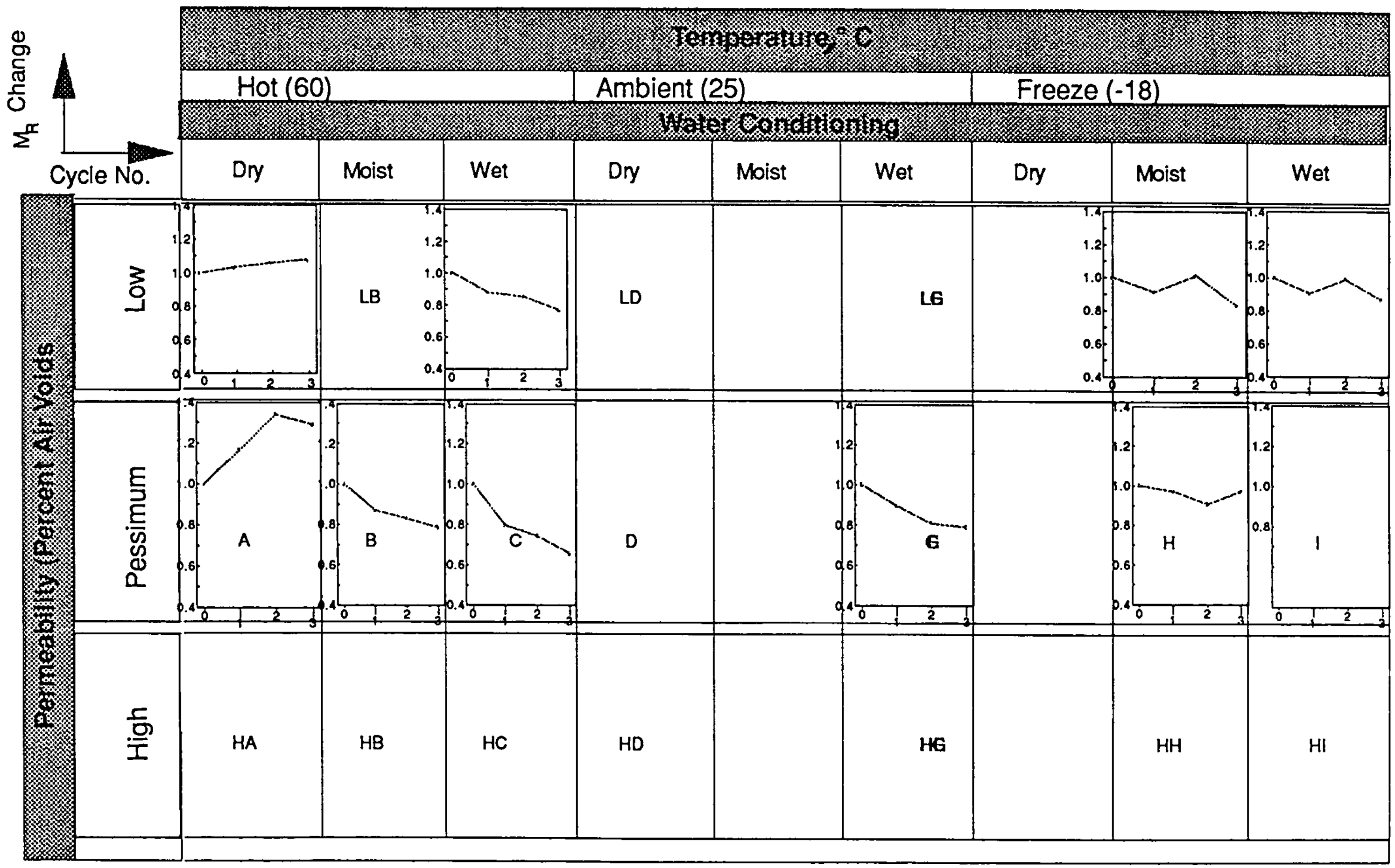


Figure 3.14. Summary of plots of different conditioning levels or codes

Table 3.8. Summary of water-conditioning test results from the Environmental Conditioning System

Specimen No.	Test ID	Cycle No.	M_R (ksi)	Retained M_R (ratio)	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
1	RLC*RL/AAK-1	0	501	1.00	4.73	1.00	
		1	441	0.88	5.23	1.11	
		2	427	0.85	3.98	0.84	
		3	384	0.77	3.55	0.75	20
2	RLC*RB/AAG-1	0	1,018	1.00	1.87	1.00	
		1	860	0.84	1.62	0.87	
		2	854	0.84	1.12	0.60	
		3	324	0.81	0.93	0.50	10
3	RC*RL/AAK-1	0	594	1.00	11.89	1.00	
		1	472	0.79	10.96	0.92	
		2	441	0.74	9.52	0.80	
		3	390	0.66	7.78	0.65	50
4	RC*RL/AAG-1	0	1,061	1.00	27.14	1.00	
		1	809	0.76	8.53	0.31	
		2	836	0.79	10.40	0.38	
		3	697	0.66	13.47	0.50	30
5	RC*RB/AAK-1	0	346	1.00	14.94	1.00	
		1	291	0.84	9.21	0.62	
		2	286	0.83	5.17	0.35	
		3	264	0.76	3.17	0.21	30
6	RC*RB/AAG-1	0	727	1.00	9.17	1.00	
		1	661	0.91	6.91	0.71	
		2	603	0.83	5.10	0.53	
		3	580	0.80	2.49	0.26	30
7	SLI111RL/AAK-1	0	1,143	1.00	0.56	1.00	
		1	1,034	0.91	0.37	0.67	
		2	1,131	0.99	0.44	0.78	
		3	991	0.87			5
8	SLI*RL/AAG-1	0	994	1.00	1.37	1.00	
		1	935	0.94	1.25	0.91	
		2	918	0.92	1.80	1.32	
		3	872	0.88			5
9	SLI*RB/AAK-1	0	587	1.00	1.37	1.00	
		1	544	0.93	1.31	0.95	
		2	545	0.93	0.87	0.64	
		3	512	0.87	1.86	0.77	5

Note: To convert from ksi to kPa, multiply by 6894.76. To convert from cm/s to ft/min, multiply by 1.969. Asterisk in text ID indicates two or more replications.

Table 3.8 (continued). Summary of water-conditioning test results from the Environmental Conditioning System

Specimen No.	Test ID	Cycle No.	M_R (ksi)	Retained M_R (ratio)	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
10	SLI*RB/AAG-1	0	789	1.00	1.62	1.00	
		1	756	0.96	1.49	0.92	
		2	726	0.92	0.93	0.58	
		3	675	0.86	1.06	0.65	5
11	SI*RL/AAK-1	0	507	1.00	1.45	1.00	
		1	471	0.93	16.87	1.16	
		2	442	0.87	16.69	1.15	
		3	433	0.85	14.58	1.00	10
12	SI59RL/AAG-1	0	1,102	1.00	3.56	1.00	
		1	971	0.88	12.39	0.39	
		2	909	0.82	25.49	0.78	
		3	962	0.87	17.74	0.56	10
13	SI*RB/AAK-1	0	437	1.00	10.15	1.00	
		1	415	0.95	8.47	0.83	
		2	407	0.93	14.75	1.45	
		3	369	0.84	12.39	1.22	5
14	SI*RB/AAG-1	0	808	1.00	16.00	1.00	
		1	756	0.94	14.94	0.93	
		2	695	0.86	13.76	0.86	
		3	684	0.85	11.14	0.70	10
15	RB*RL/AAK-1	0	435	1.00	8.47	1.00	
		1	378	0.87	5.79	0.68	
		2	361	0.83	3.61	0.43	
		3	341	0.78	3.78	0.47	20
16	SH214RL/AAK-1	0	331	1.00	16.31	1.00	
		1	321	0.97	14.38	0.88	
		2	300	0.91	13.07	0.80	
		3	321	0.97	13.26	0.81	5
17	SH*RB/AAG-1	0	803	1.00	36.04	1.00	
		1	787	0.98	50.48	1.40	
		2	695	0.87	62.06	1.72	
		3	683	0.85	46.44	1.29	5
18	SLH99RL/AAK-1	0	692	1.00			
		1	632	0.91			
		2	698	1.01			
		3	573	0.83			10

Table 3.8 (continued). Summary of water conditioning test results from the Environmental Conditioning System

Specimen No.	Test ID	Cycle No.	M_R (ksi)	Retained M_R (ratio)	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
19	RF*RL/AAK-1	0	355	1.00	11.89	1.00	
		1	318	0.90	10.77	0.91	
		2	287	0.81	9.28	0.78	
		3	281	0.79	6.66	0.56	5
20	SC*RL/AAK-1	0	411	1.00	10.52	1.00	
		1	359	0.87	8.65	0.82	
		2	322	0.78	8.53	0.81	
		3	300	0.73	5.60	0.53	30
21	VC47RL/AAK-1	0	595	1.00	55.71	1.00	
		1	657	1.10	46.69	0.84	
		2	636	1.07	48.37	0.87	
		3	605	1.02	52.54	0.94	5
22	A31RL/AAK-1	0	395	1.00	35.48	1.00	
		1	460	1.16	31.13	0.88	
		2	528	1.34	31.75	0.89	
		3	509	1.29	31.75	0.89	
23	SC214RL/AAK-1	0	281	1.00	19.92	1.00	
		1	226	0.81	13.07	0.66	
		2	195	0.70	6.85	0.34	
		3	188	0.67	5.60	0.28	40

3.3.1 ECS-M_R

Triaxial resilient modulus (ECS-M_R) was determined using the ECS at 25°C (77°F) on each specimen in the dry condition and again following each hot conditioning cycle. Retained ECS-M_R was calculated for each cycle as a ratio of ECS-M_R after conditioning to dry ECS-M_R (before conditioning).

Conditioning duration (cycle time) was investigated by conditioning two specimens from the same material and same air void level for two cycle durations (6 and 24 hours), and the test results are shown in Table 3.8 (specimen SC*RL/AAK-1 and specimen SC214RL/AAK-1). Graphical display and discussion are in chapter 4.

Since most of the previous research has been accomplished without incorporating the effect of traffic on water damage, the effect of traffic was simulated in this study by applying repeated loading on the specimen while conditioning it through temperature cycles. ECS-M_R and water permeability were monitored for two sets of specimens that were water conditioned: one with static loading under 25.4 cm (10 in.) Hg vacuum (equivalent to 5 psi) and the other set with repeated loading, 890 N, 117 kPa (200 lb, 17 psi). The data for these two sets (SC*RL/AAK-1 and RC*RL/AAK-1) are shown in Table 3.8. The effect of repeated loading is discussed later.

It is generally understood (without investigation) that water is the best fluid for conditioning asphalt concrete specimens to investigate moisture-related problems. But actually, in the field, there are pavements that show water damage resulting from moisture vapor from the water table beneath the asphalt pavement. For this reason, three fluids (air, vapor, and distilled water) were used to condition three different specimens. A specimen was conditioned with vapor by adjusting the environmental conditioning cabinet to 60°C (140°F) and relative humidity 90 percent. Vapor was pulled through the specimen by a vacuum of 25.4 cm (10 in.) Hg. The vacuum inlet inside the environmental cabinet was connected to a funnel to collect and direct the air flow, and right after the funnel, a flowmeter was connected to maintain the vacuum level at 25.4 cm Hg (10 in.) according to the ECS conditioning procedure. The same vapor conditioning setup has been used to conduct air conditioning by maintaining the same temperature and adjusting relative humidity to 0 percent. For water conditioning, the normal ECS setup was used to conduct hot-wet conditioning (conditioning code C) as described earlier for static loading.

Permeability and ECS-M_R were monitored following conditioning cycles, and the results from the three specimens are shown in Table 3.8 (VC47RL/AAK-1, A31RL/AAK-1, and RC*RL/AAK-1). The vapor-conditioning setup was constructed as shown in Figure 3.15. Besides the above investigations, the main ECS experiment included the effect of the following variables: (1) vacuum level, (2) air void level, and (3) saturation level.

3.3.2 Permeability

It is generally understood that the higher the air void content, the higher the permeability and the more water can penetrate (and remain, to some degree) in an asphalt pavement. But when aggregate type and aggregate gradation are variables, mixtures may have similar

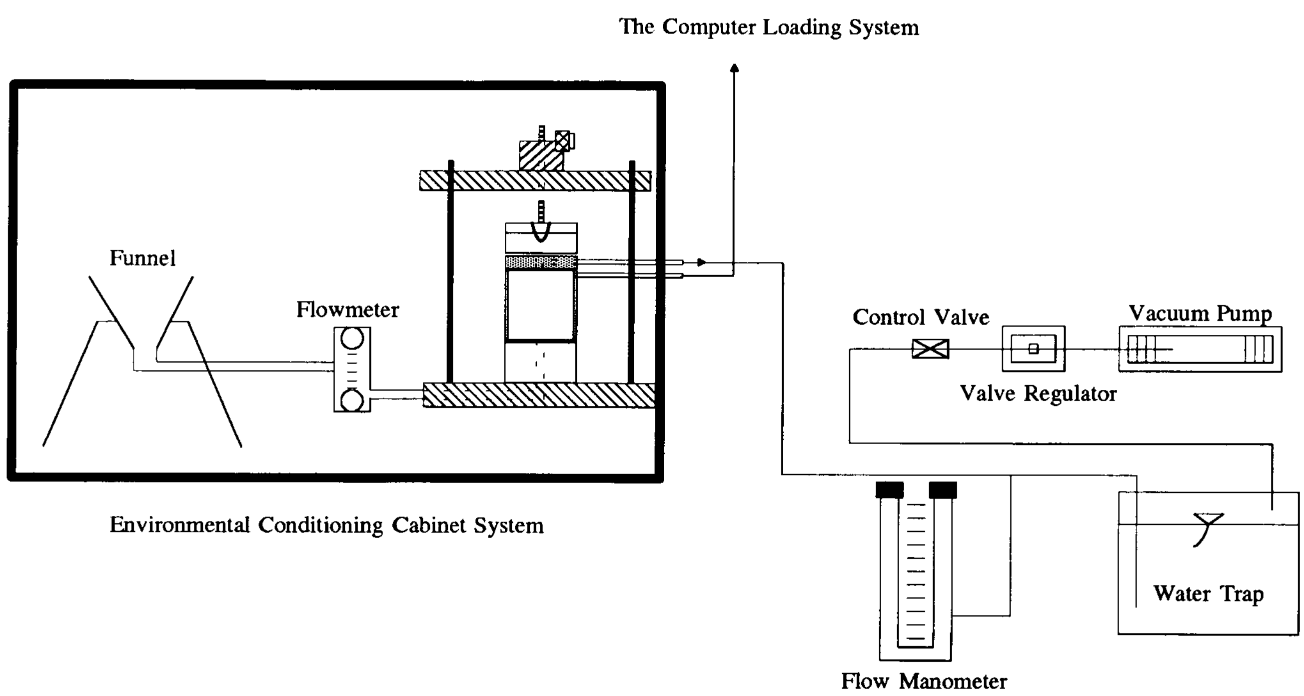


Figure 3.15. Schematic drawing of vapor-conditioning device

air void contents, but the permeability of one may be as much as twice that of the other. Hein and Schmidt (1961) studied air permeability of asphalt concrete and concluded that permeability, when influenced by gradation changes, is not always proportional to void content. Most of the customary conceptions (e.g., that permeability is proportional to void content) are concluded from studies conducted on similar aggregates.

Because it represents both the volume of air voids and their structure, permeability may be a better indicator of performance than void content alone. In this study, permeability was measured using air for each specimen before beginning water conditioning. Table 3.9 shows air permeabilities and air void content results. Since water permeability, which is measured during water conditioning, is not the true permeability because the specimen is not fully saturated, this measurement is used only as a relative indicator for the change in air void structure caused by water-conditioning.

3.3.3 Visual Evaluation

Visual evaluation of asphalt concrete specimens is a method used to determine the percentage of retained asphalt coating on the aggregate after the sample has been water conditioned. The visual evaluation method is fundamental in boiling tests and static immersion tests. However, the primary shortcoming of this method is the subjectivity of the results. Sometimes, to reduce the subjectivity, rating boards or patterns similar to those shown in Figure 3.16 are used to aid the rater and help establish consistency in the results. Another method is to use more than one rater and average the results. In addition, differences in how and when specimens are evaluated can further decrease the precision of the results. For example, for boiling tests, it is common to place the sample on a paper towel and evaluate the mixture when it has dried. Parker and Wilson (1986) found that the timing of the evaluation can significantly affect the percent-coating rating given to an asphalt sample after the boiling test. Although the asphalt on the aggregate is thinner, the visual evaluation does not account for the film thickness. This is in contrast to the static immersion tests, in which the sample is typically rated while still in the container and immersed in water.

The method used in NCHRP 246 (Lottman 1982) recommends that following the indirect tensile test, the specimen be split open and the percent stripping be evaluated on the fractured interior faces.

Lottman (1982) used a stereo zoom microscope to estimate the percent stripping in the fine aggregate and a magnifying glass for the coarse aggregate, and then calculated total percent stripping by prorating each fraction. Based on others' experience, a visual evaluation technique was modified for use in this study by considering the problem of subjectivity. The new visual evaluation technique reduced the rating patterns from the 12 levels shown in Figure 3.16 to only 6 levels (5, 10, 20, 30, 40, and 50 percent) and is described in chapter 4. This modification makes it easier to distinguish between the levels.

Table 3.9. Permeability versus percent air-voids

Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)
1	RL/AAK	5.0	11.21	85	RL/AAK	7.7	18.68	169	RB/AAK	6.9	95.00
2	RL/AAK	4.4	8.09	86	RL/AAK	7.2	18.06	170	RB/AAK	4.3	0.12
3	RL/AAK	7.1	46.56	87	RL/AAK	8.0	20.64	171	RB/AAK	9.3	4.11
4	RL/AAK	7.0	21.17	88	RL/AAK	7.2	16.19	172	RB/AAK	9.4	39.59
5	RL/AAK	7.1	21.17	89	RL/AAK	7.8	19.92	173	RB/AAK	0.0	121.57
6	RL/AAK	3.9	0.87	90	RL/AAK	8.0	34.24	174	RB/AAK	7.6	17.93
7	RL/AAK	7.7	33.74	91	RL/AAK	8.5	35.92	175	RB/AAK	8.1	31.06
8	RL/AAK	7.9	13.94	92	RL/AAK	8.1	32.31	176	RB/AAK	8.0	11.14
9	RL/AAK	7.9	27.20	93	RL/AAK	8.1	30.88	177	RB/AAK	6.3	38.22
10	RL/AAK	9.1	32.74	94	RL/AAK	8.0	19.92	178	RB/AAK	6.3	41.02
11	RL/AAK	8.5	23.59	95	RL/AAK	7.6	26.64	179	RB/AAK	6.4	37.10
12	RL/AAK	3.8	3.98	96	RL/AAK	4.9	0.93	180	RB/AAK	9.4	0.74
13	RL/AAK	8.0	29.32	97	RL/AAK	7.8	18.99	181	RB/AAK	10.7	30.60
14	RL/AAK	8.9	20.23	98	RL/AAK	7.1	41.15	182	RB/AAK	11.1	30.25
15	RL/AAK	8.8	32.43	99	RL/AAK	4.8	3.24	183	RB/AAK	6.3	38.22
16	RL/AAK	8.0	29.76	100	RL/AAK	9.0	35.48	184	RB/AAK	6.3	41.02
17	RL/AAK	6.8	16.25	101	RL/AAK	7.9	26.52	185	RB/AAK	6.4	37.10
18	RL/AAK	9.0	33.48	102	RL/AAK	9.2	17.68	186	RB/AAK	9.4	7.41
19	RL/AAK	8.4	15.31	103	RL/AAK	8.2	23.66	187	RB/AAK	10.7	30.60
20	RL/AAK	6.1	1.37	104	RL/AAK	8.3	30.60	188	RB/AAK	11.1	30.25
21	RL/AAK	6.5	1.18	105	RL/AAK	8.6	47.93	189	RB/AAK	7.4	11.83
22	RL/AAK	7.0	46.69	106	RL/AAK	9.1	82.79	190	RB/AAK	7.8	23.03
23	RL/AAK	4.2	42.33	107	RL/AAK	8.6	31.13	191	RB/AAK	7.4	14.94

Table 3.9 (continued). Permeability versus percent air-voids

Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)
24	RL/AAK	8.5	38.60	108	RL/AAK	8.3	36.73	192	RB/AAK	6.7	8.09
25	RL/AAK	8.1	79.87	109	RL/AAK	9.3	11.08	193	RB/AAK	5.7	0.00
26	RL/AAK	6.4	26.65	110	RL/AAK	8.3	36.17	194	RB/AAK	5.9	0.62
27	RL/AAK	7.0	22.35	111	RL/AAK	8.0	31.31	195	RB/AAK	6.8	64.74
28	RL/AAK	6.4	86.22	112	RL/AAK	9.5	40.21	196	RB/AAG	4.0	6.91
29	RL/AAK	6.4	59.32	113	RL/AAK	9.1	37.97	197	RB/AAG	4.3	10.58
30	RL/AAK	5.9	7.91	114	RL/AAK	8.6	31.13	198	RB/AAG	8.2	83.35
31	RL/AAK	7.1	15.31	115	RL/AAK	8.6	34.24	199	RB/AAG	7.9	55.53
32	RL/AAK	7.0	5.42	116	RL/AAK	6.6	7.47	200	RB/AAG	8.2	31.25
33	RL/AAK	8.0	46.07	117	RL/AAK	6.9	9.34	201	RB/AAG	7.7	47.93
34	RL/AAK	6.2	18.68	118	RL/AAK	5.9	7.28	202	RB/AAG	4.5	2.43
35	RL/AAK	6.1	28.39	119	RL/AAK	6.4	6.85	203	RB/AAG	5.2	7.03
36	RL/AAK	5.9	10.83	120	RL/AAK	7.2	48.07	204	RB/AAG	8.3	130.66
37	RL/AAK	6.6	11.58	121	RL/AAK	5.2	5.17	205	RB/AAG	7.0	10.96
38	RL/AAK	7.4	90.26	122	RL/AAK	5.2	4.30	206	RB/AAG	7.8	13.76
39	RL/AAK	6.7	26.21	123	RL/AAK	8.3	55.71	207	RB/AAG	8.2	23.72
40	RL/AAK	5.8	10.89	124	RL/AAK	7.1	46.56	208	RB/AAG	7.3	34.98
41	RL/AAK	5.7	11.77	125	RL/AAK	7.7	33.74	209	RB/AAG	6.6	14.94
42	RL/AAK	5.7	35.54	126	RL/AAK	8.0	126.87	210	RB/AAG	7.1	20.48
43	RL/AAK	6.4	5.73	127	RL/AAG	7.2	180.77	211	RB/AAG	5.4	0.00
44	RL/AAK	5.1	18.30	128	RL/AAG	6.9	11.39	212	RB/AAG	5.5	0.50
45	RL/AAK	6.4	1.07	129	RL/AAG	4.9	6.41	213	RB/AAG	5.0	8.96
46	RL/AAK	4.9	86.22	130	RL/AAG	4.1	1.99	214	RB/AAG	4.6	0.00

Table 3.9 (continued). Permeability versus percent air voids

Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)
47	RL/AAK	4.4	56.11	131	RL/AAG	7.3	10.15	215	RB/AAG	8.0	23.28
48	RL/AAK	4.7	8.28	132	RL/AAG	7.3	31.75	216	RB/AAG	8.1	17.93
49	RL/AAK	6.7	16.06	133	RL/AAG	6.1	1064	217	RB/AAG	7.2	10.64
50	RL/AAK	6.9	10.89	134	RL/AAG	6.4	14.32	218	RB/AAG	6.1	8.28
51	RL/AAK	6.0	5.50	135	RL/AAG	7.6	1.00	219	RB/AAG	5.1	0.00
52	RL/AAK	5.6	9.15	136	RL/AAG	6.2	1.25	220	RB/AAG	6.5	25.46
53	RL/AAK	5.3	7.47	137	RL/AAG	7.3	1.50	221	RB/AAG	7.4	28.95
54	RL/AAK	5.5	27.89	138	RL/AAG	7.1	38.60	222	RB/AAG	7.8	58.02
55	RL/AAK	7.4	44.82	139	RL/AAG	7.0	0.74	223	RB/AAG	7.4	37.66
56	RL/AAK	7.4	45.13	140	RL/AAG	8.0	13.51	224	RB/AAG	6.7	20.79
57	RL/AAK	7.6	42.70	141	RL/AAG	5.4	2.68	225	RB/AAG	5.7	0.62
58	RL/AAK	9.0	29.69	142	RL/AAG	6.6	6.10	226	RB/AAG	5.9	1.56
59	RL/AAK	7.8	31.81	143	RL/AAG	6.7	7.84	227	RB/AAG	7.6	20.64
60	RL/AAK	8.8	23.22	144	RL/AAG	7.0	43.20	228	RB/AAG	7.4	25.52
61	RL/AAK	8.1	35.48	145	RL/AAG	7.7	47.68	229	RB/AAG	7.6	26.15
62	RL/AAK	7.5	21.17	146	RL/AAG	7.2	45.63	230	RB/AAG	9.0	29.88
63	RL/AAK	7.5	29.88	147	RL/AAG	8.0	51.67	231	RB/AAG	7.8	12.45
64	RL/AAK	8.5	37.35	148	RL/AAG	7.2	41.83	232	RB/AAG	8.8	23.05
65	RL/AAK	7.7	27.39	149	RL/AAG	7.8	51.17	233	RB/AAG	6.3	14.94
66	RL/AAK	7.4	28.01	150	RL/AAG	4.2	2.06	234	RB/AAG	6.3	16.19
67	RL/AAK	7.8	33.62	151	RL/AAG	7.2	180.77	235	RB/AAG	6.4	14.94
68	RL/AAK	7.2	19.92	152	RL/AAG	7.0	10.15	236	RB/AAG	9.4	7.47
69	RL/AAK	7.6	20.64	153	RB/AAK	8.0	45.44	237	RB/AAG	10.7	30.60

Table 3.9 (continued). Permeability versus percent air voids

Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)	Specimen No.	Asphalt-Aggregate Type	Percent Air Voids (%)	Permeability (10^{-6} cm/s) (air)
70	RL/AAK	7.4	25.52	154	RB/AAK	8.1	14.32	238	RB/AAG	11.1	30.6
71	RL/AAK	7.6	26.15	155	RB/AAK	4.6	0.62	239	RB/AAG	8.9	21.17
72	RL/AAK	7.7	27.39	156	RB/AAK	4.1	5.35	240	RB/AAG	8.0	16.81
73	RL/AAK	7.4	28.01	157	RB/AAK	6.8	64.74	241	RB/AAG	8.0	26.77
74	RL/AAK	8.1	35.48	158	RB/AAK	6.4	58.52	242	RB/AAG	8.2	6.67
75	RL/AAK	7.8	33.62	159	RB/AAK	9.5	116.84	243	RB/AAG	4.0	6.91
76	RL/AAK	7.5	29.88	160	RB/AAK	7.4	2.05	244	RB/AAG	8.2	83.35
77	RL/AAK	8.5	37.55	161	RB/AAK	8.0	2.24	245	RB/AAG	8.3	11.89
78	RL/AAK	7.5	21.17	162	RB/AAK	6.5	31.13	246	RB/AAG	8.3	130.66
79	RL/AAK	7.8	21.17	163	RB/AAK	7.0	33.62	247	RB/AAG	8.2	99.23
80	RL/AAK	7.7	21.17	164	RB/AAK	6.3	3.17	248	RB/AAG	9.2	65.99
81	RL/AAK	8.0	22.41	165	RB/AAK	9.7	194.41	249	RB/AAG	8.3	122.57
82	RL/AAK	8.3	22.41	166	RB/AAK	6.2	8.59	250	RB/AAG	7.9	42.83
83	RL/AAK	7.9	21.17	167	RB/AAK	5.0	0.00	251	RB/AAG	7.2	87.52
84	RL/AAK	7.0	16.81	168	RB/AAK	6.6	35.79	252	RB/AAG	7.3	75.76

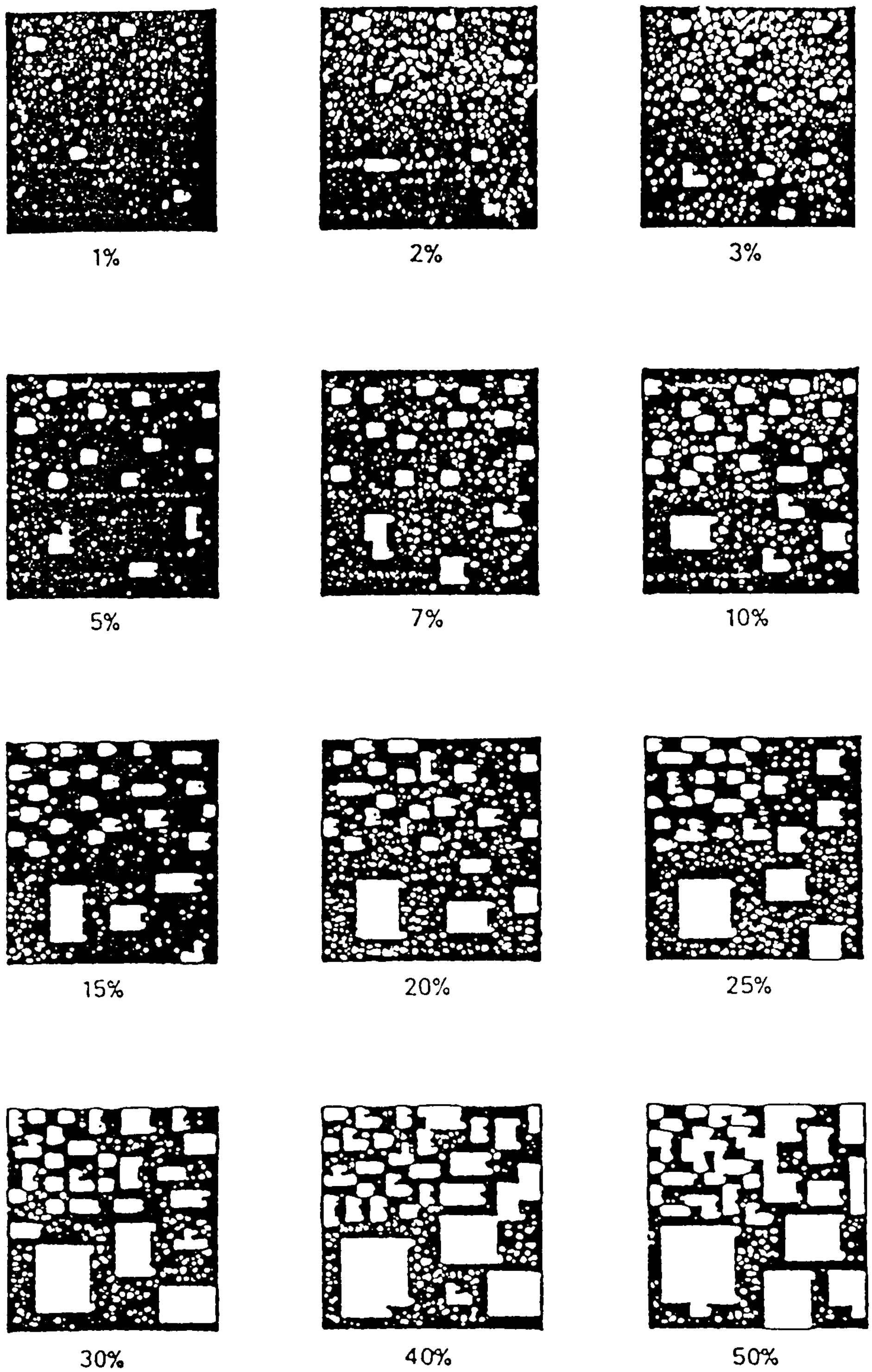


Figure 3.16. Visual evaluation rating pattern (Field and Phang 1986)

3.4 Water Sensitivity Based on Chemical and Physical Bond

SHRP contracted with Auburn University (Contract A-003b) to perform fundamental studies to elucidate the chemistry and physics of the asphalt-aggregate bond. The principal areas of research included adhesion and absorption. The impact of water on adhesion was also evaluated. The products related to water sensitivity developed from A-003B include the net adsorption test, which measures the water sensitivity of a given asphalt-aggregate combination; and specialty tests, which address specific problems involving asphalt-aggregate interactions, such as the bonding energy measurement of the asphalt-aggregate interphase region. The final A-003B report includes more details of these two tests and some other area, (Curtis et. al. 1991). Only these two tests are covered in this comparison with the ECS test results because the tests are closely related to the ECS testing plan and similar asphalt and aggregate materials were used in each experiment.

