AN ABSTRACT OF THE THESIS OF

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Title: Development of a Test Procedure for Water Sensitivity of Asphalt Concrete Mixtures

Redacted for Privacy

Abstract approved:
Ronald L. Terrel

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 due to traffic loading and the resultant distress is manifested in the form of fatigue cracking, rutting, and raveling. But, when more severe climates are coupled with poor materials and traffic, premature failure may result.

The objectives of this research are twofold and includes: (1) development of a test system to evaluate the most important factors influencing the water sensitivity of asphalt concrete mixtures; and (2) development of laboratory testing procedures that will predict field performance. This research also addresses the hypothesis that much of the water damage in pavements is due to water in the asphalt concrete void system. It is proposed that most of the water problems occur when voids are in the range of about 5% to 12%. Thus, the term "pessimum" voids is used to indicate that range (opposite of optimum).

In order to evaluate the hypothesis and the numerous variables, the Environmental Conditioning System (ECS) was designed and fabricated. The ECS consists of three

subsystems: (1) fluid conditioning, where the specimen is subjected to predetermined levels of water, air, or vapor and permeability is measured; (2) an environmental cabinet that controls the temperature and humidity and encloses the entire load frame; and (3) the loading system that determines resilient modulus (M_R) at various times during environmental cycling and also provides continuous repeated loading as needed.

The ECS has been used to evaluate four core materials and also to investigate the relative importance of mixture variables thought to be significant. Many details regarding specimen preparation and testing procedures were evaluated during a "shakedown" of the ECS. As minor variables were resolved, a procedure emerged which 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 void (<5% low; 5-12%, pessimum; >12% high). Six-hour cycles of wet-hot (60° C) and wet-freeze (-18° C) are the principle conditioning variables, while monitoring M_R at 25° C before and between cycling. A conventional testing procedure (AASHTO T-283) was also used on the core mixtures to provide a baseline for comparison.

Results to date show that the ECS is capable of discerning the relative differences in "performance" such as M_R. Three hot cycles and one freeze cycle appear to be sufficient to determine the projected relative performance when comparing different aggregates, asphalts, void levels, loading, etc. Based on these results, a water conditioning procedure has been recommended and also a procedure for water conditioning specimens prior to testing in fatigue, rutting, and thermal cracking.

DEVELOPMENT OF A TEST PROCEDURE FOR WATER SENSITIVITY OF ASPHALT CONCRETE MIXTURES

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of

the requirements for the

degree of

Doctor of Philosophy

Completed May 5, 1992

Commencement June 1992

Approved:

Redacted for Privacy

Professor of Civil Engineering in charge of major

Redacted for Privacy

Head of Department of Civil Engineering

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Dean of Graduate School

Date thesis is presented: May 5, 1992

Typed by: Gail Barnes and Saleh Al-Swailmi

ACKNOWLEDGEMENT

I would like to express my sincere appreciation to my parents, to whom this dissertation is dedicated. I would also like to thank my wife, my daughter Ruba and my son Thamir for their patience, sacrifices, and support throughout the duration of this stage of our lives.

My appreciation is also expressed to my major professor, Dr. Ronald Terrel, for his valuable direction, guidance, and consultation during the course of this study. In particular, his friendship and support is greatly acknowledged. I would also like to thank the other members of my graduate committee, Professors Harold Pritchett, Gary Hicks, Chris Bell, and the Graduate School representative, Professor Thomas Plant, for their assistance in developing my academic program.

I also wish to thank Gail Barnes and Andy and Nancy Brickman for their help and assistance in various aspects, and especially, for their friendship. My colleague Todd Scholz deserves special mention for his valuable programming abilities and computer interface skills.

This research was supported by the Strategic Highway Research Program (SHRP).

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DEVELOPMENT OF A TEST PROCEDURE FOR WATER SENSITIVITY OF ASPHALT CONCRETE MIXTURES

1. INTRODUCTION

Environmental factors such as temperature, air (vapor), 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 due to traffic loading and the resultant distress is manifested in the form of fatigue cracking, rutting, and raveling. But, when more severe climates are coupled with poor materials and traffic, premature failure may result.

Although many factors contribute to the degradation of asphalt concrete pavements, moisture* 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 (or strength) and stiffness of the asphalt film that may

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*: 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 on distress mechanisms such as stripping.

be due to several mechanisms, (2) the failure of the adhesion (or bond) between the aggregate and asphalt, and (3) degradation of the aggregate itself. When the aggregate tends to have a preference for absorbing water, the asphalt is "stripped" away. This 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 that time numerous tests have been developed in an attempt to identify asphalt concrete mixtures which are 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 which suffer premature distress from the presence of moisture can be identified prior to construction. An asphalt mixture is identified as being sensitive to moisture if the laboratory specimen(s) 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 due to water-related degradation mechanisms.

The major difficulty in developing a test procedure has been in simulating the field conditions to which the asphalt concrete is exposed. Environmental conditions, traffic and time are the factors which need to be accounted for in developing test procedures to simulate field conditions. Environmental considerations include: water from precipitation and/or groundwater sources, temperature fluctuations (including freeze-thaw conditions) as well as 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 the asphalt mixture is placed can also influence its performance in the pavement. Since most test procedures are currently used in 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 due to water effects. The conditioning processes associated with current test methods are attempts to simulate field exposure conditions but include acceleration of the rate of strength loss. Testing of the cohesive and/or adhesive properties which would identify a moisture susceptible mixture follows the conditioning process. Table 1.1 summarizes those factors that should be considered in evaluating water sensitivity (Terrel and Shute, 1989).

Moisture sensitivity (or susceptibility) test probably have a "conditioning" and an "evaluation" phase. The conditioning phases vary, but all of them attempt to simulate the deterioration of the asphalt concrete in the field. The two general methods of evaluating "conditioned" specimens are a visual evaluation or subjecting the specimen to a physical test. In the visual evaluation, observation of the retained asphalt coating is determined following the conditioning process. Typically, physical test evaluation includes strength or modulus and a ratio is computed by dividing the result from the "conditioned" specimen by the result from an "unconditioned"

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 and/or additives
Conditioning	• Curing • Dry vs. wet • Soaking • Vacuum saturation • Freeze-thaw • Repeated loading • Drying
Other	• Traffic • Environmental history • Age

specimen. If the ratio is less than a specified value, the mixture is determined to be moisture susceptible.

The overal objective of this research addresses the relationship between asphalt binder properties and the performance of asphalt concrete mixtures. The specific goal for this thesis is to:

1. Define water sensitivity of asphalt concrete mixtures with respect to performance, including fatigue, rutting, and thermal cracking.

2. Develop laboratory testing procedures that will predict field performance.

The scope of this thesis 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

Test Procedures and Moisture Sensitivity

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

1. Tests which 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). A visual assessment of the amount of stripping is estimated.

2. Tests which 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 results of these tests are generally evaluated by the ratios of conditioned to unconditioned results using a stiffness or strength test (e.g. diametral resilient modulus test, diametral tensile strength test, compresive strength, etc.).

The use of terms such as "reasonable", "good", and "fair" are often used in conjunction with the description of 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 or not the asphalt mixtures they 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
2. NCHRP 274 - Indirect Tensile Test with Tunnicliff and Root Conditioning
3. AASHTO T-283 - Combines features of 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:

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

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

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 by the number and variety of tests currently being used. From the data and experience to date, it appears that a test has yet to be established that is highly accurate in predicting moisture susceptible mixtures and estimating the life of the pavement.

Philosophy of Water Damage Mitigation

The design of asphalt paving mixtures is a multi-step 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 are part of the design process. Performance factors that are of concern in any design include at least the following goals:

1. Maximize the fatigue life
2. Minimize the potential for rutting
3. Minimize the effect of low temperature or thermal cycling on cracking
4. Minimize or control the amount and rate of age hardening
5. Reduce the effect of water

In many instances, water or moisture vapor in the pavement can reduce the overall performance life by affecting any one 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 of the variables that affects the results of current methods of evaluation are the air voids in 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 and/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 total voids, but actual field compaction may result in as much as 8 to 10 percent voids. These voids provide the major access of water into the pavement mixture.

Hypothesis. The existing mixture design method and construction practice tends to create an air void system in asphalt concrete 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 were prepared and conditioned by some process such as water saturation followed by freezing and thawing, it can be shown that the retained strength or modulus is typically somewhat lower than for the original dry mixture. However, this effect

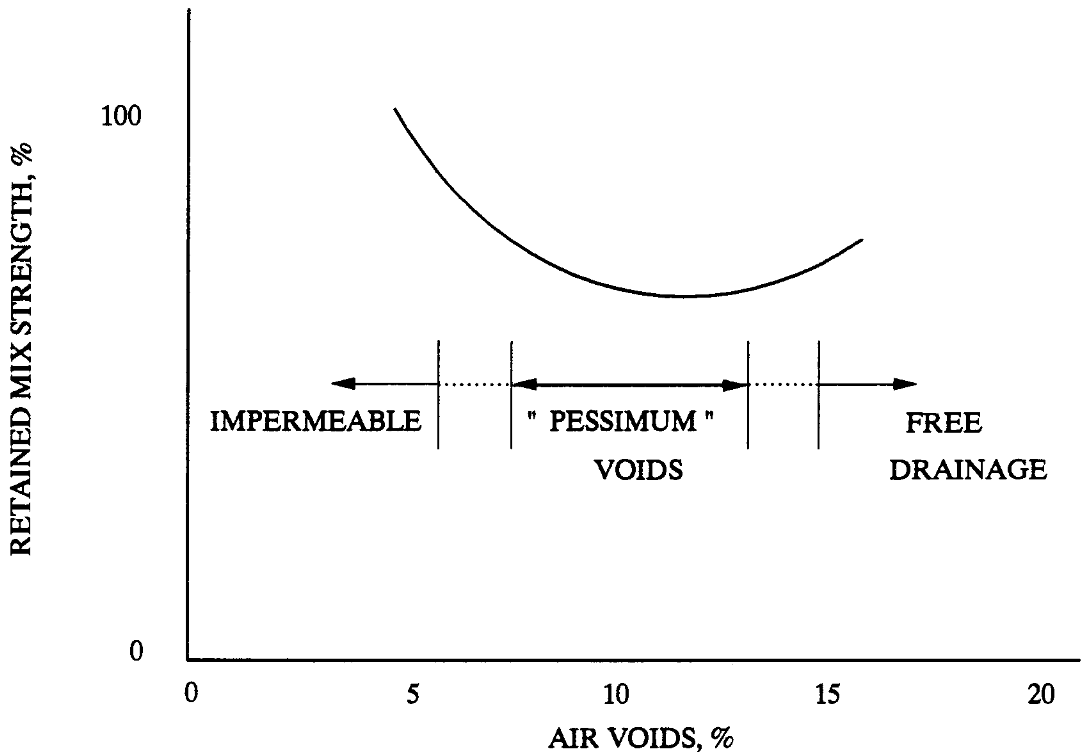


Figure 1.1 The Relative Strength of Mixtures May Depend on the Access to Water in the Void System

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. Those 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 should occur in the range where most conventional mixtures are compacted. Thus, the term "pessimum voids" can be used to describe a void system (i.e., 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 equate 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 (crushed sand, large size stone) and an improved binder containing polymers and/or fibers can be used.

2. The mid-range or pessimum voids is represented by conventional "dense graded" asphalt concrete as used in the U.S.

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.

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

Theory for Water Sensitivity Behavior

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

Voids in the asphalt concrete are the most obvious source of entry of water into the compacted mixture. Once a pavement is constructed, the majority of 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 due to incomplete drying plays a role in coating during construction and during its early service life. Also, there appears to be some indication that asphalt cements may themselves absorb water and/or allow some water to pass through films at the aggregate surface. The complexity of the water-void system will require a careful and detailed evaluation to better understand its significance.

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

Theories of Adhesion

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

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, and
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 may occur simultaneously in any one mixture, thus leading to 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 between asphalt cement and aggregate surfaces. Many researchers have noted that better adhesion may be achieved with basic aggregates compared to acidic aggregates. However, very acceptable mixtures have been produced using all types of aggregates. More recent work in the Strategic Highway Research Program (SHRP) program (Auburn University) is concentrating on the chemical interactions at the aggregate-asphalt interface (Curtis et al, 1991).

Surface Energy theory is used in an attempt to explain the relative wettability of aggregate surfaces by asphalt and/or 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 energy changes on the aggregate surface. Although some molecules in asphalt are di-polar, water is entirely di-polar and this may help explain the preference of aggregate surfaces for water rather than asphalt.

All of the above mechanisms may occur to some extent in any asphalt-aggregate system. As part of a study on microwave effects, Al-Ohaly and Terrel (1988) 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 antistrip additives as well as lime.

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 a 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 such as through intrusion into the asphalt binder film and 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

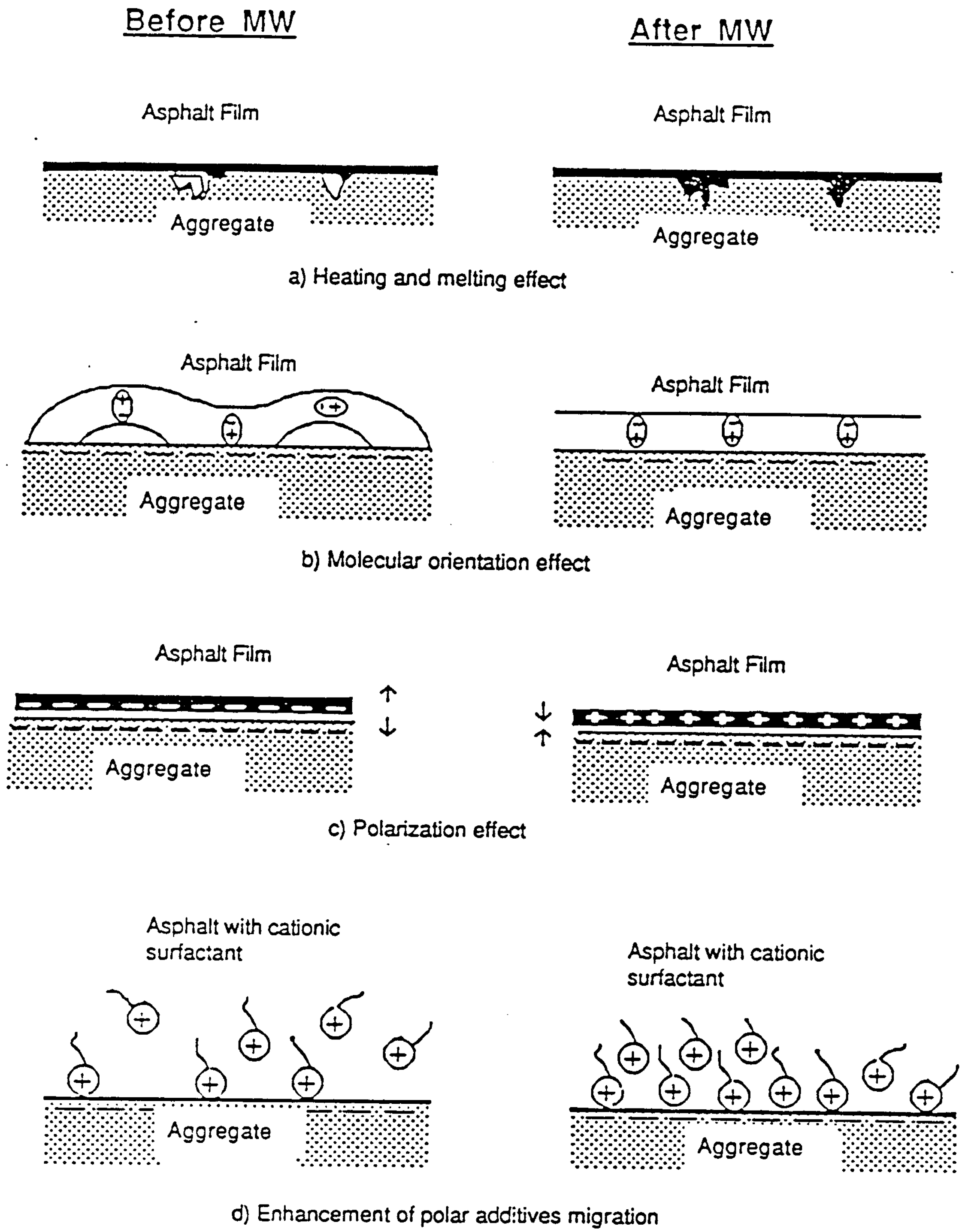


Figure 1.2 Mechanisms of Adhesion Improvement With Microwave Energy Treatment (Al-Ohaly and Terrel, 1989)

as repeated load resilient modulus tends to measure gross effects and the mechanisms of adhesion or 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. Over the 6+ month period of the conditioning process, there appeared to be a slight overall stiffening, that is probably due to age hardening of the asphalt cement. The observation made from data such as in Figure 1.3 helps in providing a better understanding of the effects of water on mixture performance.

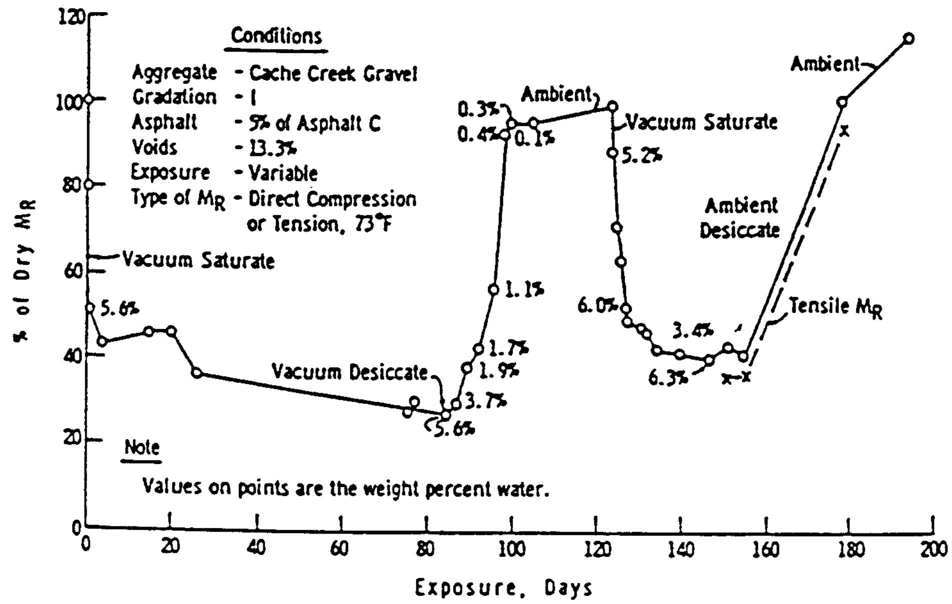


Figure 1.3 The Resilient Modulus of Asphalt Concrete is Sensitive to Changes in Moisture Conditioning (Schmidt and Graf, 1972)

1.3 Research Objectives

Keeping in mind the two-fold goal, this research is focused on investigating the most important factors influincing the water sensitivity and the development of a test procedure to assist in evaluating water sensitivity.

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

Step 1. Testing and screening of potential materials, both aggregates and asphalt binders to eliminate those candidates with non-compatible properties such as a high tendency toward stripping.

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

Step 3. Testing compacted mixtures to evaluate the overall 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 within the figure.

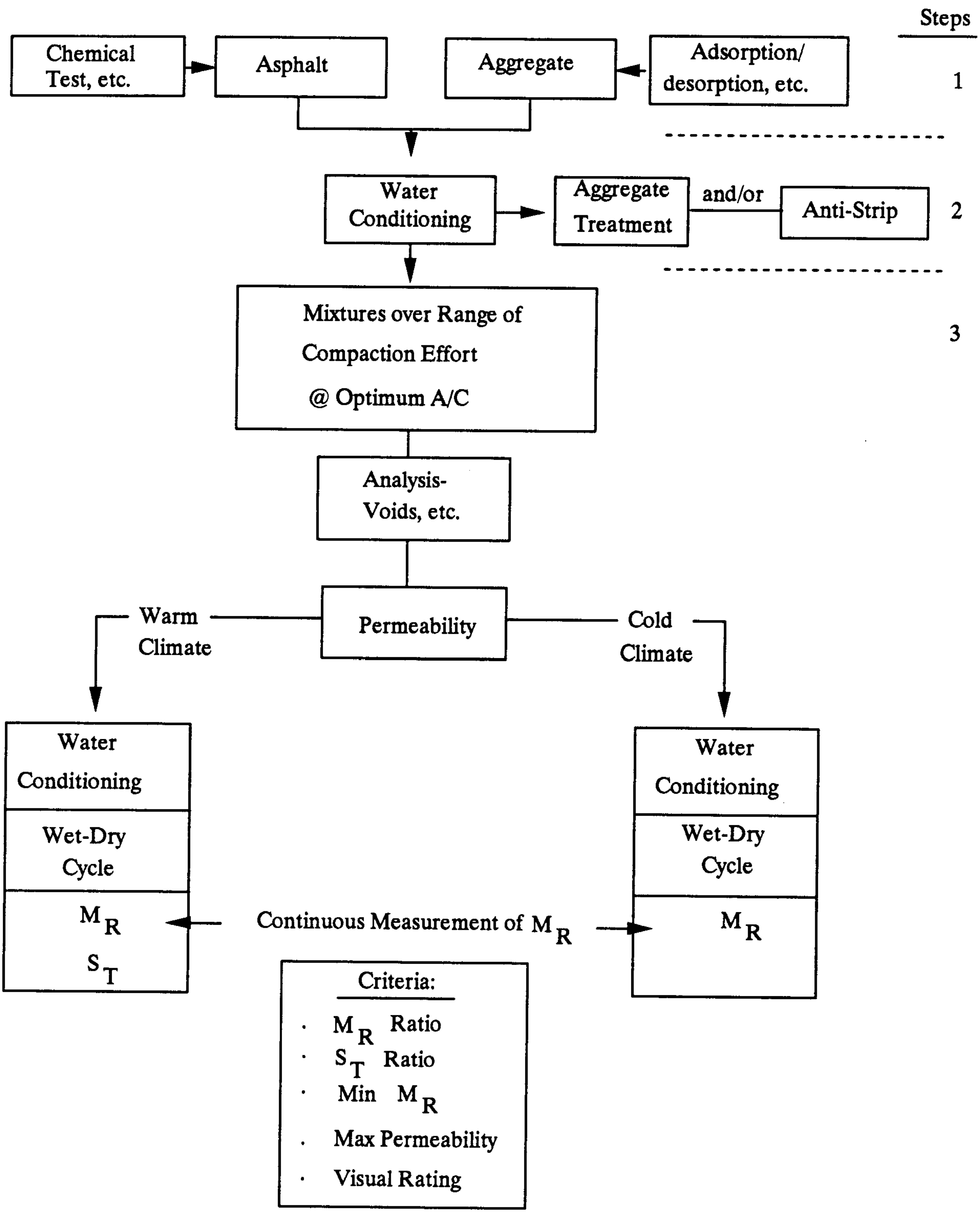


Figure 1.4 Possible Improved Test Procedure for Water Sensitivity

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

Practical coating and adhesion tests for loose (uncompacted) combinations of aggregate and asphalt will be the goal of step 2. This will be an important intermediate screening step specifically aimed at stripping potential prior to embarking on the more time-consuming final step 3.

Step 3 in Figure 1.4 is the heart of mixture evaluation for water sensitivity. Its goal will be not only to evaluate water sensitivity in some rational or comparative manner, but to also translate that information to 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 will be recommended for implementation by other highway agencies.

2. EXPERIMENT DESIGN

This study is aimed at determining the factors that most influence 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, and rate of wetting or saturation, aging, etc., would then be evaluated for a range of mixtures. Since the permeability (or air voids) is a major factor affecting mixture behavior, it is used as a controlled variable in the experiment plan (as discussed later) to characterize the response of asphalt concrete specimens to the change in water conditioning factors as time, and rate of wetting, and temperature cycling. Eventually, a water conditioning and testing procedure would be recommended for testing by various user agencies prior to final standardization.

2.1 Variables

The development of tests to determine the water sensitivity of asphalt concrete mixtures began in the 1930s. Since that time, 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 which suffer premature distress from the presence of moisture or water can be identified prior to 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 this particular combination of asphalt and aggregate would fail due to 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 in all water sensitivity tests. A water sensitivity protocol includes two major phases; a conditioning and an evaluation phase. The conditioning phases vary, but all of them attempt to simulate the performance of the asphalt concrete in the field with presence of water. The two general methods of evaluating conditioned specimens are visual evaluation and/or subjecting the specimen to a physical test.

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

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

In order to conduct the research, it was necessary to design an experimental testing program which includes all related variables. Figure 2.1 shows a 3x3 factorial-design experiment. This testing program was conducted by using the Environmental Conditioning System (ECS). The controlled variables and their treatment levels incorporated in the factorial design experiment were:

1. Temperature with three treatment levels:
    - Hot: 60°C (140°F)
    - Ambient: 25°C (77°F)
    - Freeze: -18°C (0°F)

Table 2.1 Factors Considered in The Experiment Plan

Variable	Factor
Materials	• Asphalt • Aggregate
Existing Condition	• Compaction • Voids • Permeability • Environment • Time • Water content
Conditioning	• Dry vs. wet • Vacuum saturation • Temperature Cycling • Repeated loading • Drying

a: ECS Experimental Test Plan

	CONDITIONING TEMPERATURE C								
	HOT 60 C			AMBIENT 25			FREEZE -18		
	WET CONDITIONIG								
PERMEABILITY (% Air Voids)	DRY	MOIST	SAT.	DRY	MOIST	SAT.	DRY	MOIST	SAT.
LOW PERMEABILITY	LA	LB	LC	LD	LE	LF	LG	LH	LI
PESSIMUM PERMEAB.	A	B	C	D	E	F	G	H	I
HIGH PERMEABILITY	HA	HB	HC	HD	HE	HF	HG	HH	HI

b: Specimen Identification

X X X X X X X X/X X X

- Asphalt Identification : AAK-1 or AAG-1
- Aggregate Identification : RB or RL
- Specimen no.
- Conditioning Code : According to a: above
- Letter V Indicates Vapor conditioning (90%)
  Letter A Indicates Dry Air conditioning
  No Letter Indicates Water conditioning
- Letter R Indicates Repeated Loading
  Letter S Indicates Static Loading

Figure 2.1 Experimental Test Plan and Specimen Identification

2. Permeability with three treatment levels depending on the air voids (AV):
   - Low permeability (% AV ≤6)
   - Pessimum permeability (6 < %AV < 14)
   - High permeability (% AV ≥14)
3. Wet conditioning with three treatment levels defined as follows:
   - Dry: No water conditioning
   - Moist: By running water through the specimens at 25°C under 10 inches of Hg vacuum for 30 min.
   - Wet: By running water through the specimen at 25°C under 20 inches of Hg vacuum for 30 min.

After most of the preliminary tests and mini-studies were complete, a modified test plan was initiated. During the early stages of laboratory testing, it became apparent that it is not necessary to perform all of the dry and ambient conditionings, Figure 2.1, where conditioning only one of each to show the boundaries of the conditioning variables is appropriate. The temperatures used for conditioning were limited to the extremes of 60°C and -18°C, with the intermediate 25°C range used only for limited comparisons. Early testing showed that the dry conditioning resulted in aging, which is expected, so only moist and wet were used, with the dry range used only to show the boundaries of moisture conditioning. The high air voids level was investigated only 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 void or permeability levels, hot or freezing temperatures and moist or wet moistures. Three conditioning cycles were used for the entire experiment, applying repeated loading during all the conditioning cycles except the freezing cycles.

Determination of Saturation Level

A suitable degree of saturation based on AASHTO T-283 and other previous experience, Lottman (1988), was established to be between 55% and 80% of the volume of air. 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 20 inches Hg, for a short time. If the degree of saturation was not within the limits, adjustments could be made by trial and error by changing vacuum level and/or submerging time. This saturating method worked satisfactorily for asphalt concrete mixtures, 8%±1% air voids.

The ECS method (as discussed later) attempted to standardize the wetting procedure by controlling water accessibility and vacuum level, instead of controlling water volume and degree of saturation, as in T-283.

The ECS uses a controlled vacuum for saturation by maintaining the desired vacuum level during the wetting stage according to the experimental plan and a 10-in 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 degree of saturation between 50 and 80 percent. In the case of similar gradations with one air voids level, using the controlled degree of saturation technique is appropriate. But since the objective of this study is to come up with a universal water conditioning procedure for asphalt mixtures with different air voids, using the controlled degree of saturation is not the best, as there are dense mixtures where 60 percent of their air voids are not connected or unaccessible, and in this case it is not possible to achieve the min. 50 percent saturation with any high vacuum level. Also on the other extreme, there are open graded mixtures with air voids such as 14 percent or more, where almost all the air voids are interconnected and very accessible to water. By only soaking or dipping the specimens in the water bath without applying vacuum, they will get more than 90 percent of saturation.

In order to illustrate the above 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 the effect of a 20-in. vacuum level for 30 minutes. Figure 2.2 shows the degree of saturation-air voids relationship under the same vacuum level. This confirms that in order to achieve a target saturation level for a specimen with certain air void levels, one may inadvertently destroy the specimen because of the need for the high vacuum level, as in the case of low 4 percent air voids.

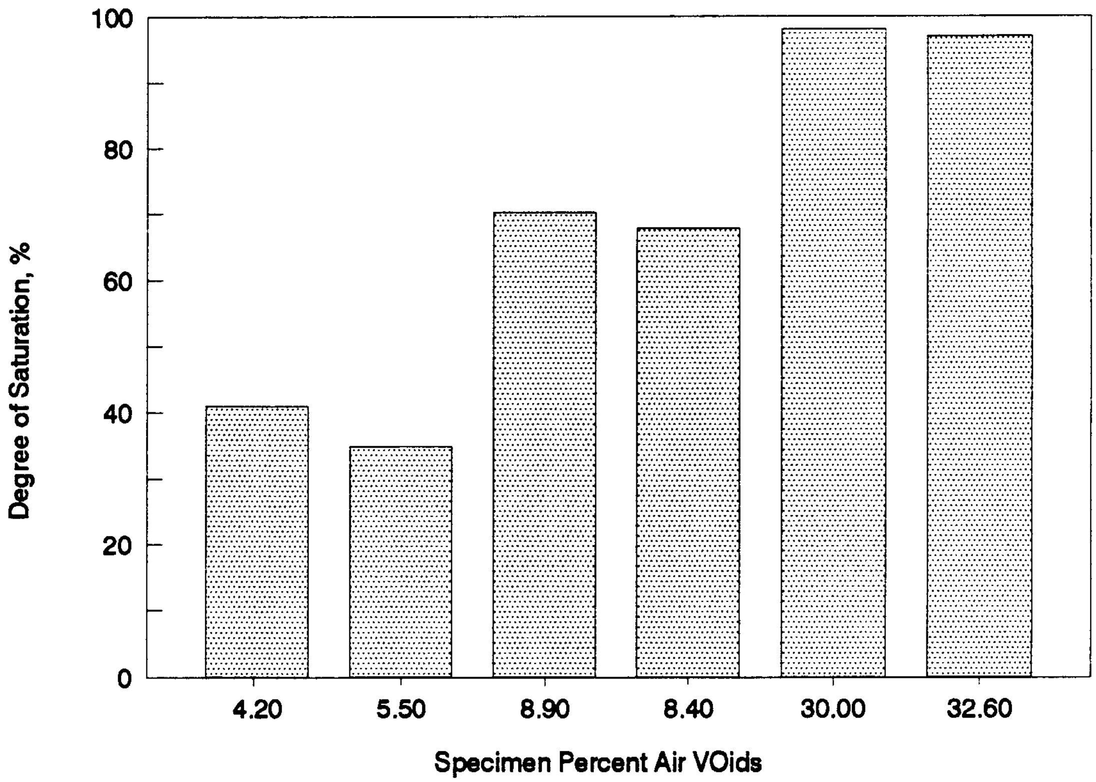


Figure 2.2 Degree of Saturation-Air Voids Relationship

In contrast, one may achieve the target degree of saturation before reaching an appropriate accelerated wetting process, such as the case of 31 percent air voids.

Based on this, for the ECS the water penetration into the mixture was used as a saturation indication, rather than the volume of water. This results in using the controlled vacuum, which actually controls the water penetration.

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

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

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

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

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

Finally, upon completing this research on water sensitivity of asphalt concrete mixtures, four goals were achieved:

1. Development of the Environmental Conditioning System (ECS) as a conditioning and testing device.
2. Evaluation of ECS
3. Recommended WET conditioning procedure as a water conditioning prior to testing in fatigue, rutting, and low temperature cracking.

4. Recommended a new water conditioning procedure for evaluating water sensitivity as a part of mix design, i.e., Mix Design and Analysis System (MIDAS).

2.2 Equipment and Procedures

In order to test the above hypothesis and variables, discussed in Chapter 1, the Environmental Conditioning System (ECS) was designed and fabricated to assist in determining the most important factors in the performance of mixtures in the presence of moisture,as shown in Table 2.1. The test set-up will permit evaluation of air voids and behavior of mixtures in several ways, including:

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

It is expected that the ECS can be used to evaluate the above factors in terms of the effectiveness of currently used testing procedures as well as lead to the development of a new testing procedure. In addition, the ECS will be used to assist in the validation of concepts developed by SHRP asphalt research. As noted above, the ECS has the capability to test a wide range of factors, but it is recognized that all of this capability may not be required in the final version of the ECS test to be used for routine mix design testing (MIDAS).

Testing System

The Environmental Conditioning System (ECS) was designed and fabricated to provide a means of simulating various conditions within an asphalt pavement. Figure 2.3 shows the ECS and its subsystems:

1. fluid conditioning,

2. environmental conditioning cabinet, and

3. loading system

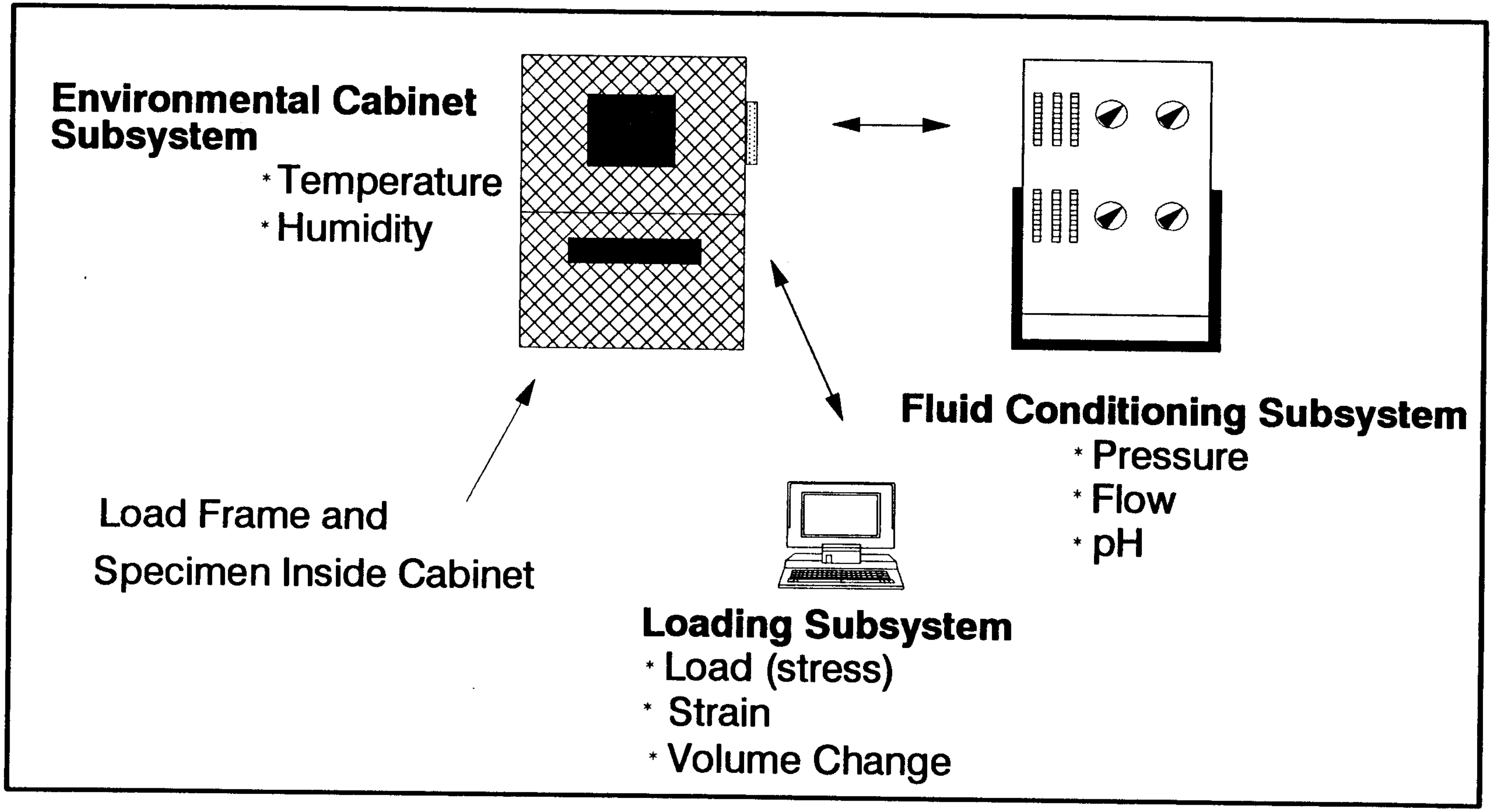


Figure 2.3 Overview of Environmental Conditioning System (ECS)

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 gages 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 type permeameter with vacuum, it is also capable of being used with back pressure if full saturation is required.
The specimen is placed in a load frame. A vacuum regulator is used to control the desired pressure gradient across the specimen. A 1/4-in. outside diameter transparent plastic tubing 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 value during the conditioning process. A thermocouple controller with four channels is connected to this system, one channel to read flow temperature right before the specimen and a second channel to read flow temperature right after the specimen. The third channel is installed inside a dummy specimen to monitor the internal temperature of the specimen which is inside the environmental cabinet, and the fourth thermocouple is connected to the water reservoir to control water flow temperature which is required to obtain actual water viscosity. Three water flow

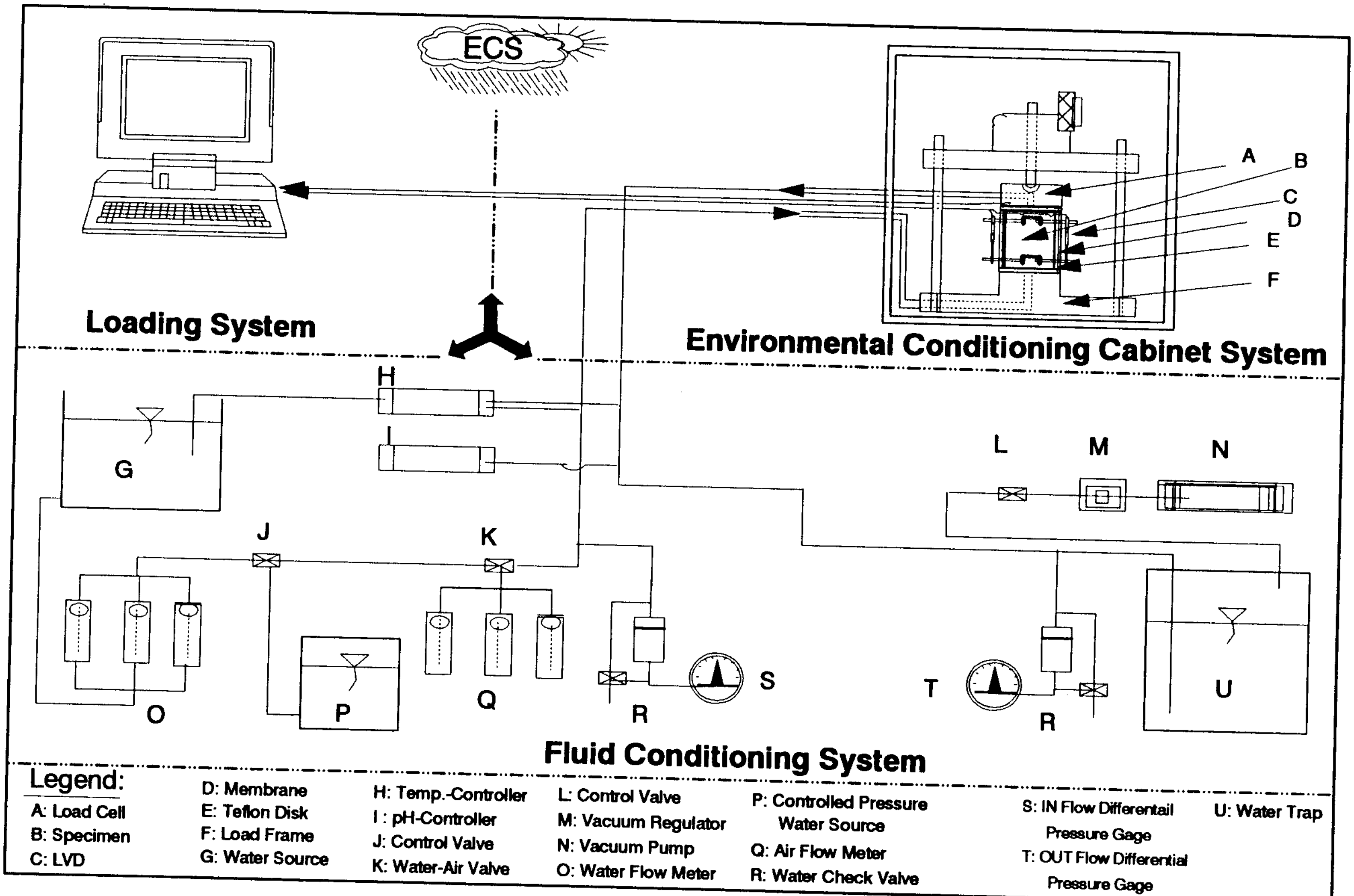


Figure 2.4 Schematic Drawing of Environmental Conditioning System (ECS)

meters of different flow capacities are connected to a fluid water conditioning system to provide a sufficiently wide flow range, from 1 to 3000 cm^3/min and another three air flow meters are also connected to the system to read a total range from 100 to 70,000 cm^3/min.

Environmental Conditioning Cabinet Subsystem

The heart of the system is a Despatch Industries 1600 series high and low temperature and/or humidity environmental conditioning cabinet. The environmental chamber has the capability of simulating high and low temperatures, and/or humidity levels. The chamber air is circulated by a fan located in the conditioning plenum at the rear of the chamber. The conditioned air is discharged into the workspace near the top of the chamber, circulated throughout the chamber and returned at the bottom of the conditioning plenum for recirculation. The chamber setpoint accuracy is ±0.5°C and 5% relative humidity (RH).

A microprocessor-based control, WALLOW series 1500, is installed in the chamber. The control is by ramping, enabling the system to move from one process variable to another in a uniform manner. Figure 2.5 is an example of programmed profiles for both humidity and temperature.

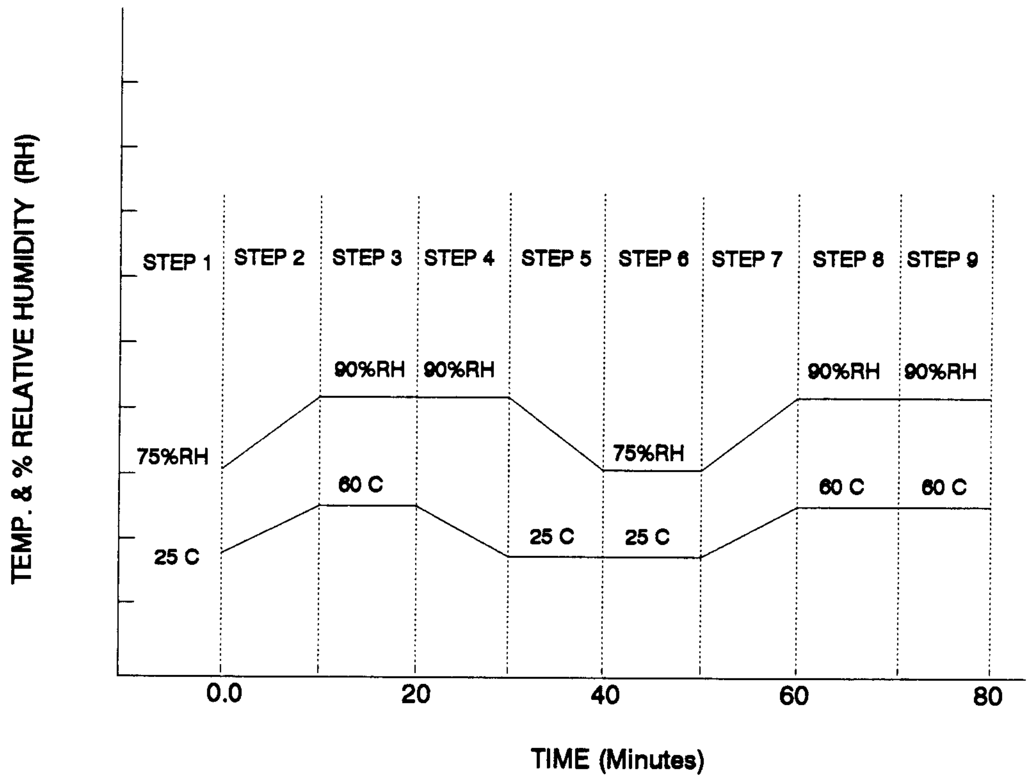


Figure 2.5 Example of Controlled Environment in the ECS Cabinet

Loading Subsystem

The repeated loading subsystem is an electro-pneumatic closed-loop system comprised of 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, serviced by compressed air and driven by a computer software 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 software program and converted to engineering units of stress and strain allowing the calculation of the resilient modulus (M_R). Although the software is capable of delivering a variety of loads and waveforms, tests in the ECS have been almost exclusively conducted 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 600 lb.