The net adsorption test was developed to provide a method for determining the affinity of an asphalt-aggregate combination and its sensitivity to water. This test is composed of two steps. First, asphalt is adsorbed onto aggregate from toluene solution, the amount of asphalt remaining in the solution is measured, and the amount of asphalt adsorbed to the aggregate is determined. Second, water is introduced into the system, asphalt is desorbed from the aggregate surface, the asphalt present in the solution is measured, and the amount remaining on the aggregate surface is calculated. The amount of asphalt remaining on the surface after the desorption step is termed *net adsorption.*

The net adsorption value offers a direct means of comparing the water sensitivity of different asphalt-aggregate combinations. In the study, 11 aggregates from the SHRP Materials Reference Library were tested with three different asphalts. Only the results for RL and RB aggregates are discussed in this report because they were common to both the ECS and net adsorption studies. The test results reported by Curtis et al. (1991) for the 11 aggregates showed that the lower the resistance to water damage, the higher the net adsorption. Results from the net adsorption test of RL and RB aggregates correlate quite well with the retained M_R after ECS water-conditioning cycles. The percent adsorption results of RB and RL aggregates with AAK-1 asphalt were 18.1 and 30, respectively, as shown in the A-003B final report. Based on the net adsorption results of the 11 aggregates, which ranged between 18.1 and 44.0, RL aggregate showed a net adsorption significantly higher than RB aggregate. This agrees with the ECS test results, in which RL aggregate is significantly more susceptible to water damage than is RB aggregate, as shown in Table 3.9 and discussed statistically in following sections.

Also, a comparison of the results from the modified Lottman study by the University of Nevada (Curtis et al. 1991) and those from the net adsorption test has been included in Auburn's final report. The comparison showed a general agreement between tensile strength ratios and the net adsorption test results.

The second study reported by Auburn, which can be directly compared with the ECS test results, is the bonding-energy measurements. Asphalt-aggregate bonding energy is based on the premise that the greater the bonding energy, the stronger the asphalt-aggregate bond. In this study, Auburn used eight aggregates and eight asphalts. To measure the bonding energy, a weighed amount of the dried aggregate was placed in an aggregate holder, which was encapsulated in a cylinder and partially immersed in asphalt contained in a microcalorimeter reaction cell. The complete assembly was transferred to a thermocouple cavity in the microcalorimeter. After thermal equilibrium had been reached, the aggregate was put in contact with the asphalt, and the energy released was detected by the microcalorimeter and recorded. The retained M_R after the ECS water conditioning and the test results from the energy study, reported by Auburn, showed good agreement. RB aggregate showed more resistance to water damage than RL aggregate; likewise, RB aggregate showed higher bonding energies than RL aggregate with the same asphalt type, as shown in Figure 3.17.

Further evaluation and comparison of net adsorption test results from Auburn are included in another SHRP A-003A report (Scholz et al. 1992), which covers validation of various test procedures. In that study, additional test results of 32 combinations of asphalt-aggregate (4 aggregates × 8 asphalts) were conducted in the net adsorption apparatus at the University of Nevada at Reno. The protocols for the test were also modified by the University of Nevada. From the results of the ECS net adsorption tests, a recommendation will likely be made to include the net adsorption test for screening aggregates and asphalts when a full ECS evaluation is not conducted.

3.5 Void Structure

As discussed earlier, the typical methods of calculating the air void content for asphalt concrete mix design by using either AASHTO T 165, ASTM D 1188, or ASTM D 2726 are not precise because such methods give only the quantity of the air voids in the mixture without considering the other factors, such as size, shape, and distribution of the air voids. Earlier, the desirability of including permeability as well as air void content in mix design evaluation has been suggested because permeability accounts for the structure and interconnection of air voids.

To accomplish an objective study, SHRP sponsored an IIR (Independent Innovative Research) project to evaluate the current methods of determining air void content and their suitability for reflecting the sizes and distributions of the air voids. The Danish Road Institute, Roskilde, Denmark, was contracted for this task to conduct a microscopical analysis for vertical and horizontal planes in specimens with different air void contents and prepared by different compaction methods. Since the objective of this study is related to the water-sensitivity task, coordination with the researchers in Denmark was established. Twelve samples representing the four asphalt-aggregate combinations, with two air void levels (4 and 8 percent), were prepared and sent to Denmark. The specimens were compacted by a kneading compactor in two layers in cylindrical molds, 10 × 10 cm (4 × 4 in.). The compaction was varied for the four mixtures, as shown in Table 2.2, so as to produce the same low and high air void contents used in the experiment design of the ECS. The preliminary results of the microscopical analysis showed a nonuniform distribution of the air voids in the compacted samples. Figure 3.18 shows two examples of air void distribution for two specimens with 4- and 8-percent air voids. One can see that air voids are unevenly distributed in both specimens. It became evident from the findings of the microscopical

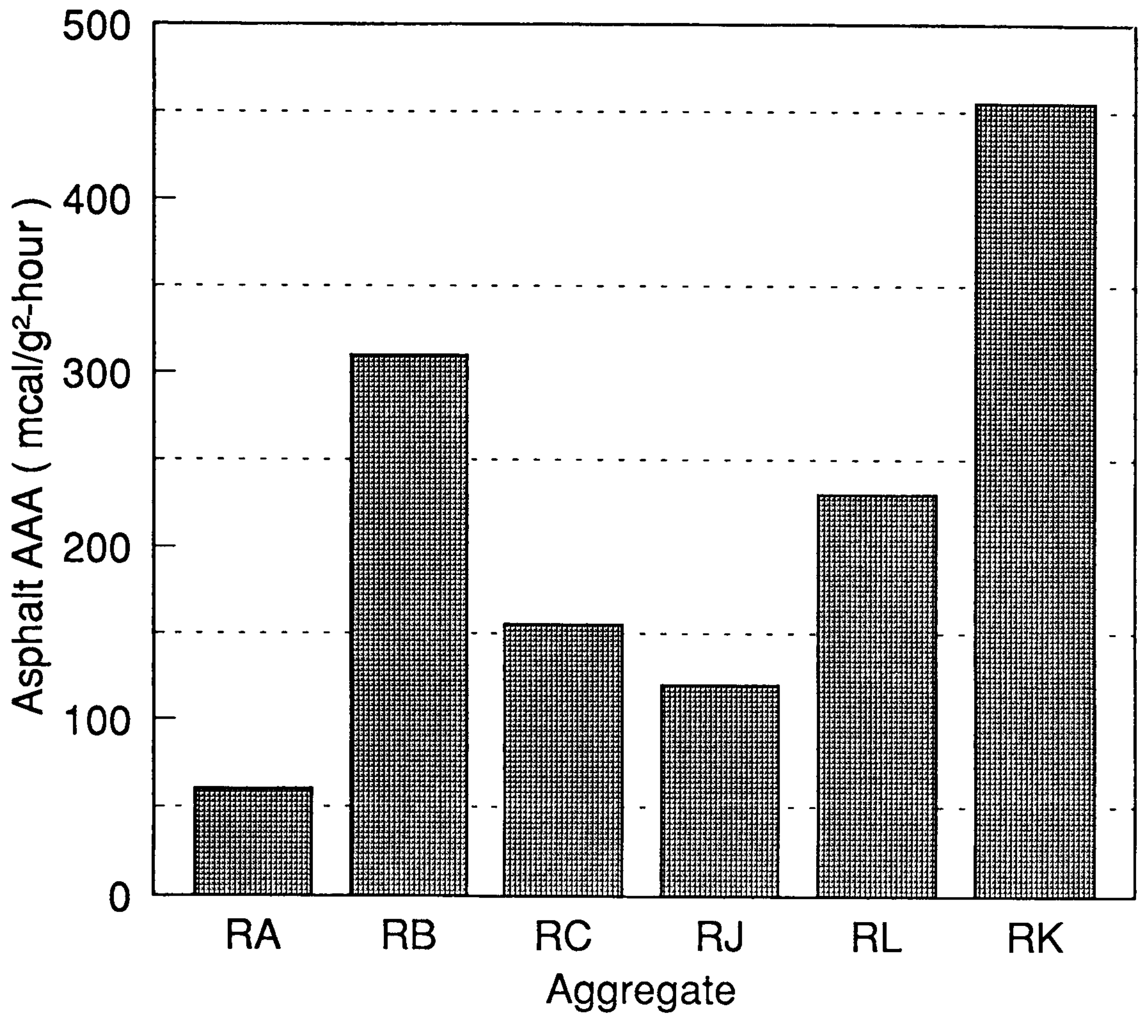


Figure 3.17 Bonding energies of core aggregates with one asphalt type, AAA-1 (Curtis et al. 1992)

analysis and the permeability study that direct comparison of air void contents from traditional methods can be misleading.

One of the major goals of the microscopical analysis of asphalt-aggregate mixtures was to evaluate compaction methods and their effect on mixture inhomogeneity. Three compaction methods are being investigated by the Danish Road Institute: gyratory, kneading, and rolling-wheel compaction. The analysis of the findings concerning mixture inhomogeneity caused by compaction method is not yet complete. Also, in the same study, the Danish Road Institute is investigating a test method for determination of air void content and sizes, as well as shapes and distribution of air voids in asphalt concrete.

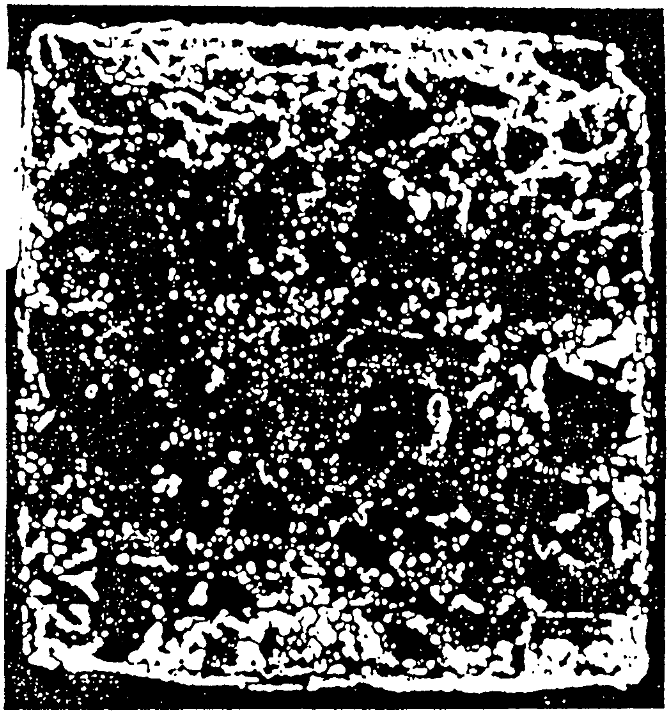
3.6 Atomic Absorption

One of the projects supporting the water-sensitivity task was SHRP Contract AII R-07 by Stanford Research Institute (SRI), Menlo Park, California. SRI conducted a surface analysis by laser ionization of the asphalt-aggregate bond. The project included several studies to investigate the asphalt-aggregate bond.

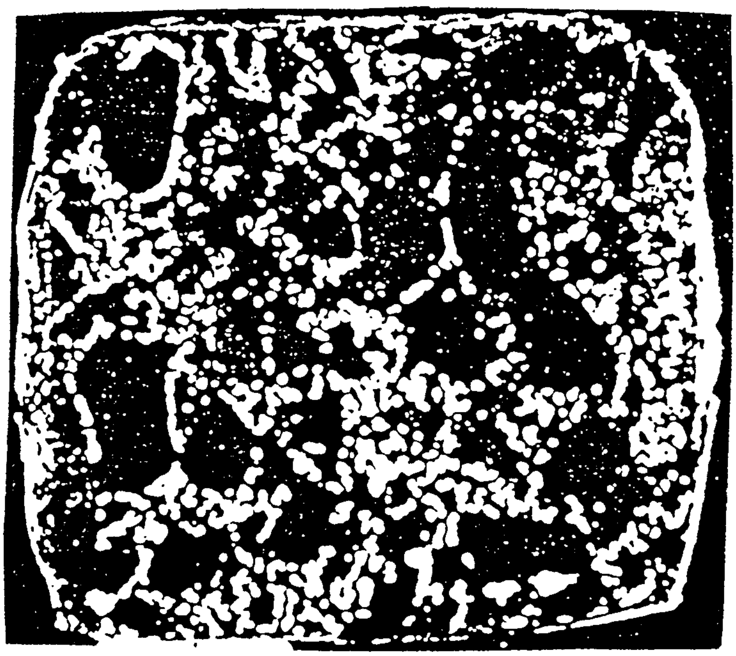
Only limited results were available for comparison. SRI investigated the water stripping of asphalts bonded from soft glass at 150°C (302°F). The test results reported by SRI showed that all investigated asphalts were easily stripped from the soft glass slides following exposure to water-saturated air. AAK-1 and AAG-1 asphalts have been used in addition to other asphalt types. AAG-1 took longer to peel and peeled in pieces rather than as a continuous film like AAK-1. Although the ECS testing results showed no statistical difference between asphalt types in retained strength, AAG-1 tended to show more resistance to water damage than AAK-1, as discussed later.

The interfacial separation of the asphalt and glass has been investigated by also recording the mass spectra from the soft glasses that were water stripped after application of asphalt. Also, mass spectra were recorded for stripped asphalts that had been debonded from an aggregate specimen.

As a follow-up to another phase of the SRI work, OSU is testing the solubility of aggregate and its relationship to adhesion or water sensitivity. SRI had found that water tends to dissolve the aggregate surface, and that the products of this dissolution could be measured. Early results showed that rate of dissolution was related to performance for mixtures conditioned in the ECS. The work will be discussed in another report (Allen and Terrel 1994).



(a) Asphalt-Aggregate: RL/AAK-1; air voids: 3.7 percent compaction: 20 blows at 300 psi and 150 blows at 400 psi



(b) Asphalt-Aggregate: RB/AAG-1; air voids: 6.6 percent compaction: 20 blows at 150 psi and 150 blows at 150 psi

Figure 3.18. Air void distributions of specimens with two air void levels (Curtis et al. 1992)

4

Discussion and Analysis of Test Results

In chapter 2, it was pointed out that the Environmental Conditioning System (ECS) testing program was designed to answer the most important questions related to the performance of mixtures in the presence of water. The test results (chapter 3) and the experiment design (Figure 2.1) were evaluated for the following variables:

- Mixture variables:

  1. Aggregate type
  2. Asphalt type
  3. Air void level

- Conditioning variables

  1. Conditioning fluid
  2. Conditioning temperature
  3. Vacuum level
  4. Repeated loading
  5. Conditioning time

4.1 Effect of Mixture Variables

4.1.1 Aggregate Type

The two aggregates used are RB and RL from the Strategic Highway Research Program (SHRP) Materials Reference Library (MRL). RL is known as a stripping aggregate, and RB is known as a nonstripper. The overall retained stiffness was monitored by determining the ECS-M_R following water-conditioning cycles. Retained modulus ratio was calculated by dividing the ECS-M_R after conditioning by the ECS-M_R before conditioning. Figure 4.1 shows the retained M_R ratio for the two aggregates (RL and RB) with AAG-1 and AAK-1

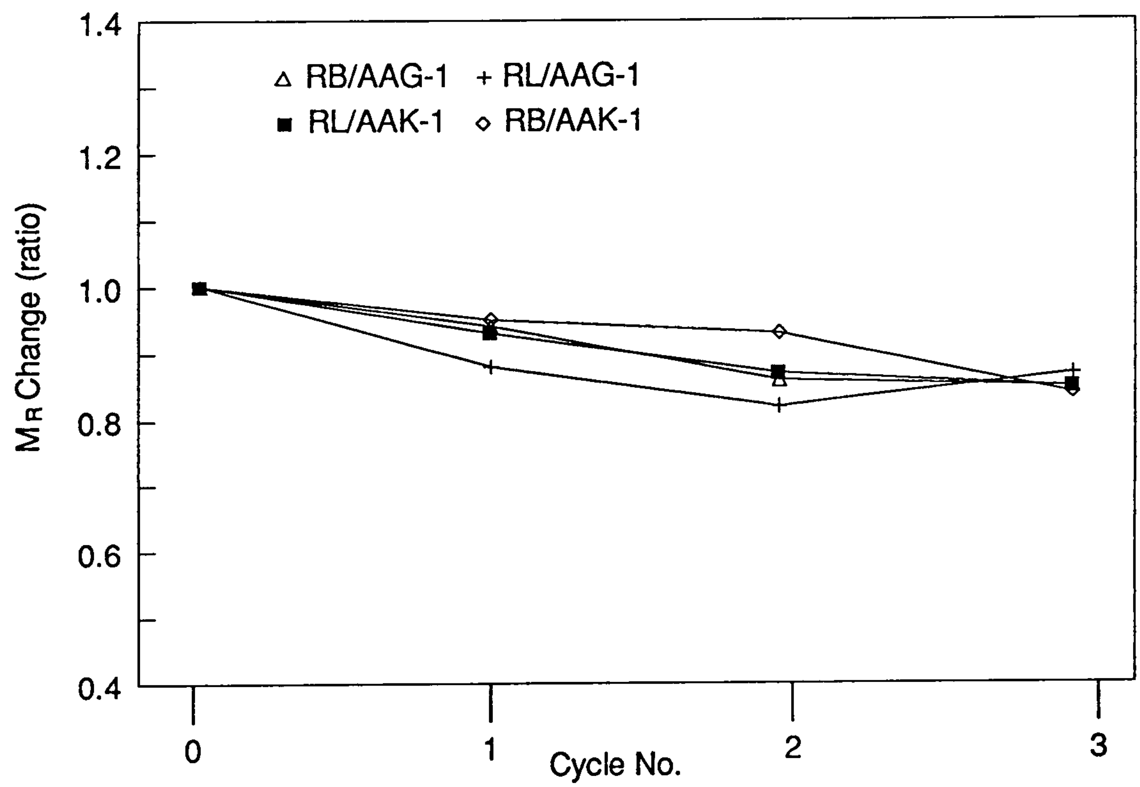


Figure 4.1. Effect of aggregate-asphalt type on resilient modulus change, after hot-wet conditioning

asphalts. The four mixtures were subjected to three 6-hour hot-wet water-conditioning cycles with continuous repeated loading. With both asphalts RB aggregate showed more resistance to water damage than RL.

Another four sets of specimens from the four asphalt-aggregate combinations were tested for freeze-wet conditioning. The results (Figure 4.2) showed that the effect of freezing cycles on M_R is not significant (at this vacuum level), and therefore there are no significant differences among the four tested materials.

To evaluate the differences presented graphically in Figure 4.1, the results were statistically analyzed by the general linear model procedure (GLM). GLM was selected for the analysis of variance (ANOVA) because GLM accounts for unequal cell sizes, which are present in this study. The plan of this phase of the project (development phase) was to evaluate the most related variables to narrow them down and select those having the most effect on water damage. Because of this plan, different test replicates were performed according to the effect of each conditioning code (shown in Figure 2.1). Table 4.1 presents the results of the GLM analysis for M_R ratios at the end of the first, second, and third cycles (6, 12, and 18 hours, respectively). The difference between the M_R ratios of the three conditioning cycles is significant at the 90-percent confidence level, except for the second cycle, where the difference is significant at 80 percent. GLM (as shown here in a brief format) does not give enough information about within treatments, so a least significant difference (LSD) method was used to rank the four asphalt-aggregate combinations. Table 4.2 shows LSD ranking results of the three cycles, in which the four combinations were ranked logically according to their aggregate types. RB aggregate showed the lowest water damage, with LSD less than 0.143 at the 95-percent confidence level for the first and third cycles. M_R ratios after the second cycle followed the same ranking, but with a lower LSD between the means, which was 0.113 at the 80-percent confidence level. RL aggregate experienced the highest water damage with the same statistical confidence levels that showed RL aggregate with a low resistance to water damage. On the other hand, asphalt type showed no significant effect.

This outcome means that aggregate type has a significant response to the water-conditioning procedure, which confirms the graphical results and agrees with the known performance of the two aggregates.

4.1.2 Asphalt Type

Two MRL asphalts were used for this study: AC-30 (AAK-1), which has low temperature susceptibility, and AR-4000 (AAG-1), which has high temperature susceptibility. Figure 4.1 includes the effect of the two asphalts with RL and RB aggregates.

The difference between the two plots of AAK-1 asphalt with RL and RB aggregates is not significant. Similarly, the difference between the two plots of AAG-1 asphalt with RL and RB aggregates is not significant.

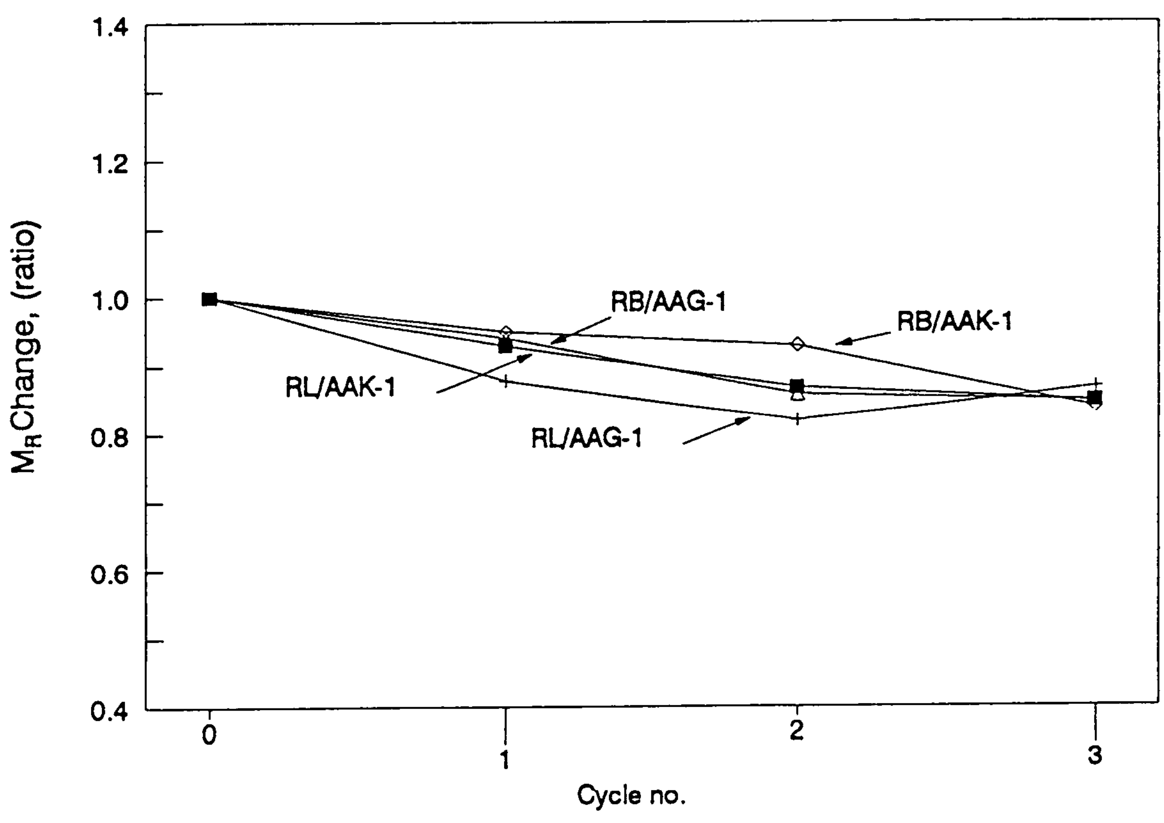


Figure 4.2. Effect of aggregate-asphalt type on resilient modulus change, after freeze-wet conditioning

Table 4.1. Analysis of variance of the difference between M_R ratios after three hot-wet conditioning cycles for the four asphalt-aggregate combinations

Cycle 1

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.032	0.011	4.56*	3.07
Error	7	0.016	0.002		
Corrected Total	10	0.049			

Cycle 2

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.016	0.005	0.66	3.07
Error	7	0.057	0.008		
Corrected Total	10	0.073			

Cycle 3

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.045	0.015	3.27*	3.07
Error	7	0.032	0.004		
Corrected Total	10	0.077			

*Significant at the 90-percent confidence level.

Table 4.2. Asphalt-aggregate ranking by least significant difference

Cycle 1

Alpha = 0.05, degrees of freedom = 7, mean square of the errors = 0.00237
Least significant difference = 0.1024
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.9075	4	RB/AAG-1
A	0.8500	2	RB/AAK-1
B	0.7967	3	RL/AAK-1
B	0.7750	2	RL/AAG-1

Cycle 2

Alpha = 0.20, degrees of freedom = 7, mean square of errors = 0.00817
Least significant difference = 0.113
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.8400	2	RB/AAK-1
A	0.8275	4	RB/AAG-1
B	0.8150	2	RL/AAG-1
B	0.7433	3	RL/AAK-1

Cycle 3

Alpha = 0.05, degrees of freedom = 7, mean square of the errors = 0.00817
Least significant difference = 0.143
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.7950	4	RB/AAG-1
A	0.7700	2	RB/AAK-1
B	0.6750	2	RL/AAG-1
B	0.6500	3	RL/AAK-1

The same data for hot-wet conditioning that were used for Figure 4.1 were expressed statistically in Table 4.2 after conducting the LSD, as discussed above. The same table was used to show the ranking of the effect of asphalt types. As shown in Table 4.2, asphalt type showed no consistent response, since neither asphalt type showed the same LSD ranking for the three cycles. For more clarification, a direct comparison between the two asphalts with the same aggregate type (RB/AAG-1 and RB/AAK-1) was conducted by using GLM. The effect of asphalt type was found not significant at a very low confidence level, less than 50 percent for the second and third cycles and less than 80 percent for the first cycle, as shown in Table 4.3. This means that the four combinations cannot be ranked according to their asphalt types even within a small difference between their means and as low a confidence level as 50 percent.

As shown earlier, specimens from the four asphalt-aggregate combinations were subjected to three freeze-wet conditioning cycles. Figure 4.2 shows the retained strengths for the two aggregates and two asphalts. The freeze-wet conditioning showed no significant effect at this vacuum level (50.8 cm [20 in.] Hg) and for this number of cycles (three 6-hour cycles).

The same conclusion was drawn from GLM analysis, which was conducted on the same data shown in Figure 4.2; that is, the difference between the means is not significant at the 80-percent confidence level for the first cycle, and not significant at lower than 40 percent for the second and third cycles, as shown in Table 4.4. A trial of ranking the four combinations after freeze-wet conditioning cycles was made by conducting the LSD (Table 4.5).

Although there is a ranking at the 70-percent confidence level, it was not consistent throughout the three cycles with either asphalt or aggregate type. This means there is no ranking for asphalt types or aggregate types at the typical confidence levels, such as 70 percent or more. So, it was concluded that the hot-wet cycling is more severe than freeze-wet cycling.

4.1.3 Air Void Level

As shown in the experiment plan (Figure 2.1), three permeability levels were defined by three air void levels; low, such as 4 percent; medium such as 8 percent; and high, as more than 14 percent. Specimens with high air void contents deformed under the high temperatures and repeated loading, so a special conditioning treatment was developed for porous mixtures, which is discussed later. Therefore, only low and medium air void contents are included in this discussion.