Test Procedures

The water conditioning procedure includes several steps, depending on the mixture and variables being evaluated. The conditioning procedure is described in detail in Appendix B. Figure 2.7 shows a summarized chart for the conditioning

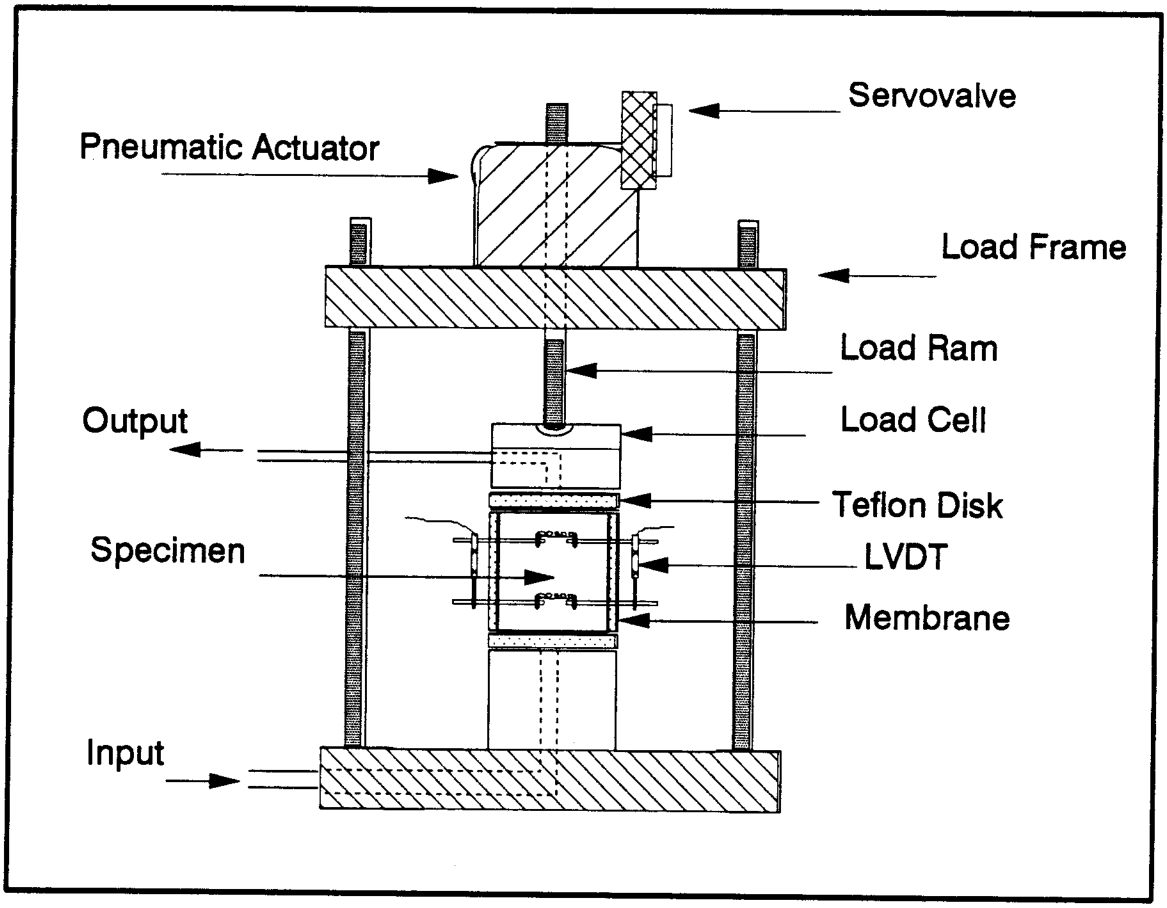


Figure 2.6 Load Frame Inside Environmental Cabinet

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	YS	YS	YS	NO
Ambient Temp.(C) **	25	60	60	60	-18
Duration (hr.)	0.5	6	6	6	6

* WETTING : Wetting the Specimen Prior Conditioning Cycles
** Inside the Environmental Cabinet

Figure 2.7 Typical Conditioning Information Chart variables. Mainly, each test procedure includes three stages. First is the evaluation of the specimen in dry conditions by performing the dry "original" resilient modulus (M_R) and permeability (k) tests. Second is the "wetting stage" by running water through the specimen for 30 minutes under the effect of the desired vacuum level (either 10-in or 20-in.). The wetting procedure is described in detail in Appendix C. Third, the conditioning stage includes three 6-hour cycles with maintaining a 10-in. vacuum and continuous repeated loading on the specimen during the conditioning cycles. In the case of freeze cycles, there is no repeated loading was performed, but the 10-in. vacuum is maintained, which is equivalent to 5 psi. Loading of the conditioning cycles with 10-in. vacuum and without a continuous repeated loading is identified as static loading. In summary, the steps of the conditioning procedure can be summarized as follows:

1) A 4-in. diameter by 4-in. high specimen is mixed and compacted
2) Physical measurements, density, voids, etc. determined.
3) Preconditioned resilient modulus determined.
4) Circumferential silicon seal applied, specimens mounted in load frame.
5) Measure (air) permeability.
6) LVDs mounted.
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) The resilient modulus (M_R) and water permeability (k) are measured following each cycle at 25° C.

10) Split open specimen.

11) Observe and report stripping rate.

2.3 Materials

Two aggregates and two asphalts were used from the Materials Reference Library (MRL) at the University of Texas (Austin). The two aggregates and two asphalts are as follows:

1. Aggregates: Watsonville granite, RB, a non-stripper and Gulf Coast gravel, RL, a stripper.
2. Asphalts: Boscan, AAG-1, and California Valley, AAK-1. These were selected because of their vastly different compositional and temperature-susceptibility characteristics.

From these two asphalts and two aggregates four asphalt-aggregate combinations were used to fabricate mixtures. Table 2.2 shows asphalt content for each mixture which was compacted using kneading compactor (ASTM D 1561), ASTM D 1560, (see Appendix D for sample preparation protocol). For the two aggregates, Watsonville granite (RB) and Gulf Coast gravel (RL), the gradation shown in Table 2.3 and plotted in Figure 2.8, was used in this study. It corresponds to a typical

Table 2.2 Mix Design Results and Compaction Efforts

Agg. Type	Asph. Type	Percent Asph. by Weight of Agg.	Compaction Effort on Each Lift	% 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

Table 2.3 RL and RB Aggregate Gradation used in this study (from MRL data)

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

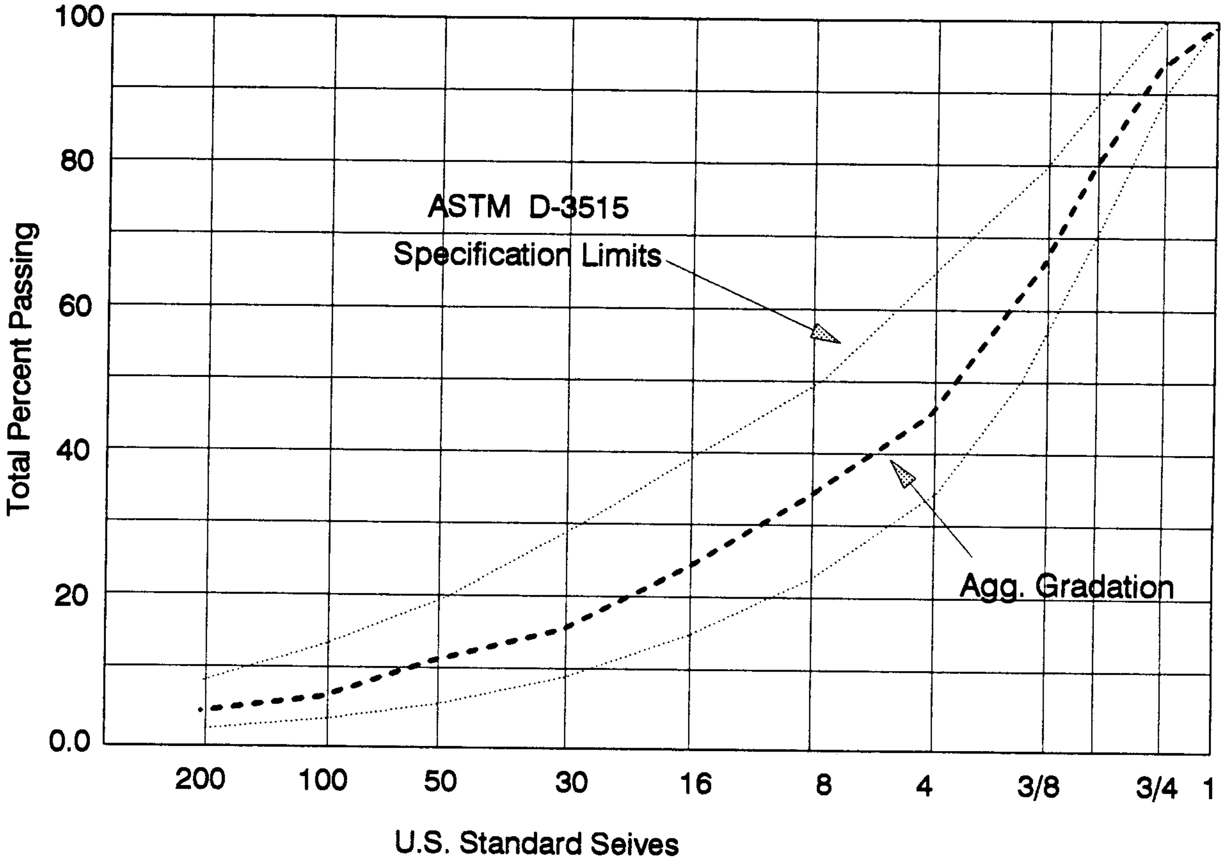


Figure 2.8 Aggregate Gradation

dense-graded aggregate with 3/4-inch maximum size.

The two sources of asphalt differing in both composition and temperature susceptibility (low, high) 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 the are low and high. Table 2.5 shows the physical and chemical properties of each aggregate. For each asphalt-aggregate mixture, there are two levels of compaction effort, which were established to satisfy the two levels of air voids targets. Table 2.2 shows the compaction effort used to fabricate each asphalt-aggregate mixture.

Table 2.4 Physical Properties of Asphalt Materials (from MRL data)

Property	Asphalt	
	AAK-1	AAG-1
Asphalt Grade	AC-30	AR4000
Crude	Boscan	CA 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, 5s)	70	53
Ductility, cm (39°F, 1 cm/min)	27.8	0.0
Softening Point (RAB), °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

Table 2.5 Aggregate Properties (from MRL data)

		AGGREGATE IDENTIFICATION	
		RL Lithonia Granite	RB Watsonville Granite
Total Aggregate	Apparent Sp. Gr.	2.656	2.821
	Bulk Sp. Gr.	2.634	2.742
	Water Absorb. %	0.31	1.03
Coarse Aggregate	Apparent Sp. Gr.	2.664	2.829
	Bulk Sp. Gr.	2.629	2.735
	Water Absorb. %	0.50	1.21
Fine Aggregate	Apparent Sp. Gr.	2.649	2.815
	Bulk Sp. Gr.	2.639	2.748
	Water Absorb. %	0.14	0.87
Surface Capacity	Exper. %	3.0	2.8
	Corrected %	3.0	2.9
C.K.E.	Exper. %	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 to the existing procedures and current practice. The conditioning phase includes partial saturation at 20 in. Hg vacuum for 30 minutes, 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) prior to testing (see Appendix E for testing protocol). Evaluation includes measurement of both resilient modulus (M_R) and tensile strength (St) and reporting their retained ratios.

Additional testing was also conducted during the AASHTO T-283 procedure that will become part of the data base. Permeability of each dry specimen was measured using air (testing device is described in Appendix E). For those specimens which 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 conditioning wet) is shown in Table 3.1. All data tables are in Appendix E.

Table 3.1 Typical Data Calculations of AASHTO T 283 Test Results

Agg. Type: RL — Mix Date: 7-10-90 — Compaction Effort: 20 blows @ 250 psi and 150 blows @ 250 psi

Asph. Type: AAK1 — Cond. Date: 10-10-90 — Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ -9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T141RL/AAG1	2.680	2.442	2.58	1248.3	700.6	1249.	2.280	6.7	452.3	184.5		
T142RL/AAG1	2.671	2.442	1.75	1246.8	698.4	1247.	2.274	6.9	429.5	175.8		
T143RL/AAG1	2.696	2.434	0.89	1249.6	703.5	1250.	2.289	6.0	434.6	165.0		
T144RL/AAG1	2.671	2.434	1.47	1245.3	706.8	1248.	2.299	5.6			2.681	725.1
T145RL/AAG1	2.684	2.434	1.20	1245.1	707.2	1247.	2.304	5.3			2.67	725.1
T146RL/AAG1	2.669	2.434	4.48	1242.2	706.5	1246.	2.301	5.5			2.671	724.7

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1266.8	71.5	0.000	2.694	731.0	1279.4	114.10	0.594	407.8	0.928	125.5	0.68	
1265.1	69.6	-0.056	2.682	730.9	1278.3	116.00	0.390	394.4	0.928	114.1	0.68	
1264.5	75.5	-0.019	2.683	730.1	1277.6	120.70	0.765	342.6	0.928	109.4	0.68	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water-conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/ S_{td}) or (23) = (22)/(10)

% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

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 Test Methods

The intent of this section is to describe the development and evaluation of the Environmental Conditioning System (ECS). Generally, prior to embarking on a full-scale test scheme, numerous questions and details needed to be evaluated in developing a testing device. Likewise, prior to starting the ECS experiment plan (Figure 2.1) at Oregon State University, the ECS was subjected to detailed evaluation and refinement to demonstrate its reliability and reproducibility in three aspects: resilient modulus measurement, permeability measurement, and methods of air voids calculations. These are discussed in the following sections.

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

Table 3.2 Summary Table for AASHTO T−283 Test Results
(For more information see Table E−1)

Testing ID	Dry Tensile Strength, psi (TS)	Conditioned Tens. Stren. (Stm)	Dry ksi (M_R)	Cond. M_R (Mrm)	TS Ratio (TSR)	M_R Ratio (MrR)
T,24,RL/AAG1	194	181	80	72	0.49	0.40
T,25,RL/AAG1	256	107	130	44	0.49	0.40
T,26,RL/AAG1	331	120	158	59	0.49	0.40
T,32,RL/AAG1	428	146	182	91	0.30	0.40
T,30,RL/AAG1	544	147	210	66	0.30	0.40
T,34,RL/AAG1	464	168	174	76	0.30	0.40
T,36,RL/AAG1	543	316	187	106	0.57	0.63
T,40,RL/AAG1	542	325	182	125	0.57	0.63
T,42,RL/AAG1	583	366	207	133	0.57	0.63
T,45,RL/AAG1	556	414	229	146	0.61	0.47
T,47,RL/AAG1	518	217	210	95	0.61	0.47
T,49,RL/AAG1	509	236	225	68	0.61	0.47
T,144,RL/AAG1	109	59	210	120	0.53	0.60
T,145,RL/AAG1	107	54	203	127	0.53	0.60
T,146,RL/AAG1	117	62	231	138	0.53	0.60
T,150,RL/AAG1	111	46	254	98	0.40	0.38
T,151,RL/AAG1	125	52	285	113	0.40	0.38
T,152,RL/AAG1	120	46	265	96	0.40	0.38
T,153,RL/AAG1	137	50	186	141	0.43	0.69
T,154,RL/AAG1	100	52	225	167	0.43	0.69
T,155,RL/AAG1	113	50	205	119	0.43	0.69
T,35,RL/AAK1	123	72	167	163	0.54	0.74
T,38,RL/AAK1	121	60	167	84	0.54	0.74
T,52,RL/AAK1	415	371	208	104	0.60	0.82
T,53,RL/AAK1	570	283	220	86	0.60	0.82
T,56,RL/AAK1	520	386	241	106	0.60	0.82
T,58,RL/AAK1	368	311	156	105	0.83	0.62
T,59,RL/AAK1	370	295	167	99	0.83	0.62
T,60,RL/AAK1	363	277	165	106	0.83	0.62
T,65,RL/AAK1	331	223	169	79	0.53	0.53
T,66,RL/AAK1	375	194	159	82	0.53	0.53
T,67,RL/AAK1	411	217	153	86	0.53	0.53
T,125,RL/AAK1	452	408	185	126	0.93	0.68
T,126,RL/AAK1	430	394	176	114	0.93	0.68
T,127,RL/AAK1	435	343	165	109	0.93	0.68
T,164,RL/AAK1	145	45	292	82	0.30	0.26
T,165,RL/AAK1	153	45	336	80	0.30	0.26
T,166,RL/AAK1	145	41	300	83	0.30	0.26

Table 3.2 (cont.)

Testing ID	Dry Tensile Strength, psi (TS)	Conditioned Tens. Stren. (Stm)	Dry ksi (M_R)	Cond. M_R (Mrm)	TS Ratio (TSR)	M_R Ratio (MrR)
T,80,RB/AAK1	352	238	148	99	0.64	0.60
T,81,RB/AAK1	402	249	167	97	0.64	0.60
T,83,RB/AAK1	365	271	165	105	0.64	0.60
T,87,RB/AAK1	369	286	140	106	0.65	0.61
T,88,RB/AAK1	380	259	175	93	0.65	0.61
T,92,RB/AAK1	463	366	183	130	0.65	0.61
T,102,RB/AAK1	389	354	158	122	0.81	0.72
T,103,RB/AAK1	412	322	178	115	0.81	0.72
T,104,RB/AAK1	422	373	168	135	0.81	0.72
T,187,RB/AAK1	161	108	278	361	0.67	1.12
T,188,RB/AAK1	170	98	292	322	0.67	1.12
T,189,RB/AAK1	148	116	289	277	0.67	1.12
T,193,RB/AAK1	134	98	275	286	0.79	0.93
T,194,RB/AAK1	113	86	227	225	0.79	0.93
T,195,RB/AAK1	114	100	281	215	0.79	0.93
T,96,RB/AAG1	477	660	262	136	1.24	0.62
T,97,RB/AAG1	478	585	242	171	1.24	0.62
T,98,RB/AAG1	526	666	269	167	1.24	0.62
T,109,RB/AAG1	435	537	225	187	1.16	0.83
T,111,RB/AAG1	506	654	223	233	1.16	0.83
T,113,RB/AAG1	520	523	232	147	1.16	0.83
T,117,RB/AAG1	494	434	215	137	0.58	0.77
T,118,RB/AAG1	498	339	214	116	0.58	0.77
T,120,RB/AAG1	503	282	191	101	0.58	0.77
T,204,RB/AAG1	165	76	256	148	0.51	0.62
T,205,RB/AAG1	111	64	211	154	0.51	0.62
T,206,RB/AAG1	162	81	255	144	0.51	0.62
T,210,RB/AAG1	131	102	404	158	0.77	0.55
T,211,RB/AAG1	143	104	143	204	0.77	0.55
T,212,RB/AAG1	137	111	137	225	0.77	0.55

by using either 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: (1) the Standard Test Method for Dynamic Modulus of Asphalt Mixtures, (ASTM D 3497) and (2) 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.

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 electro-pneumatic closed loop testing system. Applied stress is controlled by a load cell placed on the top of the specimen. Recoverable axial strain is monitored by 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 8-in. for a 4-in. diameter specimen. However, it was not feasible to water condition these tall specimens, because of the long distance for the water to flow under vacuum. To compromise between the ASTM D 3497 requirement and typical pavement layer thicknesses, a mini-study was conducted to investigate the effect of height-to-diameter (L/D) ratio, on resilient modulus. In addition, other mini-studies were conducted to investigate other details including:

1) Effect of glue type for strain gages (strain gages were later replaced by LVDTs)

2) Repeatability of ECS resilient modulus and necessity of using teflon disks.

Test Specimen Preparation

One mix, combination RB/AAK-1, was used to prepare three 4-in. diameter by 7 in. high specimens. After density determinations were completed, a vertical alignment jig was used with capping compound to maintain caps perpendicular with the specimen axis according to the requirements of ASTM C 617, "Capping Cylindrical Concrete Specimens". After testing the specimens with the full height, 1.0 in. was trimmed from each end with a diamond saw. Capping and testing were repeated for the new 5-in. specimen. Finally, 1.25 in. were trimmed from each end of the 5-inch specimen which resulted in 2.5 in. specimens and 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.

Test Equipment and Instrumentation

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

Table 3.3 Density and Air Void Calculations for the Three Specimen Thicknesses

Specimen ID	Original Thickness (≈ 7" thickness)		After first cut (≈ 5" thickness)		After second cut (≈ 2.5" thickness)	
	Bulk spec. gravity	% Air Voids	Bulk spec. gravity	% Air Voids	Bulk spec. gravity	% 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

1. Linear variable differential transformers, LVDTs, attached to the specimen by a pair of clamps which were cemented to the specimen by plates, maintaining a 2-in for all specimens heights. Deformations were measured by chart recorder.
2. A pair of 1-in. long strain gages and strain indicator for recording strains.

The test set-up is shown in Figure 3.1.

Axial loading of the specimens was performed using two modes: (1) continuous repeated loading of haversine wave form, and (2) continuous repeated loading of square wave form. A dynamic load of 600 lb. was used after seating the specimen

with a 60 lb. static load. The same loading time 0.1 s, and rest period, 0.9 s, were used for the two loading modes.

Effect of L/D 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 2.5-in. thickness is significantly higher than the moduli from the specimens with 5-in. and 7-in. thicknesses. The wave form (haversine or square) and strain measurement device (LVDTs or strain gages) have no effect on the trend or general relationship, but do affect the magnitude. For the same method of strain

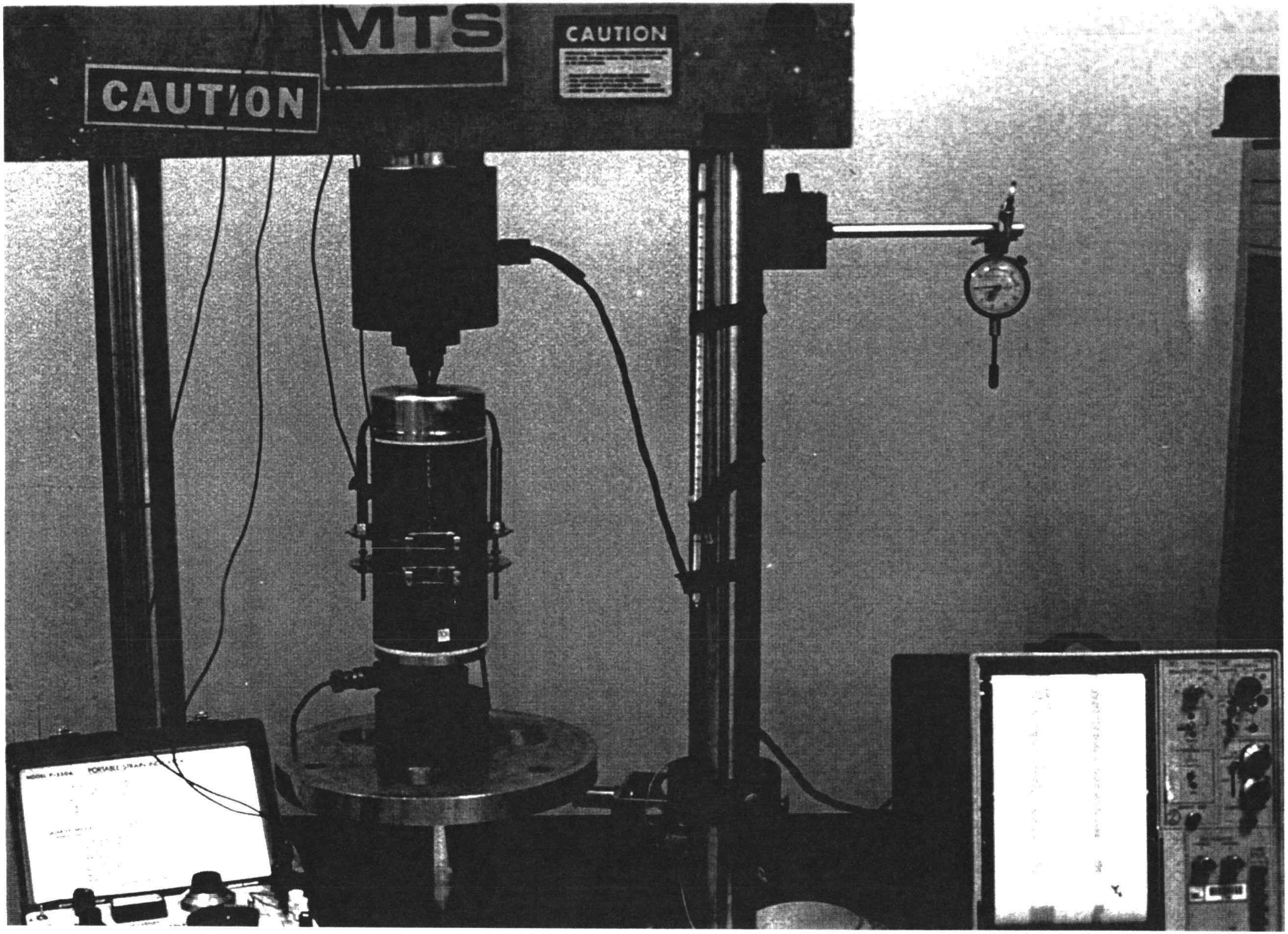


Figure 3.1 Overview of the Test Setup

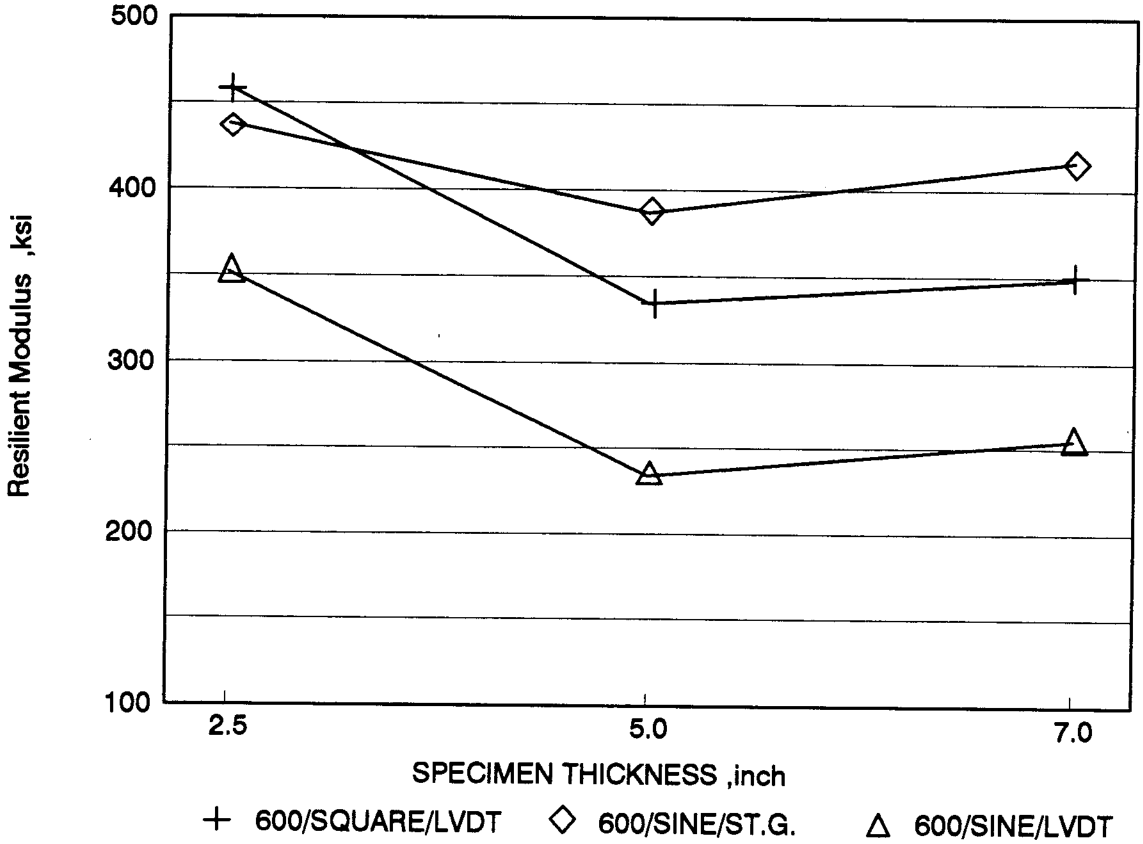


Figure 3.2 The Relationship Between Resilient Modulus and Specimen Thickness for Two Testing Conditions (Spec. no. 1)

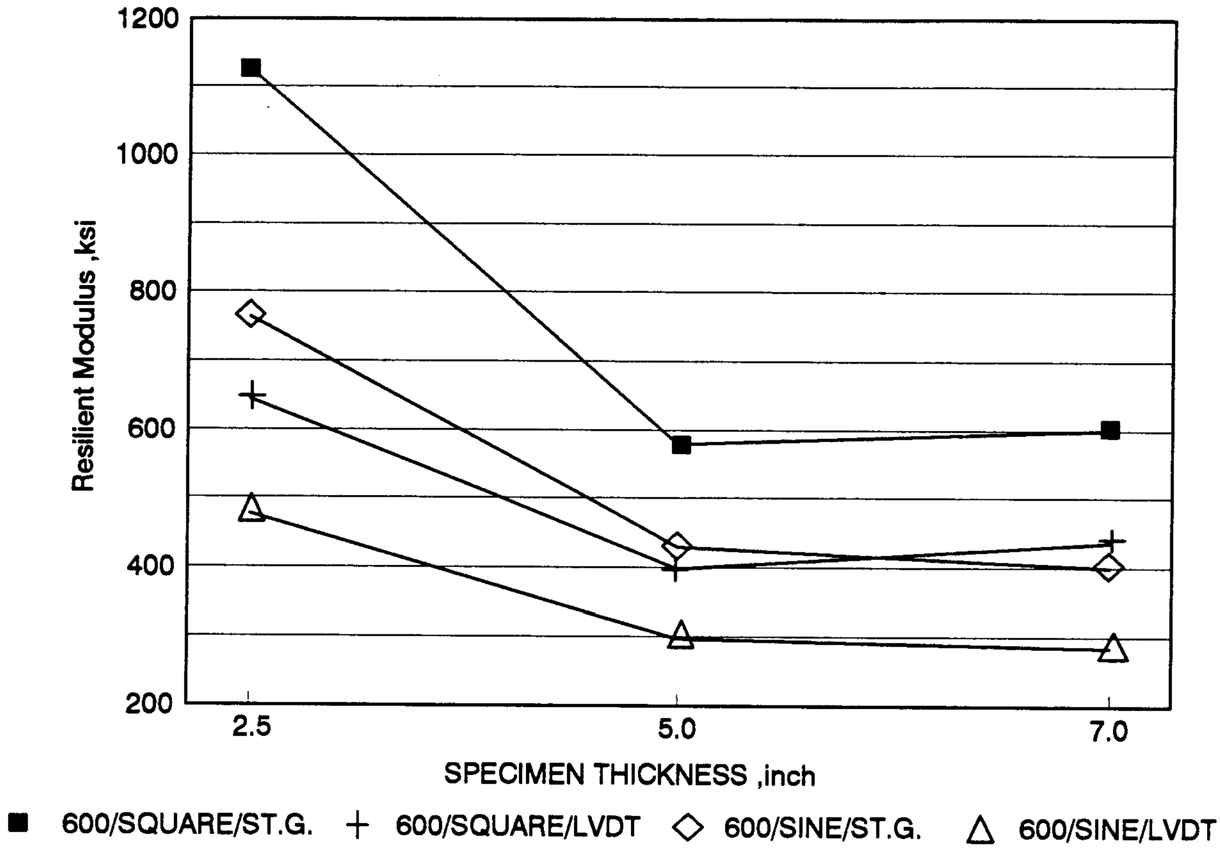


Figure 3.3 The Relationship Between Resilient Modulus and Specimen Thickness for Two Testing Conditions (Spec. no. 2)

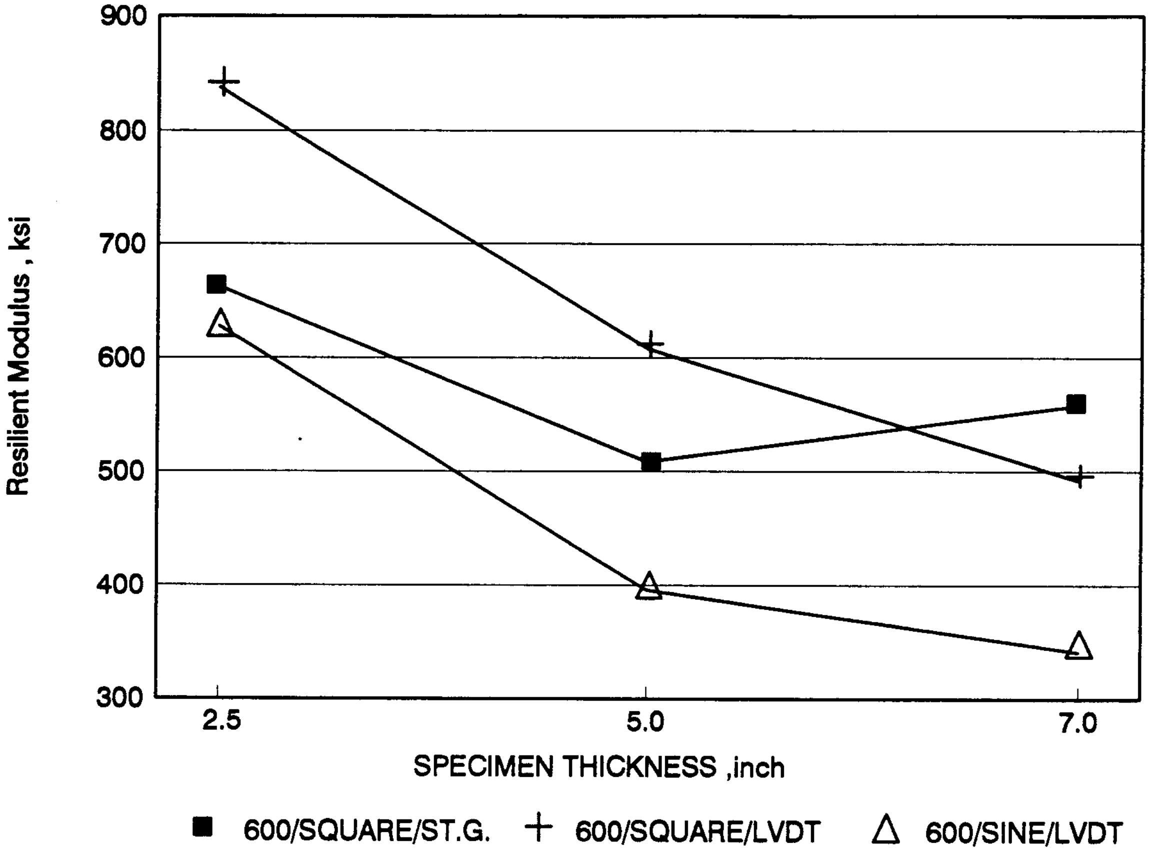


Figure 3.4 The Relationship Between Resilient Modulus and Specimen Thickness for Two Testing Conditions (Spec. no. 3)

measurement and load level, the M_R from the square wave mode is higher than the M_R from the haversine wave form, as shown in Figures 3.2, 3.3, and 3.4.

For the same wave form, strain gages detect less strain, which resulted in a higher M_R than with the LVDTs. Strain gages may not indicate the total strain as the LVDTs do because large stones located behind the strain gages may not transmit the total strain. In contrast, LVDTs measure the cumulative strain between two points, which may be more realistic. In addition, during the ECS testing program it has been noticed that the strain gages mounted on specimens with high air voids (such as 10%) experienced major wrinkles under the effect of repeated loading with hot water conditioning. The deformed strain gages were most likely caused by large total deformation due to compaction or densification. Because of such deficiencies associated with the strain gages and due to their cost, a decision was made to switch to LVDTs after a significant part of the ECS testing program was completed using strain gages, particularly the low air void specimens.

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 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 4-in. specimen has been used as a compromise for an 8-in. specimen (4-in. specimens are easier to produce and test and are more representative of actual pavement lift thicknesses). Thus, a 4-in. high 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 paper for 4-in. specimens. Therefore, there are two important differences between the ECS-M_R and the dynamic modulus defined in ASTM D 3497: 1) the height of the specimen is 4 in. instead of 8 in., and 2) the specimen is encapsulated in a rubber membrane throughout the test. In addition to "ECS-M_R," a diametral M_R is measured for each specimen prior to 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.

Effect of Strain Gage Glue Type

Six strain gages: X_1, X_2, X_3, Y_1, Y_2, and Y_3, were bonded on a 7.5 in. high by 4 in. in diameter plastic specimen. The strain gages were divided into two groups and each group was mounted at mid-height and opposite to the other group. The two groups are: (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 gages with to the following identification:

X_1 and Y_1: 1 inch strain gage with "super glue"

X_2 and Y_2: 1 inch strain gage with Ca-200LS glue

X_3 and Y_3: 1 inch strain gage with Testors "airplane" glue

Specimens were subjected to dynamic repeated loading by using the MTS and strains were monitored by strain indicator. Figure 3.5 shows resilient modulus results from each strain gage. The difference among glue types is not significant. The M_R on side X was higher than on side Y due to eccentricity but was later corrected. As a result of this experiment, super glue was selected for future strain gage application because it needs very short time to cure.

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 in reducing the friction between the specimen and the top cap and bottom base. The following specimens were used in the study:

1) 1 PLAS and 2 PLAS: 4 inches in diameter by 2.5 inches in height, plastic specimen
2) 54TB and 62TB: 4 inches in diameter by 2.5 inches in height, asphalt concrete specimen
3) TG61 and WG77: 4 inches in diameter by 4 inches in height, asphalt concrete specimen

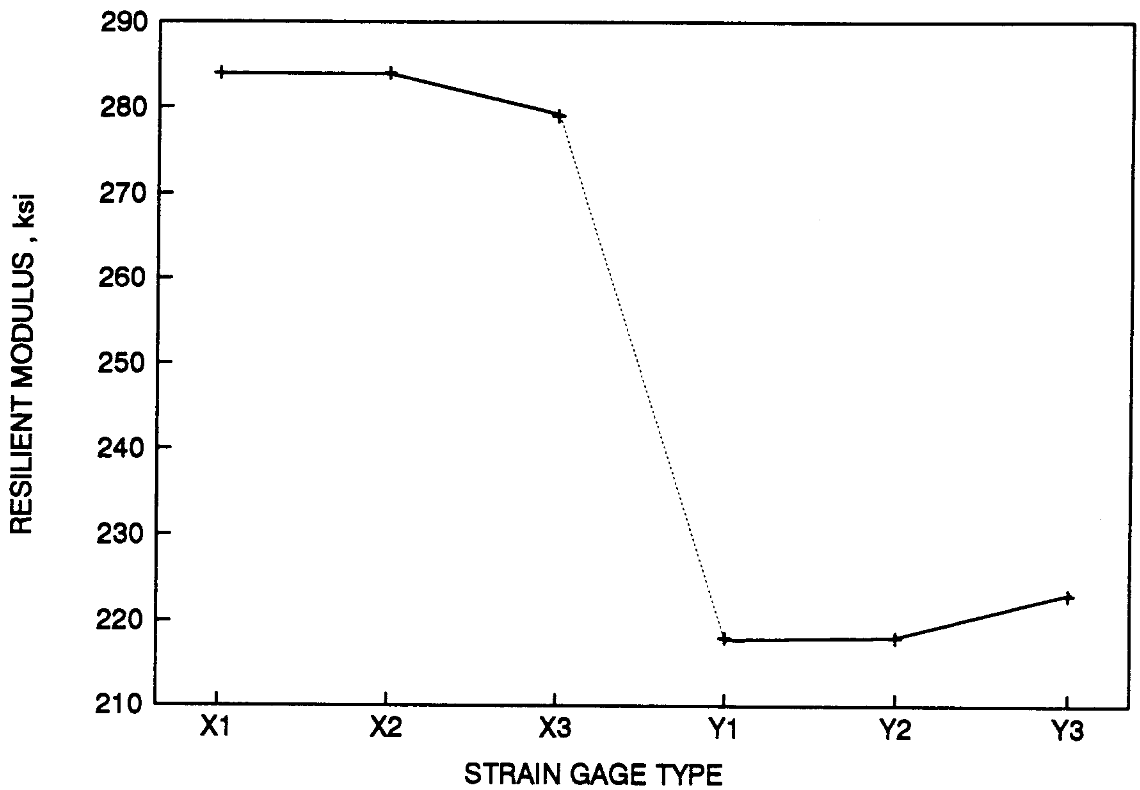


Figure 3.5 Effect of Strain Gage Mounting Glue on Resilient Modulus

Strain gages 1 in. long were used on 2.5 in. high specimens, and 2 in. strain gages were used on the 4 in. specimens. The ECS was used to conduct resilient modulus tests. Two types of 1/8 in. thick teflon disk were used: solid and perforated. Table 3.4 shows test results of tests performed on each specimen according to the following combinations:

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

The test of the one disk setting was repeated twice to show the repeatability of ECS-M_R for the test setting which 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 of one disk setting is very high. Teflon disk and test orientation does not affect the results for the plastic specimen because of the frictionless surfaces and high uniformity of this material. Teflon disks and test orientation has a significant effect on ECS-M_R of 2.5 inch asphalt concrete specimens,

Table 3.4 Resilient Modulus (ECS-M_R) for Different Test Conditions

Spec. ID	RESILIENT MODULUS (ECS-M_R), ksi					
	54TB	62TB	1PLAS.	A1PLAS.	TG61	WG77
No disks	646	546	154	137	918	904
One disk	406	433	152	138	882	900
Per. 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

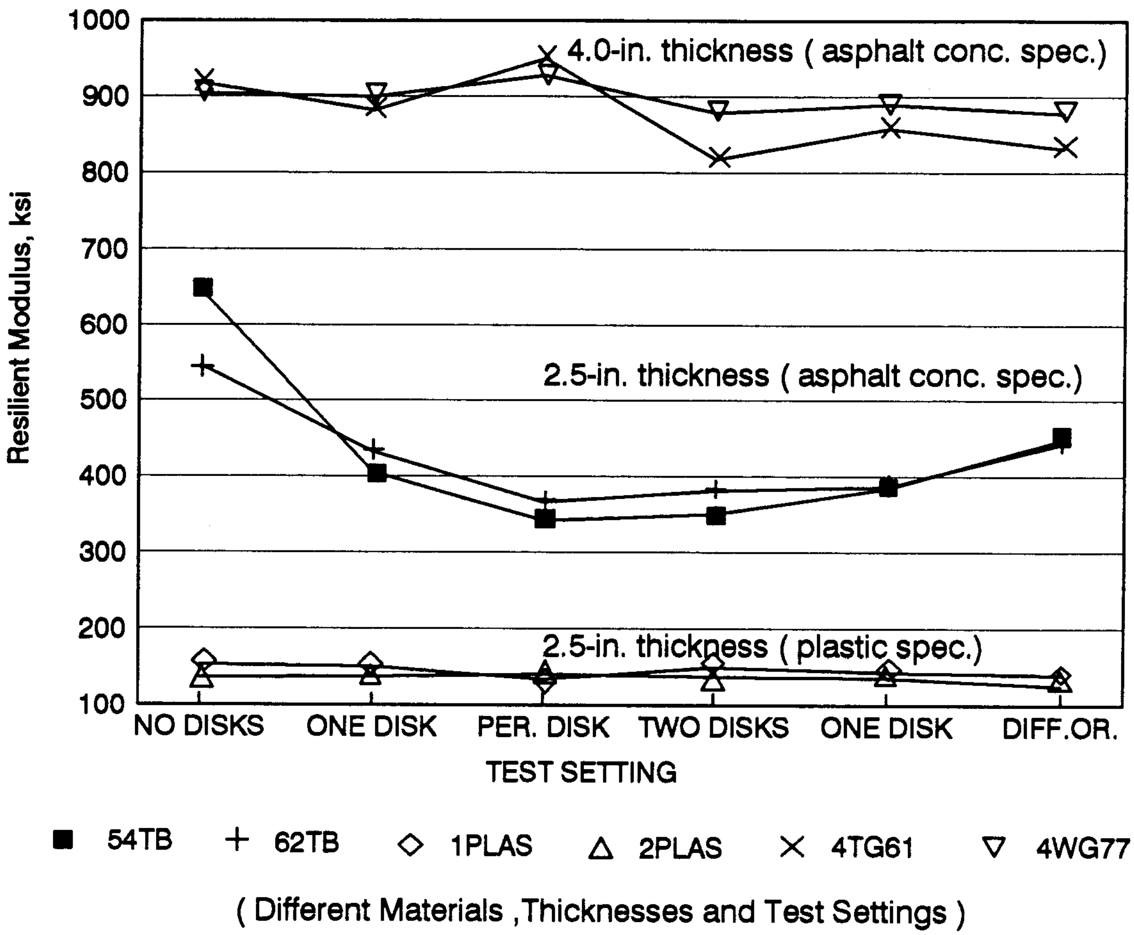


Figure 3.6 Variability of ECS-M_R for Different Test Conditions

54TB and 62TB. The effect of teflon disks and test orientation on ECS-M_R from 4 inch asphalt concrete specimens is not significant.

It was found necessary to use perforated spacers between the specimen and top cap and base plate to collect any stripped asphalt which may stick on the bottom of the top cap during the water conditioning process and change its serviceability condition, also to permit water to pass through. Perforated teflon disk top and bottom are recommended to be used with the ECS testing program. Perforation pattern, hole diameter, and groove pattern for base and top cap are shown in Figure 3.7.

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.

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

There is a general belief 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 by water. In

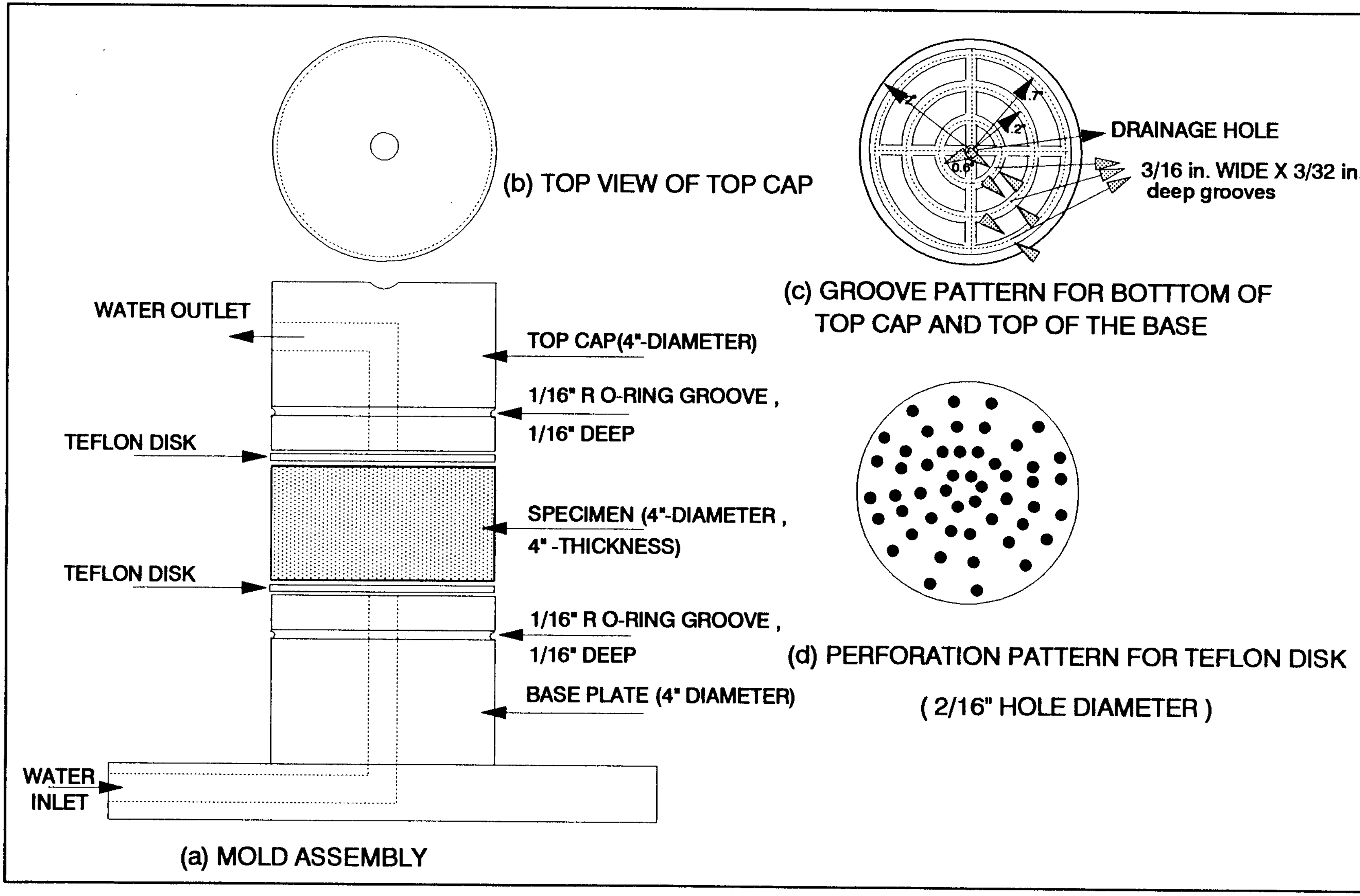


Figure 3.7 Water Conditioning Setup for Cylindrical Specimen

the ECS testing program, a relationship was hypothesized between permeability and water damage.

Based on the above introduction, it was necessary to conduct several mini-studies to investigate factors related either to permeability testing technique or the role of permeability in the testing program. The topics covered by these mini-studies are as follows:

1. Effect of specimen surface flow control on permeability.
2. Effect of compaction procedure on specimen surface sealing.
3. Differential pressure level-permeability relationship.
4. Permeability as a measure of specimen volume change.
5. Specimen internal coloring indicator.

Effect of Specimen Surface Flow on Permeability

In order 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 disadvantage of this method is that deformation of the specimen may be caused by the air pressure in the membrane.