According to the experiment plan, two sets of specimens from the same asphalt-aggregate combination with two air void contents were subjected to three hot wet conditioning cycles combined with a continuous repeated loading. Figure 4.3 shows the average of retained modulus ratios for each set. Specimens with medium air void contents (8 percent) showed more significant water damage than specimens with low air void contents (4 percent).

Table 4.3. Analysis of variance of the differences between M_R ratios after three hot-wet conditioning cycles for RB/AAG-1 versus RB/AAK-1

Cycle 1

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.004	0.004	1.90	2.35
Error	4	0.009	0.002		
Corrected Total	5	0.013			

Cycle 2

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.0002	0.0002	0.04	0.32
Error	4	0.023	0.005		
Corrected Total	5	0.023			

Cycle 3

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.0008	0.0008	0.28	0.32
Error	4	0.0117	0.0029		
Corrected Total	5	0.0125			

Table 4.4. Analysis of variance of the difference between M_R ratios after three freeze-wet conditioning cycles for the four asphalt-aggregate combinations

Cycle 1

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.005	0.002	2.40	2.48
Error	4	0.003	0.001		
Corrected Total	7	0.008			

Cycle 2

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.023	0.008	0.67	0.60
Error	4	0.046	0.011		
Corrected Total	7	0.069			

Cycle 3

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	3	0.004	0.001	0.07	0.60
Error	4	0.072	0.018		
Corrected Total	7	0.076			

Table 4.5. Asphalt-aggregate ranking by least significant difference

Cycle 1

Alpha = 0.3, degrees of freedom = 4, means of square of the errors = 0.000679
Least significant difference = 0.0335
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.9650	2	RB/AAK-1
B	0.9367	3	RB/AAG-1
B	0.9300	2	RL/AAK-1
C	0.8800	1	RL/AAG-1

Cycle 2

Alpha = 0.3, degrees of freedom = 7, mean square of the errors = 0.011479
Least significant difference = 0.1377
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.980	2	RB/AAK-1
B A	0.875	2	RL/AAK
B A	0.867	3	RB/AAG-1
B	0.820	1	RL/AAG-1

Cycle 3

Alpha = 0.3, degrees of freedom = 7, mean square of the errors = 0.018112
Least significant difference = 0.1729
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.910	2	RB/AAK-1
A	0.870	1	RL/AAG-1
A	0.860	3	RB/AAG-1
A	0.850	2	RL/AAK-1

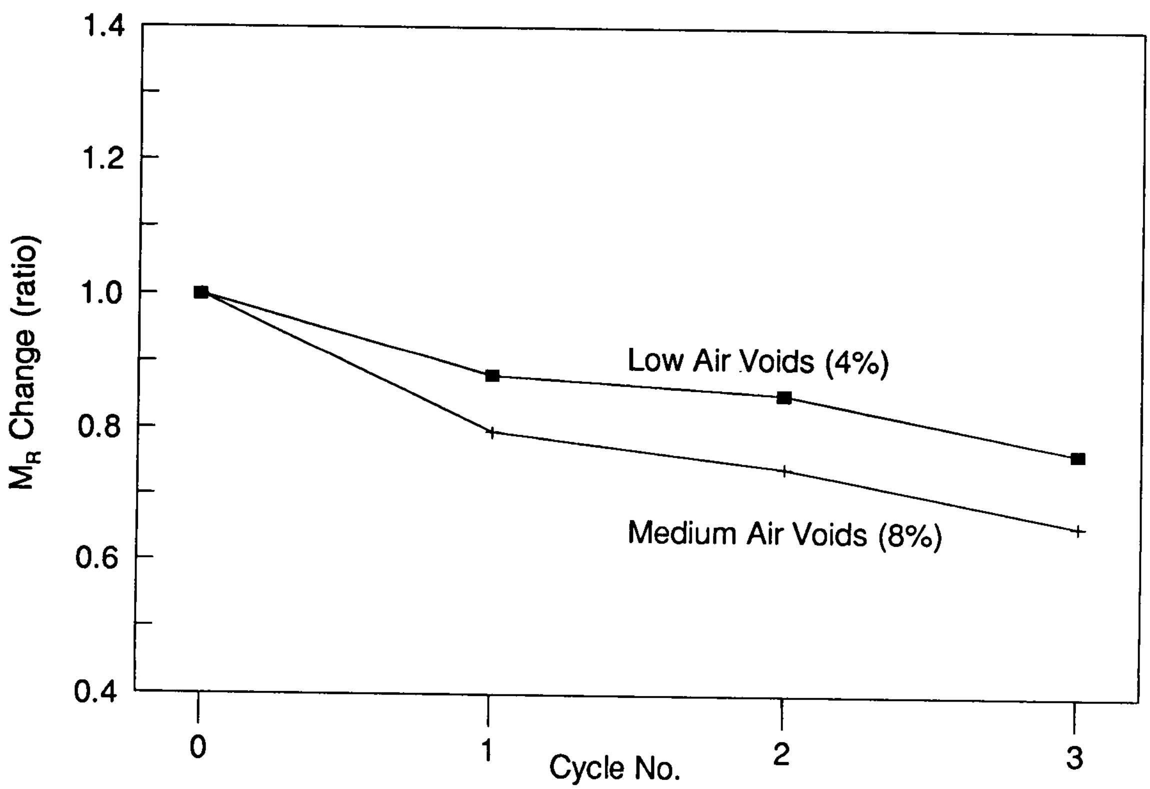


Figure 4.3. Effect of air void level on resilient modulus change the (hot-wet conditioning with continuous repeated loading)

A GLM statistical analysis was performed on the data and the results in Table 4.6 show that the effect of air void content is significant at the 90-percent confidence level. Also, the LSD was conducted to show the ranking of M_R ratios according to their air void contents, and the results are shown in Table 4.7. M_R ratios of the three cycles were ranked significantly based on their air void contents levels at the 90-percent confidence level with LSD more than 0.071. Specimens with low air void contents showed more resistance to water damage because of their low accessibility to water penetration. The result of these comparisons confirms the very important role of air void content in asphalt concrete response to water conditioning.

4.2 Effect of Conditioning Variables

It has been observed that there are significant variations among the current methods in the final evaluation of resistance of an asphalt concrete mixture to water damage (Terrel and Shute 1989). Since most of the structural evaluation techniques are usually the same (using either the resilient modulus or the tensile strength), the source of the variability in test results is mainly the conditioning technique.

For the ECS, the types of conditioning variables to be included and method of including each variable in the new technique are carefully considered. To decide which variables should be included in the proposed moisture-conditioning procedure and at what level they should be incorporated, the role of each variable in asphalt concretes response to water damage must be evaluated. So, each conditioning variable was isolated and evaluated independently.

4.2.1 Conditioning Fluid

In the field, asphalt pavements are exposed to three types of fluids: (1) air in dry climates and dry soils (subgrades), (2) moist air (vapor) in wet climates or wet subgrades (caused by evaporation from ground water), and (3) water in wet climates. Three fluids (air, vapor, and distilled water) were used to condition three sets of specimens from the same asphalt-aggregate combination (RL/AAK-1). Each set was subjected to three 6-hour cycles of hot conditioning with static loading under a 25.4 cm (10 in.) Hg vacuum. The results for the three specimens are presented in Figure 4.4. The data from the three specimens show logical and expected ranking and trends. Air tends to stiffen the mixture by aging (specimen A31RL/AAK-1), and water tends to soften the mixture (specimen RC53RL/AAK-1). Using vapor combines the two phenomena—aging and moisture damage (specimen VC33RL/AAK-1). This investigation indicated the boundaries of conditioning fluids and that the vapor may not be the best fluid for accelerated moisture conditioning. Distilled water was selected as the conditioning fluid for further testing because it resulted in a more pronounced effect and would tend to reduce variability. Also, using tap water might influence the results because of its chemistry, which would vary among locations.

Table 4.6. Analysis of variance of the difference between M_R ratios of specimens with two air void levels

Cycle 1

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.008	0.008	5.60*	5.53
Error	3	0.004	0.001		
Corrected Total	4	0.013			

Cycle 2

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.015	0.015	13.53*	5.50
Error	3	0.003	0.001		
Corrected Total	4	0.018			

Cycle 3

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	(P = 0.10) F Crit
Model	1	0.016	0.016	6.39*	5.50
Error	3	0.007	0.002		
Corrected Total	4	0.023			

*Significant at the 90-percent confidence level.

Table 4.7. Asphalt-aggregate ranking by least significant difference based on air void level

Cycle 1

Alpha = 0.1, degrees of freedom = 3, mean square of the errors = 0.001489
Least significant difference = 0.0829
Means with the same letter are not significantly different.

T Grouping	Mean	N	Void Level
A	0.8800	2	Low
B	0.7967	3	High

Cycle 2

Alpha = 0.1, degrees of freedom = 3, mean square of the errors = 0.001106
Least significant difference = 0.0714
Means with the same letter are not significantly different.

T Grouping	Mean	N	Void Level
A	0.8550	2	Low
B	0.7433	3	High

Cycle 3

Alpha = 0.1, degrees of freedom = 3, mean square of the errors = 0.002483
Least significant difference = 0.1071
Means with the same letter are not significantly different.

T Grouping	Mean	N	Void Level
A	0.7650	2	Low
B	0.6500	3	High

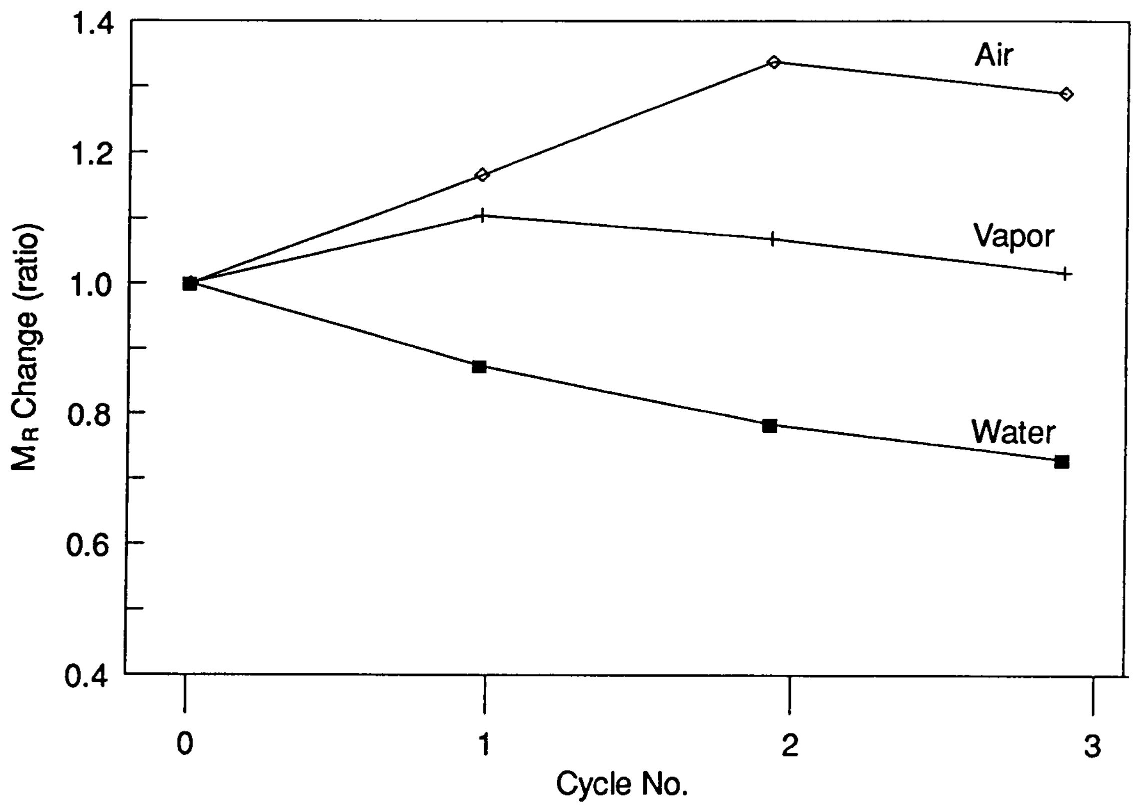


Figure 4.4. Effect of conditioning fluid on resilient modulus change (hot-dry air, hot-moist air, and hot-water saturated)

4.2.2 *Conditioning Temperature*

For evaluation of the conditioning temperature, three conditioning codes—C, F and I—were selected from the experiment plan (Figure 2.1). The three codes have the same factors but different temperatures: 60°C (140°F), 25°C (77°F), and -18°C (-0.4°F). Three sets of specimens were compacted from the same asphalt-aggregate mixture (RL/AAK-1) and subjected to different water-conditioning codes. The three specimen sets according to their water-conditioning codes are hot, set 3; ambient, set 19; and freeze, set 11, as shown in Table 3.8. All conditioning codes include three 6-hour cycles with continuous repeated loading applied for hot and ambient temperatures, codes C and F. Freeze conditioning (code I) was performed with static loading under 25.4 cm (10 in.) Hg. The plots of the three sets are shown in Figure 4.5. Hot conditioning shows the most significant water damage. Freeze conditioning alone does not show a significant effect because freeze cycling, at this vacuum level (wetting), is a weathering process more than a water-damage process and requires too many cycles to significantly affect specimen strength. To determine the difference between the three temperature levels statistically, the GLM analysis of the variance was performed on the data in Figure 4.5. The results of the statistical analysis for the three cycles are summarized in Table 4.8. Significant differences were found among the three temperature levels at the 90-percent confidence level. LSD was carried out to rank the effect of the temperature on M_R ratio. Table 4.9 shows that there is a significant difference at the 90-percent confidence level; the specimen subjected to 60°C (140°F) showed the highest water damage, while the specimen subjected to -18°C (-0.4°F) showed the lowest water damage. This means that the highest temperature leads to the highest water damage because high temperature accelerates water penetration into the specimen. Finally, it was concluded that hot (60°C [140°F]) cycling is appropriate to simulate and accelerate field conditions in hot climates. Hot and freeze (60°C [140°F] and -18°C [-0.4°F], respectively) cycling is better to simulate the mechanism of the deterioration process in cold climates.

4.2.3 *Vacuum Level*

Another concern about water conditioning was the effect of degree of saturation. In the ECS water-conditioning procedure, the degree of saturation is defined by a standardized vacuum level. The wetting vacuum level, before the water-conditioning cycling, was selected as either 25.4 cm (10 in.) Hg for "moist" level or 50.8 cm (20 in.) Hg for "saturated" level. A vacuum level of 25.4 cm (10 in.) Hg is then maintained during conditioning cycles. Vacuum level appears to be more representative of the ECS procedure because retaining some vacuum (25.4 cm [10 in.]) Hg during water-conditioning cycles maintains a constant degree of wetting better than for static immersion conditioning.

To investigate the effect of vacuum level, similar specimens (RL/AAK-1) were subjected to four different conditioning codes: B, C, H, and I (Figure 2.1). The four codes were divided into two sets. The two sets, according to their conditioning codes, are as follows (see Table 3.8):

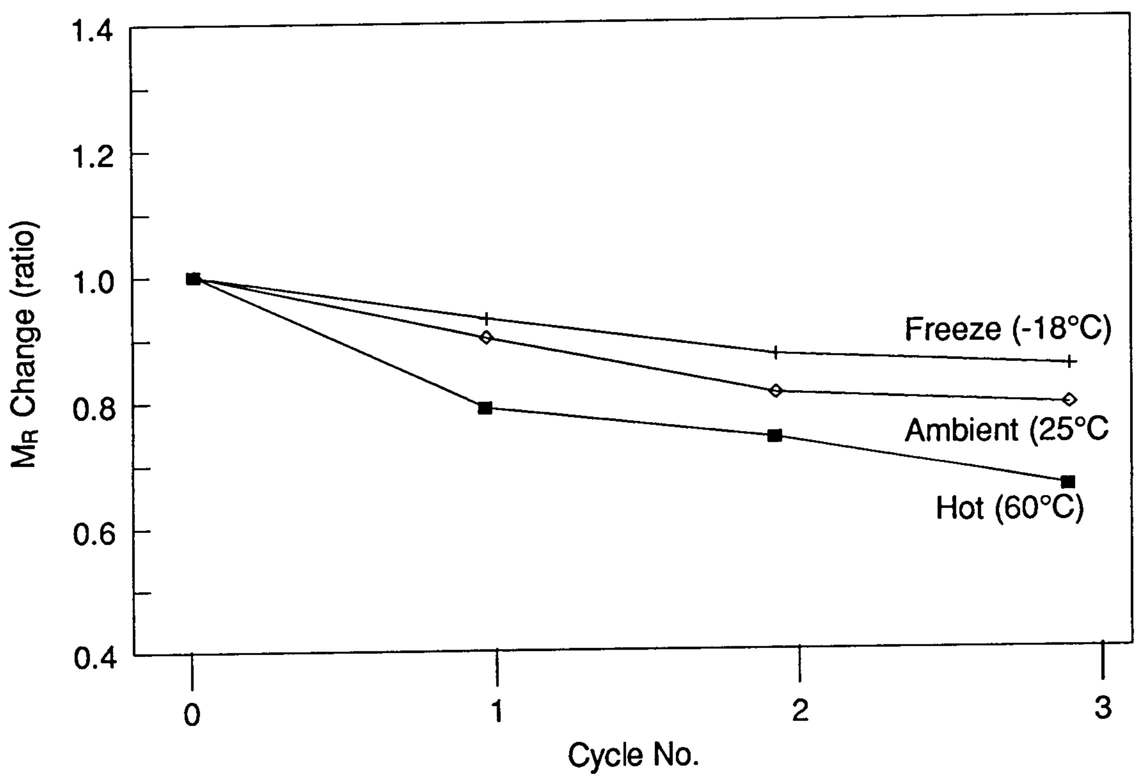


Figure 4.5. Effect of conditioning temperature on resilient modulus change

Table 4.8. Analysis of variance of the difference between M_R ratios after three conditioning cycles with three temperature levels

Cycle 1					
	Sum of Mean				
Source	Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	2	0.024	0.012	36.80*	4.32
Error	4	0.001	0.003		
Corrected Total	6	0.026			
Cycle 2					
	Sum of Mean				
Source	Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	2	0.021	0.010	4.47*	4.32
Error	4	0.009	0.002		
Corrected Total	6	0.030			
Cycle 3					
	Sum of Mean				
Source	Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	2	0.055	0.027	9.82*	4.32
Error	4	0.011	0.003		
Corrected Total	6	0.066			

*Significant at the 90-percent confidence level.

Table 4.9. Asphalt-aggregate ranking by least significant difference with varying conditioning temperature

Cycle 1			
Alpha = 0.1, degrees of freedom = 4 mean square of the errors = 0.00329 Least significant difference = 0.0262 Means with the same letter are not significantly different.			
T Grouping	**Mean**	**N**	**Temperature (°C)**
A	0.9300	2	18
B	0.8950	2	25
C	0.7967	3	60
Cycle 2			
Alpha = 0.1, degrees of freedom = 4, mean square of the errors = 0.002342 Least significant difference = 0.0699 Means with the same letter are not significantly different.			
T Grouping	**Mean**	**N**	**Temperature (°C)**
A	0.8750	2	18
B	0.8050	2	25
C	0.7433	3	60
Cycle 3			
Alpha = 0.1, degrees of freedom = 4 mean square of the errors = 0.002812 Least significant difference = 0.0767 Means with the same letter are not significantly different.			
T Grouping	**Mean**	**N**	**Temperature (°C)**
A	0.8550	2	18
B	0.7900	2	25
C	0.6500	3	60

Note: To convert from °C to °F, multiply by 9/5 and add 32.

1. Freeze—codes H and I: Sets 16 and 11, respectively.
2. Hot—codes B and C: Sets 15 and 3, respectively.

Figure 4.6 shows retained M_R for the freeze-conditioned specimens. There is no significant difference between the two levels because freezing cycles do not generally affect asphalt mixture strength (without also cycling hot). Figure 4.7 shows retained M_R for hot conditioning. High vacuum had a more significant effect than low vacuum because at high temperatures, water penetration increases, resulting in more water damage. By comparing the stripping rates as shown in Table 3.8, sets 16 and 11 experienced similar stripping rates of 5 and 10 percent, respectively. By contrast, there is a significant difference between the stripping rates resulting from the two vacuum levels with hot conditioning: Set 15 experienced 20 percent, while set 3 experienced a 50-percent stripping rate. The above comparison indicates that 50.8 cm (20 in.) Hg vacuum is appropriate for accelerating the saturation process.

To confirm the above findings, the data were reanalyzed statistically. Since the effect of vacuum level with freezing cycles is obviously not significant (Figure 4.6), only the data from hot conditioning (B and C) were statistically analyzed. GLM was carried out on the data shown in Figure 4.7. The statistical analysis results (Table 4.10), showed a significant difference between the two vacuum levels at the 90-percent confidence level. In addition to the GLM analysis, the M_R ratios of hot conditioning cycles (Figure 4.7) were ranked statistically according to their vacuum levels by conducting LSD. As shown in Table 4.11, the two levels were ranked statistically significant at the 90-percent confidence level with less than 0.044.

From the above results, it was concluded that the 50.8 cm (20 in.) Hg vacuum level for the wetting stage and the 25.4 cm (10 in.) Hg retained vacuum during water-conditioning cycles (either hot or freeze cycles) are appropriate for the standard ECS water-conditioning procedure.

4.2.4 Repeated Loading

One of the most difficult variables to simulate in asphalt concrete testing is traffic loading. A previous study found that heavy traffic volume appeared to accelerate moisture damage more effectively than climatic extremes of precipitation and temperature (Lottman 1971). Although many water-sensitivity researchers agree on the importance of including the traffic variable in any water-sensitivity test, most have not included this variable because of the difficulty of simulation and the need for costly instrumentation. Repeated loading was selected to simulate traffic and was combined with two other variables, temperature cycling and water conditioning. Repeated loading in the ECS is intended to induce part of the deterioration, while the other variables contribute the remainder, unlike the typical fatigue and rutting test procedures, in which repeated loading dominates the asphalt concrete deterioration. Three parameters were considered in selecting the repeated-loading mode: loading level, loading time, and stress-strain condition.

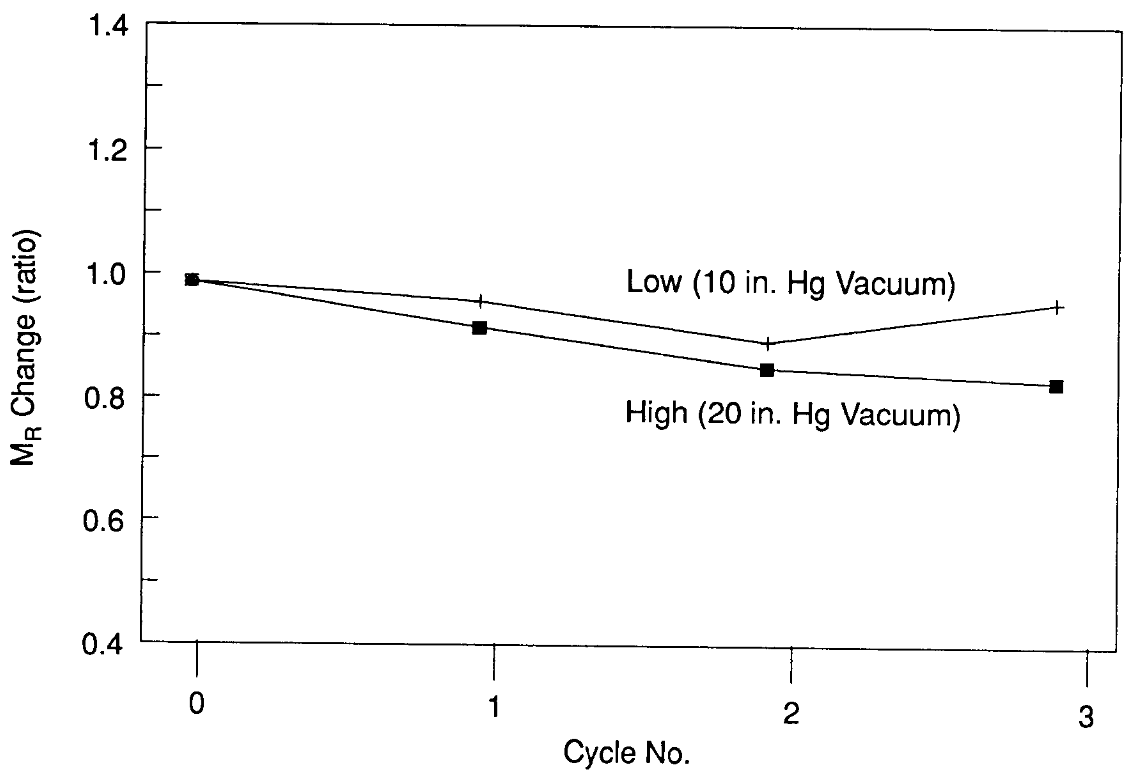


Figure 4.6. Effect of vacuum level on resilient modulus change, after freeze-wet conditioning

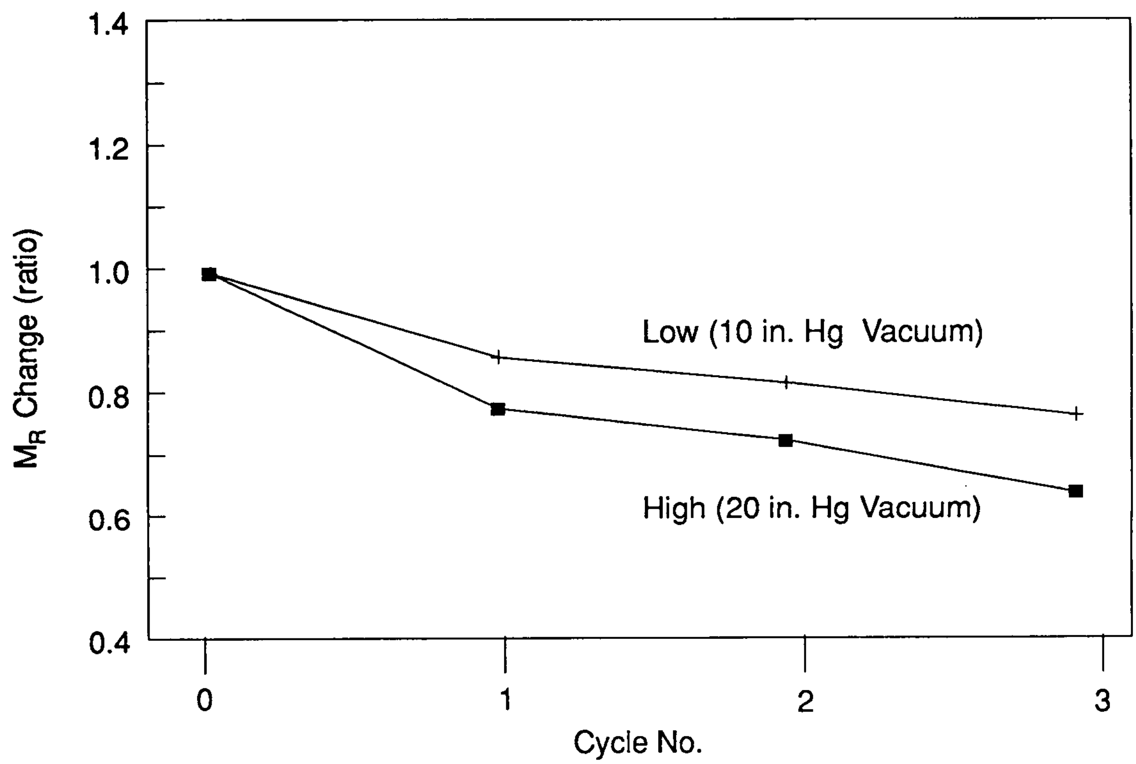


Figure 4.7. Effect of vacuum level on resilient modulus change, after hot-wet conditioning

Table 4.10. Analysis of variance of the difference between M_R ratios after three hot conditioning cycles with varying vacuum level

Cycle 1

	Sum of Mean				
Source	**Degrees of Freedom**	**Squares**	**Square**	**F Value**	**(P = 0.10) F Crit**
Model	1	0.006	0.006	15.28*	5.54
Error	3	0.001	0.004		
Corrected Total	4	0.008			

Cycle 2

	Sum of Mean				
Source	**Degrees of Freedom**	**Squares**	**Square**	**F Value**	**(P = 0.10) F Crit**
Model	1	0.008	0.008	5.83*	5.54
Error	3	0.004	0.001		
Corrected Total	4	0.012			

Cycle 3

	Sum of Mean				
Source	**Degrees of Freedom**	**Squares**	**Square**	**F Value**	**(P = 0.10) F Crit**
Model	1	0.020	0.020	9.51*	5.54
Error	3	0.006	0.002		
Corrected Total	4	0.027			

*Significant at the 90-percent confidence level.

Table 4.11. Vacuum levels ranking by least significant difference

Cycle 1

Alpha = 0.1, degrees of freedom = 3, mean square of the errors = 0.000422
Least significant difference = 0.0441
Means with the same letter are not significantly different.

T Grouping	Mean	N	Vacuum Level
A	0.8700	2	10 in.
B	0.7967	3	20 in.

Cycle 2

Alpha = 0.1, degrees of freedom = 3, mean of square of the errors = 0.001372
Least significant difference = 0.0796
Means with the same letter are not significantly different.

T Grouping	Mean	N	Vacuum Level
A	0.8250	2	10 in.
B	0.7433	3	20 in.

Cycle 3

Alpha = 0.1, degrees of freedom = 3, mean square of the errors = 0.002133
Least significant difference = 0.0992
Means with the same letter are not significantly different.

T Grouping	Mean	N	Vacuum Level
A	0.7800	2	10 in.
	0.6500	3	20 in.