Kumar and Goetz (1977) 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 part of both collars in order to bind the collars to the specimen. This method prevented the 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 one-third of the specimen's surface is coated with silicone and then enveloped with a cylindrical rubber membrane 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 envelope the sample base and sample top cap. This procedure has been adopted after investigating three levels of silicone seals on the surface of the specimen and under the rubber membrane which showed that the "standard" procedure of a single seal at the mid-point was adequate as shown in Figure 3.8. For additional details about the permeability protocol, see Appendix F.

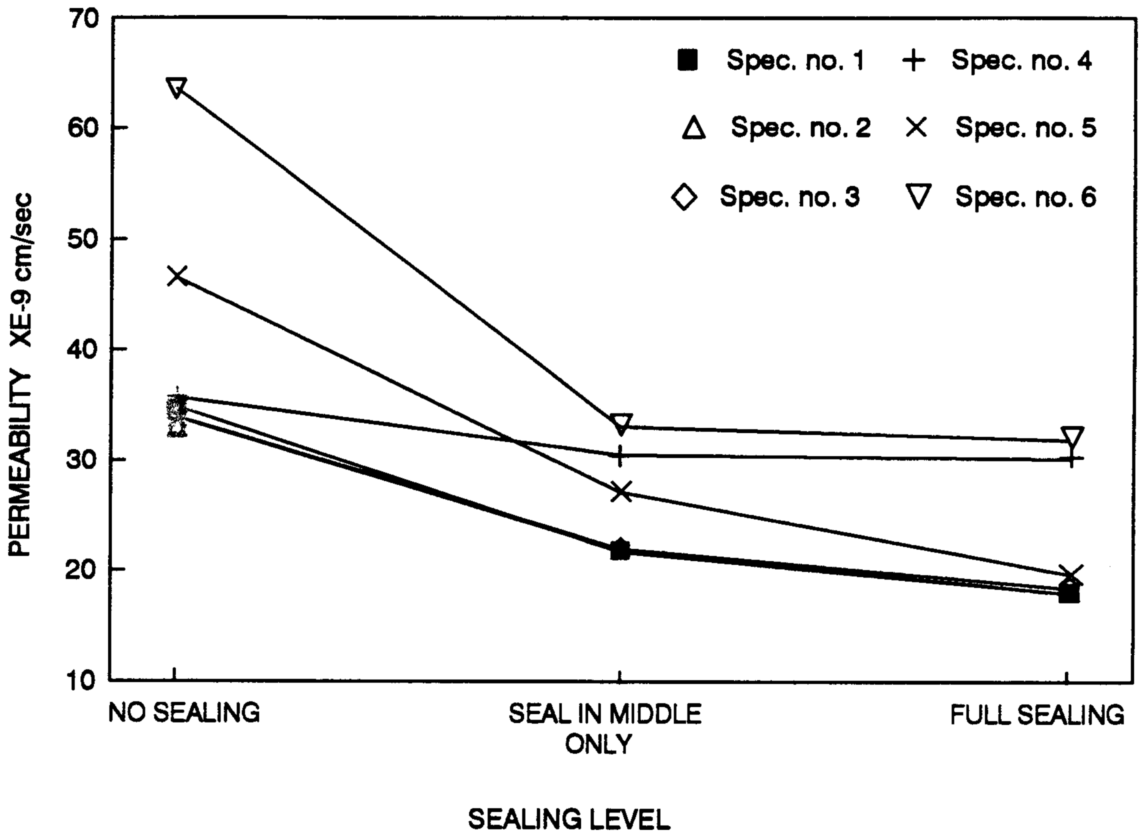


Figure 3.8 Effect of Different Methods of Specimen Sealing on Permeability

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. Both wet sawing and dry sawing were used. Table 3.5 shows a summary of permeability measurements comparing as-molded briquets and briquets with 1/4 in. sawed off each end (dry and wet sawing). Dry sawing at ambient temperature shows a 40% decrease in permeability compared to as-molded permeability. This unexpected result was due to the high temperature created by the friction between the saw and the aggregate which resulted in melting the asphalt and creation of 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 CO_2 to reduce the effect of heating during sawing. Cold dry sawing shows higher permeability (Table 3.5) than the wet sawing; however, both wet and dry sawing at ambient temperature resulted in lower permeability. From the above comparison, it was concluded that cold dry sawing is appropriate for the "standard" ECS specimen preparation, which is used for slab and field specimens.

Table 3.5 Summary of Permeability Measurements Comparing as-Molded Briquets With 1/4" Sawed of Each End

Spec. No.	% Air Voids	PERMEABILITY $k_1 \times 10^{-9}$ cm/sec			
		Before Sawing	After Wet Sawing	After Dry Sawing	Av. 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	--	

AGG.:RB
ASPH:AAG-1

Differential Pressure Level- Permeability Relationship

The permeability test is not only critical to the test parameter setup as explained earlier, but it is 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.
3. Flow in the steady state with no changes in pressure gradient.

In order to be sure 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, $\frac{Q}{\Delta P}$, of the straight line portion of the curve using linear regression equation is obtained (Kummer, 1977). By using 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 r-squared (r^2) value.

study was conducted to investigate the relation between r^2 and differential pressure level. A permeameter, Figure 3.9, was fabricated with three levels of air flow meters and four levels of differential pressure meters. The differential pressure meters are as follows:

1. Differential pressure meter with a range of 2 cm of water and minor division of 0.1 mm.
2. Differential pressure meter with a range of 5 cm of water and minor division of 1.0 mm.
3. Water manometer with a range of 30 cm. and minor division of 1.0 mm.
4. Mercury manometer with a range of 76 cm. and minor divisions of 0.25 cm.

An open-graded asphalt concrete specimen was prepared with 20% air voids so that a wide range of air flow rates and differential pressures could be used. Sixty-four air flow rates and differential pressure readings were reported for a range of differential pressure from 0.03 to 34.5 cm of water and a range of air flow rate from 110 to 18,876 cm^3/min, see Table 3.6.

Figure 3.10 shows a plot of flow rate vs. differential pressure which is divided into five ranges according to the differential pressure meters which are indicated in

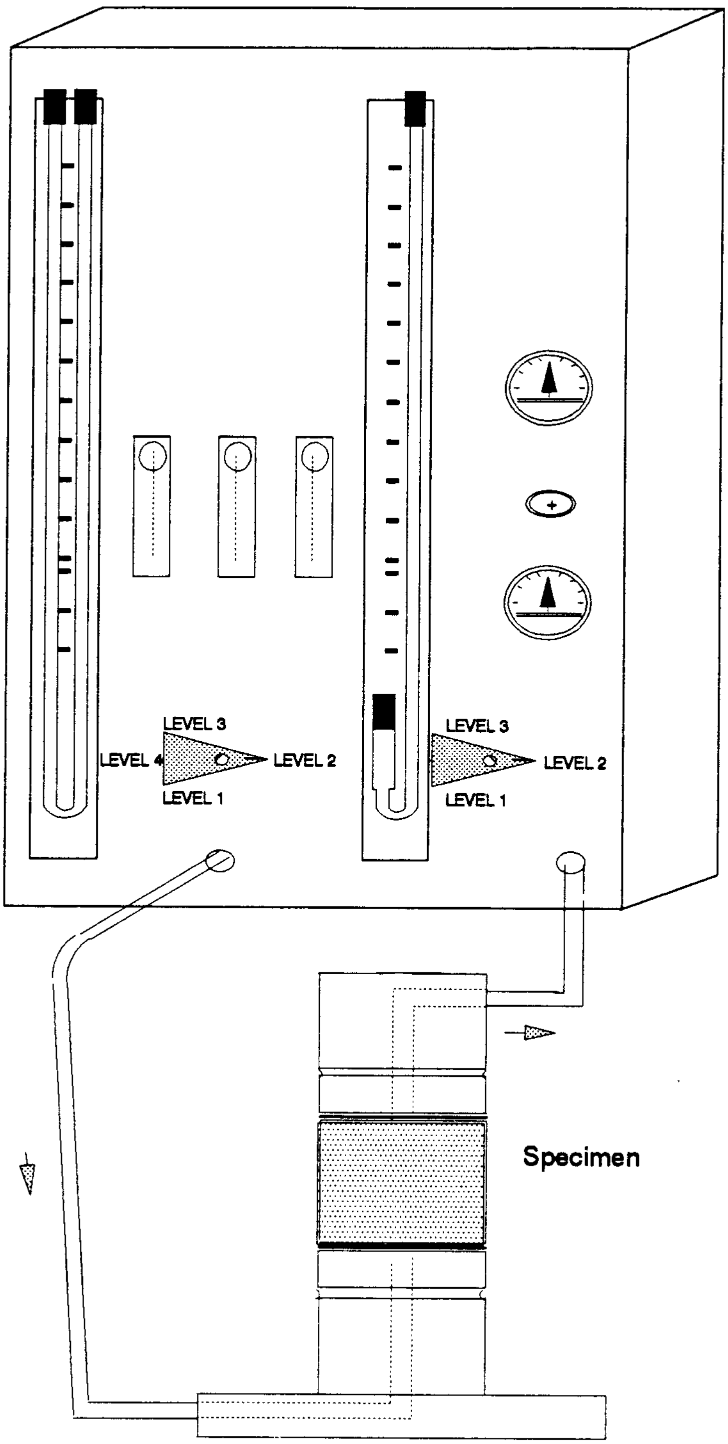


Figure 3.9 Schematic Diagram of Permeability Apparatus

Table 3.6 Rate of Air Flow Versus Differential Pressure for Open-graded Asphalt Concrete Specimen

PRESSURE mm H2O	PRESSURE cm H2O	PRESSURE in H2O	AIR FLOW cc/min	AIR FLOW SCFH
0.3	0.03	0.012	110	0.23
0.4	0.04	0.016	130	0.28
0.5	0.05	0.020	150	0.32
0.6	0.06	0.024	180	0.38
0.7	0.07	0.028	200	0.42
0.8	0.08	0.031	210	0.45
0.9	0.09	0.035	230	0.49
1.0	0.10	0.039	260	0.55
1.2	0.12	0.047	290	0.61
1.4	0.14	0.055	350	0.74
1.6	0.16	0.063	390	0.83
1.8	0.18	0.071	410	0.87
2.0	0.20	0.079	430	0.91
2.2	0.22	0.087	460	0.97
2.4	0.24	0.094	500	1.06
2.6	0.26	0.102	530	1.12
2.8	0.28	0.110	550	1.17
3.0	0.30	0.118	580	1.23
3.2	0.32	0.126	610	1.29
3.4	0.34	0.134	660	1.40
3.6	0.36	0.142	690	1.46
3.8	0.38	0.150	730	1.55
4.0	0.40	0.157	750	1.59
4.2	0.42	0.165	790	1.67
4.4	0.44	0.173	800	1.70
4.6	0.46	0.181	840	1.78
4.8	0.48	0.189	870	1.84
5.0	0.50	0.197	900	1.91
5.2	0.52	0.205	930	1.97
5.4	0.54	0.213	950	2.01
5.6	0.56	0.220	980	2.08
6.0	0.60	0.236	944	2.00
7.7	0.77	0.303	1180	2.50
9.9	0.99	0.390	1416	3.00
6.5	0.65	0.256	1652	3.50
7.5	0.75	0.295	1888	4.00
9.5	0.95	0.374	2124	4.50
12.0	1.20	0.472	2360	5.00

Table 3.6 (Cont.)

PRESSURE mm H2O	PRESSURE cm H2O	PRESSURE in H2O	AIR FLOW cc/min	AIR FLOW SCFH
14.5	1.45	0.571	2595	5.50
16.5	1.65	0.650	2831	6.00
19.0	1.90	0.748	3067	6.50
21.0	2.10	0.827	3303	7.00
23.5	2.35	0.925	3539	7.50
26.0	2.60	1.024	3775	8.00
27.5	2.75	1.083	4011	8.50
31.5	3.15	1.240	4247	9.00
35.5	3.55	1.398	4483	9.50
38.0	3.80	1.496	4719	10.00
31.5	3.15	1.240	4719	10.00
42.5	4.25	1.673	5663	12.00
61.0	6.10	2.402	6607	14.00
73.0	7.30	2.874	7550	16.00
92.0	9.20	3.622	8494	18.00
107.0	10.70	4.213	9438	20.00
121.0	12.10	4.764	10382	22.00
140.0	14.00	5.512	11326	24.00
159.0	15.90	6.260	12269	26.00
181.0	18.10	7.126	13213	28.00
200.0	20.00	7.874	14157	30.00
223.0	22.30	8.780	15101	32.00
254.0	25.40	10.000	16045	34.00
289.0	28.90	11.378	16988	36.00
314.0	31.40	12.362	17932	38.00
345.0	34.50	13.583	18876	40.00

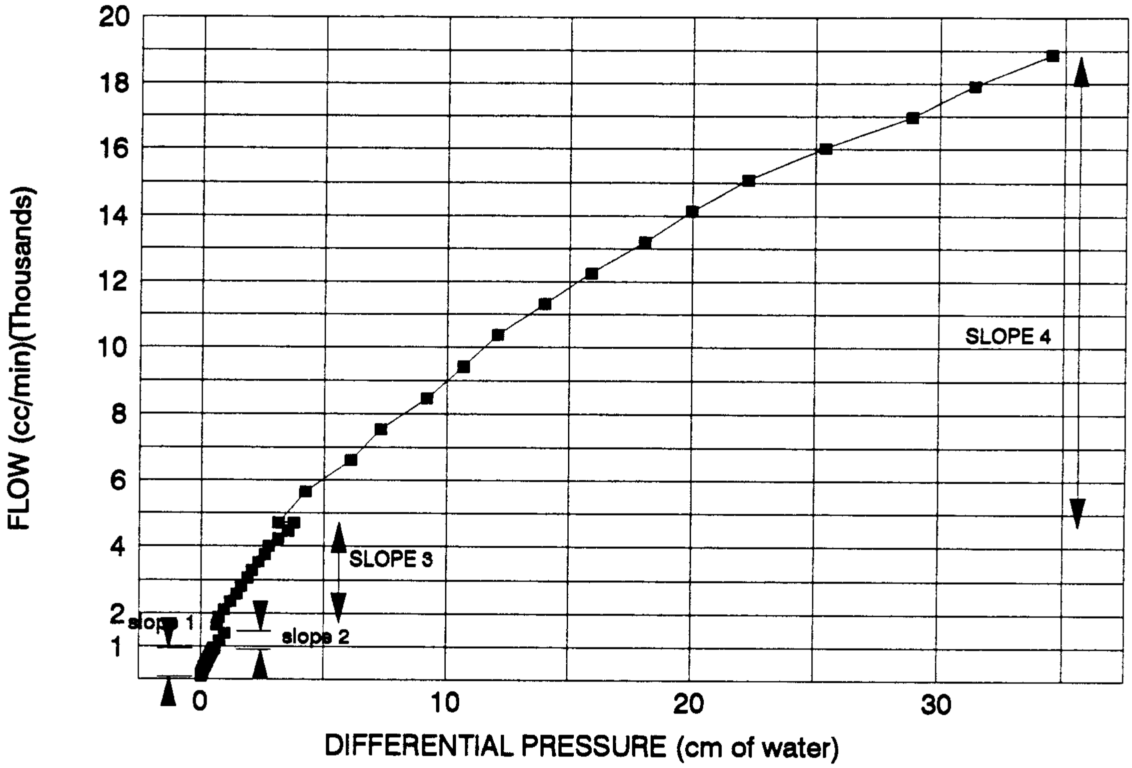


Figure 3.10 Air Flow Rate vs Differential Pressure for Open-Graded Specimen

Figure 3.10 by different slopes. The discontinuity in the data (plot) is due to changing either the flow meter or the differential pressure gage. Permeability was calculated for each range and over the entire range as well. Table 3.7 shows permeability "K," slope, and r^2. No significant relationship exists between permeability and r^2 for two of the ranges with r^2 equal 1.0. the permeabilities, K_2 and K_4, are significantly different (4.05E-08 and 2.75E-07, respectively), however.

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 rate-differential pressure measurements, as shown in Figure 3.10.

Permeability as a Measure of Specimen Volume Change

Volume change of specimen, swell or shrinkage, often occurs during water conditioning and is important for understanding asphalt pavement behavior during the water damage process. Specimen volume change was determined for AASHTO T-283 specimens (see Section 3) by reporting specimen bulk specific gravity and saturated surface dry weight for the three conditioning stages: dry, partially saturated, and at the conclusion of water conditioning. Likewise, specimen thickness

Table 3.7 The Relationship Between r-squared and Permeability

	SLOPE	PERMEABILITY, cm/s, (K)	r-squared
First Range	1661	5.81 E-07	0.99
Second Range	116	4.05 E-08	1.00
Third Range	976	3.42 E-07	0.99
Fourth Range	785	2.75 E-07	1.00
Fifth Range	449	1.57 E-07	0.97
Whole Range	638	2.24 E-07	0.95

was measured using ASTM D 3549 for the specimen for the same three conditioning stages. Logically, any thickness increase should be combined with volume increase. In contrast, the results show no significant relation between specimen thickness change and specimen volume change, as shown in Figure 3.11. This means that bulk specific gravity test is not the 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 LVDT attached to the top of the specimen and connected to a PC computer for data acquisition.
2. Monitoring the internal voids volume changes by determining water permeability at the end of each water conditioning cycle.

Specimen Internal Coloring Indicator

In order to investigate water accessibility to the internal air voids of asphalt concrete specimens, dye-treated water was used to wet specimens under the effect of the ECS standard vacuum, 20 inches of Hg. The specimens were then split open diameterally and examined. All interior voids appeared to be dye-stained, thus water access was

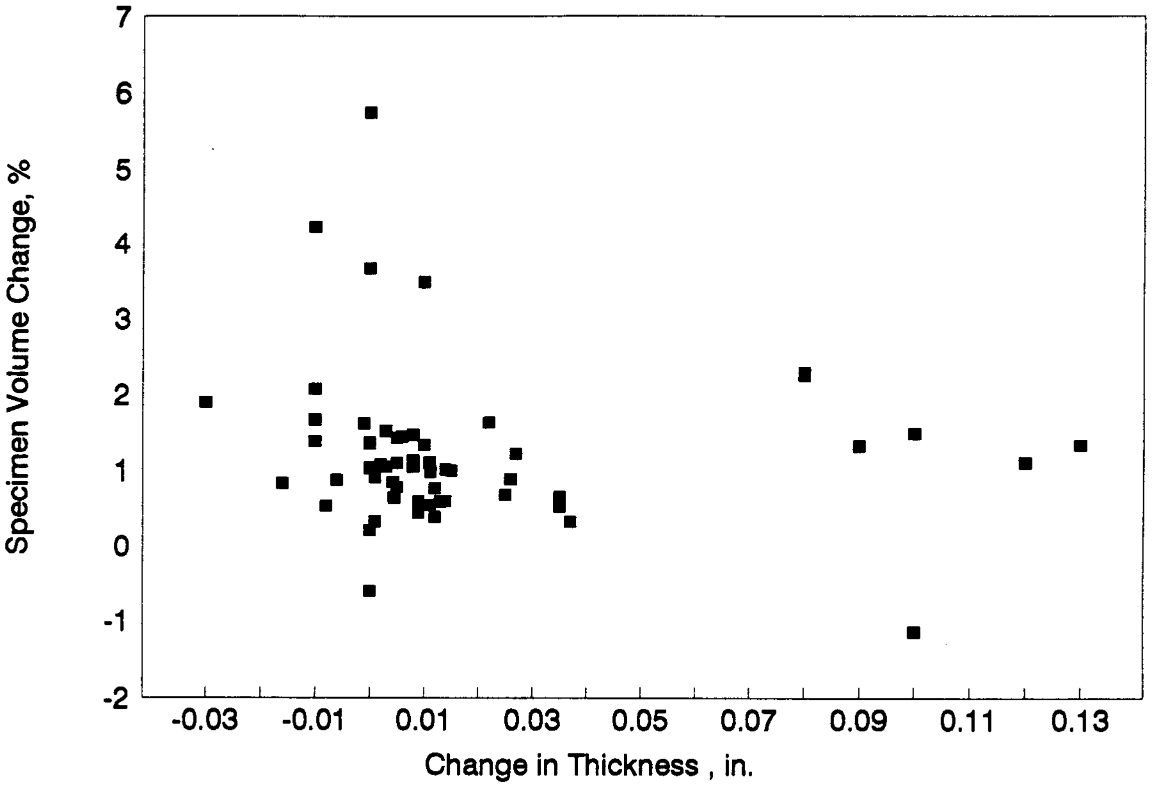


Figure 3.11 Relationship Between Specimen Thickness and Volume Change

complete. Figure 3.12 shows the setup that was used to investigate the accessibility of the water through compacted asphalt concrete specimens.

Methods of Air Voids 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 method ASTM D 1188. Percent air voids have been calculated by the two methods for each size specimens 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 the four combinations. There is significant but consistance difference between the two methods, as might be expected.