Loading Level. As established earlier, the loading is fixed at 0.01 kN (200 lb) repeated load with a 0.003 kN (60 lb) static load to keep the specimen from rebounding. The selection of loading level was made after a trial-and-error process of changing the load level and monitoring total permanent deformation of the specimen after each conditioning cycle. This loading level was selected from others (not reported here) to be moderate enough to minimize permanent deformation. Permanent deformation is monitored by a linear variable differential transducer (LVDT) located at the top of the load cell and integrated with the signal- conditioning unit and personal computer.

Loading Time. Although the ECS is capable of providing a variety of frequencies and waveforms, it uses a square pulse load with a pulse-load time of 0.1 s and rest period of 0.9 s.

Stress-Strain Conditions. Since the ECS uses an electropneumatic closed-loop system for the repeated-loading subsystem, the tests are conducted under controlled stress conditions, which appear reasonable in light of previous experience. It was necessary to select a loading level to provide an appropriate traffic simulation without inducing significant permanent deformation. The main factors affecting the permanent deformation in this controlled experiment are the loading and air void levels.

To measure the entire accumulated permanent deformation of the specimen during the conditioning cycles, a temporary arrangement for the test setup was used. Besides the two original LVDTs, a third LVDT was mounted on top of the load cell. The third LVDT was integrated with the computer program through the signal-conditioning unit to collect the permanent deformation of the specimen during the conditioning cycle (6 hours) and during the 3 hours of cooling time to the testing temperature, 25°C (77°F).

To demonstrate the effect of air voids on the permanent deformation, two specimens were prepared from the same asphalt-aggregate combination, RB/AAG-1, and compacted at two air-void levels: specimen RLC58RB/AAG-1, with low (5 percent) air voids, and specimen RC53RB/AAG-1, with medium (8 percent) air voids. Figure 4.8 shows the permanent deformation that accumulated under repeated loading and during three 6-hour hot-water-conditioning cycles with a 3-hour cooling period after each hot cycle. Generally, most permanent deformation took place during the first conditioning cycle. In addition, the specimens recovered most of the deformation during the 3-hour cooling time. Moreover, because of differences in susceptibility to consolidation under repeated loading, the specimen with 8-percent air voids exhibited higher permanent deformation than the specimen with 4-percent air voids. This investigation indicates that 0.01 kN (200 lb) repeated loading during water-conditioning cycles is appropriate.

To investigate the effect of repeated loading on the retained M_R during water conditioning, two sets of specimens from the same asphalt-aggregate mixture with the same air void level were subjected to hot-wet water conditioning (code C, Figure 2.1). One set was water conditioned with static loading, and the second was conditioned with repeated loading.

From Table 3.9, two mixtures were selected: no. 20 for static loading and no. 3 for repeated loading. Figure 4.9 shows retained M_R versus conditioning cycle time, and the

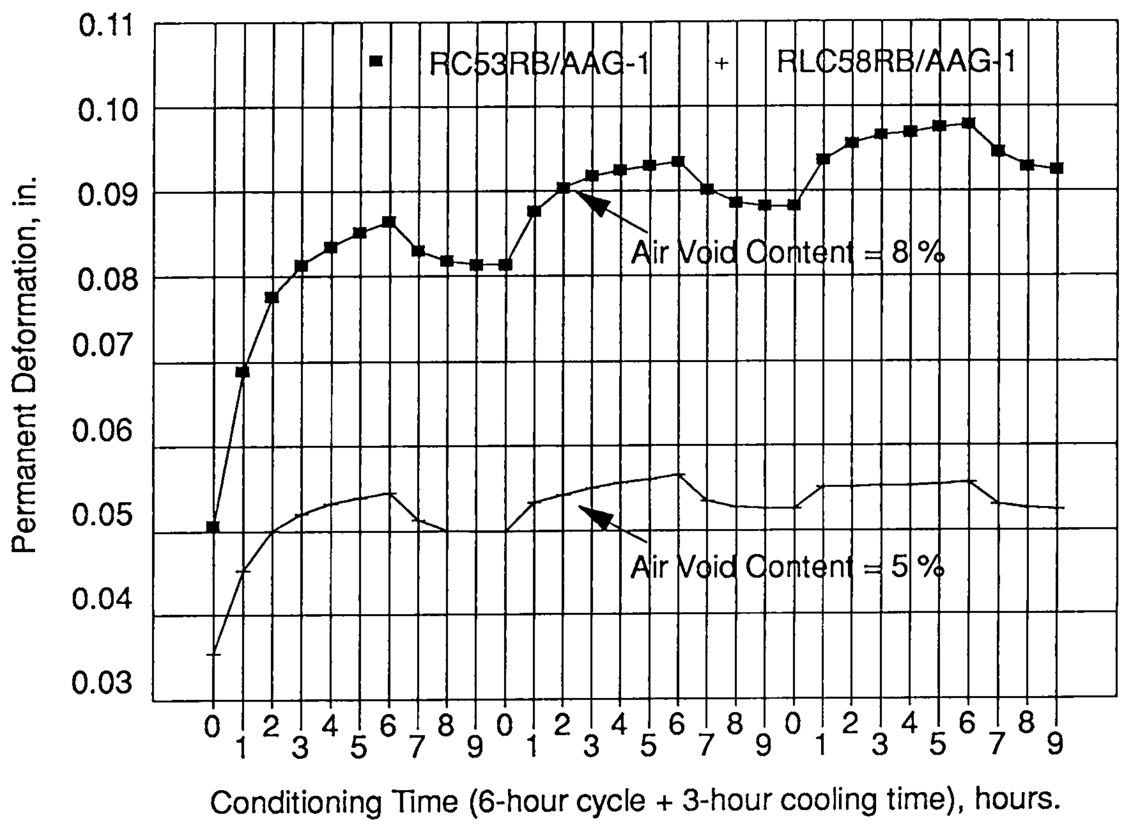


Figure 4.8. Effect of hot-wet conditioning and repeated loading on permanent deformation

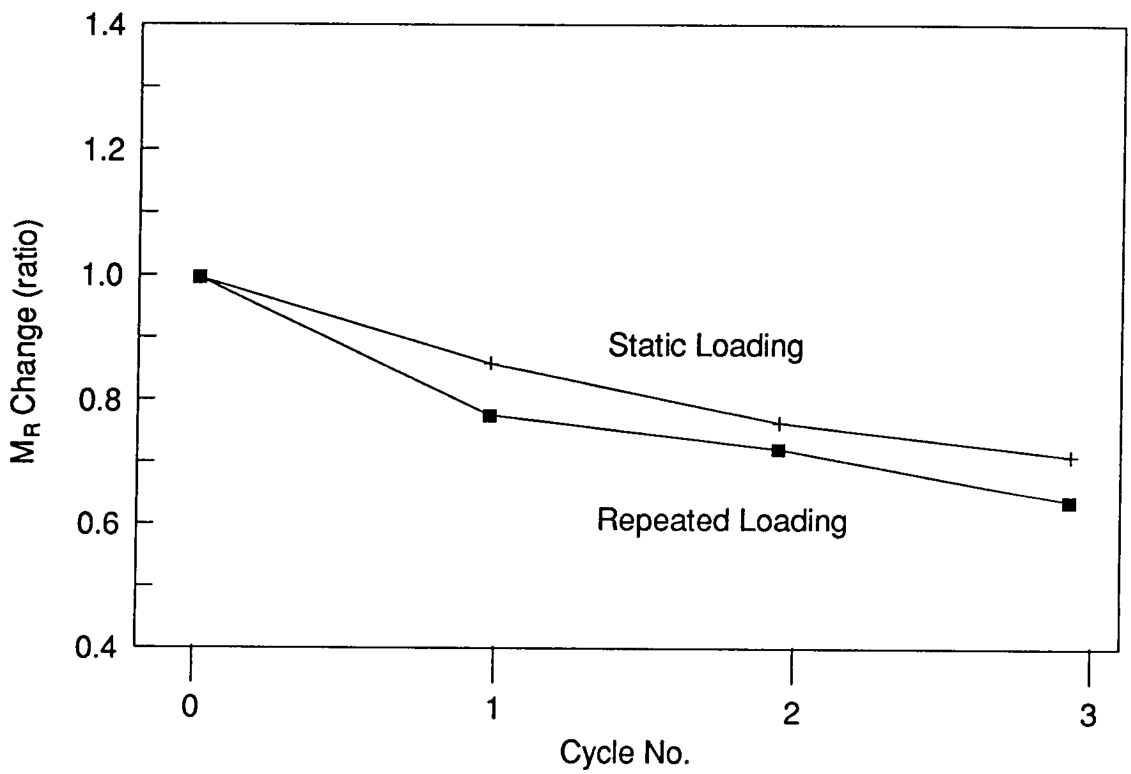


Figure 4.9. Effect of continuous repeated loading on resilient modulus change

effect of the repeated loading is noticeable. In addition, stripping rates were reported for the two specimens in Table 3.9: 30-percent stripping for static loading and 50-percent stripping for repeated loading, which is a significant difference. One can recognize that stripping response may be more significant than stiffness response, which indicates that repeated loading has more effect on adhesion. Finally, it was concluded that repeated loading during water conditioning is an important variable to include in water-conditioning protocols. Therefore, 0.01 N (200 lb) was adopted for the ECS procedure as a repeated loading, although other loads may be evaluated as time permits.

4.2.5 Conditioning Time

Another concern about the practicality of this new conditioning and testing procedure was the whole conditioning time, which depends on two components: cycle length and number of cycles. Highway agencies and contractors generally do not support any new testing technique unless it satisfies what one might call a "new test triangle," which includes time, cost, and complexity.

The typical cycle length specified by previous studies and by AASHTO T 283 was 40 hours (16 hours freeze and 24 hours hot). To examine the effect of cycle length, two similar sets of specimens were subjected to the same conditioning code (code C, Figure 2.1). One set was conditioned with 6-hour cycles, and the other with 24-hour cycles. The data from the two sets are plotted in Figure 4.10, which shows only a slight difference between the two cycle lengths after completing three cycles. Since the cycling process contributes more to damage than cycle length does, a 6-hour cycle length was established for the ECS water conditioning, either freeze or hot conditioning.

It is known that as the number of cycles increases, the simulation comes closer to field cycling conditions, in which the number of cycles represents day-night and summer-winter cycles. After establishing the cycle length at 6 hours, three cycles for hot conditioning were proposed. So, after selecting three cycles, the question was, do the second and third cycles have a significant effect on the deterioration process? If there is insignificant water damage after the first cycle, one can end the test after the first cycle; the same is true between the second and the third cycles. The question is, if the second and third cycles do induce more water damage, is it consistent? In other words, are the three slopes of the three M_R ratios (the slopes of the first cycle; first and second cycles; and first, second, and third cycles) similar? If there is an insignificant difference between the slopes of the three combinations of the three M_R ratios, one can predict the effect of the second cycle without performing it, and the same is true for the third cycle.

To answer these questions, M_R ratios of three specimens from the same combination, which were subjected to three hot-wet cycles with continuous repeated loading, have been statistically analyzed. The slopes were calculated and are shown in Table 4.12 (the original data were extracted from Table 3.8).

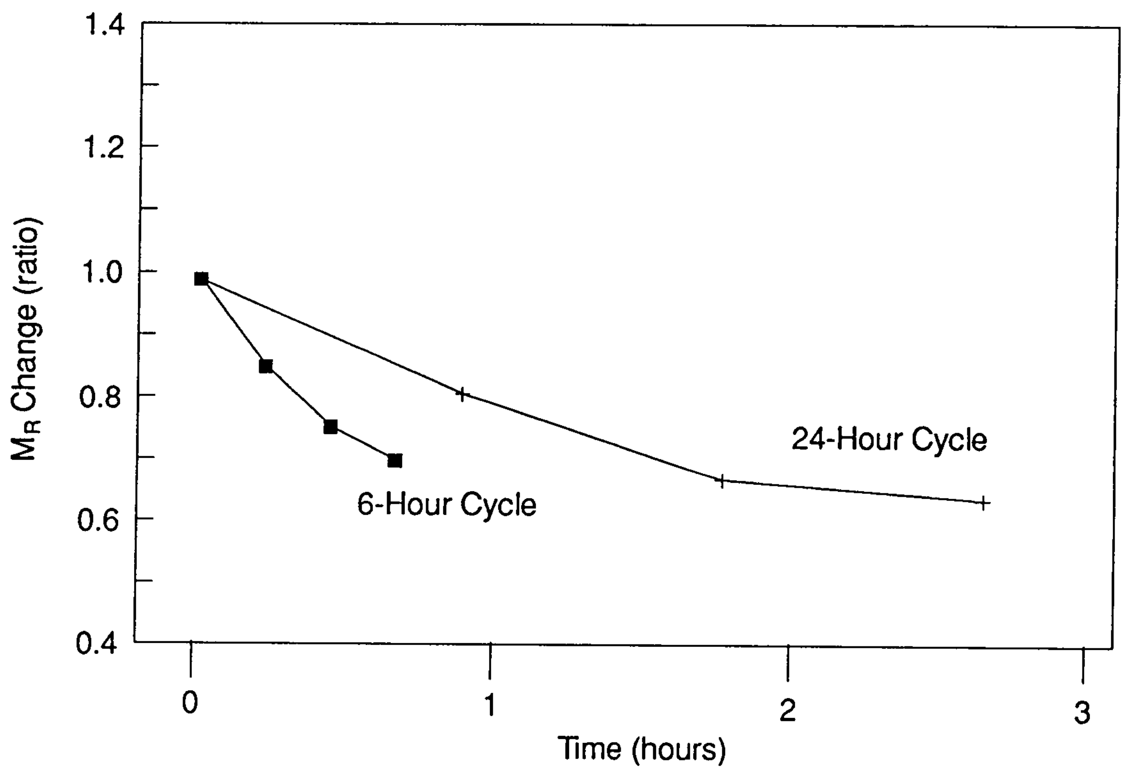


Figure 4.10. Effect of conditioning time on resilient modulus change

Table 4.12. Slope of M_R ratios

Specimen and Test ID	Cycle No.	M_R, ksi*	M_R Change (Ratio)	Slopes of M_R Ratios: First Cycle	First+Second Cycles	First+Second+ Third Cycles
RC53RL/AAK	0	699	1.00			
	1	537	0.77			
	2	541	0.77	0.038	0.019	0.015
	3	497	0.71			
RC201RL/AAK	0	660	1.00			
	1	530	0.80			
	2	460	0.70	0.033	0.025	0.020
	3	420	0.64			
RC209RL/AAK	0	420	1.00			
	1	345	0.82			
	2	320	0.76	0.030	0.020	0.020
	3	250	0.60			
RC56RL/AAG	0	1,310	1.00			
	1	942	0.72			
	2	910	0.69	0.047	0.026	0.021
	3	776	0.59			
RC79RL/AAG	0	808	1.00			
	1	672	0.83			
	2	757	0.94	0.28	0.005	0.010
	3	615	0.76			
RC103RB/AAK	0	290	1.00			
	1	260	0.90			
	2	270	0.93	0.017	0.006	0.008
	3	240	0.83			
RC104RB/AAK	0	400	1.00			
	1	320	0.80			
	2	299	0.75	0.003	0.021	0.015
	3	285	0.71			
RC61RB/AAG	0	779	1.00			
	1	750	0.96			
	2	689	0.88	0.007	0.010	0.009
	3	664	0.85			
RC105RB/AAG	0	716	1.00			
	1	628	0.88			
	2	610	0.85	0.020	0.013	0.011
	3	562	0.78			
RC106RB/AAG	0	703	1.00			
	1	620	0.88			
	2	539	0.77	0.020	0.019	0.014
	3	534	0.76			
RC113RB/AAG	0	701	1.00			
	1	640	0.91			
	2	570	0.81	0.015	0.016	0.012
	3	554	0.79			

Note: To convert from ksi to kPa, multiply by 6,894.76.

GLM was performed to see whether there was a significant difference between the three cycles, by comparing M_R ratios resulting from the first conditioning cycle to M_R ratios resulting from the second and third conditioning cycles. Table 4.13 includes the GLM results, which show a significant difference among the three cycles at the 95-percent confidence level. Moreover, M_R ratios from the three cycles are ranked clearly by LSD analysis at the 90-percent confidence level, as shown in Table 4.14. This means that more conditioning cycles lead to more deterioration.

To analyze the differences between the three deterioration trends (slopes) linear regression analyses were performed to calculate the slopes resulting from the three conditioning cycles (first cycle; first and second cycles; and first, second, and third cycles), as shown in Table 4.12. Then GLM was performed on the slopes of M_R ratios of the three specimens.

The statistical analysis (Table 4.15) shows that there are significant differences among the three slopes at the 95-percent confidence level. Also, the three slopes were ranked by LSD at the 90-percent confidence level, as shown in Table 4.16. This comparison indicates that one cannot predict the effect of the second or third cycle from the results of the first cycle within an acceptable confidence level. Three conditioning cycles enhances the prediction capabilities of the data.

Although additional cycles do not increase the degrees of freedom (because the slopes are in the same direction), the results of each cycle confirm the preceding cycles. A later section includes an extended discussion with more details about this approach to developing the ECS water-conditioning procedure.

4.3 Visual Evaluation

Direct observation of a broken-open specimen can provide insight into the nature and extent of stripping. The primary disadvantage of visual evaluation of stripping is that the results are subjective. Sometimes, in an attempt to limit the subjectivity of the visual evaluation, rating patterns are compared with actual specimens to aid the rater and help establish consistency in the results (Field and Phang 1986). Another technique used to provide insight on the stripping potential of the fine aggregate is use of a stereo zoom microscope.

A new evaluation technique was developed that includes six levels of rating patterns—5, 10, 20, 30, 40, and 50 percent stripping—as shown in Figure 4.11. In addition, a stereo zoom microscope is used to make it practical and easy to distinguish between the detail levels. The standard six levels were established using compacted asphalt concrete specimens made from a range of aggregate types and subjected to different water-conditioning levels. The fractured interior faces were adjusted manually to six stripping levels (standards). The six standard specimens are mounted in a plywood frame with nine rectangular openings arranged in a three-by-three square as shown in Figure 4.11. The three empty slots are used for the specimens that are to be rated.

Table 4.13. Analysis of variance of the difference between M_R ratios after three hot-wet conditioning cycles for the four asphalt-aggregate combinations

Source	Sum of Mean Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	2	0.001	0.001	3.19	3.32
Error	30	0.002	0.001		
Corrected Total	32	0.003			

Table 4.14. Ranking differences between M_R ratios after three hot-wet conditioning cycles

Alpha = 0.2, degrees of freedom = 30, mean square of the errors = 0.00082
Least significant difference = 0.0051
Means with the same letter are not significantly different.

T Grouping	Mean	N	Cycle No.
A	0.02345	11	1
B	0.01636	11	2
C	0.01409	11	3

Table 4.15. Analysis of variance of the difference between the slopes of M_R ratios after three hot-wet conditioning cycles for the four asphalt-aggregate combinations

Source	Sum of Mean Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	2	0.033	0.017	9.60	5.14
Error	6	0.010	0.002		
Corrected Total	8	0.043			

Table 4.16. Ranking differences between M_R ratios after three hot-wet conditioning cycles

Alpha = 0.2, degrees of freedom = 6, mean square of the errors = 0.001722
Least significant difference = 0.0488
Means with the same letter are not significantly different.

T Grouping	Mean	N	Cycle No.
A	0.7967	3	1
B	0.7433	3	2
C	0.6500	3	3

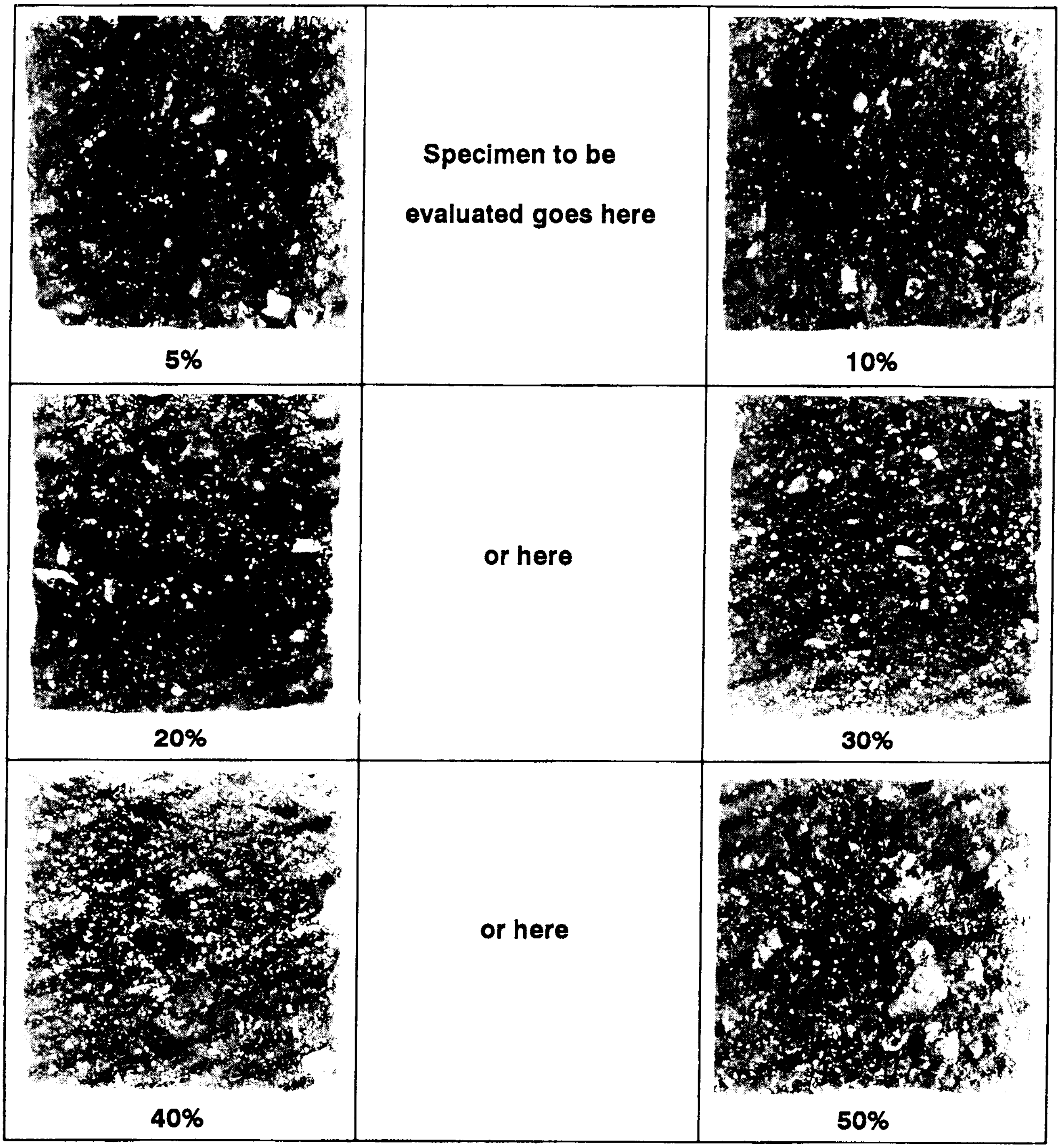


Figure 4.11. Chart for comparing stripping in a specimen compared with different levels

This technique was used on all the ECS-conditioned specimens tested in this study. Following the last test, the specimen was split apart and stripping rate was determined. This study was aimed at determining how engineers might use visual evaluation and retained mechanical properties (M_R) after water conditioning. One asphalt-aggregate combination, RB/AAG-1, will be discussed here to illustrate the procedure.

Five specimens were prepared from the same asphalt-aggregate combination, RB/AAG-1, and compacted to the same air void level, 8 ± 1 percent. Each specimen was subjected to three 6-hour cycles of one type of different water conditioning. The five conditioning codes and the five test results are shown in Table 4.17. Figure 4.12 shows the stripping rate for the five conditioning procedures. A correlation between the severity of the specimen-conditioning procedure and the resulting stripping rate is apparent. The most severe conditioning procedure—three cycles of hot-wet conditioning with repeated loading (specimen 5)—induced the highest water damage, 40 percent. On the other hand, a milder conditioning procedure, such as three cycles of freeze-moist conditioning with static loading (static loading means only holding vacuum level at 25.4 cm (10 in.) Hg during the conditioning cycle without repeated axial loading) (specimen 1) induced the lowest stripping rate.

As explained earlier, the part of the study attempted to correlate the visual evaluation method with the mechanical properties of specimens. Therefore, the retained resilient modulus results after each conditioning cycle, as shown in Table 4.17 for all five specimens, were plotted versus the conditioning cycles, as shown in Figure 4.13. In general, the five mixtures are ranked in the same order as that determined by visual stripping.

Figure 4.13 shows that hot-wet conditioning with static loading is more severe than hot-moist conditioning with repeated loading. This result indicates that the degree of saturation has a more significant effect than repeated loading on the water-damage process, at least for this mixture. Moreover, a close match between stripping rates and M_R change (by comparing Figure 4.12 with Figure 4.13) indicates the possibility of using a visual estimate of stripping as part of the evaluation system. Using only mechanical tests, such as M_R, tends to mask the relative importance of different mechanisms of water damage—cohesion or adhesion loss—that may occur simultaneously.

The overall mechanism of stripping is complex and is being studied from several points of view in the SHRP research. Adsorption and desorption of asphalt on aggregate surfaces (see the final report on water sensitivity based on the chemical and physical bond by Curtis et al. 1992) is a key factor and will most likely play a role in the emerging new test procedure. Other studies, such as a detailed evaluation of the size, shape, and distribution of voids in the mixture, may help confirm the pessimum-voids concept. Still other ideas include the loss of (dissolving of) aggregate surface minerals as a source or cause of asphalt stripping. The other SHRP studies are expected to contribute to the understanding of stripping and may be incorporated or recognized in the final procedure.

Table 4.17. Summary of water conditioning test results

Specimen No.	Conditioning Factors	Cycle No.	M_R (ksi)	Retained M_R Ratio	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
1	Freeze, moist, with static loading	0	707	1.00	64.62	1.00	5
		1	680	0.96	94.37	1.46	
		2	651	0.92	119.71	1.85	
		3	652	0.92	89.14	1.38	
2	Freeze, wet, saturated with static loading	0	610	1.00	19.24	1.00	10
		1	577	0.95	17.68	0.90	
		2	510	0.84	13.63	0.71	
		3	521	0.85	12.95	0.67	
3	Hot, moist, with repeated loading	0	770	1.00	8.34	1.00	10
		1	667	0.87	6.66	0.80	
		2	656	0.85	2.68	0.32	
		3	587	0.76	1.49	0.18	
4	Hot, wet, saturated with static loading	0	845	1.00	15.56	1.00	30
		1	757	0.90	11.77	0.76	
		2	652	0.77	12.01	0.77	
		3	568	0.67	11.02	0.71	
5	Hot, wet, saturated with repeated loading	0	1,278	1.00	6.91	1.00	40
		1	800	0.63	8.47	1.23	
		2	878	0.69	9.03	1.31	
		3	747	0.58	6.41	0.93	

Note: To convert from ksi to kPa, multiply by 6,894.76. To convert from cm/s to ft/min, multiply by 1.969.

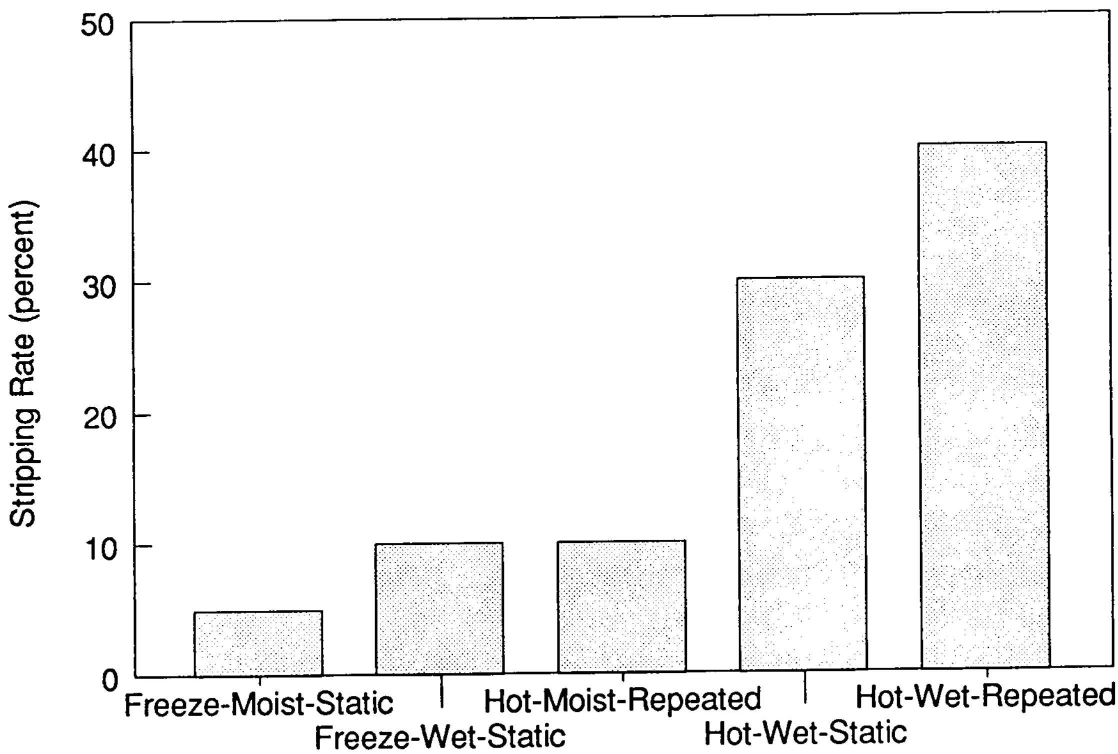


Figure 4.12. Effect of conditioning factors on stripping rate

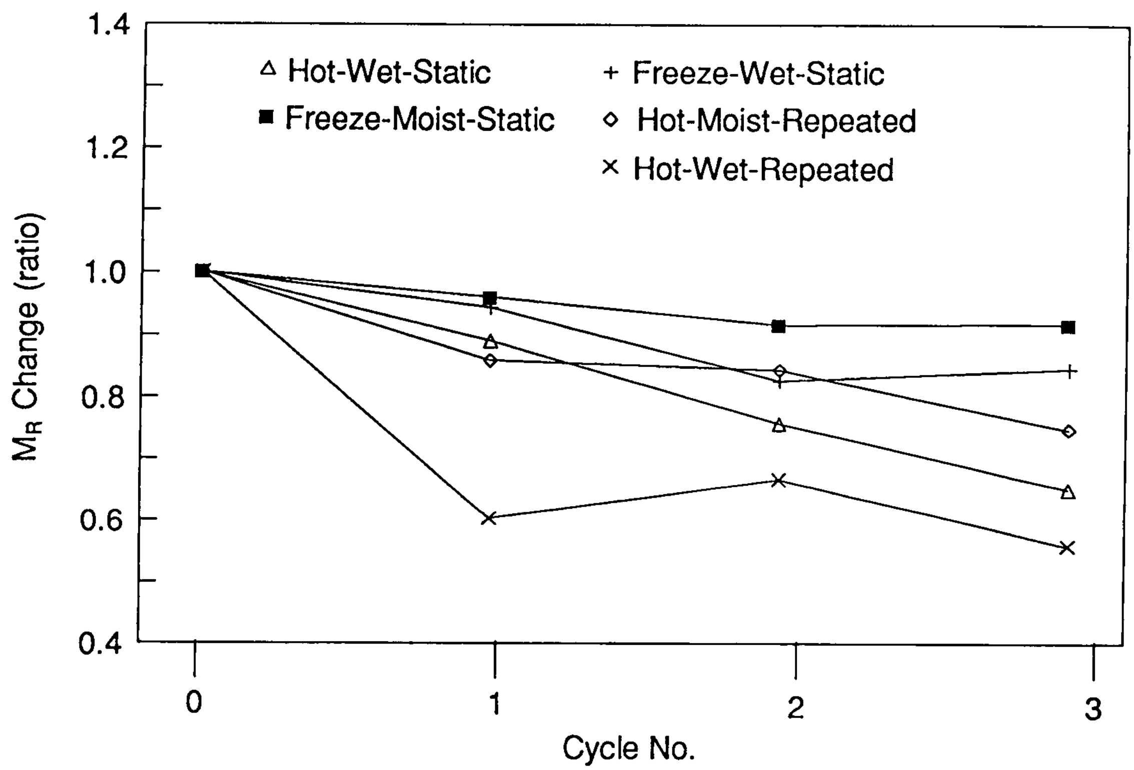


Figure 4.13. Effect of conditioning factors on resilient modulus change

4.4 Permeability

There is a general perception that permeability is a better indicator of mixture durability than percent air voids because permeability measures fluid accessibility through the asphalt concrete. Moreover, studies by Hein and Schmidt (1961) show that permeability, when induced by mix design changes, is not always proportional to void content. The permeability and air void data shown in Table 3.9 are displayed in Figure 4.14, which shows that the relationship between permeability and air void content is not proportional, especially when the data are obtained from different asphalt-aggregate combinations. This finding is contrary to customary conceptions. Early investigators (Ellis and Schmidt 1960), were concerned with obtaining permeabilities low enough to prevent liquid water from entering the base but high enough to allow water vapor to escape and to provide free drainage.

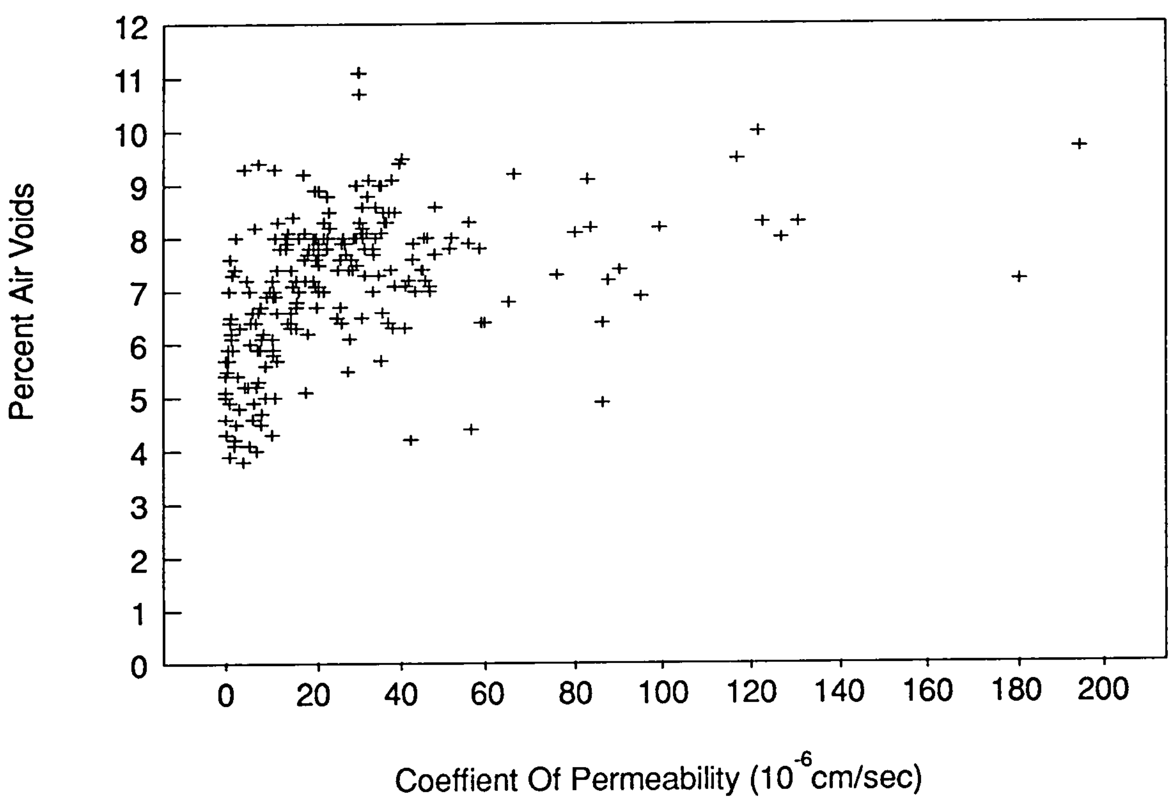
The influence of permeability on asphalt concrete deterioration during water-conditioning cycles was discussed earlier. In this section, the discussion covers the capability of the permeability test to monitor the internal structure change during the water-conditioning process and then addresses the possibility of using that permeability change as a water-sensitivity index to help explain the mechanism of water damage.

The ECS was fabricated with the capability of performing both air and water permeability measurements. The permeability test was designed in the ECS testing program to monitor the internal void structure during the water-conditioning cycle, as with the resilient modulus test. To measure the sensitivity of the permeability test in detecting the change of the internal air void structure of the asphalt concrete, four specimens from two asphalt-aggregate combinations—RB/AAK-1 and RL/AAK-1—were placed in the environmental cabinet and connected with the rest of the ECS. The permeability test using air was performed at four temperature levels— -18, 0, 25, and 60°C (-0.4, 32, 77, and 140°F) and the data are shown in Figure 4.15. The figure shows the permeability test to be sensitive in detecting slight changes, such as specimen contraction and expansion caused by temperature changes.

It has been difficult to provide the same reliability using water rather than air for permeability tests because permeability is sensitive to the test conditions. The following conditions must be maintained for the permeability test:

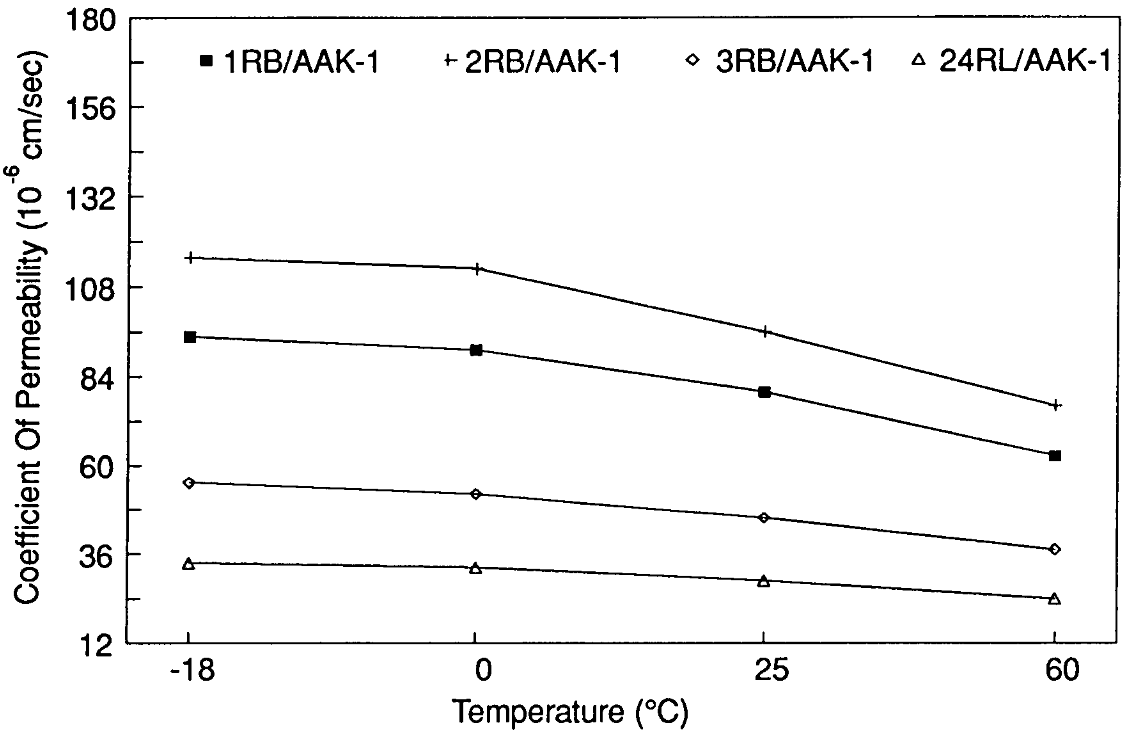
1. Continuity of flow with no volume change.
2. Flow with the voids fully saturated with fluid.
3. Steady-state flow with no changes in pressure gradient.

To provide a water flow with voids fully saturated with water, a very high back pressure is required. Vallerga and Hicks (1968) tested water permeability with 50 psi (345 kPa) back pressure. The vacuum level used for the ECS procedure is 50.8 cm (20 in.) Hg, which is equivalent to only 10 psi (69 kPa). Using higher pressure for ECS water conditioning was constrained by the desirable maximum 80-percent saturation (partially saturated) level to reduce the destructive effect of hydrostatic pressure inside the specimen.



Note: To convert from cm/s to ft/min, multiply by 1.969.

Figure 4.14. Relationship between permeability and percent air voids



Note: To convert from cm/s to ft/min, multiply by 1.969. To convert from °C to °F, multiply by 9/5 and add 32.

Figure 4.15. Relationship between permeability and temperature

In an attempt to provide consistent permeability test results with the available wetting or saturation levels used in the ECS water conditioning, the water permeability test (in addition to air permeability, which is used for dry specimens) was conducted on each specimen before water conditioning and again after each 6-hour conditioning cycle. The retained permeability versus conditioning cycles is plotted in Figure 4.16 for the five specimens listed in Table 4.17. The data show considerable variation in the general trends, especially since all the specimens were prepared from the same asphalt-aggregate combination.

The results were somewhat unexpected but indicate that the conditioning procedure plays an important role in the behavior of mixtures and the void structure. However, the results appear to be inconsistent with the retained M_R (see Figure 4.13). Although the research is ongoing, it appears that measuring permeability of partially saturated mixtures is a major source of the variability. Further study may reveal how best to use the water permeability data or improve the testing technique.

4.5 Confirmation of Hypothesis

The pessimum-voids hypothesis suggests that the water in the void system of asphalt concrete plays an important role in its performance. If mixtures of asphalt concrete are water conditioned, the retained strength is typically lower than the original, unconditioned strength. This effect can be characterized by the voids in the mixture. Mixtures with very low air void content, such as 4 percent, which are almost impermeable to water, are essentially not affected by water. Mixtures with air void contents more than some critical value, such as 14 percent, do not show significant water damage even though they are very permeable to water because there is free drainage and the mixture does not hold the water long. Between these two extremes of impermeable and free-drainage mixtures is a range of air void contents for which the mixture is accessible to water but lacks free drainage and thus tends to retain water. Mixtures in this range experience the greatest water damage.

Therefore, it was necessary to use a different procedure to prove of the pessimum-voids hypothesis in the laboratory, since the ECS laboratory experiment plan was not appropriate to use directly for this purpose. The ECS experiment was designed to simulate field service conditions in such a way as to accelerate damage by retaining the water inside the specimen under vacuum during the conditioning cycles. Free drainage is not provided in the ECS experiment and is a very important condition to show the behavior of open-graded mixtures in retaining a high ratio of their original strength after water conditioning.

Another water-conditioning study was conducted exclusively to prove the pessimum-voids hypothesis by providing free drainage. A separate conditioning setup was constructed to permit this conditioning to simulate the action of free drainage following wetting. Three sets of mixtures (two replicates) were prepared from the same asphalt-aggregate combination (RL/AAK-1) and compacted at three air void contents: low (4 percent), pessimum (8 percent), and free drainage (30 percent). The diametral resilient modulus, M_R, was then

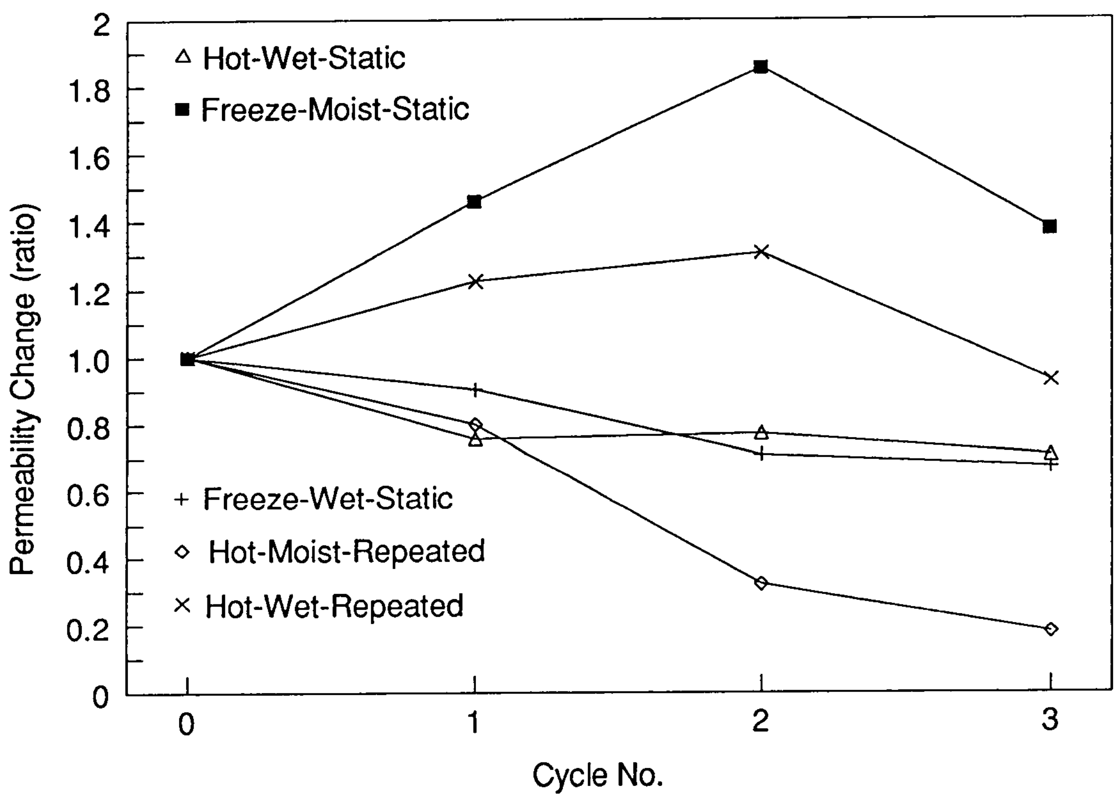


Figure 4.16. Effect of conditioning factors on permeability change

determined for each specimen. The six specimens were placed in a vacuum container, and a partial vacuum of 55.88 cm (22 in.) Hg was applied for 10 min. Then the vacuum was removed, and the specimens were left submerged in the water for 30 min. This wetting process was selected by trial and error to provide partial saturation of 70 percent for the specimens with 8-percent air voids. Using the same procedure, open-graded and low-air void specimens resulted in average degrees of saturation of 98 and 38 percent, respectively, as shown in Table 4.18.

The relationship between air void content and degree of saturation implies that specimens with high air void contents are totally accessible to water, and that voids in specimens with very low air void contents are not interconnected and essentially not accessible. The wetting mechanism of the specimens with 8 percent air voids falls between the two extremes.

After water saturation, the specimens were placed in an air bath (environmental cabinet) for 6 hours at 50°C (122°F), then 5 hours at 25°C (77°F), and allowed to drain. Diametral resilient modulus, M_R, was determined at the end of each conditioning cycle and retained M_R was expressed as the ratio of conditioned to the original, dry M_R. Conditioning temperature was chosen as 50°C (122°F) instead of 60°C (140°F) because of the tendency of open-graded specimens to deform under their own weight at the higher temperature. In addition, open-graded specimens were enclosed with a cylindrical membrane 10 cm (4 in.) in diameter during condition cycles to help preserve their original geometry.

This conditioning process—partial saturation, 6 hours at 50°C (122°F), then 5 hours at 25°C (77°F)—was performed 20 times (cycles). Table 4.19 summarizes the test results, and Figure 4.17 shows the data and the average curve of retained M_R for the three specimen sets throughout 20 cycles. Each data point is the average of two specimens. The impermeable set shows no water damage, and the open-graded set shows a slight decrease in retained M_R. The set with the middle, or pessimum, void content shows significant water damage.

To display the test results in a format similar to that used earlier to introduce the pessimum-voids concept, plots of M_R change versus air void content (Figure 4.18) were prepared for selected cycles (1 to 5, 19, and 20). These results confirm the hypothesis that air voids in the pessimum range play an important role in asphalt concrete performance in the presence of water. Water retained in these voids during the service life (as represented by water-conditioning cycles) of the pavement would tend to cause more damage than in mixtures with either more or fewer voids.

4.6 Repeatability of the Environmental Conditioning System

In the preceding section it was shown that the ECS test procedure was subjected to a screening process to establish the proper degree of control and field simulation over the conditioning factors. This result has been achieved by evaluating the effect of each conditioning variable. Once the development stage was successfully completed, it was necessary to provide a preliminary overview of the repeatability of the ECS test system and test procedure.

Table 4.18. Coefficient of permeability, air voids, and degree of saturation data

Specimen ID	Thickness (in.)	Coefficient of Permeability (10^{-6} cm/s)	Percent Air Voids	Degree of Saturation (%)
1H	4.660	3,554	32.60	97
2H	4.450	1,892	30.00	98
1M	4.380	4,283	8.40	68
2M	4.230	3,467	8.90	70
1L	4.200	Impermeable	5.50	35
2L	4.180	Impermeable	4.20	41

Note: To convert from in. to cm, multiply by 2.54. To convert from cm/s to ft/min, multiply by 1.969.
H: High air voids
M: Pessimum air voids
L: Low air voids

Table 4.19. Resilient modulus test data

Cycle No.	L-M_R Avg, ksi	L-M_R Ratio	M-M_R Avg, ksi	M-M_R Ratio	H-M_R Avg, ksi	H-M_R Ratio
0	620.00	1.00	347.25	1.00	33.75	1.00
1	616.00	0.99	277.00	0.80	30.68	0.91
2	644.25	1.04	271.00	0.78	29.00	0.86
3	618.50	1.00	242.25	0.70	29.50	0.87
4	606.50	0.98	213.00	0.61	28.50	0.84
5	630.00	1.02	217.75	0.63	28.75	0.85
6	600.50	0.97	208.00	0.60	28.25	0.84
7	649.75	1.05	198.25	0.57	30.00	0.89
8	617.00	1.00	208.25	0.60	27.75	0.82
9	655.25	1.06	215.25	0.62	30.25	0.90
10	644.25	1.04	194.75	0.56	28.75	0.85
11	608.25	0.98	206.50	0.59	29.25	0.87
12	605.50	0.98	196.50	0.57	29.00	0.86
13	630.00	1.02	197.00	0.57	30.00	0.89
14	599.75	0.97	172.00	0.50	28.25	0.84
15	616.50	0.99	167.75	0.48	29.00	0.86
16	600.75	0.97	171.00	0.49	28.50	0.84
17	615.75	0.99	170.00	0.49	29.00	0.86
18	634.00	1.02	170.50	0.49	28.50	0.84
19	623.75	1.01	164.25	0.47	28.25	0.84
20	629.00	1.01	164.00	0.47	29.25	0.87

Note: To convert from ksi to kPa, multiply by 6,894.76.

$$M_R \text{ Ratio} = \frac{M_R \text{ Conditioned}}{M_R \text{ Original}}$$

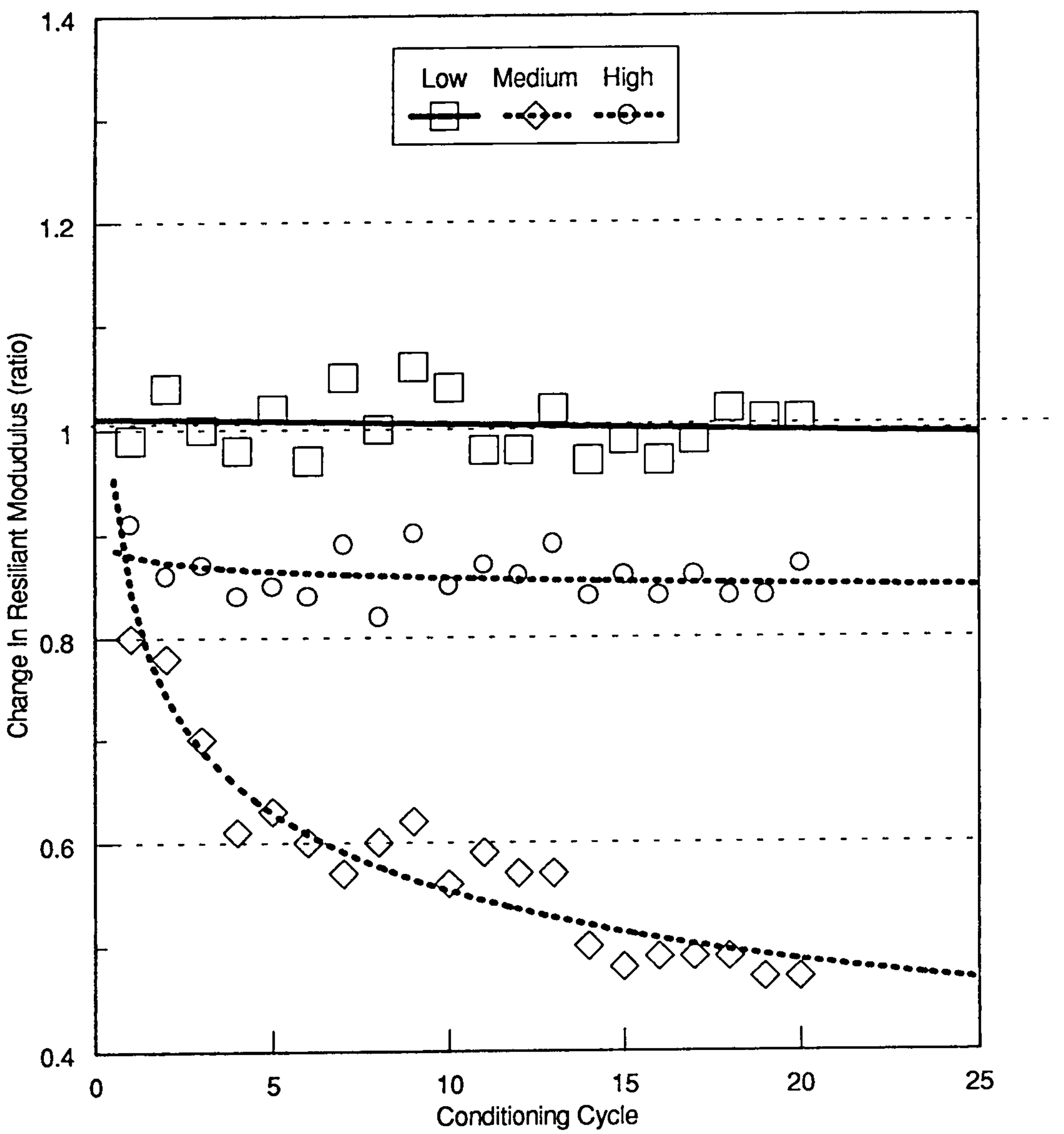
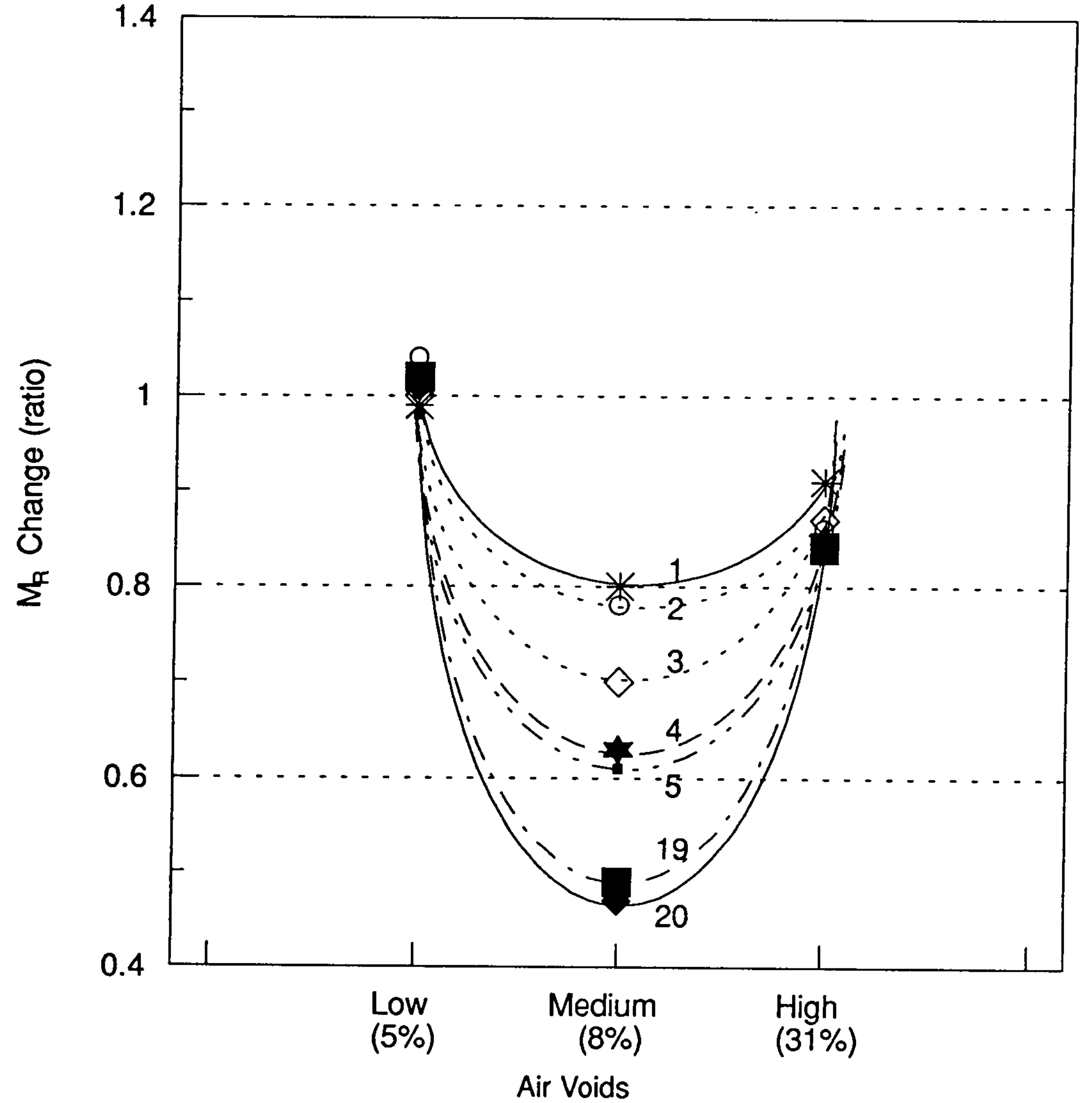


Figure 4.17. M_R Change after free-drainage water conditioning



Cycle No.	Legend	Low	Medium	High
1	—✳—	0.99	0.80	0.91
2	- - - -○- - - -	1.04	0.78	0.86
3	- - - ◇- - - -	1.00	0.70	0.87
4	— —★— — -	0.98	0.61	0.84
5	— - - ▪— - - -	1.02	0.63	0.85
19	— - ■- — -	1.01	0.47	0.84
20	——◆——	1.01	0.47	0.87

Figure 4.18. Relationship between M_R change and air void content after free-drainage water conditioning

Repeatability refers to the test result variability associated with a limited set of specifically defined sources of variability within a single laboratory (ASTM E 456). A major advantage of the ECS is its ability to serve as both a conditioning and a testing device for which all the tests are performed on the same conditioning setup. Because of this integration, a test determination may be described as follows:

1. The value obtained at the end of the ECS-M_R test to reflect the repeatability of the test system.

2. The value obtained at the end of the water-conditioning procedure to represent the repeatability of the conditioning procedure.