Aggregate type has considerable effect on the difference, because aggregate gradation and aggregate shape influence specimen surface air voids which are

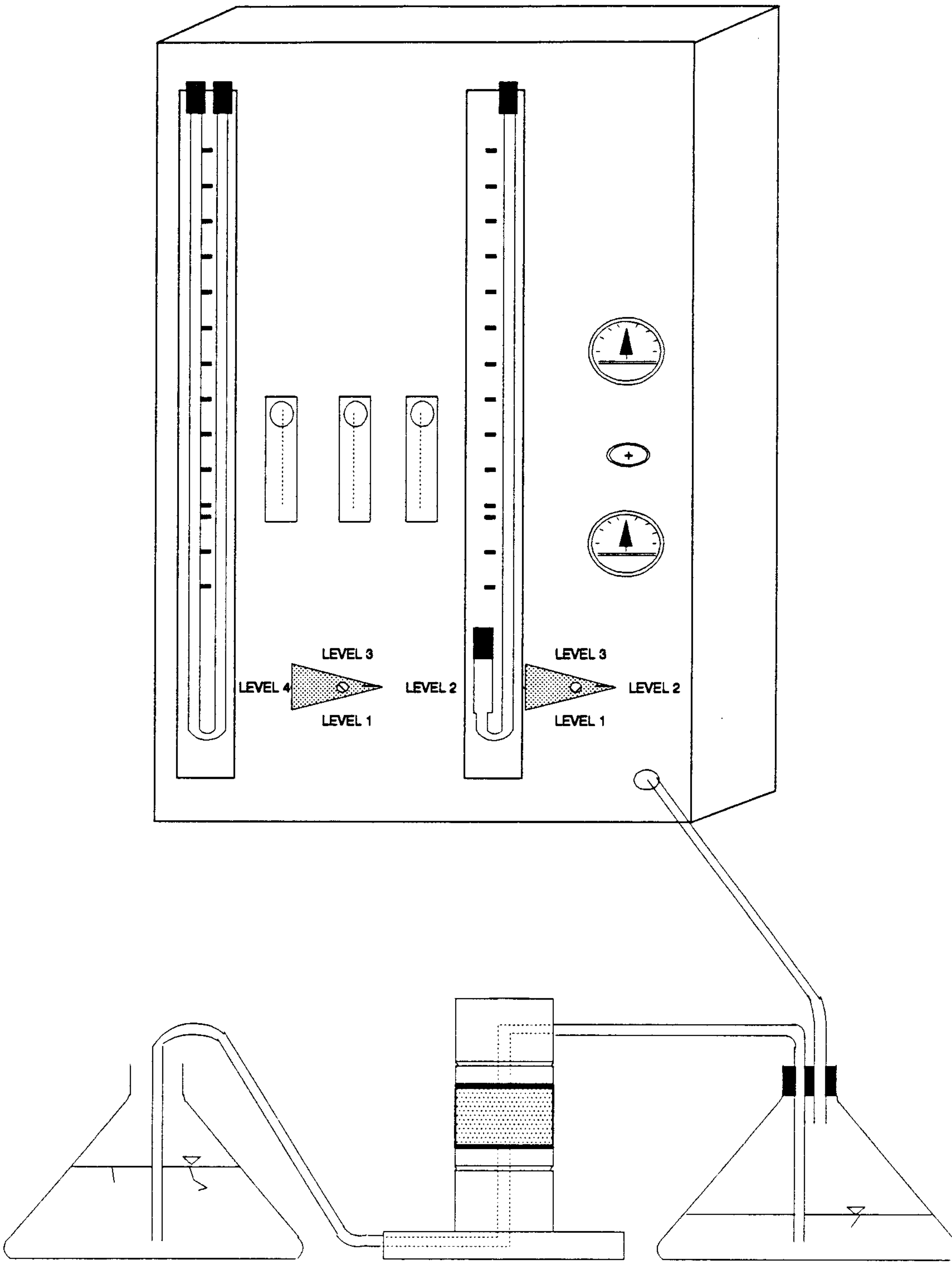


Figure 3.12 Schematic Diagram of Dye - Treatment Setup

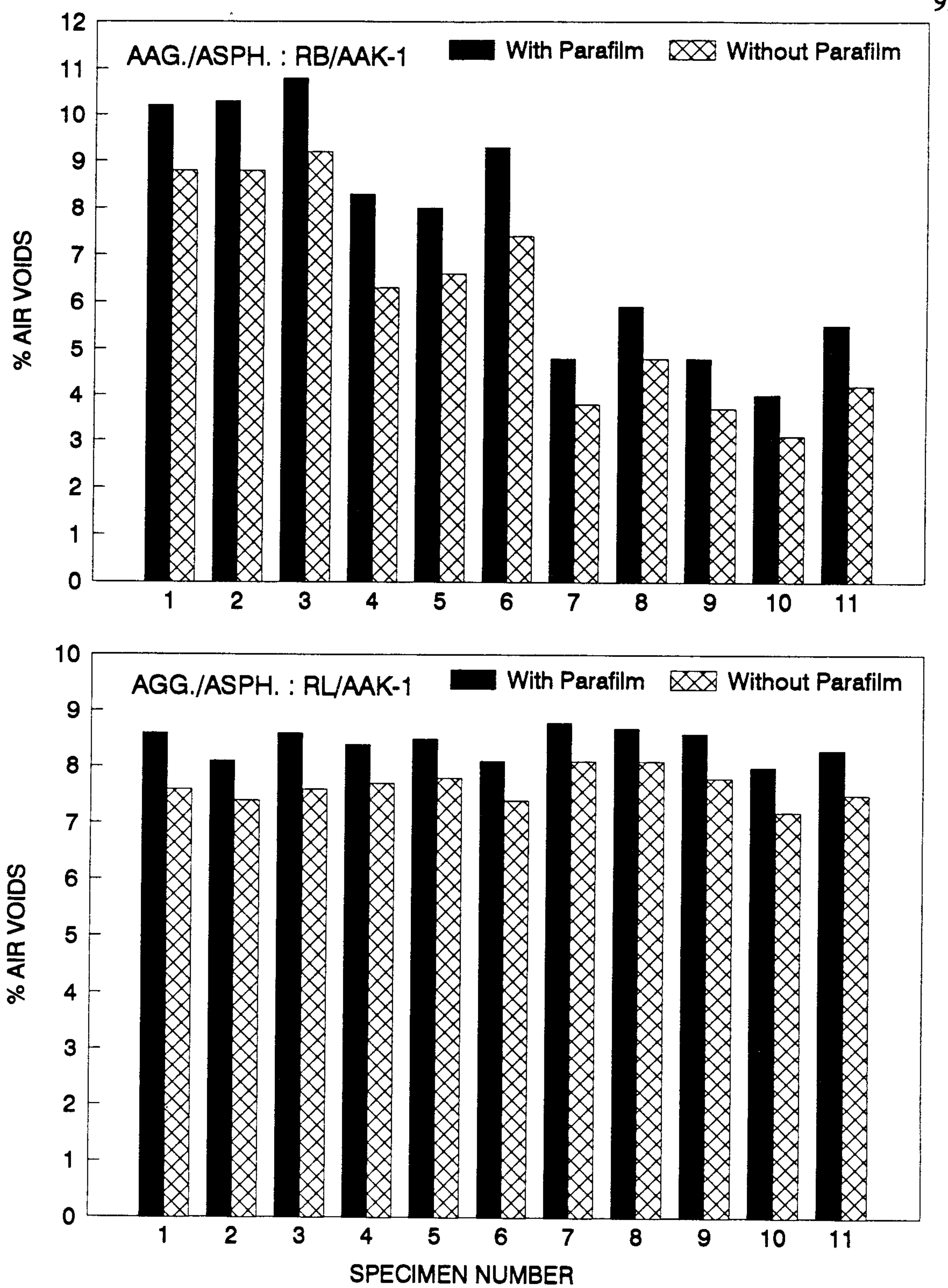


Figure 3.13 Comparison of Percent Air Void Calculation With and Without Parafilm

included in the percent air voids in the case "with parafilm," and excluded in the case "without parafilm."

The resulting air voids from the RB/AAK-1 mixture with parafilm are 1.5% higher than without parafilm for the same mixture. Aggregate type has a significant effect on the difference, because aggregate texture 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."

AASHTO T-283 is part of the water sensitivity testing program. As part of this procedure specimen specific gravity is required for three conditions: dry condition, 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. Due to this difficulty, it was decided to test AASHTO T-283 dry specimens using both methods and test partially saturated and water conditioned specimens by only the "without parafilm" method. Degree of saturation and water conditioning criteria on AASHTO T-283 test will be based on "without" parafilm specific gravities, saturated surface dry weight.

The ECS testing program was based only on specific gravity and air voids calculated from ASTM D 1188 "with parafilm" wrapping, because this procedure has an advantage over the ASTM D 2726 in that the parafilm keeps the specimen dry. Another advantage over ASTM D 1188 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 previously discussed in section 2. 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 on each asphalt-aggregate combination. Specimens 4-in. in diameter by 4-in. high were used for the ECS testing program. Only one combination, RL aggregate, 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 (early 1990) testing, numerous 4-in. diameter by 2.5-in. high specimens were tested for several conditioning codes and these results are included in Appendix B. Because a 4 in. high specimen was established for the ECS testing (as discussed earlier), only 4-in. high specimens results were used in the following analysis sections.

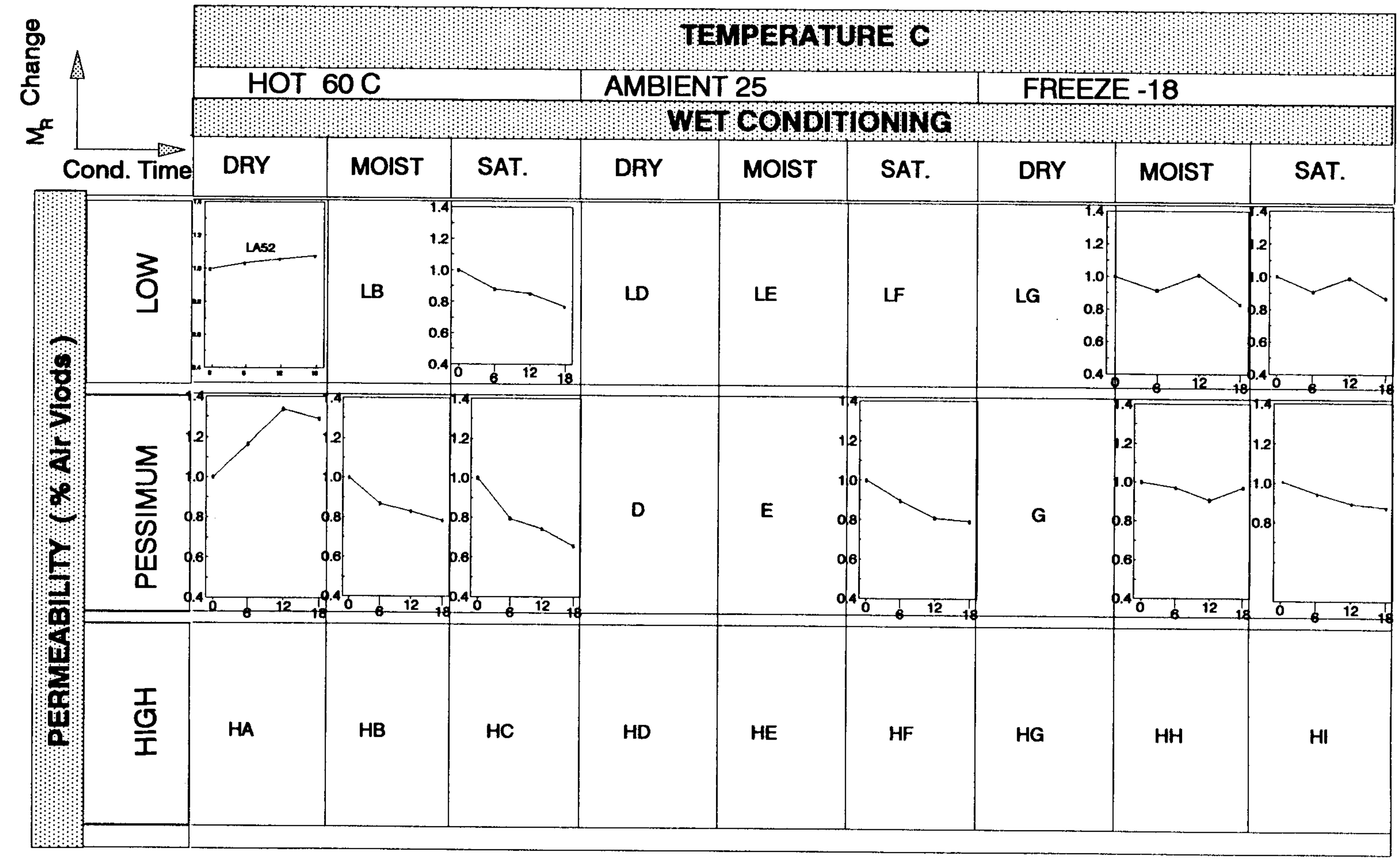


Figure 3.14 Summary of Plots of Different Conditioning Levels

Table 3.8 Summary of The ECS Water Conditioning Test Results

Spec. No.	Test Ident.	Time (hr)	M_R (ksi)	Ret. M_R (ratio)	Perm. cm/s XE-9	Ret. Perm. (ratio)	Stripping Rate
1	RLC*RL/AAK-1	0	501	1.00	0.76	1.00	
		6	441	0.88	0.84	1.11	
		12	427	0.85	0.64	0.84	
		18	384	0.77	0.57	0.75	20
2	RLC*RB/AAG-1	0	1018	1.00	0.30	1.00	
		6	860	0.84	0.26	0.87	
		12	854	0.84	0.18	0.60	
		18	324	0.81	0.15	0.50	10
3	RC*RL/AAK-1	0	594	1.00	1.91	1.00	
		6	472	0.79	1.76	0.92	
		12	441	0.74	1.53	0.80	
		18	390	0.66	1.25	0.65	50
4	RC*RL/AAG-1	0	1061	1.00	4.36	1.00	
		6	809	0.76	1.37	0.31	
		12	836	0.79	1.67	0.38	
		18	697	0.66	2.18	0.50	30
5	RC*RB/AAK-1	0	346	1.00	2.4	1.00	
		6	291	0.84	1.48	0.62	
		12	286	0.83	0.83	0.35	
		18	264	0.76	0.51	0.21	30
6	RC*RB/AAG-1	0	727	1.00	1.56	1.00	
		6	661	0.91	1.11	0.71	
		12	603	0.83	0.82	0.53	
		18	580	0.80	0.40	0.26	30
7	SLI111RL/AAK-1	0	1143	1.00	0.09	1.00	
		6	1034	0.91	0.06	0.67	
		12	1131	0.99	0.07	0.78	
		18	991	0.87			5
8	SLI*RL/AAG-1	0	994	1.00	0.22	1.00	
		6	935	0.94	0.2	0.91	
		12	918	0.92	0.29	1.32	
		18	872	0.88			5
9	SLI*RB/AAK-1	0	587	1.00	0.22	1.00	
		6	544	0.93	0.21	0.95	
		12	545	0.93	0.14	0.64	
		18	512	0.87	0.17	0.77	5

Specimen No.	Test Ident.	Time (hr)	M_R (ksi)	Ret. M_R (ratio)	Perm. cm/s XE-9	Ret. Perm. (ratio)	Stripping Rate
10	SLI*RB/AAG-1	0	789	1.00	0.26	1.00	
		6	756	0.96	0.24	0.92	
		12	726	0.92	0.15	0.58	
		18	675	0.86	0.17	0.65	5
11	SI*RL/AAK-1	0	507	1.00	2.33	1.00	
		6	471	0.93	2.71	1.16	
		12	442	0.87	2.67	1.15	
		18	433	0.85	2.33	1.00	10
12	SI59RL/AAG-1	0	1102	1.00	5.07	1.00	
		6	971	0.88	1.99	0.39	
		12	909	0.82	3.95	0.78	
		18	962	0.87	2.85	0.56	10
13	SI*RB/AAK-1	0	437	1.00	1.63	1.00	
		6	415	0.95	1.36	0.83	
		12	407	0.93	2.37	1.45	
		18	369	0.84	1.99	1.22	5
14	SI*RB/AAG-1	0	808	1.00	2.57	1.00	
		6	756	0.94	2.40	0.93	
		12	695	0.86	2.21	0.86	
		18	684	0.85	1.79	0.70	10
15	RB*RL/AAK-1	0	435	1.00	1.36	1.00	
		6	378	0.87	0.93	0.68	
		12	361	0.83	0.58	0.43	
		18	341	0.78	0.64	0.47	20
16	SH214RL/AAK-1	0	331	1.00	2.62	1.00	
		6	321	0.97	2.31	0.88	
		12	300	0.91	2.1	0.80	
		18	321	0.97	2.13	0.81	5
17	SH*RB/AAG-1	0	803	1.00	5.79	1.00	
		6	787	0.98	8.11	1.40	
		12	695	0.87	9.97	1.72	
		18	683	0.85	7.46	1.29	5
18	SLH99RL/AAK-1	0	692	1.00			
		6	632	0.91			
		12	698	1.01			
		18	573	0.83			10

Table 3.8(Continued)

Specimen No.	Test Ident.	Time (hr)	M_R (ksi)	Ret. M_R (ratio)	Perm. cm/s XE-9	Ret. Perm. (ratio)	Stripping Rate
19	RF*RL/AAK-1	0	355	1.00	1.91	1.00	
		6	318	0.90	1.73	0.91	
		12	287	0.81	1.49	0.78	
		18	281	0.79	1.07	0.56	5
20	SC*RL/AAK-1	0	411	1.00	1.69	1.00	
		6	359	0.87	1.39	0.82	
		12	322	0.78	1.37	0.81	
		18	300	0.73	0.9	0.53	30
21	VC47RL/AAK-1	0	595	1.00	8.95	1.00	
		6	657	1.10	7.5	0.84	
		12	636	1.07	7.77	0.87	
		18	605	1.02	8.44	0.94	5
22	A31RL/AAK-1	0	395	1.00	5.7	1.00	
		6	460	1.16	5	0.88	
		12	528	1.34	5.1	0.89	
		18	509	1.29	5.1	0.89	
23	SC214RL/AAK-1	0	281	1.00	3.2	1.00	
		24	226	0.81	2.1	0.66	
		48	195	0.70	1.1	0.34	
		72	188	0.67	0.9	0.28	40

RLC*RL/AAK-1: * Indicates two or more replicatios

ECS-M_R

Triaxial resilient modulus (ECS-M_R) was performed using the ECS at 25°C on each specimen in the dry condition and again following each water 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 hrs) and the test results are shown in Table 3.8 (specimens 20 and 23). Graphical display and discussion are in Chapter 4.

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 (10 in. Hg vacuum, equivalent to 5 psi) and the other set with repeated loading (200 lb. or 17 psi). The data for these two sets (Specimens 20 and 1) are shown in Table 3.8. The effect of repeated loading is discussed later.

It is generally understood (without investigation) that the water is the best fluid to be used for conditioning asphalt concrete specimens to investigate moisture-related problems. But actually, in the field, there are pavements that show water damage resulting from evaporation 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. Conditioning a specimen with vapor was conducted by adjusting the environmental conditioning cabinet at temperature 60°C and at relative humidity 90%. Vapor was pulled through the specimen by vacuum (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 flow meter was connected to maintain the vacuum level according to the ECS conditioning procedure (10 in. Hg). The same vapor conditioning setup has been used to conduct "air" conditioning by maintaining the same temperature (60°C) and adjusting relative humidity to 0%. For water conditioning, the normal ECS setup was used to conduct hot-wet conditioning (C-conditioning code) 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 (Specimens 21, 22, and 3). The vapor conditioning setup was fabricated as shown in Figure 3.15.

In addition to the above investigations, the main ECS experiment included the effect of the following variables:

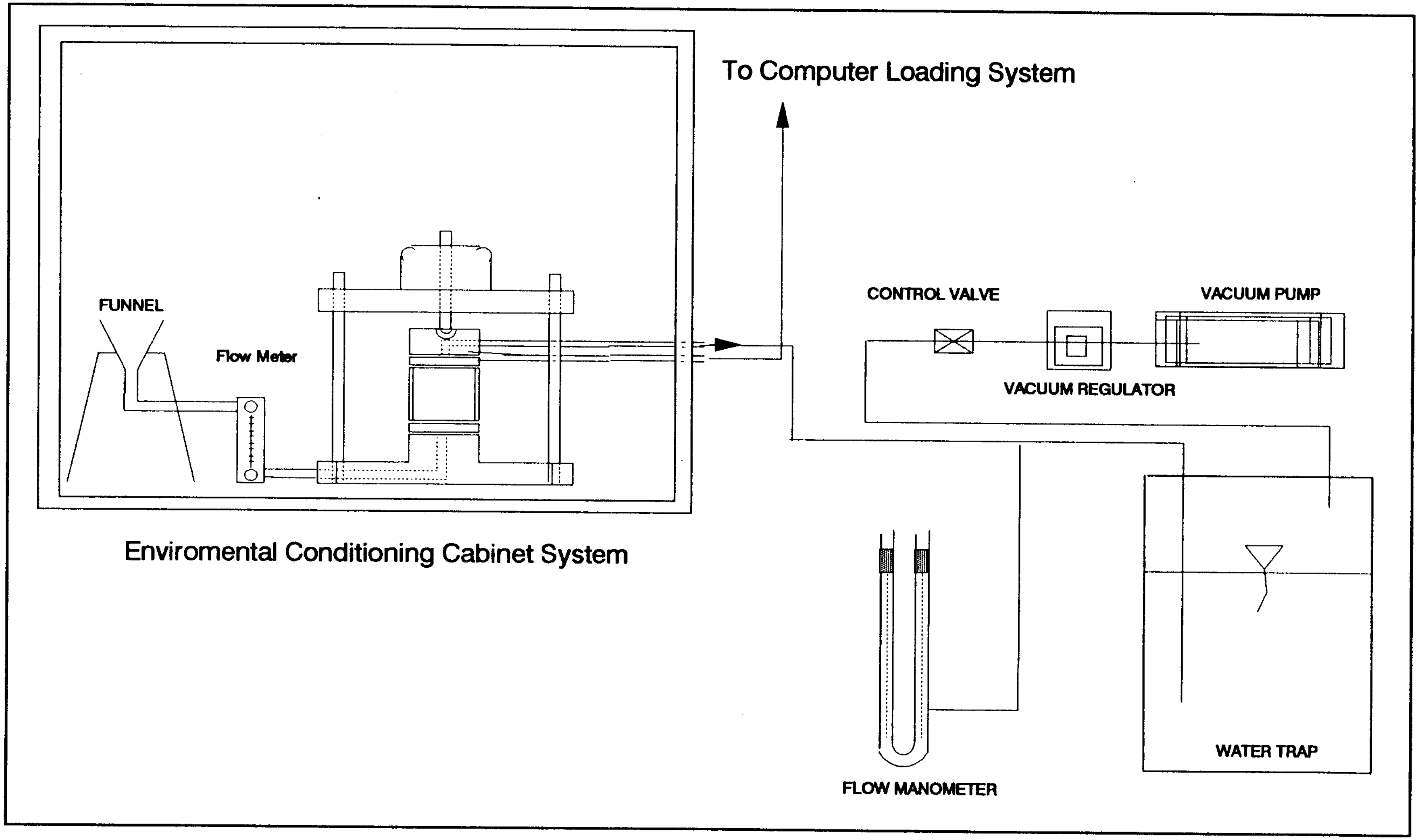


Figure 3.15 Schematic Drawing of Vapor Conditioning Setup

- Vacuum level,
- Air void level, and
- Saturation level.

Permeability

It is generally understood that the higher the air voids, the higher permeability and the more water that can penetrate (and remain, to some degree) in an asphalt pavement. But when aggregate type and aggregate gradation are variables, mixtures may have similar air voids but the permeability of one may be as much as twice that of the other one. 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 (i.e., permeability is proportional to voids content) are concluded from studies conducted on similar aggregates.

Since the permeability represents both the volume of air voids and their structure, this parameter may be a better indicator of performance than voids alone. In this study, permeability was measured using air for each specimen before beginning water conditioning. Table 3.9 shows air permeability and air voids 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

Table 3.9 Permeability Versus Percent Air Voids

Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)	Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)	Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)
1	RL/AAK	5.0	1.80	44	RL/AAK	5.1	2.94	87	RL/AAK	8.0	3.30
2	RL/AAK	4.5	1.30	45	RL/AAK	6.4	0.17	88	RL/AAK	7.2	2.60
3	RL/AAK	7.1	7.48	46	RL/AAK	4.9	13.85	89	RL/AAK	7.8	3.20
4	RL/AAK	7.0	3.40	47	RL/AAK	4.4	9.03	90	RL/AAK	8.0	5.50
5	RL/AAK	7.1	3.40	48	RL/AAK	4.7	1.33	91	RL/AAK	8.5	5.77
6	RL/AAK	3.9	0.14	49	RL/AAK	6.7	2.58	92	RL/AAK	8.1	5.19
7	RL/AAK	7.7	5.42	50	RL/AAK	6.9	1.75	93	RL/AAK	8.1	4.96
8	RL/AAK	7.9	2.24	51	RL/AAK	6.0	0.89	94	RL/AAK	8.0	3.20
9	RL/AAK	7.9	4.37	52	RL/AAK	5.6	1.47	95	RL/AAK	7.6	4.60
10	RL/AAK	9.1	5.26	53	RL/AAK	5.3	1.20	96	RL/AAK	4.9	0.15
11	RL/AAK	8.5	3.79	54	RL/AAK	5.5	4.48	97	RL/AAK	7.8	3.05
12	RL/AAK	3.8	0.64	55	RL/AAK	7.4	7.20	98	RL/AAK	7.1	6.61
13	RL/AAK	8.0	4.71	56	RL/AAK	7.4	7.25	99	RL/AAK	4.8	0.52
14	RL/AAK	8.9	3.25	57	RL/AAK	7.6	6.86	100	RL/AAK	9.0	5.70
15	RL/AAK	8.8	5.21	58	RL/AAK	9.0	4.77	101	RL/AAK	7.9	4.26
16	RL/AAK	8.0	4.78	59	RL/AAK	7.8	5.11	102	RL/AAK	9.2	2.84
17	RL/AAK	6.8	2.61	60	RL/AAK	8.8	3.73	103	RL/AAK	8.2	3.80
18	RL/AAK	9.0	5.70	61	RL/AAK	8.1	5.70	104	RL/AAK	8.3	4.90
19	RL/AAK	8.4	2.46	62	RL/AAK	7.5	3.40	105	RL/AAK	8.6	7.70
20	RL/AAK	6.1	0.22	63	RL/AAK	7.5	4.80	106	RL/AAK	9.1	13.30
21	RL/AAK	6.5	0.19	64	RL/AAK	8.5	6.00	107	RL/AAK	8.6	5.00
22	RL/AAK	7.0	7.50	65	RL/AAK	7.7	4.40	108	RL/AAK	8.3	5.90
23	RL/AAK	4.2	6.80	66	RL/AAK	7.4	4.50	109	RL/AAK	9.3	1.78
24	RL/AAK	8.5	6.20	67	RL/AAK	7.8	5.40	110	RL/AAK	8.3	5.81
25	RL/AAK	8.1	12.83	68	RL/AAK	7.2	3.20	111	RL/AAK	8.0	5.03
26	RL/AAK	6.4	4.25	69	RL/AAK	7.6	3.30	112	RL/AAK	9.5	6.46
27	RL/AAK	7.0	3.59	70	RL/AAK	7.4	4.10	113	RL/AAK	9.1	6.10
28	RL/AAK	6.4	13.85	71	RL/AAK	7.6	4.20	114	RL/AAK	8.6	5.00
29	RL/AAK	6.4	9.53	72	RL/AAK	7.7	4.40	115	RL/AAK	8.6	5.50
30	RL/AAK	5.9	1.27	73	RL/AAK	7.4	4.50	116	RL/AAK	6.6	1.20
31	RL/AAK	7.1	2.46	74	RL/AAK	8.1	5.70	117	RL/AAK	6.9	1.50
32	RL/AAK	7.0	0.87	75	RL/AAK	7.8	5.40	118	RL/AAK	5.9	1.17
33	RL/AAK	8.0	7.40	76	RL/AAK	7.5	4.80	119	RL/AAK	6.4	1.10
34	RL/AAK	6.2	3.00	77	RL/AAK	8.5	6.00	120	RL/AAK	7.2	7.72
35	RL/AAK	6.1	4.56	78	RL/AAK	7.5	3.40	121	RL/AAK	5.2	0.83
36	RL/AAK	5.9	1.74	79	RL/AAK	7.8	3.40	122	RL/AAK	5.2	0.69
37	RL/AAK	6.6	1.86	80	RL/AAK	7.7	3.40	123	RL/AAK	8.3	8.95
38	RL/AAK	7.4	14.50	81	RL/AAK	8.0	3.60	124	RL/AAK	7.1	7.48
39	RL/AAK	6.7	4.21	82	RL/AAK	8.3	3.60	125	RL/AAK	7.7	5.42
40	RL/AAK	5.8	1.75	83	RL/AAK	7.9	3.40	126	RL/AAK	8.0	20.38
41	RL/AAK	5.7	1.89	84	RL/AAK	7.0	2.70	127	RL/AAG	7.2	29.04
42	RL/AAK	5.7	5.71	85	RL/AAK	7.7	3.00	128	RL/AAG	6.9	1.83
43	RL/AAK	6.4	0.92	86	RL/AAK	7.2	2.90	129	RL/AAG	4.9	1.03

Table 3.9 (cont.)

Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)	Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)	Spec. no.	Asph.–Agg. Type	Air Voids (%)	Air Perm. X E–9 (cm/s)
130	RL/AAG	4.1	0.32	173	RB/AAK	0.0	19.53	216	RB/AAG	8.1	2.88
131	RL/AAG	7.0	1.63	174	RB/AAK	7.6	2.88	217	RB/AAG	7.2	1.71
132	RL/AAG	7.3	5.10	175	RB/AAK	8.1	4.99	218	RB/AAG	6.1	1.33
133	RL/AAG	6.1	1.71	176	RB/AAK	8.0	1.79	219	RB/AAG	5.1	0.00
134	RL/AAG	6.4	2.30	177	RB/AAK	6.3	6.14	220	RB/AAG	6.5	4.09
135	RL/AAG	7.6	0.16	178	RB/AAK	6.3	6.59	221	RB/AAG	7.4	4.65
136	RL/AAG	6.2	0.20	179	RB/AAK	6.4	5.96	222	RB/AAG	7.8	9.32
137	RL/AAG	7.3	0.24	180	RB/AAK	9.4	1.19	223	RB/AAG	7.4	6.05
138	RL/AAG	7.1	6.20	181	RB/AAK	10.7	4.90	224	RB/AAG	6.7	3.34
139	RL/AAG	7.0	0.12	182	RB/AAK	11.1	4.86	225	RB/AAG	5.7	0.10
140	RL/AAG	8.0	2.17	183	RB/AAK	6.3	6.14	226	RB/AAG	5.9	0.25
141	RL/AAG	5.4	0.43	184	RB/AAK	6.3	6.59	227	RB/AAG	7.6	3.30
142	RL/AAG	6.6	0.98	185	RB/AAK	6.4	5.96	228	RB/AAG	7.4	4.10
143	RL/AAG	6.7	1.26	186	RB/AAK	9.4	1.19	229	RB/AAG	7.6	4.20
144	RL/AAG	7.0	6.94	187	RB/AAK	10.7	4.90	230	RB/AAG	9.0	4.80
145	RL/AAG	7.7	7.66	188	RB/AAK	11.1	4.86	231	RB/AAG	7.8	2.00
146	RL/AAG	7.2	7.33	189	RB/AAK	7.4	1.90	232	RB/AAG	8.8	3.70
147	RL/AAG	8.0	8.30	190	RB/AAK	7.8	3.70	233	RB/AAG	6.3	2.40
148	RL/AAG	7.2	6.72	191	RB/AAK	7.4	2.40	234	RB/AAG	6.3	2.60
149	RL/AAG	7.8	8.22	192	RB/AAK	6.7	1.30	235	RB/AAG	6.4	2.40
150	RL/AAG	4.2	0.33	193	RB/AAK	5.7	0.00	236	RB/AAG	9.4	1.20
151	RL/AAG	7.2	29.04	194	RB/AAK	5.9	0.10	237	RB/AAG	10.7	4.90
152	RL/AAG	7.0	1.63	195	RB/AAK	6.8	10.40	238	RB/AAG	11.1	4.90
153	RB/AAK	8.0	7.30	196	RB/AAG	4.0	1.11	239	RB/AAG	8.9	3.40
154	RB/AAK	8.1	2.30	197	RB/AAG	4.3	1.70	240	RB/AAG	8.0	2.70
155	RB/AAK	4.6	0.99	198	RB/AAG	8.2	13.39	241	RB/AAG	8.0	4.30
156	RB/AAK	4.1	0.86	199	RB/AAG	7.9	8.92	242	RB/AAG	8.2	1.07
157	RB/AAK	6.8	10.40	200	RB/AAG	8.2	5.02	243	RB/AAG	4.0	1.11
158	RB/AAK	6.4	9.40	201	RB/AAG	7.7	7.70	244	RB/AAG	8.2	13.39
159	RB/AAK	9.5	18.77	202	RB/AAG	4.5	0.39	245	RB/AAG	8.3	1.91
160	RB/AAK	7.4	0.33	203	RB/AAG	5.2	1.13	246	RB/AAG	8.3	20.99
161	RB/AAK	8.0	0.36	204	RB/AAG	8.3	20.99	247	RB/AAG	8.2	15.94
162	RB/AAK	6.5	5.00	205	RB/AAG	7.0	1.76	248	RB/AAG	9.2	10.60
163	RB/AAK	7.0	5.40	206	RB/AAG	7.8	2.21	249	RB/AAG	8.3	19.69
164	RB/AAK	6.3	0.51	207	RB/AAG	8.2	3.81	250	RB/AAG	7.9	6.88
165	RB/AAK	9.7	31.23	208	RB/AAG	7.3	5.62	251	RB/AAG	7.2	14.06
166	RB/AAK	6.2	1.38	209	RB/AAG	6.6	2.40	252	RB/AAG	7.3	12.17
167	RB/AAK	5.0	0.00	210	RB/AAG	7.1	3.29				
168	RB/AAK	6.6	5.75	211	RB/AAG	5.4	0.00				
169	RB/AAK	6.9	15.26	212	RB/AAG	5.5	0.08				
170	RB/AAK	4.3	0.02	213	RB/AAG	5.0	1.44				
171	RB/AAK	9.3	0.66	214	RB/AAG	4.6	0.00				
172	RB/AAK	9.4	6.36	215	RB/AAG	8.0	3.74				

only as a relative indicator for air voids structure change due to water conditioning as well as repeated loading.

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. The primary shortcoming with this method is the subjective nature of the results. Sometimes, in an attempt to limit the subjectivity of the visual evaluation, 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 the use of more than one rater and then averaging 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 play a significant role in percent coating rating given to an asphalt sample after the boiling test. This is due to the hot asphalt recoating the stripped aggregate from the remaining asphalt. 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

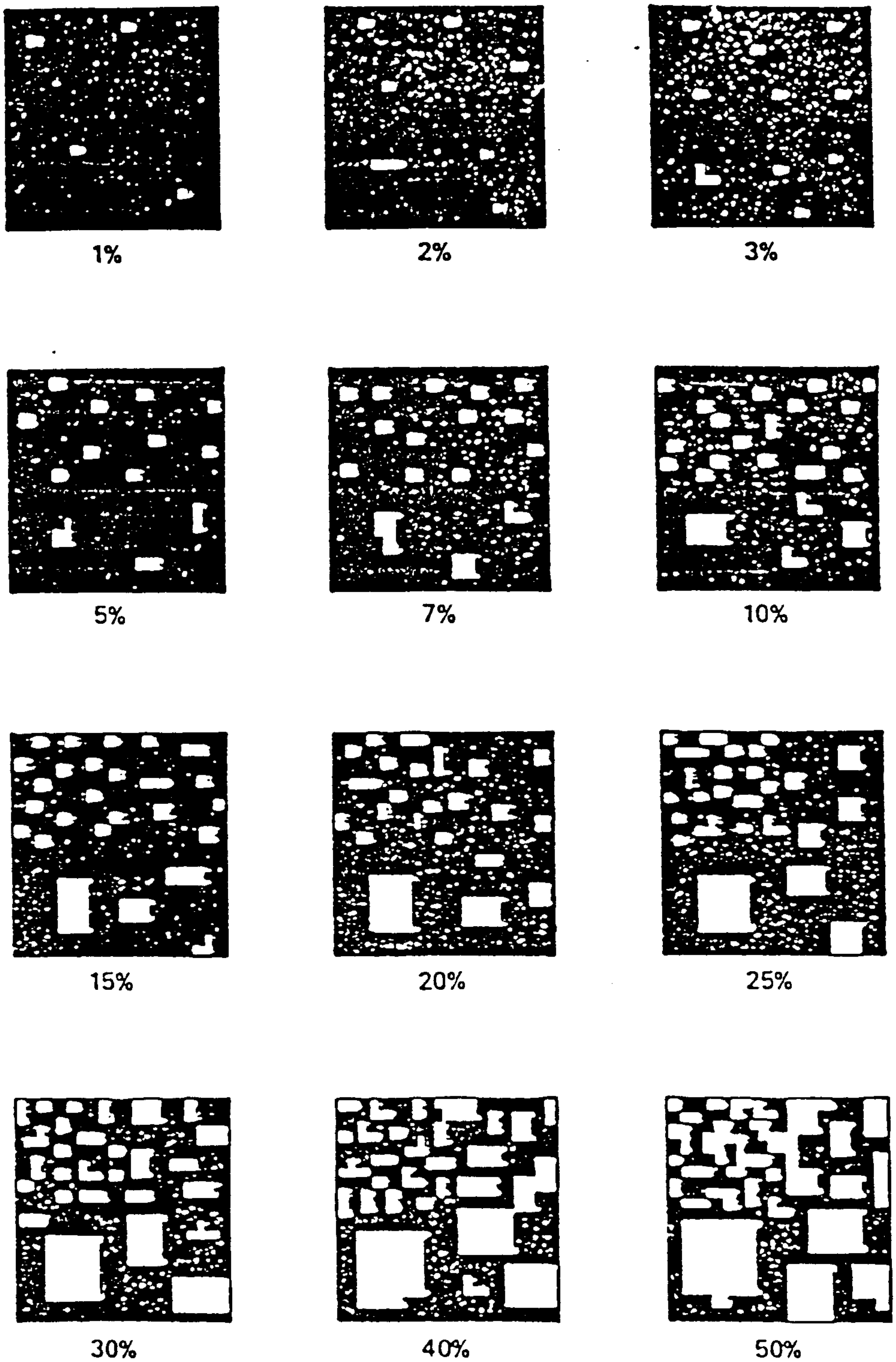


Figure 3.16 Visual Evaluation Rating Pattern (Field and Phang, 1986)

immersion tests where the sample is typically rated while still in the container and immersed in water.

The method used in NCHRP 246 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, then calculated total percent stripping by pro-rating each fraction on a 60-40 basis. Based on others' experience, a visual evaluation technique was modified for use in this study by considering the above problems 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%) and is described in Chapter 4. This modification makes it practical and easy to distinguish between the detail levels.

4. DISCUSSION AND ANALYSIS OF TEST RESULTS

In Chapter 2, it was pointed out that the ECS testing program was designed to answer the most important questions related to the performance of mixtures in the presence of water. From the test results (Table 3.8), and according to the experiment design (Figure 2.1), the effect of the following variables on mixtures response to water conditioning were analyzed in some detail:

Mixture Variables

1 - Aggregate type

2 - Asphalt type

3 - Air voids level

Conditioning Variables

1 - Conditioning fluid

2 - Conditioning temperature

3 - Vacuum level

4 - Repeated loading

5 - Conditioning time

4.1 Effect of Mixture Variables

Mixture variables are more limited than the conditioning variables, both in terms of the number of the variables and in terms of simulating the real pavement, as shown in Table 2.1. At this point in the study, only the three mixture variables will be discussed in this section.

Aggregate Type

The two aggregates used are RB and RL from MRL materials. RL is known as a stripping aggregate and RB is known as a non-stripper. The overall retained strength was monitored by performing resilient modulus (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 asphalts. The four mixtures were subjected to three hot-wet conditioning cycles (6-hour cycle) with continuous repeated loading.

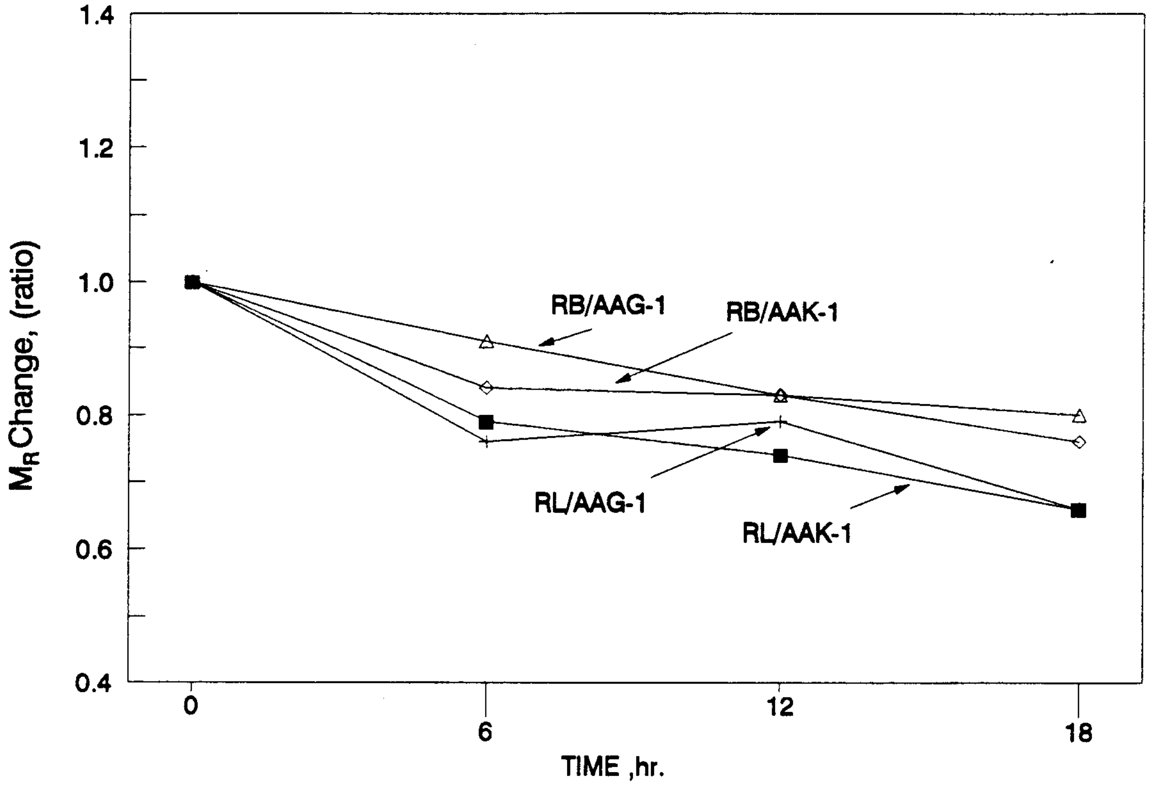


Figure 4.1 Effect of Aggregate/Asphalt Type on Resilient Modulus Change, After Hot-Wet Conditioning

RB aggregate showed more resistance to water damage than RL, with both asphalts. Another four sets of specimens from the four asphalt-aggregate combinations were tested for freeze-wet conditioning. The results are shown in Figure 4.2. The results showed that the effect of freezing cycles on M_R is not significant (at this vacuum level), and therefore no significant differences among the four tested materials.

In order to evaluate the differences presented graphically in Figure 4.1, the results were statistically analyzed by using the General Linear Model Procedure (GLM) . The GLM was selected in favor of the Analysis of Variance (ANOVA), because GLM counts 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 in order to narrow them down and select those having the most effect on water damage. This concept resulted in performing different test replicates according to the effect of each conditioning code, as 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 (times 6, 12, and 18 respectively). The difference between the M_R ratios of the three conditioning cycles is significant at the 90.0 % confidence level, except the second cycle where the difference is significant at 80 percent.

The GLM (as shown here in a brief format) does not give enough information about within treatments. So, a Least Significant Difference (LSD) was used to rank the four combinations according to the aggregate and asphalt types.

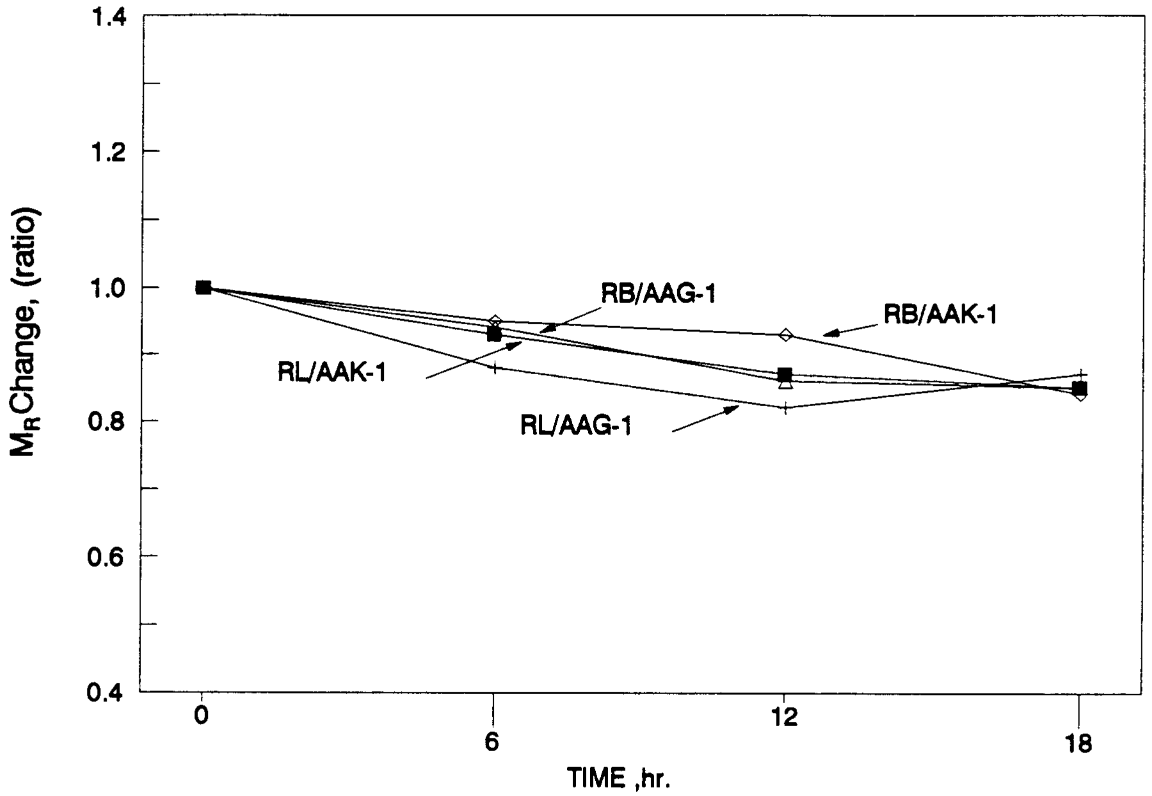


Figure 4.2 Effect of Aggregate/Asphalt Type on Resilient Modulus Change, After Freeze-Wet Conditioning

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

---------------------------------- TIME=6 ---------------------------

Source	DF	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			

---------------------------------- TIME=12 -------------------------

Source	DF	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			

---------------------------------- TIME=18 -------------------------

Source	DF	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 90.0 percent confidence level

Table 4.2 shows LSD ranking results of the three cycles, where the four combinations were ranked logically according to their aggregate types. RB aggregate showed the lowest water damage with a least significant difference less than 0.143 at the 95.0 percent confidence level for the first and third cycles. M_R ratios after the second cycle followed the same ranking, but with a lower Least Significant Difference (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 RB aggregate with a low resistance to water damage. On the other hand, asphalt type did not show a significant effect, which is discussed in the following section.

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

Asphalt Type

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

Table 4.2 Asphalt/Aggregate Ranking by LSD

---------------------------------- TIME=6 ---------------

Alpha= 0.05 df= 7 MSE= 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

---------------------------------- TIME=12 ---------------

Alpha= 0.20 df= 7 MSE= 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

---------------------------------- TIME=18 ---------------

Alpha= 0.05 df= 7 MSE= 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 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.

The same data for hot-wet conditioning which was used for Figure 4.1 were expressed statistically in Tables 4.2 after conducting the LSD, as pointed out above. And the same table was used to show the ranking of the effect of asphalt types. As shown in Table 4.2, asphalt type did not show a consistent response, since neither asphalt type showed the same LSD ranking with the three cycles. For more clarification, a direct comparison between the two asphalts with the same aggregate type (RB/AAG-1 versus RB/AAK-1) was conducted by using the 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 (20 in. Hg) and for this number

Table 4.3 Analysis of Variance of the Difference Between M_R Ratios After Three Hot-Wet Conditioning Cycles for RB/AAG-1 Versus RB/AAK-1 Combination

---------------------------------- TIME=6 ---------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.20 F Crit
Model	1	0.004	0.004	1.90	2.35
Error	4	0.009	0.002		
Corrected Total	5	0.013			

--------------------------------- TIME=12 ---------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.60 F Crit
Model	1	0.0002	0.0002	0.04	0.32
Error	4	0.023	0.005		
Corrected Total	5	0.023			

--------------------------------- TIME=18 ----------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.60 F Crit
Model	1	0.0008	0.0008	0.28	0.32
Error	4	0.0117	0.0029		
Corrected Total	5	0.0125			

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 the difference between the means is not significant at the 80 percent confidence level for the first cycle, and 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, shown in Table 4.5. Although there is a ranking at the 70.0 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 nor 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.

Air Voids Level

As shown in the experiment plan, Figure 2.1, three permeability levels were defined by three air voids levels; low such as 4 percent, medium such as 8 percent, and high as more than 14 percent. Specimens with high air voids deformed under the effect of high temperature and repeated loading, so a special conditioning treatment was performed which is discussed later. Therefore, only two air voids level are included in this discussion.