4.6.1 Test System Repeatability

Although the repeatability of ECS-M_R with different test settings is discussed in a previous section of this report, it is repeated here exclusively with one test setting, which represents the actual process of the ECS to give a complete picture of the test system. There are several statistical techniques to describe the variability associated with the test performance. Coefficient of variation (CV) is used here because it is simple, and statistical terms are avoided to the greatest extent. CV expresses the standard variations as a percentage of data mean x, CV=100(s/x) (Mandel 1964).

Two dry specimens were tested for ECS-M_R seven times, seven test replicates at one setting. The test results (Table 4.20) are very repeatable, with CVs for the two specimens of 0.9 and 0.6. Such low CVs show the high consistency of the ECS. Since graphs are generally useful in visualizing the statistical conclusions, the test results are shown in Figure 4.19. The test results of each specimen make almost a straight line, which confirmed the repeatability.

Since the ECS is an automated control, closed-loop system, the variation indicated by this analysis expresses only the variation of the test system performance, excluding the variation associated with the conditioning variables and specimen properties such as air void content and strength.

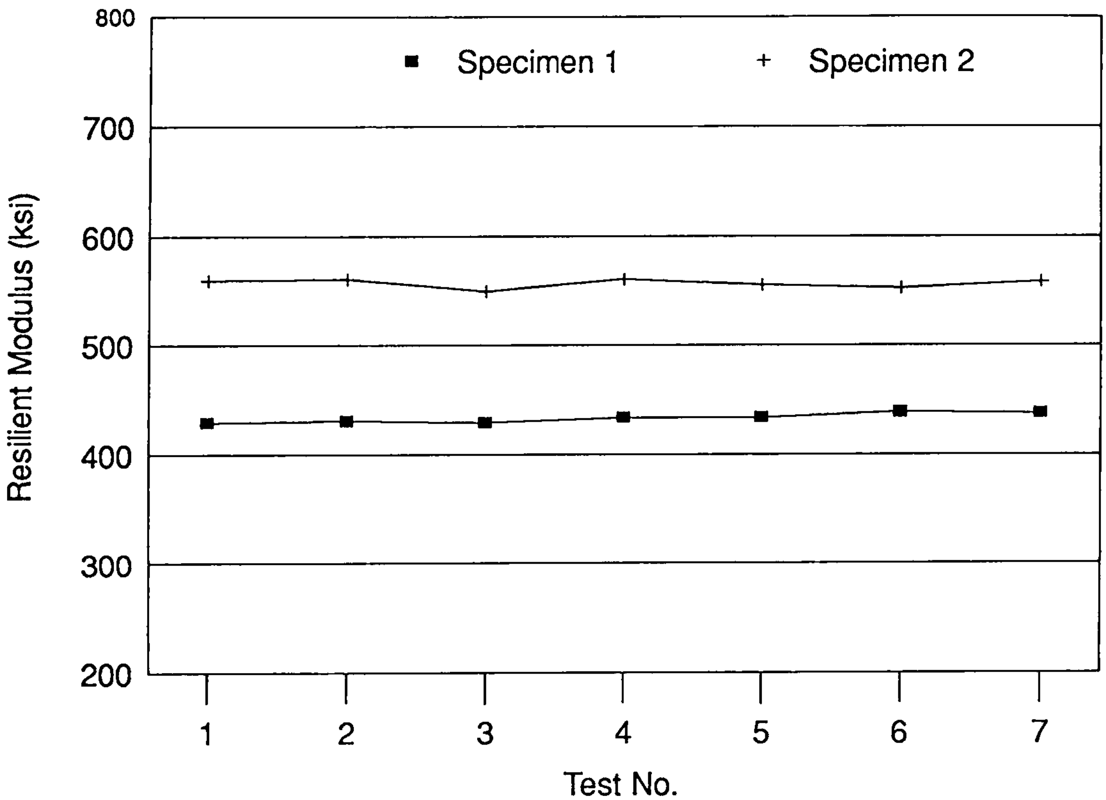
4.6.2 Repeatability of Water-Conditioning Procedure

This section is intended to provide a preliminary overview for the repeatability of the conditioning evaluation procedure. Additional data gathered during the field validation testing provided sufficient replicates to provide a measure of the test repeatability. Although this technique evaluates an asphalt-aggregate mixture's response to a water-conditioning procedure by three indices—resilient modulus change, stripping rate, and permeability change—only resilient modulus change (M_R ratio) will be discussed in this analysis. M_R change is the major index to monitor the deterioration process during the water-conditioning cycles, while stripping rate is a subjective evaluation, to which conventional statistical

Table 4.20. M_R test results of two specimens tested seven times at the same test setting

Test No.	Resilient Modulus, ksi	
	Specimen 1	Specimen 2
1	429	559
2	431	560
3	429	549
4	434	560
5	434	555
6	439	552
7	438	558
Coefficient of Variation (CV)	0.9	0.6

Note: To convert from ksi to kPa, multiply by 6,894.76.



Note: To convert from ksi to kPa, multiply by 6,894.76.

Figure 4.19. Repeatability of ECS-M_R test

methods are not as applicable. The repeatability of the test system discussed earlier, in which M_R test results were analyzed using the same measuring process conducted on the same dry specimens, provided the simplest case of the general problem of the adjustment of observations. A more complicated case arises here, where the retained M_R at the end of the conditioning procedure is derived from combined test values by dividing the conditioning M_R by the original dry M_R. In addition to the complexity associated with this test method, there is another difficulty related to the limited number of test replicates used for the ECS development program. Fewer replicates were used because the ECS developing testing evaluated a wide range of variables. Moreover, there are several variables contributing to the variation of the final retained M_R, which can be summarized as follows:

1. Effect of conditioning time.
2. Mixture properties (i.e., air void content, strength, and permeability).
3. Effect of water by introducing a hydrostatic pressure.
4. Temperature cycling.
5. Conditioning variables (i.e., repeated loading).

Because of the wide range of variables, a compromise was made to decrease the sources of variability. Rather than representing the whole conditioning procedure by one M_R ratio value, the repeatability was analyzed for the M_R ratio after each conditioning cycle. Only the hot water-conditioning procedure, three hot cycles with repeated loading, is included in this analysis because it was conducted on two asphalt-aggregate combinations with enough specimen replicates. The data used for this analysis were extracted from the experiment test plan Table 3.9, and RL/AAK-1 and RB/AAG-1 combinations were tested for three and four replicates, respectively. CV was calculated for each cycle for the same asphalt-aggregate combination, as shown in Table 4.21. The data exhibit very good repeatability, with CVs less than 10 percent for the two combinations with each cycle. It was preferred to express the repeatability of the conditioning by one CV value. But since it is not possible to pool CVs in the same manner as variances and standard deviations, the simple arithmetic average of the six CV values was used (ASTM C 802), which is 5.3 percent.

To display M_R ratios, Figure 4.20 was prepared for the two asphalt-aggregate combinations and confirms the above conclusion; the variation of M_R ratios for each conditioning is quite reasonable. Interestingly, one can see from CV analysis and Figure 4.20 that the test variation does not depend on the number of conditioning cycles. In other words, CV increases for the RL/AAK-1 combination (3.2, 5.1, and 8.6, in Table 4.21), while no trend can be seen for RB/AAG-1 combination (4.2, 5.8, and 4.9).

If a more sophisticated technique is desired to express the repeatability of the water-conditioning procedure, the appropriate one is the ASTM standard repeatability index, as explained in ASTM E 456. To obtain a quantitative estimate of repeatability, the standard deviations were calculated for the same M_R ratios in Table 4.21, as shown in Table 4.22. The repeatability estimate may be referred to as s_r, and the formula of a specific estimate is.

Table 4.21. Coefficient of variation of M_R ratios

Specimen No.	Asphalt-Aggregate Type	Resilient Modulus Ratio		
		Cycle 1	Cycle 2	Cycle 3
1	RL/AAK	0.77	0.77	0.71
2	RL/AAK	0.80	0.70	0.64
3	RL/AAK	0.82	0.76	0.60
Coefficient of variation (%)		3.2	5.1	8.6
1	RB/AAG	0.96	0.88	0.85
2	RB/AAG	0.88	0.85	0.78
3	RB/AAG	0.88	0.77	0.76
4	RB/AAG	0.91	0.81	0.79
Coefficient of variation (%)		4.2	5.8	4.9

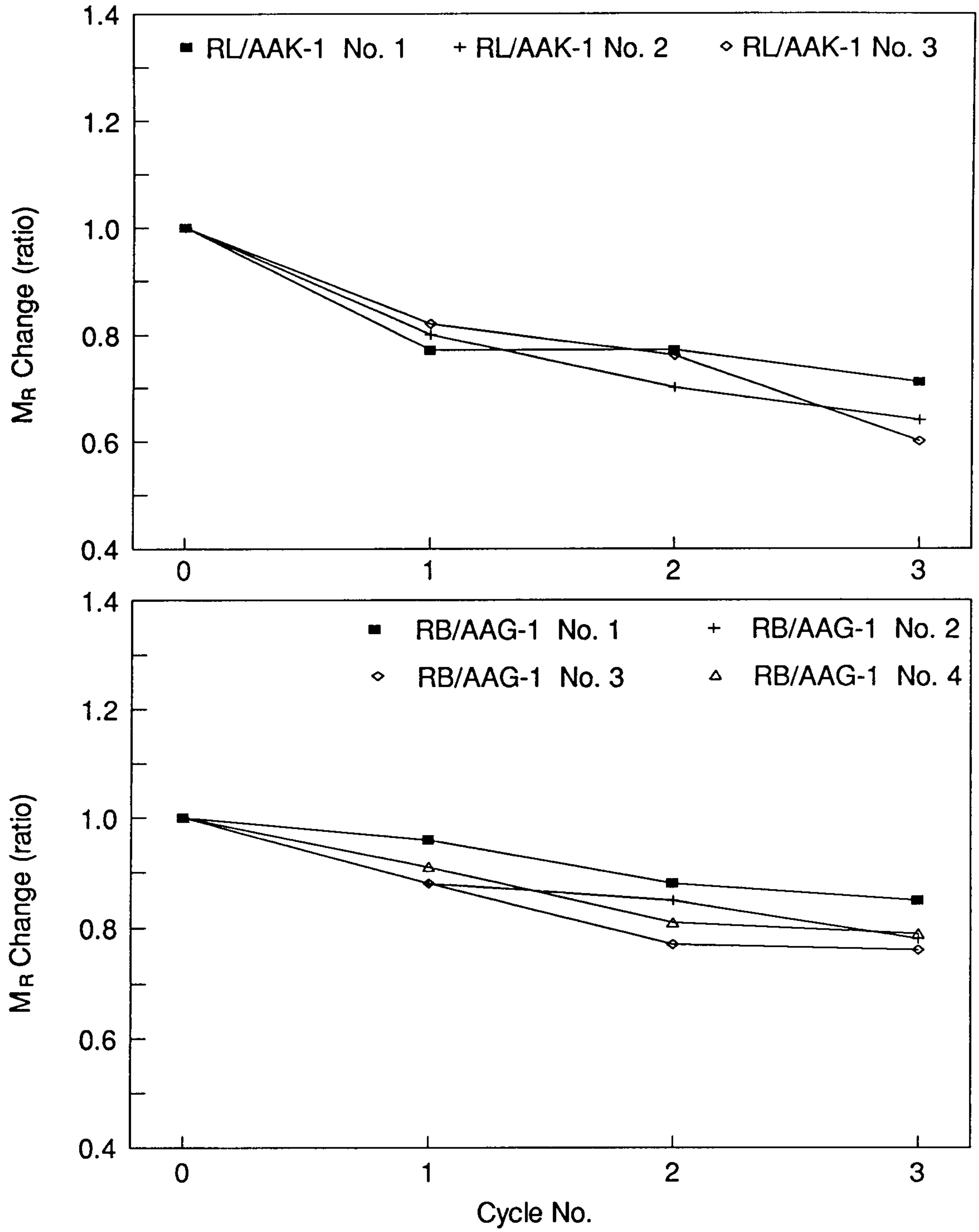


Figure 4.20. Repeatability of water-conditioning procedure for two asphalt-aggregate combinations

$$s_r = \sqrt{\sum \frac{s_i}{k_i}}$$

where: s_i = represents the sample component of variance for assessing repeatability for each source of variability included in the repeatability measure, and k_i = is the number of sample elements for each source used to obtain the measure.

In this case, the repeatability is explained by a standard deviation of the test results in the form of the averages of observed values within one laboratory, based on two material combinations (source 1: $k_1=2$) with three samples of one combination and four of the other (source 2: $k_2=3+4=7$).

Hence:

$$s_r = \sqrt{\frac{s_1}{2} + \frac{s_2}{7}}$$

where: s_1 = estimates the sample variance, and s_2 = estimates the measurement variance.

Based on the data shown in Table 4.22, the estimated repeatability for cycle 1 is as follows:

$$s_r = \sqrt{\frac{0.006}{2} + \frac{0.004}{7}} = 0.060$$

The repeatability (s_r) values of the other cycles are shown in Table 4.22. All the values indicate the high repeatability associated with the ECS procedure, which confirms the conclusion of the CV analysis.

When the conditioning procedure is subject only to the type of variability specified above, the probability of the largest difference between two M_R ratios can be estimated by what is known as a repeatability limit. The 90-percent repeatability limit is approximated by 1.65 $\sqrt{2}$ s_r, (ASTM E 456). This formula is based on the assumption that the standard deviation s_r derived from a normal distribution.

Accordingly, the 90-percent repeatability limit is $1.65\sqrt{2}\, s_r = 1.65\sqrt{2}\,(0.060) = 0.14$. The repeatability limits of the other conditioning cycles are shown in Table 4.22. All the limits fall in a range less than 0.19 (0.14, 0.13, 0.19), which indicates a consistency lower

Table 4.22. Variance and repeatability of M_R ratios

Asphalt-Aggregate Type	Specimen No.	Original M_R ratio	Cycle 1 M_R ratio	Cycle 2 M_R ratio	Cycle 3 M_R ratio
RL/AAK-1	1	1.00	0.77	0.77	0.71
RL/AAK-1	2	1.00	0.80	0.70	0.64
RL/AAK-1	3	1.00	0.82	0.76	0.60
Average M_R ratios			0.80	0.74	0.65
RB/AAG-1	1	1.00	0.96	0.88	0.85
RB/AAG-1	2	1.00	0.88	0.85	0.78
RB/AAG-1	3	1.00	0.88	0.77	0.76
RB/AAG-1	4	1.00	0.91	0.81	0.79
Average M_R ratios			0.91	0.83	0.80
Sample Variance (s_1)		NA	0.006*	0.004	0.011
Measurement variance (s_2)		NA	0.004**	0.004	0.008
Repeatability (s_r)		NA	0.060	0.051	0.082
Repeatability limit (90% confidence level)			0.14	0.12	0.19

NA: Not applicable.

$$\text{Variance (s)} = \frac{n\Sigma x_i^2 - (\Sigma x_i)^2}{n(n-1)}$$

*: $\text{Sample Variance } (s_1) = \frac{2(0.80^2+0.91^2) - (0.80+0.91)^2}{2(2-1)} = 0.006$

**: Measurement Variance (s_2) =

$$\frac{[7(0.77^2+0.80^2+0.82^2+0.96^2+0.88^2-0.88^2+0.91^2) - (0.77+0.80+0.82+0.96+0.88+0.88+0.91)^2]}{[7(7-1)]} = 0.004$$

than that from the CV analysis. The variation between the two conclusions, CV and variance analysis, results from the fact that the variance analysis is highly dependent on the degree of freedom (which is too low here) in evaluating the variation between the test results.

Although the above conclusion appears warranted, it should be noted that this is based only on the limited development-phase data and that the above conclusions should be regarded as tentative.

In addition to the repeatability, the reproducibility of the new conditioning procedure can be determined by the validation testing (Scholz et al. 1992). *Reproducibility* means test result variability associated with specifically defined components of variance both within a single laboratory and between laboratories (ASTM E 456). Then the reproducibility will be used for estimating a statement of precision because such a statement needs data from at least six laboratories and at least three materials (ASTM E 177).

4.7 Water-Conditioning Procedure

From the previous analysis, water-conditioning factors have been established as follows:

1. Conditioning temperature: hot conditioning, 60°C (140°F); freeze conditioning, -18°C (-0.4°F).

2. Vacuum level: 50.8 cm (20 in.) Hg for wetting stage and 25.4 cm (10 in.) Hg during the conditioning process.

3. Cycle length: 6 hours (however, this is likely to be reduced to 5 hours).

4. Conditioning fluid: distilled water.

5. Repeated loading during hot-conditioning cycles: a square pulse load with a pulse-load duration of 0.1 s, a pulse-load frequency of 1 Hz, and a pulse-load magnitude of 0.01 kN (200 lb).

During the development of the ECS conditioning procedure, three aspects were carefully considered: (1) simulation of service conditions, (2) repeatability and reproducibility of the test results, and (3) practicality of the test procedure. Service conditions were established in this test procedure after a detailed investigation of the effect of each variable. The repeatability and reproducibility were determined after performing a statistical analysis of the test results. The practicality of the test procedure was one of the major aspects in the minds of Oregon State University researchers during the development process. Since the test procedure was mostly automated by the ECS, the potential simplification was in the test duration and the number of specimens needed for a complete test. One freezing cycle was considered enough to account for the modest effect of cold climate and to provide simulation for regions that have cold climates. This consideration resulted in two conditioning procedures: (1) warm-climate conditioning procedure, which would include only hot cycles, and (2) cold-climate conditioning procedure, which would include hot conditioning cycles and one freeze cycle.

To investigate the possibility of conducting the two climate conditioning procedures on one specimen (dual procedure), two requirements needed to be satisfied:

1. The effect of freeze cycles must be moderate.
2. There must be no effect for climate sequences (i.e., no difference between hot-freeze and freeze-hot cycles).

As discussed earlier, ECS test results confirmed that the effect of freeze cycles is not significant, which satisfies the first requirement. The second requirement was investigated by conducting two cycles of the hot-freeze conditioning procedure in two orders—hot-freeze and freeze-hot—as shown in Figure 4.21. Four specimens were prepared from the same asphalt-aggregate combination and compacted to the same air void content target of 8 percent. The four specimens were divided into two sets, and each set was conditioned in a different sequence. Figure 4.22 shows the plots of the averages of M_R ratios of two specimens. The difference between the final M_R ratios for the two orders, as shown graphically, is apparent but not significant. This fact confirms that there is no significant effect of the sequence of the conditioning procedure on M_R change. Based on this finding, it would be possible to perform the freeze cycle at the end of the hot conditioning procedure. This process provides the dual conditioning procedure, which can be performed on one specimen. For example, if the mix design is for a warm-climate region, one can stop at the end of the hot conditioning procedure, and if the mix design is for a cold-climate region, one freeze cycle on the same specimen can be added after the hot conditioning procedure.

Earlier, it was found statistically that more hot cycles, lead to more water damage, and also that the difference between the slope combinations of three hot cycles (first cycle, first and second cycles; and first and second, and third cycles) is significant, which indicates that the deterioration from the second cycle cannot be predicted by using a regression equation from the first cycle, and the same is true for the third cycle. Since one freeze cycle was found to be appropriate at the end of the hot conditioning cycles for cold climate, it was desirable to investigate the possibility of a shorter conditioning procedure that retained the freeze conditioning cycle at the end. For this purpose, a separate study was conducted by investigating three conditioning procedures, as shown in Figure 4.23. The three procedures are one hot cycle, two hot cycles, and three hot cycles. Hot-freeze conditioning with one hot cycle was taken from the previous sequence investigation. For the other two conditioning procedures, two 2-specimen sets were prepared from the same aggregate-asphalt combination (RL/AAK-1) and compacted to the same air void content. Figure 4.24 shows the average M_R ratios for each set after the three conditioning procedures. There is a significant difference between the three-hot-cycle procedure and each of the two-hot-cycle and one-hot-cycle procedures. In other words, the three hot cycles and one freeze cycle cannot be

Conditioning Factor	Conditioning Stage		
	Wetting*	Cycle 1	Cycle 2
Vacuum level (in. Hg)	20	10	10
Repeated loading	No	Yes	No
Ambient temp. (°C)**	25	60	-18
Duration (hours)	0.5	6	6

(a) Hot-Freeze Sequence

Conditioning Factor	Conditioning Stage		
	Wetting*	Cycle 1	Cycle 2
Vacuum level (in. Hg)	20	10	10
Repeated loading	No	No	Yes
Ambient temp. (°C)**	25	-18	60
Duration (hours)	0.5	6	6

(b) Freeze-Hot Sequence

* Wetting the specimen before conditioning cycles
**Inside the environmental cabinet

Figure 4.21. Conditioning information charts for climate sequence investigation

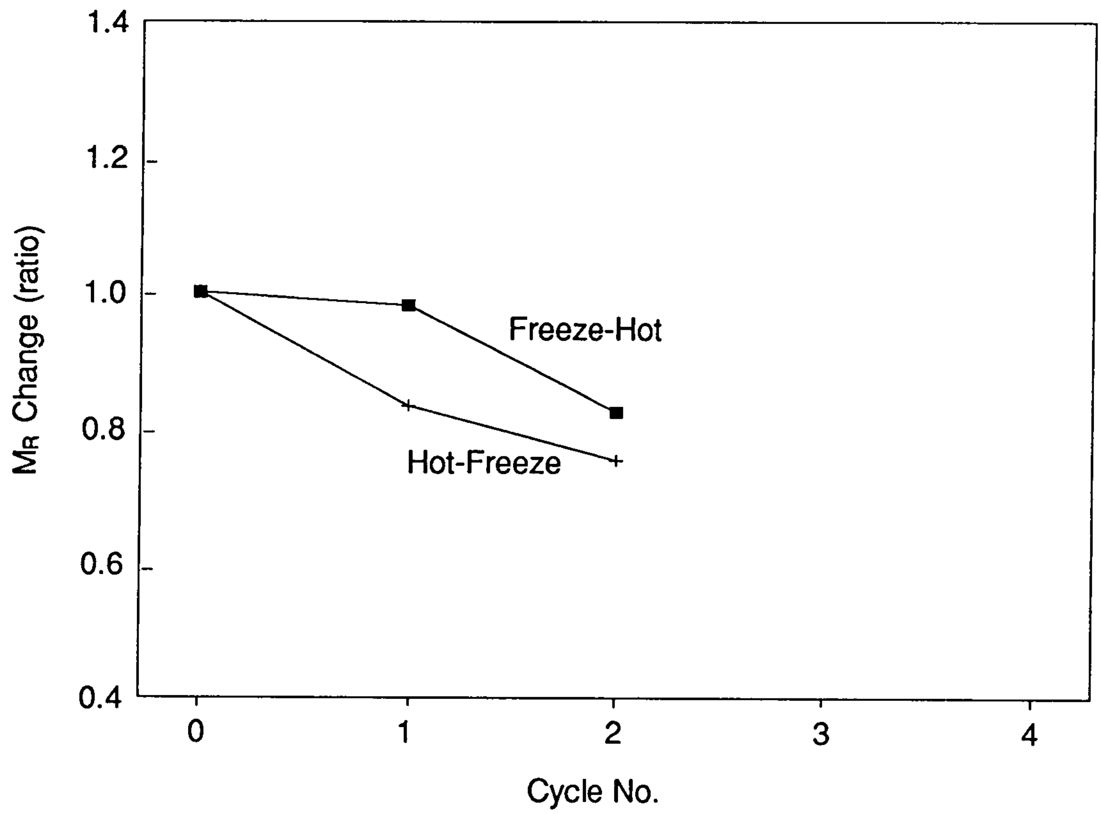


Figure 4.22. Effect of conditioning sequence on resilient modulus change

(a) 1 Hot + 1 Freeze

Conditioning Factor	Conditioning Stage		
	Wetting*	Cycle 1	Cycle 2
Vacuum level (in. Hg)	20	10	10
Repeated loading	No	Yes	No
Ambient temp. (°C)**	25	60	-18
Duration (hours)	0.5	6	6

(b) 2 Hot + 1 Freeze

Conditioning Factor	Conditioning Stage			
	Wetting*	Cycle 1	Cycle 2	Cycle 3
Vacuum level (in. Hg)	20	10	10	10
Repeated loading	No	Yes	Yes	No
Ambient temp. (°C)**	25	60	60	-18
Duration (hours)	0.5	6	6	6

(c) 3 Hot + 1 Freeze

Conditioning Factor	Conditioning Stage				
	Wetting*	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Vacuum level (in. Hg)	20	10	10	10	10
Repeated loading	No	Yes	Yes	Yes	No
Ambient temp. (°C)**	25	60	60	60	-18
Duration (hours)	0.5	6	6	6	6

* Wetting the specimen before conditioning cycles
**Inside the environmental cabinet

Figure 4.23. Conditioning information charts for water-conditioning procedure investigation

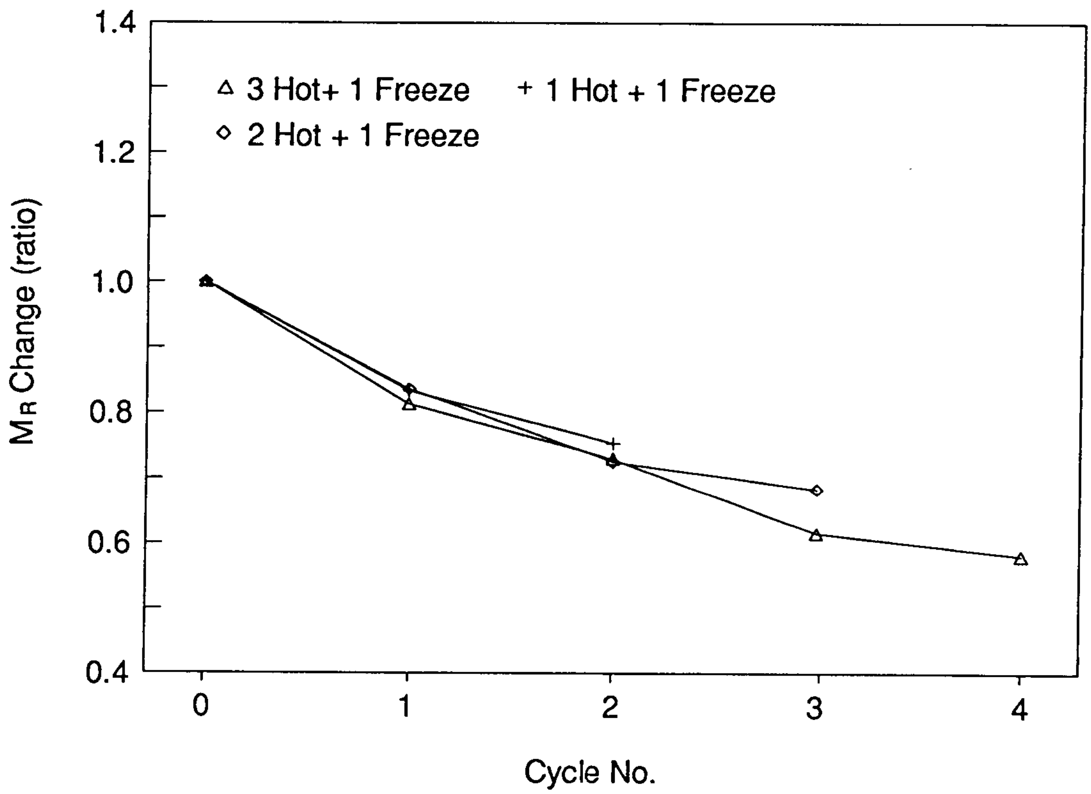


Figure 4.24. Effect of number of hot cycles on resilient modulus change

substituted by the one or two hot cycles, and one freeze cycle. Therefore, it is concluded that three hot cycles with continuous repeated loading is an appropriate water-conditioning procedure for hot climates, and three hot cycles with continuous repeated loading plus one freeze cycle is an appropriate conditioning procedure for cold climates.

4.8 AASHTO T 283: Resistance of Compacted Bituminous Mixtures to Moisture-Induced Damage

Several different tests were used to determine the moisture sensitivity of an asphalt mixture. AASHTO T 283 is the best known test procedure among the highway agencies and therefore was used in this study as a benchmark for comparison. More than 100 specimens were prepared and tested for evaluation. For each test, six specimens were divided into two sets (dry and conditioned). Internal water pressure in the conditioned specimens was produced by vacuum saturation followed by a freeze-thaw cycle. Two numerical indices of retained resilient modulus (M_R) and indirect tensile strength (TS) were obtained by comparing the retained indirect tensile strength and resilient modulus of conditioned laboratory specimens with the similar values for dry specimens.

Table 4.23 summarizes the test data shown in Table 3.2. Retained M_R results after water conditioning for the four asphalt-aggregate combinations are displayed graphically in Figure 4.25. The data show a significant variation within each combination; for example, one combination (RB/AAK-1) showed M_R ratios varying between 0.60 and 1.12 (Table 4.23), which was unexpectedly high. Likewise, retained TS results after water conditioning are shown in Figure 4.26. Also, TS ratios showed a significant variation within each combination, particularly RB/AAG-1, which showed TS ratios between 0.50 and 1.24.

Since the variation associated with M_R and TS indices is relatively large, the repeatability of the test, the CV, was calculated for M_R and TS ratios for each asphalt-aggregate combination shown in Table 4.23. CV varied between 11 and 39 percent, whereas the corresponding CV for the ECS procedure did not exceed 10 percent with the four asphalt-aggregate combinations tested.

Because of the variation within each asphalt-aggregate combination, it is difficult to distinguish between the four sets of data in Figures 4.25 and 4.26. Therefore, it was necessary to express the difference among the four combinations statistically. GLM was performed on the data (M_R and TS) and showed that the difference among the four combinations is significant at the 90-percent confidence level for M_R and TS ratios, as shown in Tables 4.24 and 4.25, respectively.

Using GLM in this manner to compare the four sets of data with each other indicates that the difference is significant, even if it is significant between only two combinations without providing more details about the differences among the other combinations. So, it was necessary to use the LSD procedure to rank the four sets according to their response (expressed by M_R and ST ratios) to the water conditioning. Table 4.26 shows LSD ranking results based on the retained M_R. LSD results showed that the AASHTO T 283 test ranks

Table 4.23. Summary table of AASHTO T 283 test results

Specimen No.	Asphalt-Aggregate Type	TS Ratio	M_R Ratio
1	RL/AAK-1	0.54	0.74
2	RL/AAK-1	0.60	0.82
3	RL/AAK-1	0.83	0.62
4	RL/AAK-1	0.53	0.53
5	RL/AAK-1	0.93	0.68
6	RL/AAK-1	0.30	0.26
Coefficient of variation (%)		36.5	32.5
1	RB/AAG-1	0.49	0.40
2	RB/AAG-1	0.30	0.40
3	RB/AAG-1	0.57	0.63
4	RB/AAG-1	0.61	0.47
5	RB/AAG-1	0.53	0.60
6	RB/AAG-1	0.40	0.38
7	RB/AAG-1	0.43	0.69
Coefficient of variation (%)		16	24.5
1	RB/AAK-1	0.64	0.60
2	RB/AAK-1	0.65	0.61
3	RB/AAK-1	0.81	0.72
4	RB/AAK-1	0.67	1.12
5	RB/AAK-1	0.79	0.93
Coefficient of variation (%)		11.4	28.2
1	RB/AAG-1	1.24	0.62
2	RB/AAG-1	1.16	0.83
3	RB/AAG-1	0.58	0.77
4	RB/AAG-1	0.51	0.62
5	RB/AAG-1	0.77	0.55
Coefficient of variation (CV)		39.1	17.2

Note: Each tensile strength ratio or M_R ratio is an average of three test replicates resulting from dividing M_R or TS results for three conditioned specimens by M_R or TS results of three dry specimens (see Table 3.2 for more details).

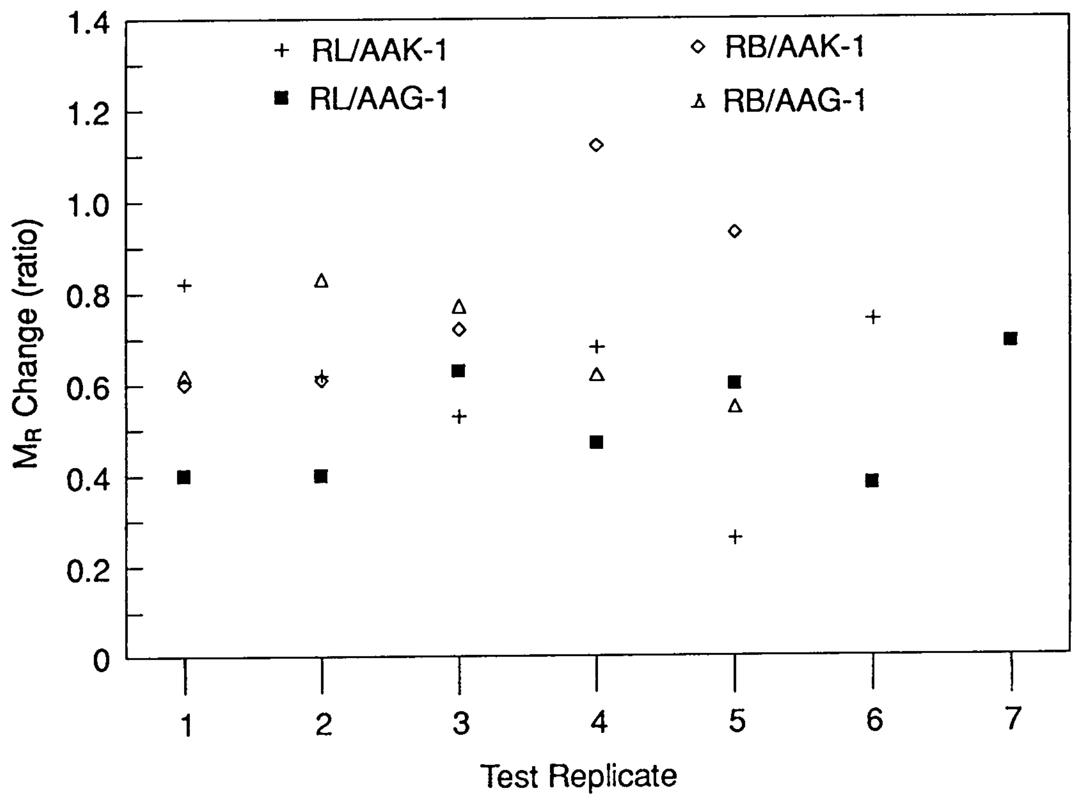


Figure 4.25. Resilient modulus change after AASHTO T 283 test

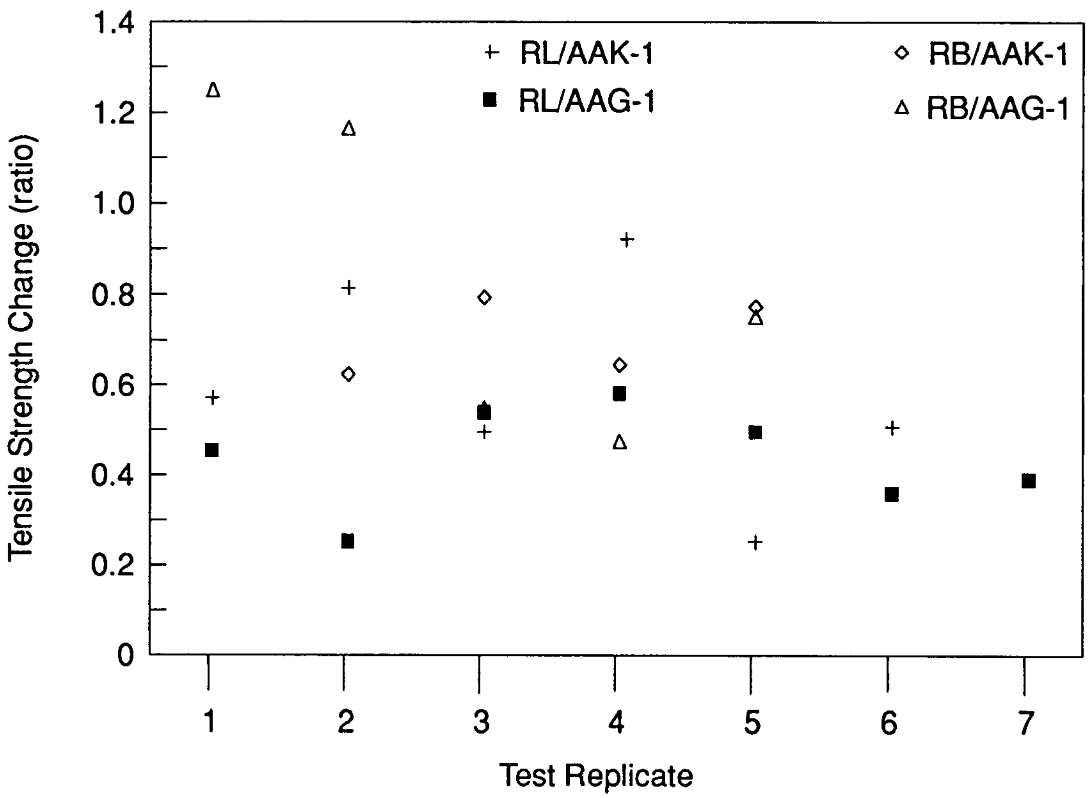


Figure 4.26. Retained tensile strength after AASHTO T 283 test

Table 4.24. Analysis of variance of the difference between M_R ratios after AASHTO T 283 conditioning for the four asphalt-aggregate combinations

Source	Sum of Mean Degrees of Freedom	Squares	Square	F Value	(P = 0.10) P Crit
Model	3	0.252	0.84	2.91	2.40
Error	19	0.548	0.028		
Corrected Total	22	0.804			

Table 4.25. Analysis of variance of the difference between tensile strength ratios after AASHTO T 283 conditioning for the four asphalt-aggregate combinations

Source	Sum of Mean Degrees of Freedom	Squares	Square	F Value	(P = 0.10) F Crit
Model	3	0.440	0.146	3.51	2.40
Error	19	0.796	0.042		
Corrected Total	22	1.236			

Table 4.26. Asphalt-aggregate ranking by M_R

Alpha = 0.10, degree of freedom = 19, main square for the errors = 0.028889
Least significant difference = 0.2119
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.796	5	RB/AAK-1
B A	0.678	5	RB/AAG-1
B A	0.608	6	RL/AAK-1
B	0.510	7	RL/AAG-1

the four combinations according to the aggregate type at the 90-percent confidence level, with LSD of 0.211. On the other hand, LSD did not significantly rank the four combinations according to their asphalt type, which indicates that the effect of asphalt type is not significant. Similarly, Table 4.27 shows the results of the LSD based on TS ratios. Although M_R and TS ratios in Table 4.23 appear different, LSD based on TS ratios gave the same ranking of the materials as M_R ratios. The ranking by AASHTO T 283 agrees with the ranking showed by ECS-M_R ratios, which confirms that the aggregate type has more effect than the asphalt type on the response of asphalt concrete to water damage.

The objective of conducting AASHTO T 283 on the same asphalt-aggregate combinations used for the ECS testing program was to use it as a benchmark to compare the new technique with current practice. Although AASHTO T 283 ranked the four combinations statistically according to their known durability, the number of the tested specimens available for the statistical analysis is significantly higher than the corresponding number used for the ECS. Each M_R and TS ratio in Table 4.23 resulted from averaging the test results of six specimens (three dry and three wet), so the total specimens used for this comparison were 22(6) = 132. On the other hand, only 11 specimens (hot-wet conditioning) were used for the statistical analysis to rank the four combinations according to ECS-M_R ratios. The major difference between the two techniques is that for AASHTO T 283 six specimens are needed to get one M_R ratio (or TS ratio), whereas with the ECS procedure three M_R ratios are obtained by testing one specimen (and the fourth value after a freeze cycle).

The larger variation of M_R and TS ratios using AASHTO T 283 with the same asphalt-aggregate combination (expressed by high CV) compared with those from the ECS procedure suggests that using AASHTO T 283 as a water-sensitivity test is less desirable.

The significant difference in repeatability between AASHTO T 283 and ECS results confirms that the role of simulating the mechanisms of asphalt-aggregate interaction in the presence of water is important to the repeatability of the test. Also, ECS test results show that using one device for conditioning, and testing all the tests on the same test setup with the same specimen orientation decreases the variability of the test results and reduces the error sources compared with AASHTO T 283.

In summary, it is concluded that the ECS procedure is better suited than AASHTO T 283 for measuring potential water damage in asphalt-aggregate mixtures.

Table 4.27. Asphalt-aggregate ranking by least significant difference

Alpha = 0.10, degree of freedom = 19, mean square for the errors = 0.041885
Least significant difference = 0.2551
Means with the same letter are not significantly different.

T Grouping	Mean	N	Treatment
A	0.852	5	RB/AAG-1
B A	0.712	5	RB/AAK-1
B A	0.622	6	RL/AAK-1
B	0.476	7	RL/AAG-1

5

Conclusions

The following conclusions are based on the test results obtained in this laboratory research and their analysis as presented.

1. Comparisons between linearly variable different transducers (LVDTs) and strain gauges showed no significant difference for dry specimens. However, the use of strain gauges presented problems of practicality during actual testing; that is, the strain gauges wrinkled under the effect of repeated loading with hot-water conditioning. Therefore, the use of LVDTs was adopted for strain measurement during the ECS-M_R tests.

2. Although the use of strain gauges for the Environmental Conditioning System (ECS) was abandoned, tests on the type of glue used to bond the gauges to the specimens showed no significant difference between glue types.

3. The modulus tests on specimens having a height-to-diameter (L/D) ratio of 5/4 showed essentially the same very low variability and the same magnitude as those on specimens with an L/D ratio of 7/4. Based on these results and the fact that specimens 10 cm (4 in.) high and 10 cm (4 in.) in diameter are more representative of actual pavement lift thicknesses, it was concluded that specimens of 10 cm (4 in.) in diameter and 10 cm (4 in.) high are more suitable than conventional 6.35 cm (2.5 in.) high specimens.

4. Tests investigating and evaluating the difference between perforated and solid Teflon disks (employed to minimize shear stresses at the top and bottom of the specimen during modulus testing) indicated that perforated disks are suitable and that no significant difference exists between the two types. Therefore, perforated disks are used rather than solid disks, to provide openings for air and water flow.

5. Regarding permeability measurements, it was shown that partially sealing the specimen (sealing the middle third) with silicone cement is adequate; that is,

fully sealing the specimen is unnecessary, and there is no significant difference, between the two methods.

6. Permeability appears to be an appropriate measure of the void system in a mixture, but further analysis is needed.

7. Retained resilient modulus, permeability, and stripping rate are suitable measures for monitoring mixture behavior following conditioning treatments in which degree of wetting, temperature, and air void content are varied.

8. Three 6-hour temperature cycles are adequate to evaluate the effect of conditioning. Longer (24-hour) cycles do not increase the ability to discern differences among mixtures. Shorter (5-hour) cycles should be evaluated to shorten the time requirements.

9. Hot-wet cycling in the ECS is more detrimental than freeze-wet (without hot cycling) and appears suitable for warm climates.

10. Continuous repeated loading with a 0.01 kN (200-lb) load during hot-wet cycling had a modest effect on resilient modulus but affected the stripping rate significantly. That is, repeated loading has more effect on adhesion.

11. Specimens with void contents or permeabilities higher or lower than the pessimum range resist water damage more than specimens within the pessimum range (e.g., 5 to 15-percent voids).

12. The comparison between the ECS and the current methods (represented by AASHTO T 283) showed that the ECS has better repeatability and needs fewer specimens than AASHTO T 283 for evaluating a mix design.

13. The ECS as a test system is using today's technology, which provides for continuous improvement of test precision and convenient data acquisition.

14. The ECS as a test method provides a number of parameters from the tested specimen, (e.g. retained M_R, permeability, stripping rate), and more, such as stress-strain information at different temperatures during conditioning, through the data-acquisition capability of the system. These data and capabilities will provide a better understanding of asphalt-aggregate interaction and establish a reliable base for a continuous education process. Further, the validation testing (e.g., Allen and Terrel 1994) of field projects has shown reasonable correlation with field performance to date.

15. The studies showed that the system is sensitive enough to detect an adequate level of water damage by measuring degree of saturation, conditioning temperature, and air void content. In summary, the ECS has been demonstrated to be suitable for and capable of determining the effect of water damage for a range of asphalt concrete mixtures.

6

Recommendations

6.1 Conditioning Equipment and Procedures

The overall goal of this task was to relate asphalt mixture properties to performance of mixtures. The water-sensitivity task comprised the following five phases:

C.5.a. Evaluation of current technology.
C.5.b. Development of testing techniques and equipment.
C.5.c. Laboratory implementation of new technique.
C.5.d. Field validation of new technique .
C.5.e. Final report (development of new specifications).

The study reported here is that for Phase C.5.b. The Environmental Conditioning System (ECS) was developed and constructed as a conditioning and testing device. The ECS was used to explore the basic factors that influence the response of compacted mixtures to water conditioning and was then used for modifying the water-conditioning procedure. Figure 6.1 shows the recommendations chart at this phase of the water-sensitivity study.

6.1.1 Testing Equipment

The ECS was devised and constructed for water-sensitivity testing and evaluation. This device has been used for more than 2 years at different environmental conditioning levels created by varying or holding constant parameters, such as permeability, time of conditioning, rate of wetting, aging, loading, and air void content. The ECS shows a wide capability for environmental conditioning and testing of compacted asphalt mixtures. Although precision of tests has not yet been developed, the ECS is better able than previous methods to simulate field conditions to which the asphalt concrete is exposed.

Correspondingly, the ECS is a reliable testing device for water sensitivity and has the following advantages over previous methods:

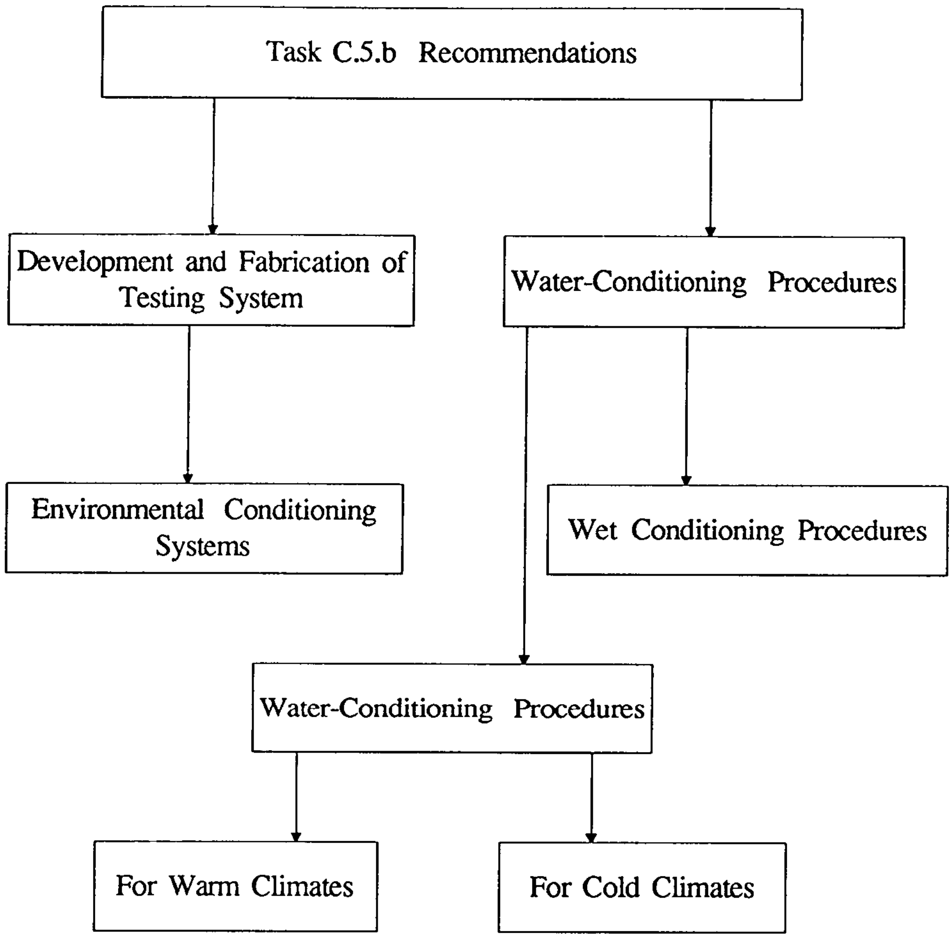


Figure 6.1. Recommendations developed for water-sensitivity study

1. The ECS monitors the permeability of the specimens after each conditioning cycle, either thawing or freezing.

2. The ECS eliminates leaking (drainage) and specimen deformation during the test.

3. The ECS decreases the variability of resilient modulus, since only one specimen setup is required.

4. The ECS eliminates handling and transferring the specimen from water bath to testing device, which is a possible major source of error.

5. The ECS allows the evaluation of the specimen after each phase of a cycle, either freezing or thawing, rather than following a complete conditioning cycle (freezing and thawing together).

6. The ECS conditions and tests compacted asphalt specimens with any air void content.

7. The ECS applies repeated loads throughout the test.

8. The ECS shows better repeatability than the current methods represented by AASHTO T 283.

9. The number of specimens needed for a mix evaluation using the ECS is less than the number required for AASHTO T 283.

6.1.2 Water-Conditioning Techniques

A series of tests was performed on four different Materials Reference Library materials according to an experiment plan that was established to include the most important related variables. Figure 6.2 shows the two recommended conditioning procedures.

6.1.2.1 Water-Conditioning Procedure

To test the behavior of compacted asphalt mixtures, the ECS was used to assist in determining the most important variables in the performance of mixtures in the presence of moisture. The test results were analyzed to show asphalt mixtures' behavior in several way as follows:

1. Saturation versus moisture.
2. Wet versus dry.
3. Water versus vapor.
4. Water versus air.

Conditioning Factor	Conditioning Stage				
	Wetting*	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Vacuum level (in. Hg)	20	10	10	10	10
Repeated loading	No	Yes	Yes	Yes	No
Ambient temp. (°C)**	25	60	60	60	-18
Duration (hours)	0.5	6	6	6	6

◄── Conditioning Procedure for Hot Climate (Wetting through Cycle 3) ──►

◄── Conditioning Procedure for Cold Climate (Wetting through Cycle 4) ──►

* Wetting the specimen before conditioning cycles
**Inside the environmental cabinet

Figure 6.2. Conditioning charts for hot and cold climates

5. Permeability versus air void content.
6. Freeze versus hot.
7. Volume-change effect.
8. Conditioning time, such as cycle length.
9. Dynamic loading versus static loading.
10. Coating.

The effect of each controlled variable in water sensitivity was measured by the following three response variables:

1. Resilient modulus (ECS-M_R).
2. Permeability.
3. Stripping rate.

From the analysis of the above variables, two water-conditioning procedures were recommended to provide optimum simulation for asphalt mixture variables and practical test acceleration for the highway agencies. The two water-conditioning procedures, as shown in Figure 6.2, are as follows:

1. Water conditioning for warm climate: Three hot-wet cycles of 6-hour duration at 60°C (140°F) with continuous repeated loading.

2. Water conditioning for cold climate: Three hot-wet cycles of 6-hour duration at 60°C (140°F) with continuous repeated loading (as for hot climate), plus one freeze-wet cycle of the same duration as the hot cycle with static loading at -18°C (-0.4°F).

Repeated loading is continuously applied during hot cycling for both procedures.

6.1.2.2 Wet-Conditioning Procedure

Wet conditioning is identified by the term wetting in Figure 6.2. Wet conditioning is a process of running water (under vacuum) through compacted asphalt concrete specimens at ambient 25°C (77°F) temperature for 30 min. Wet conditioning is recommended as an optional procedure to be performed before testing in fatigue, rutting, and low-temperature cracking.

6.2 Role of Water Sensitivity in Mix Design and Analysis

A major goal of SHRP was to relate asphalt binder properties to field performance of asphalt concrete mixtures. Consequently, much of this research program has focused on the factors that influence field performance. Although many factors contribute to the degradation of asphalt concrete pavement, damage caused by moisture is considered a key element in the deterioration of asphalt mixtures.

Recognizing that moisture damage can significantly influence pavement performance, a part of the SHRP research effort has been concerned with developing a system and procedure having two purposes: (1) to determine whether an asphalt-aggregate mixture is susceptible to moisture-induced damage, and (2) for mixtures that meet the criteria dictated by the first purpose, to moisture-condition asphalt concrete specimens to be tested for mixture properties including thermal cracking, fatigue, and permanent deformation (rutting).

Although it is recognized that many factors play a role in the effect of water on asphalt mixtures, it is difficult and perhaps unnecessary to precisely determine each of these factors. The asphalt, aggregate, and additives, as well as water, all have effects through their chemistry. Most of these are interactive within the mixture when subjected to environmental changes. Consequently, the role of water sensitivity in mixtures is manifested through physical behavioral changes, and these changes have been the focus of this research.

During this phase of the research, numerous ideas and approaches to using of the ECS were considered. The final version of the role of the ECS in the mix design procedure will not be recommended until the companion studies (i.e., validation) are completed. Therefore, the following discussion is a snapshot of the system envisioned before all research was completed, and the system will undoubtedly be modified.

As indicated earlier, water sensitivity plays two roles in evaluation of mixtures, and these are indicated in Figure 6.3, which is a summary of a tentative mix design and analysis system. Three parts of the mix design and analysis system are noted in Figure 6.3 as follows:

A. Initial mix design.
B. ECS water conditioning.
C. Wet conditioning for accelerated performance tests.

The initial mix design (aggregate and asphalt selection, optimum asphalt content) is used as the starting point for ECS conditioning, as shown in Figure 6.4. The points A, B, and C are also shown in Figure 6.4 to illustrate how the ECS procedure fits into the overall scheme of Figure 6.3. Procedure B (ECS) is for mixture evaluation and acceptability judgment, while procedure C is a method to precondition various specimens with water and temperature cycling before they are tested in other modes such as fatigue, rutting, or cracking.

Before fabrication, it is suggested that the compatibility of aggregate and asphalt be evaluated using the net adsorption test developed by A-003B. An indication of suitability would include recommendations as to the probable need for an antistrip additive or other treatment. The test has been reevaluated and modified by the University of Nevada at Reno for Oregon State University and further correlated with the ECS (Scholz et al. 1994).

Specimens for the testing shown in Figure 6.4 can be laboratory compacted or cored from slabs or from field sites. When feasible, specimens with three different void contents should be fabricated from the same mixture, by varying the compaction effort. Each specimen would then be tested in the ECS following the appropriate conditioning for the climate. Compacting over a range of void contents eliminates the problem of attempting to achieve a given standard void content, which is time consuming and wasteful because many

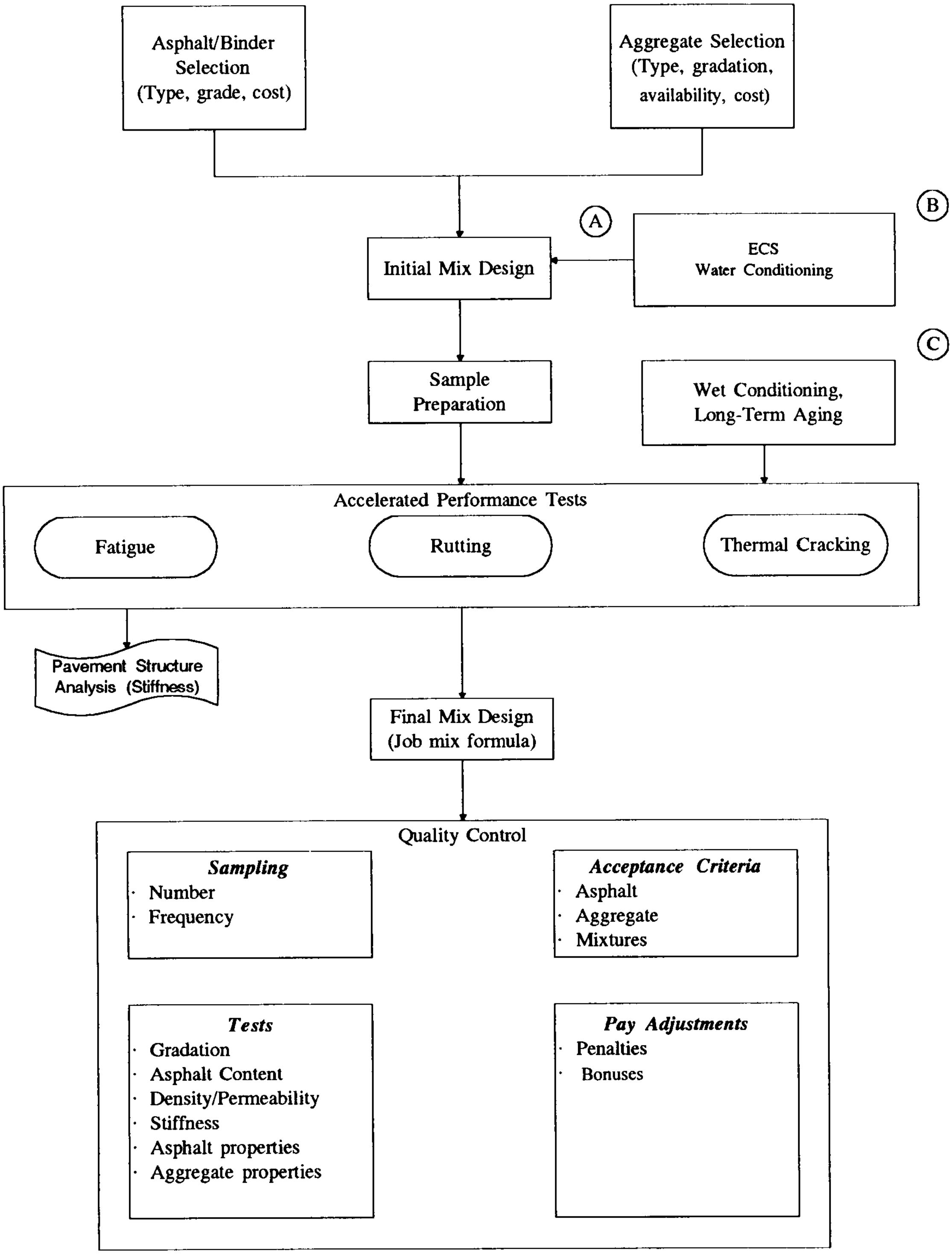


Figure 6.3. Proposed mix design system

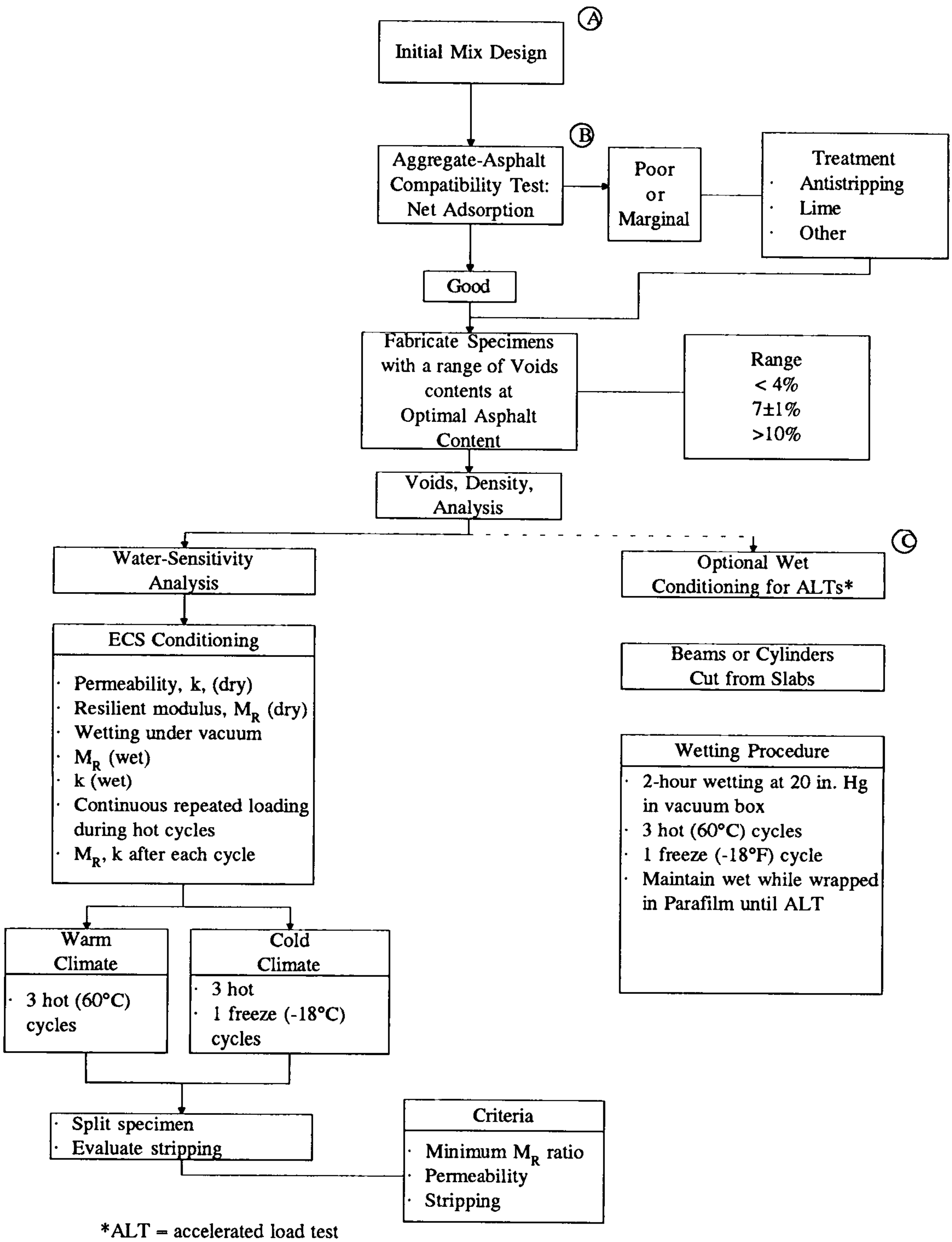


Figure 6.4. Mix evaluation for water sensitivity

trial mixtures are discarded. Further, the range of void contents provides some tie-in to the pessimum-voids concept. An added feature is that the water sensitivity would be known for the range of void contents and would serve as an indicator of the sensitivity of the mixture to compaction in the field (i.e., the importance of good compaction). This idea is illustrated in Figure 6.5.

Following specimen preparation and measurement of void content, density, etc., the ECS is used to condition and test each specimen. Slightly different cycling is used for climates with and without freezing conditions, and the procedure selected should be based on local climate (see Figure 6.2). For hot climates, the procedure includes three hot-wet cycles. For cold climates, the procedure includes three hot-wet cycles plus one freeze-wet cycle. The total procedure time includes cycle duration (6 hours each), 2 hours of ramping time to the testing temperature 25°C (77°F), and 1 hour for performing the test. So, 9 hours are needed for a complete cycle (testing a specimen, then conditioning it, then testing it again), which can be done during a long working day. Shorter (5-hour) cycles are being considered for the final protocol.

The second cycle, which will be longer than 9 hours, can be completed during the following evening, but this cycle can be compromised by extending the 25°C (77°F) time more than the standard time (2 hours). The third cycle starts at the beginning of the second day and finishes at the end of the same day. Thus, the procedure for hot climates takes two working days and one night, while the procedure for cold climates takes two working days and two nights. When the system is fully automated (which is the ultimate objective) and no one is needed to perform the test at the end of each conditioning cycle, the total procedure time for hot and cold climates will be reduced to 30 and 40 hours, respectively. Upon completion of ECS cycling, the specimens are broken open and evaluated for stripping based on a standard scale for comparison (see Figure 4.11). The results are then compared with the appropriate criteria, as was shown in Figure 6.4.

Criteria or specification guidelines are not yet established, but an acceptable mixture might have the following limits, for example:

1. ECS-M_R ratio following conditioning, greater than 0.70.
2. Permeability (dry), k, less than 1×10^{-6} cm/s
   (alternatively, report the permeability at each void content).
3. Percent stripping less than 20.

The optional part C in Figure 6.4 provides a procedure to wet condition specimens before testing in accelerated performance tests (APTs). It is generally understood that wetted mixtures will behave differently from the original dry mixtures, and should be tested in the appropriate field state. It is quite possible that mixtures that only marginally pass the ECS criteria may perform well in the APTs and vice versa.

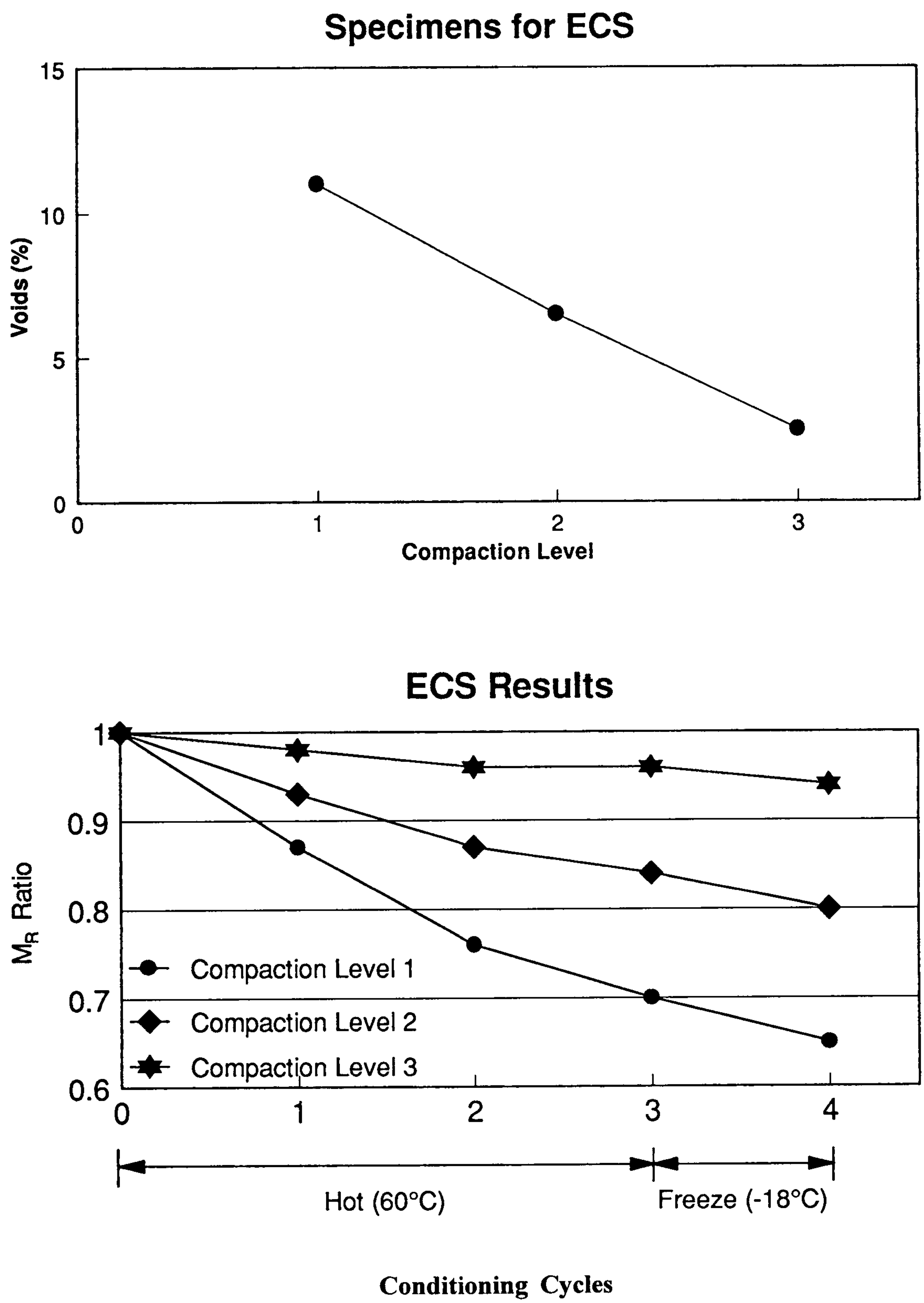


Figure 6.5. Concept of varying compaction and voids in specimens tested in the Environmental Conditioning System

6.2.1 Concluding Comments on the Role of the Environmental Conditioning System

The testing conducted during the validation phase showed that the wetting procedure, C, was not sufficient to induce significant damage before testing in the LCPC (Laboratories des Ponts at Chausées) wheel tracker used at OSU. Therefore, a modified approach to the system is shown in Figure 6.6. Specimens from the ECS would be tested using the repeated-load simple shear device, and the ratio between dry and conditioned would be evaluated as part of the mix design procedure.

There is some question about using the net adsorption test to screen materials. Very little data were available, so use of the test will remain uncertain until more data can be developed. Additional test results will be reported elsewhere (Scholz et al. 1994).

Finally, it appears that mix design and analysis will ultimately include three levels, the choice of which will depend on the traffic and climate. At the time of this research, it appeared that the ECS might play a slightly different role in each design level. The final approach will be discussed and recommended in a later report.

6.3 Future Research

Additional research on moisture damage in asphalt concrete is recommended. The following suggested research should be conducted in follow-up studies:

1. Although the rating standard for visual evaluation developed in this study has been found practical, it still includes human subjectivity in deciding the rate of stripping. Since the stripping rate is a good evaluation method for water damage because it is related to adhesion, there is a need for an objective stripping rate test. Using an electronic scanner could be the key for the required development. Although a scanner includes the broken aggregate as a stripped aggregate, this problem can be overcome by adapting imaging techniques currently used in other fields. Further consideration should also be given to developing an improved splitting technique using warmed specimens to reduce aggregate fracture.

2. The recommended wetting procedure in this study should be applied to wet asphalt concrete specimens to determine the effect of the wetting on fatigue life, low-temperature cracking, rutting, and the aging process.

3. Follow-up evaluation for field projects (Allen and Terrel 1994) should be continued for several years to establish a correlation between ECS results and field performance.

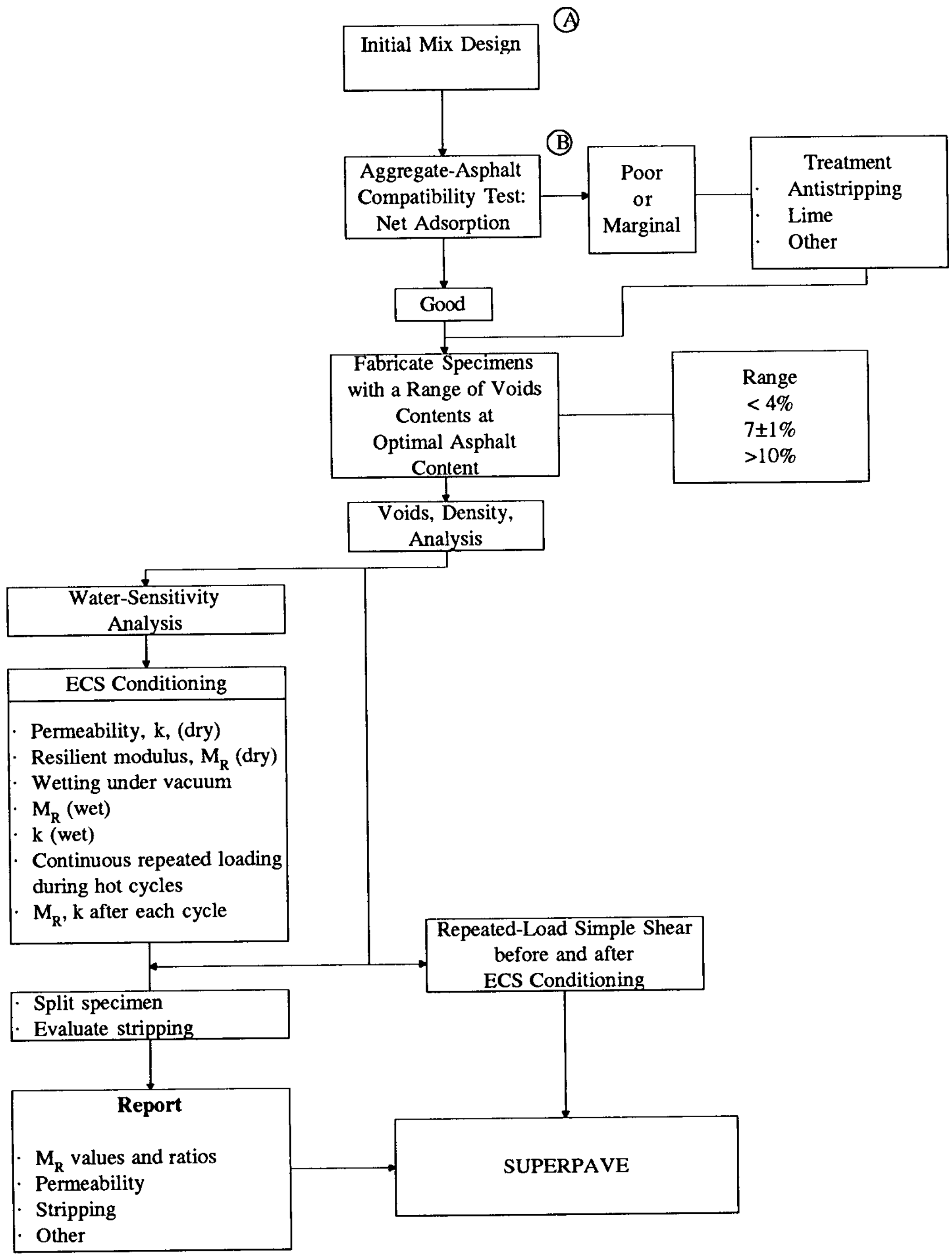


Figure 6.6. Revised water-sensitivity analysis system

7

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Appendix A

ECS Test Results

To facilitate additional studies, this appendix includes all the Environmental Conditioning System data. Two groups of data are included:

1. Table A.1: the original data from the ECS tests on specimens from 10 cm (4 in.) high, which appear in Table 3.8 after averaging,

2. Table A.2: the original data from the ECS tests on specimens 6.35 cm (2.5 in.) high, which are not discussed in this report because of the high variability associated with M_R, but still could be used for further analysis of the variability of the M_R test or studies on the other reported data (air voids, permeability, etc.).

Table A.1. Summary of ECS test results

Specimen ID and Date	Percent Air Voids	k (10^{-6} cm/s) (air)	Time (hours)	ECS-M_R (ksi)	Retained ECS-M_R (ratio)	k (10^{-5} cm/s) (water)	Retained k (ratio)	Stripping Rate (%)
RLC204RL/AAK	5.0	11.21	0	500	1.00	10.12	10.66	20
10-16-91			6	420	0.84	10.55	11.10	
			12	419	0.84	8.10	8.52	
			18	370	0.74	7.35	7.74	
RLC91RL/AAK	4.5	8.09	0	500	1.00	5.97	10.66	20
10-18-91			6	460	0.92	7.25	12.94	
			12	433	0.87	5.43	9.70	
			18	395	0.79	4.69	8.37	
RLC58RB/AAG	4.0	6.91	0	1102	1.00	3.30	10.66	10
10-05-90			6	869	0.79	2.56	8.25	
			12	953	0.86	1.92	6.19	
			18	964	0.87	1.39	4.47	
RLC118RB/AAG	4.3	10.58	0	929	1.00	3.09	1.00	10
02-08-91			6	846	0.91	2.88	0.93	
			12	750	0.81	1.92	0.62	
			18	680	0.80	1.70	0.55	
RC53RL/AAK	7.1	46.56	0	699	1.00	18.54	10.66	40
10-03-90			6	537	0.77	15.77	9.06	
			12	541	0.77	10.44	6.00	
			18	497	0.71	6.93	3.98	
RC201RL/AAK	7.0	21.17	0	660	1.00	22.16	10.66	50
10-12-91			6	530	0.80	20.99	10.09	
			12	460	0.70	21.20	10.19	
			18	420	0.64	15.88	7.63	
RC209RL/AAK	7.1	21.17	0	420	1.00	20.35	10.66	50
10-27-91			6	345	0.82	19.61	10.26	
			12	320	0.76	17.16	8.98	
			18	250	0.60	17.26	9.04	
RC56RL/AAG	7.2	18.77	0	1310	1.00	73.20	10.66	40
03-14-90			6	942	0.72	23.65	3.44	
			12	910	0.69	32.82	4.78	
			18	776	0.59	44.22	6.44	
RC79RL/AAG	6.9	11.39	0	808	1.00	19.71	1.00	20
03-18-91			6	672	0.83	5.43	0.28	
			12	757	0.94	2.77	0.14	
			18	615	0.76	2.24	0.11	
RC103RB/AAK	8.0	45.44	0	290	1.00	27.81	10.66	30
10-22-91			6	260	0.90	16.30	6.25	
			12	270	0.93	12.15	4.65	
			18	240	0.83	8.63	3.31	
RC104RB/AAK	8.1	14.32	0	400	1.00	23.23	10.66	30
10-29-91			6	320	0.80	15.13	6.94	
			12	299	0.75	5.54	2.54	
			18	285	0.71	2.24	1.03	

Table A.1. Summary of ECS test results (continued)

Specimen ID and Date	Percent Air Voids	k (10^{-6} cm/s) (air)	Time (hours)	ECS-M_R (ksi)	Retained ECS-M_R (ratio)	k (10^{-5} cm/s) (water)	Retained k (ratio)	Stripping Rate (%)
RC61RB/AAG	8.2	83.35	0	779	1.00	16.84	10.66	30
10-17-90			6	750	0.96	12.57	7.96	
			12	689	0.88	13.43	8.50	
			18	664	0.85	8.42	5.33	
RC105RB/AAG	7.9	55.53	0	716	1.00	17.58	1.00	30
01-24-91			6	628	0.88	16.09	0.92	
			12	610	0.85	8.52	0.48	
			18	562	0.78	3.73	0.21	
RC106RB/AAG	8.2	31.25	0	703	1.00	18.75	1.00	30
02-04-91			6	620	0.88	13.85	0.74	
			12	539	0.77	3.52	0.19	
			18	534	0.76	1.75	0.09	
RC113RB/AAG	7.7	47.93	0	701	1.00	13.32	1.00	30
02-02-91			6	640	0.91	4.58	0.34	
			12	571	0.81	9.33	0.70	
			18	554	0.79	3.15	0.24	
SLI111RL/AAK	3.9	0.87	0	1140	1.00	0.96	1.00	5
04-26-91			6	1032	0.91	0.64	0.67	
			12	1129	0.99	0.75	0.78	
			18	989	0.87			
SLI81RL/AAG	4.9	6.41	0	926	1.00	3.73	1.00	5
05-04-91			6	889	0.96	3.52	0.94	
			12	855	0.92	3.09	0.83	
			18	811	0.88			
SLI65RL/AAG	4.1	1.99	0	1058	1.00	0.96	1.00	5
04-13-91			6	976	0.92	0.75	0.78	
			12	976	0.92			
			18	929	0.88			
SLI71RB/AAK	4.6	6.16	0	581	1.00	1.60	1.00	5
04-26-91			6	506	0.87	1.49	0.93	
			12	518	0.89	1.28	0.80	
			18	460	0.79	1.28	0.80	
SLI66RB/AAK	4.1	5.35	0	591	1.00	3.09	1.00	5
04-29-91			6	580	0.98	2.88	0.93	
			12	570	0.97	1.70	0.55	
			18	561	0.95	2.24	0.72	
SLI115RB/AAG	4.5	2.43	0	888	1.00	1.92	1.00	5
02-10-91			6	847	0.95	1.81	0.94	
			12	825	0.93	1.11	0.58	
			18	699	0.79	0.96	0.50	
SLI168RB/AAG	5.2	7.03	0	685	1.00	3.52	10.66	5
10-26-91			6	660	0.96	3.30	10.01	
			12	623	0.91	2.13	6.46	
			18	649	0.95	2.56	7.75	

Table A.1. Summary of ECS test results (continued)

Specimen ID and Date	Percent Air Voids	k (10^{-6} cm/s) (air)	Time (hours)	ECS-M_R (ksi)	Retained ECS-M_R (ratio)	k (10^{-5} cm/s) (water)	Retained k (ratio)	Stripping Rate (%)
SI61RL/AAK 11-14-90	7.7	33.74	0	454	1.00	26.00	10.66	5
			6	424	0.93	37.40	15.33	
			12	414	0.91	38.68	15.85	
			18	392	0.86	32.18	13.19	
SI101RL/AAK 02-26-91	7.9	13.94	0	557	1.00	23.65	1.00	10
			6	516	0.93	20.35	0.86	
			12	468	0.84	18.11	0.77	
			18	471	0.85	17.37	0.73	
SI59RL/AAG 12-10-90	7.0	10.15	0	1100	1.00	54.02	10.66	10
			6	969	0.88	21.20	4.18	
			12	907	0.82	42.09	8.30	
			18	960	0.87	30.37	5.99	
SI55RB/AAK 11-10-90	6.8	64.74	0	276	1.00	23.97	10.66	5
			6	275	1.00	19.18	8.52	
			12	308	1.12	37.51	16.67	
			18	297	1.08	35.27	15.68	
SI57RB/AAK 03-04-91	6.4	58.52	0	596	1.00	110.66	1.00	5
			6	553	0.93	9.70	0.91	
			12	503	0.84	13.00	1.22	
			18	439	0.74	7.03	0.66	
SI63RB/AAG 10-22-90	8.3	13.66	0	610	1.00	32.93	10.66	10
			6	577	0.95	29.73	9.62	
			12	510	0.84	23.34	7.55	
			18	521	0.85	22.16	7.17	
SI85RB/AAG 03-06-91	7.0	10.96	0	1099	1.00	21.52	1.00	10
			6	1024	0.93	22.48	1.04	
			12	923	0.84	23.23	1.08	
			18	853	0.78	18.11	0.84	
SI161RB/AAG 10-24-91	7.8	13.76	0	710	1.00	27.60	10.66	5
			6	660	0.93	24.40	9.42	
			12	650	0.92	23.97	9.26	
			18	675	0.95	16.84	6.50	
RB205RL/AAK 10-15-91	7.9	27.20	0	530	1.00	15.98	10.66	20
			6	460	0.87	11.61	7.74	
			12	450	0.85	4.79	3.20	
			18	420	0.79	4.79	3.20	
RB206RL/AAK 10-22-91	9.1	32.74	0	338	1.00	13.00	10.66	20
			6	293	0.87	8.10	6.64	
			12	270	0.80	7.57	6.20	
			18	260	0.77	8.74	7.16	
SH214RL/AAK 11-09-91	8.5	23.59	0	330	1.00	27.92	10.66	5
			6	320	0.97	24.61	9.39	
			12	299	0.91	22.38	8.54	
			18	320	0.97	22.70	8.66	

Table A.1. Summary of ECS test results (continued)

Specimen ID and Date	Percent Air Voids	k (10^{-6} cm/s) (air)	Time (hours)	ECS-M_R (ksi)	Retained ECS-M_R (ratio)	k (10^{-5} cm/s) (water)	Retained k (ratio)	Stripping Rate (%)
SH62RB/AAG	8.2	23.72	0	707	1.00	110.60	10.66	5
10-29-90			6	680	0.96	161.54	15.56	
			12	651	0.92	204.90	19.74	
			18	652	0.92	152.59	14.70	
SH108RB/AAG	7.3	34.98	0	894	1.00	12.79	10.66	5
02-06-91			6	889	9.99	11.19	9.32	
			12	737	0.82	7.46	6.22	
			18	712	0.80	6.39	5.33	
SLH99RL/AAK	3.8	0.00	0	690	1.00			10
02-12-91			6	631	0.91			
			12	697	1.01			
			18	571	0.83			
RF208RL/AAK	8.0	29.32	0	325	1.00	16.41	10.66	5
10-28-91			6	293	0.90	13.64	8.86	
			12	246	0.76	8.31	5.40	
			18	240	0.74	4.79	3.11	
RF209RL/AAK	8.9	20.23	0	383	1.00	24.29	10.66	5
10-28-91			6	340	0.89	23.12	10.14	
			12	325	0.85	23.34	10.23	
			18	320	0.84	18.01	7.90	
SC207RL/AAK	8.8	32.43	0	250	1.00	16.84	10.66	30
10-27-91			6	215	0.86	13.64	8.63	
			12	195	0.78	13.43	8.50	
			18	188	0.75	8.42	5.33	
SC208RL/AAK	8.0	29.76	0	570	1.00	19.07	10.66	30
10-30-91			6	500	0.88	15.88	8.87	
			12	447	0.78	15.66	8.75	
			18	410	0.72	10.76	6.01	
VC47RL/AAK	6.8	16.25	0	594	1.00	95.37	10.66	5
07-29-90			6	656	1.10	79.92	8.93	
			12	635	1.07	82.79	9.25	
			18	604	1.02	89.93	10.05	
A31RL/AAK	9.0	35.48	0	394	1.00	60.74	10.66	
07-03-90			6	459	1.16	53.28	9.35	
			12	527	1.34	54.34	9.53	
			18	508	1.29	54.34	9.53	
SC214RL/AAK	8.4	15.31	0	280	1.00	34.10	10.66	40
10-20-91			24	226	0.81	22.38	6.99	
			48	195	0.70	11.72	3.66	
			72	188	0.67	9.59	3.00	

Table A.2. Summary of water conditioning test results. (This table includes specimens 6.35 cm [2.5 in.] high for specimens 10 cm [4 in.] high, see Table A.1.)

Specimen ID and Date	Cycle No.	M_R (ksi)	Retained M_R (ratio)	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
A31RL/AAK-1	0	394	1.00	25.48	1.00	
7-3-90	1	459	1.16	31.13	0.88	
	2	527	1.34	31.75	0.89	
	3	508	1.29	31.75	0.89	
B26RL/AAK-1	0	394	1.00			50
6-6-90	1	330	0.84			
	2	302	0.77			
	3	285	0.72			
C13RL/AAK-1	0	434	1.00	17.43	1.00	10
5-14-90	1	320	0.74	8.72	0.50	
C17RL/AAK-1	0	374	1.00	23.66	1.00	
5-8-90	1	357	0.95	3.74	0.16	
C11RL/AAK-1	0	240	1.00	30.50	1.00	
5-6-90	1	236	0.98	8.72	0.29	
C20RL/AAK-1	0	305	1.00			
5-22-90	1	265	0.87			
	2	243	0.80			
	3	235	0.77			
	4	206	0.68			
C20RL/AAK-1	0	474	1.00			40
5-18-90	1	337	0.71			
	2	360	0.76			
	3	330	0.70			
	4	346	0.73			
	5	301	0.64			
	6	324	0.68			
C23RL/AAK-1	0	397	1.00	9.46	1.00	
6-1-90	1	389	0.98	6.85	0.69	
	2	266	0.67	3.11	0.31	
	3	237	0.60	2.49	0.25	
F25RL/AAK-1	0	297	1.00	29.26	1.00	10
6-3-90	1	247	0.83	19.30	0.66	
	2	279	0.94	19.30	0.66	
	3	200	0.67	20.54	0.70	
F29RL/AAK-1	0	394	1.00	21.69	1.00	
6-19-90	1	260	0.66	6.23	0.29	
	2	270	0.69	5.60	0.26	
	3	300	0.76	2.49	0.12	
H28RL/AAK-1	0	340	1.00	14.32	1.00	20
6-15-90	1	329	0.97	0.00	0.00	
	2	244	0.72	0.00	0.00	
	3	245	0.72	0.00	0.00	

Table A.2. Summary of water conditioning test results. (This table includes specimens 6.35 cm [2.5 in.] high for specimens 10 cm [4 in.] high, see Table A.1.) (continued)

	Cycle No.	M_R (ksi)	Retained M_R (ratio)	k (10^{-6} cm/s)	Retained k (ratio)	Stripping Rate (%)
127RL/AAK-1	0	218	1.00	19.30	1.00	10
6-10-90	1	248	1.14	0.00	0.00	
	2	218	1.00	0.00	0.00	
	3	242	1.11		0.00	
132RL/AAK-1	0	312	1.00	14.99	1.00	
7-7-90	1	215	0.69	16.81	1.13	
	2	228	0.72	48.56	3.25	
	3	210	0.67	60.38	4.04	
L12RL/AAK-1	0	331	1.00	37.97	1.00	
5-17-90	1	191	0.58	5.60	0.15	
AG19RL/AAK-1	0	266	1.00	31.12	1.00	0
5-25-90	1	332	1.25	33.62	1.08	
	2	354	1.33	33.62	1.08	
	3	350	1.32	34.86	1.12	
	4	365	1.37	33.62	1.08	
	5	401	1.51	34.86	1.12	
AG22RL/AAK-1	0	248	1.00	34.24	1.00	0
5-27-90	1	311	1.25	34.86	1.02	
	2	368	1.48	36.11	1.05	
	3	309	1.25	26.73	1.07	
	4	303	1.22	36.11	1.05	
	5	402	1.62	36.11	1.05	
	6	492	1.98	37.35	1.09	
VLC47RL/AAK-1	0	594	1.00	4.30	1.00	
7-29-90	1	656	1.10	3.86	0.90	
	2	635	1.07	3.92	0.91	
	3	604	1.02	3.98	0.93	
VC33RL/AAK-1	0	427	1.00	55.71	1.00	5
8-1-90	1	601	1.41	46.69	0.84	
	2	558	1.31	48.37	0.87	
	3	519	1.22	52.54	0.94	