According to the experiment plan, two sets of specimens from the same asphalt-aggregate combination with two air voids levels were subjected to three hot wet conditioning cycles combined with a continuous repeated loading. Figure 4.3

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

---------------------------------- TIME=6 ---------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.20 F Crit
Model	3	0.005	0.002	2.40	2.48
Error	4	0.003	0.001		
Corrected Total	7	0.008			

---------------------------------- TIME=12 ---------------

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

---------------------------------- TIME=18 ---------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.60 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 LSD

---------------------------------- TIME=6 ---------------

Alpha= 0.3 df= 4 MSE= 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

---------------------------------- TIME=12 ---------------

Alpha= 0.3 df= 4 MSE= 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

---------------------------------- TIME=18 ---------------

Alpha= 0.3 df= 4 MSE= 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

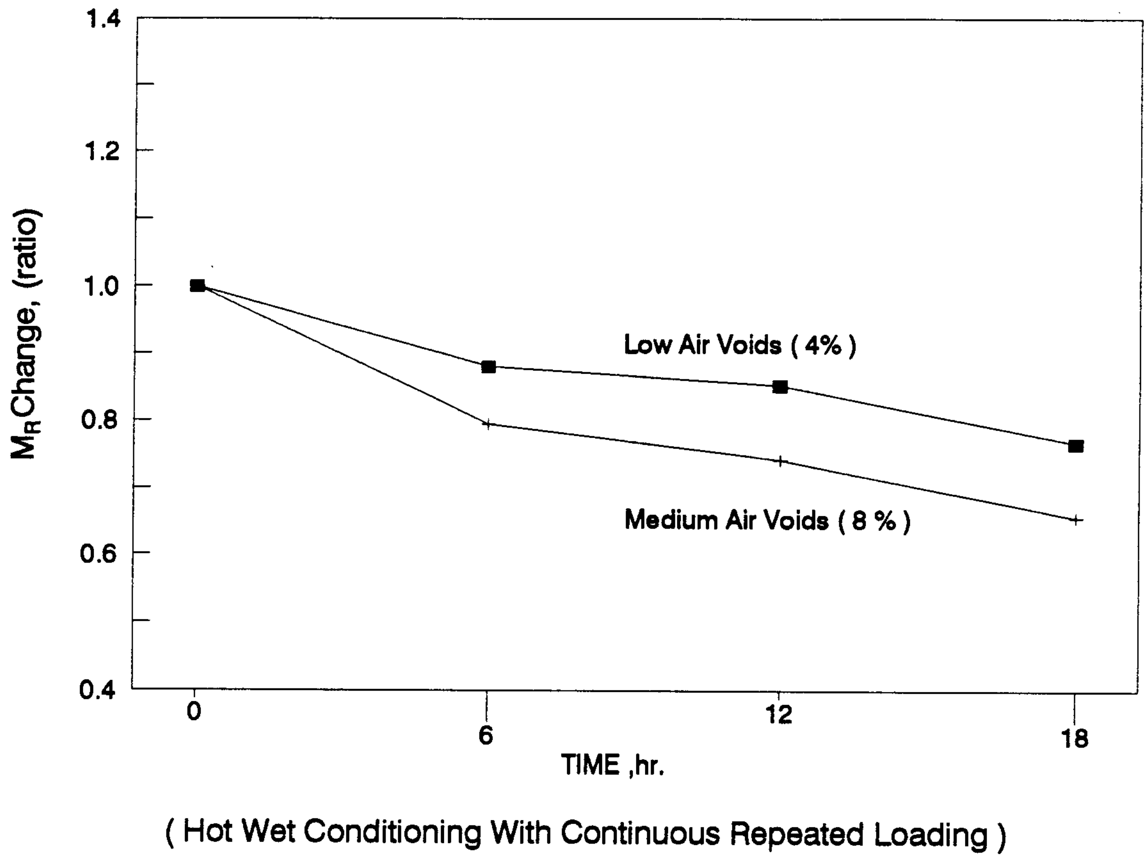


Figure 4.3 Effect of Air Voids Level on Resilient Modulus Change

shows the average of retained modulus ratios for each set. Specimen with high air voids (8 percent) showed more significant water damage than specimens with low air voids (4 percent).

A GLM statistical analysis was performed on the data and the results in Table 4.6 show that the effect of air voids 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 voids and the results are in Table 4.7. M_R ratios of the three cycles were ranked significantly based on their air voids levels at the 90 confidence level with a least significant difference more than 0.071. Specimens with low air voids 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 voids on the asphalt concrete response to water conditioning, and additional details are discussed later.

4.2 Effect of Conditioning Variables

It has been observed that there is a significant variation among the current methods in the final evaluation of a 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 variations is mainly the conditioning techniques.

Table 4.6 Analysis of Variance of the Difference Between M_R Ratios of Specimen With Two Air Voids Levels

---------------------------------- TIME=6 ----------------------------------

Source	DF	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			

---------------------------------- TIME=12 ----------------------------------

Source	DF	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			

---------------------------------- TIME=18 ----------------------------------

Source	DF	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 90.0 percent confidence level

Table 4.7 Asphalt/Aggregate Ranking by LSD Based on Air Voids Level

---------------------------------- TIME=6 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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

---------------------------------- TIME=12 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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

---------------------------------- TIME=18 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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

For the ECS, the types of conditioning variables to be included and the method of including each variable in the new technique are carefully considered. In order to decide which variables should be included in the proposed moisture conditioning procedure and at what level should be incorporated, it was necessary to evaluate the role of each variable in the asphalt concrete response to water damage. So, each conditioning variable was isolated and evaluated independently , as discussed in the following sections.

Conditioning Fluid

In the field, asphalt pavement is exposed to three types of fluids: air in dry climates and dry soils (subgrades), moist air (vapor) either in wet climates or wet subgrades (due to evaporation from ground water), and water in wet climates. To give an overall picture, three fluids (air, vapor, and distilled water) have been 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, 10 in. Hg of vacuum. The results for these three specimens are presented in Figure 4.4 and the data show logical and expected ranking and trends. Air tends to stiffen the mixture by aging (specimen no. 22) and water tends to soften the mixture (specimen no. 20). Using vapor combines the two phenomena, aging and moisture damage (specimen no. 21). This investigation indicated the boundaries of conditioning fluids and that the vapor may not be the best fluid to be used for accelerated

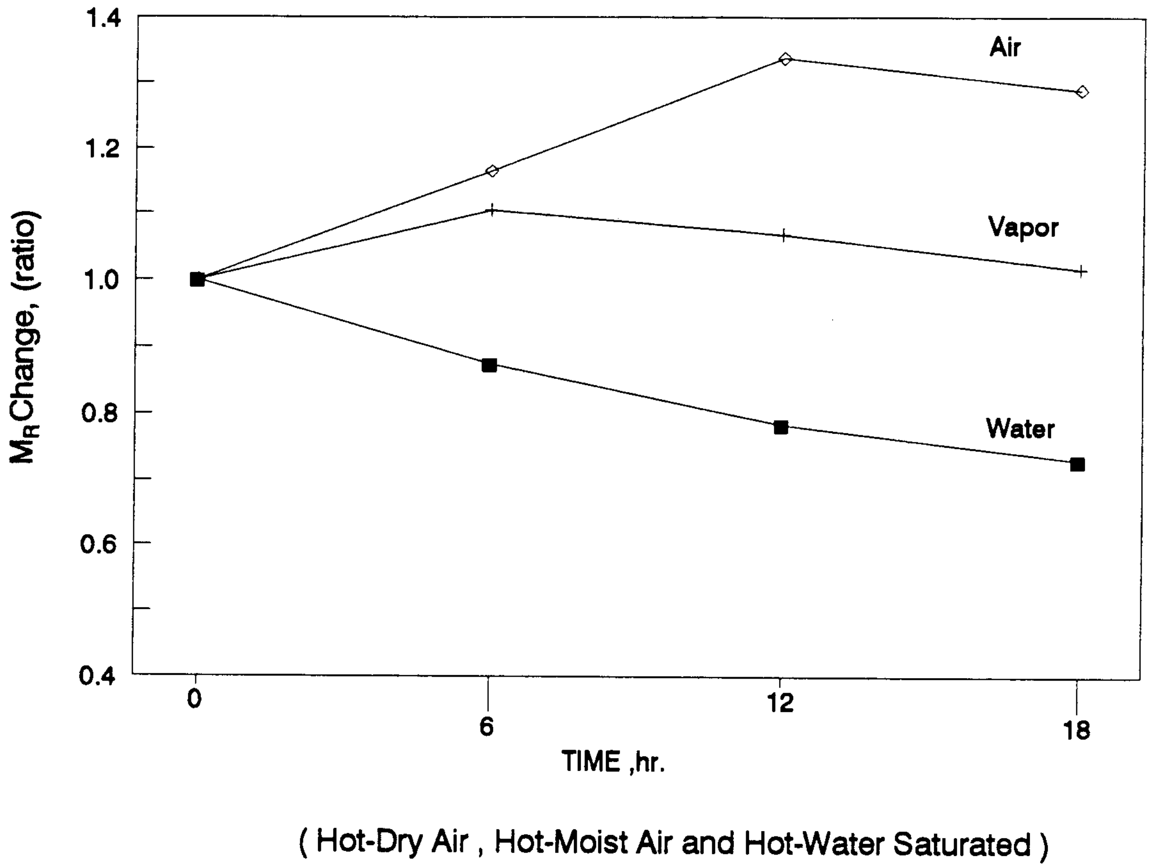


Figure 4.4 Effect of Conditioning Fluid on Resilient Modulus Change

moisture conditioning. Distilled water was selected as the conditioning fluid for further testing.

Conditioning Temperature

One of the capabilities of the ECS is to isolate and evaluate a single factor among a wide range of factors. 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, 25°C, and -18°C. 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 No. 3; ambient, set No. 19; and freeze, set No. 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, C and F codes. Freeze conditioning (I-code) was performed with static loading (10 in. Hg vacuum). The plots of the three sets are shown in Figure 4.5. Hot conditioning shows the most significant water damage. Freezing conditioning 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 show significant effect on the specimen strength. In order 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

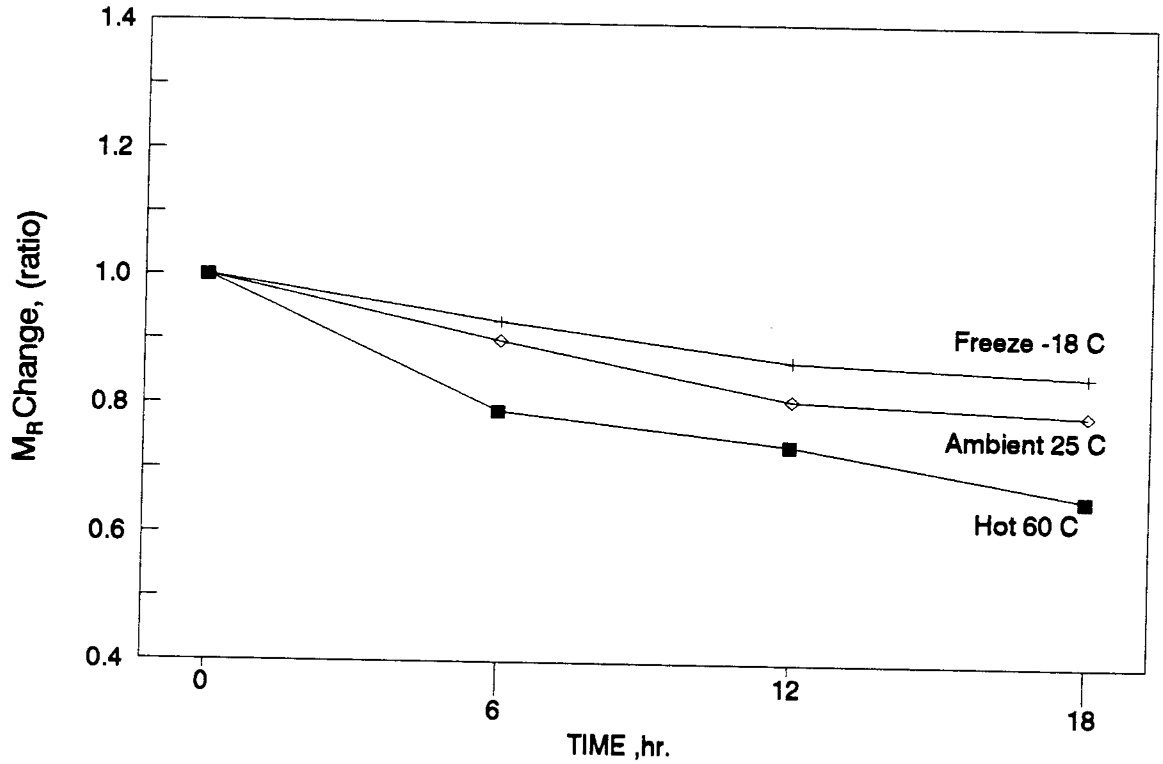


Figure 4.5 Effect of Conditioning Temperature on Resilient Modulus Change

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. The LSD was carried out to rank the impacts of the temperature on M_R ratio. Table 4.9 shows that there is a significant ranking at the 90 percent confidence level, where the specimen subjected to 60°C showed the highest water damage, while the specimen subjected to -18°C showed the lowest water damage. This means that the highest temperature is the highest water damage, because high temperature accelerates water penetration into the specimen. Finally, it was concluded that the hot, 60°C, cycling is appropriate to simulate and accelerate field conditions in the hot climates. Hot and freeze, 60°C and -18°C respectively, cycling is better to simulate the mechanism of the deterioration process in the cold climates.

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, prior to the water conditioning cycling, is either 10-in. Hg for "moist" level or 20-in. Hg for "saturated" level. A vacuum level of 10-in. Hg is then maintained during conditioning cycles. Vacuum level appears to be more representative for the ECS procedure because retaining some vacuum (10-in.) during water conditioning cycles

Table 4.8 Analysis of Variance of the Difference Between M_R Ratios After Three Conditioning Cycles With Three Temperature Levels

---------------------------------- TIME=6 ----------------------------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.10 F Crit
Model	2	0.024	0.012	36.80*	4.32
Error	4	0.001	0.0003		
Corrected Total	6	0.026			

---------------------------------- TIME=12 ----------------------------------

Source	DF	Sum of Squares	Mean 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			

---------------------------------- TIME=18 ----------------------------------

Source	DF	Sum of Squares	Mean 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 90.0 percent confidence level

Table 4.9 Asphalt/Aggregate Ranking by LSD With Varying Conditioning Temperature

---------------------------------- TIME=6 ----------------------------------

Alpha= 0.1 df= 4 MSE= 0.000329
Least Significant Difference= 0.0262
Means with the same letter are not significantly different.

T Grouping	Mean	N	Temp
A	0.9300	2	18
B	0.8950	2	25
C	0.7967	3	60

---------------------------------- TIME=12 ----------------------------------

Alpha= 0.1 df= 4 MSE= 0.002342
Least Significant Difference= 0.0699
Means with the same letter are not significantly different.

T Grouping	Mean	N	Temp
A	0.8750	2	18
B	0.8050	2	25
C	0.7433	3	60

---------------------------------- TIME=18 ----------------------------------

Alpha= 0.1 df= 4 MSE= 0.002812
Least Significant Difference= 0.0767
Means with the same letter are not significantly different.

T Grouping	Mean	N	Temp
A	0.8550	2	18
B	0.7900	2	25
C	0.6500	3	60

maintains a constant degree of wetting better than for static immersion conditioning.

In order 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:

- Freeze - conditioning H and I: Set No. 16 and No. 11
- Hot - conditioning B and C: Set No. 15 and No. 3, respectively (Table 3.8)

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

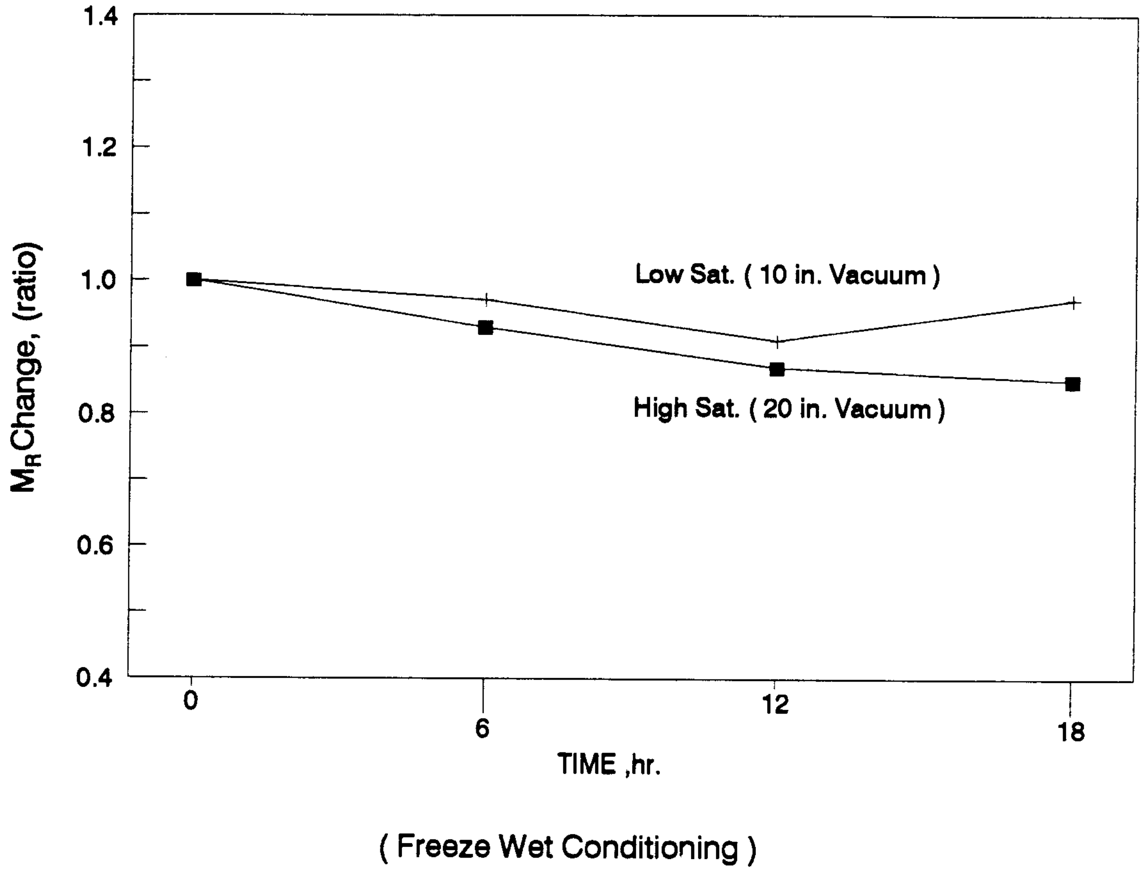


Figure 4.6 Effect of Vacuum Level on Resilient Modulus Change, After Freeze Wet Conditioning

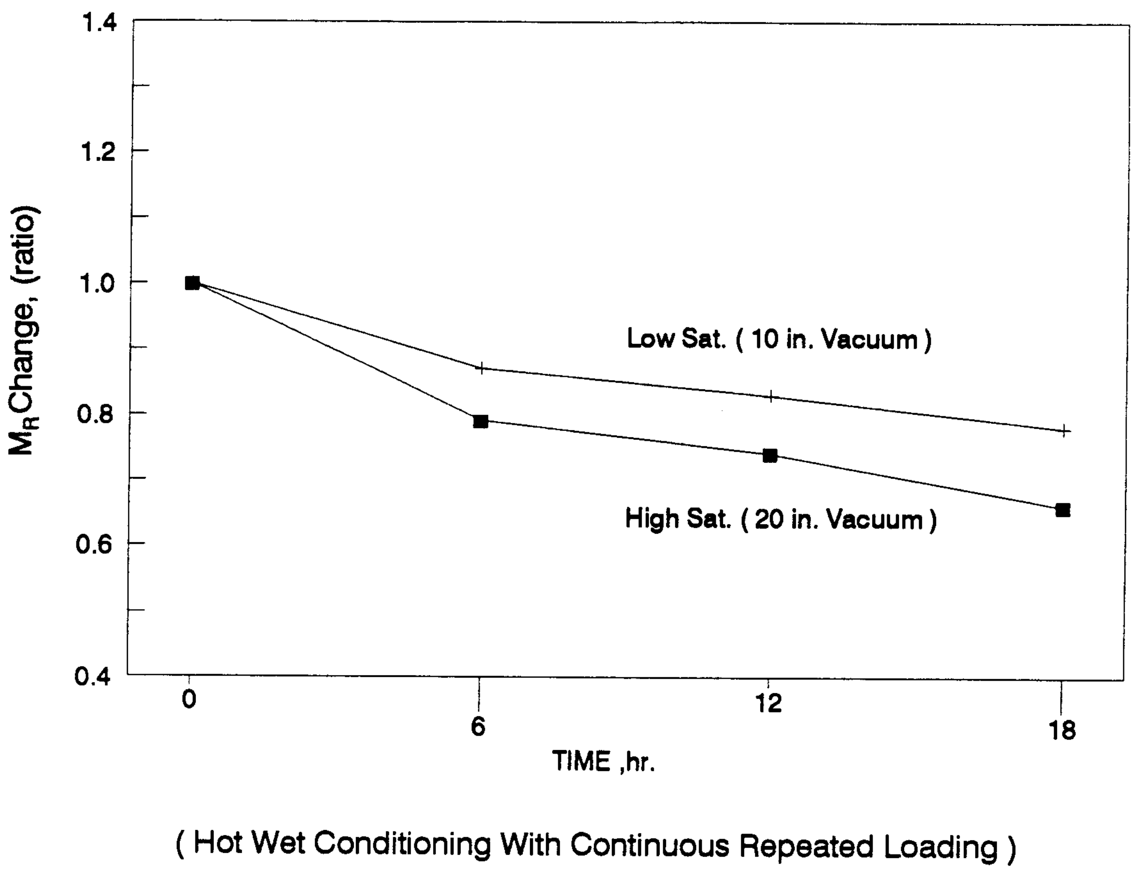


Figure 4.7 Effect of Vacuum Level on Resilient Modulus Change, After Hot Wet Conditioning

In order to confirm the above findings, the data were re-analyzed statistically. Since the effect of vacuum level with freezing cycles is obviously not significant (Figure 4.6), only the data of hot conditioning (B and C) were statistically analyzed. The 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 the LSD. As shown in Table 4.11, the two levels were ranked statistically significant at the 90 percent confidence level with a least significant difference less than 0.044.

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

Repeated Loading

The general approach to this study has been to test the asphalt concrete under conditions as similar as possible to those likely to occur in the field. One of the most difficult variables to simulate in asphalt concrete testing is the traffic loading. A previous study found that heavy traffic volume appeared to increase the rate of

Table 4.10 Analysis of Variance of the Difference Between M_R Ratios After Three Hot Conditioning Cycles With Varying Vacuum Level

---------------------------------- TIME=6 ----------------------------------

Source	DF	Sum of Squares	Mean Square	F Value	P=0.10 F Crit
Model	1	0.006	0.006	15.28*	5.54
Error	3	0.001	0.0004		
Corrected Total	4	0.008			

---------------------------------- TIME=12 ----------------------------------

Source	DF	Sum of Squares	Mean 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			

---------------------------------- TIME=18 ----------------------------------

Source	DF	Sum of Squares	Mean 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 90.0 percent confidence level

Table 4.11 Vacuum Levels Ranking by LSD

---------------------------------- TIME=6 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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

---------------------------------- TIME=12 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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

---------------------------------- TIME=18 ----------------------------------

Alpha= 0.1 df= 3 MSE= 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
B	0.6500	3	20-in

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 of them have tried to compromise this variable due to 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 where 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, which are discussed as follows:

1-Loading Level

The loading is fixed at 200 lbs (1.0 kN) repeated load with a 60 lbs (0.1 kN) 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 sufficiently moderate 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.

2-Loading Time

Although the ECS is capable of providing a variety of frequencies and wave forms, the ECS uses a square pulse load with a pulse load time of 0.1 s and rest period of 0.9s.

3-Stress-Strain Conditions

Since the ECS uses an electro-pneumatic closed loop system for the repeated loading subsystem, the ECS 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 voids levels. Loading level is discussed above.

In order to measure the entire accumulated permanent deformation of the specimen during the conditioning cycles, a temporary arrangement for the test setup was used. In addition to 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 three hours of cooling time to the testing temperature 25 °C.

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 voids 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, the major permanent deformation took place during the first conditioning cycle. In addition, the specimens recovered much of the deformation during the 3-hour cooling time. Moreover, due to differences in susceptibility to consolidation under repeated loading, the specimen with high air voids exhibited higher permanent deformation than the specimen with low air voids. This investigation indicates that 200 lbs repeated loading during water conditioning cycles is appropriate.

In order to investigate the effect of repeated loading on the deterioration process (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-saturated water conditioning (code C, Fig. 2.1). One set was water conditioned with static loading and the second was conditioned with repeated loading.

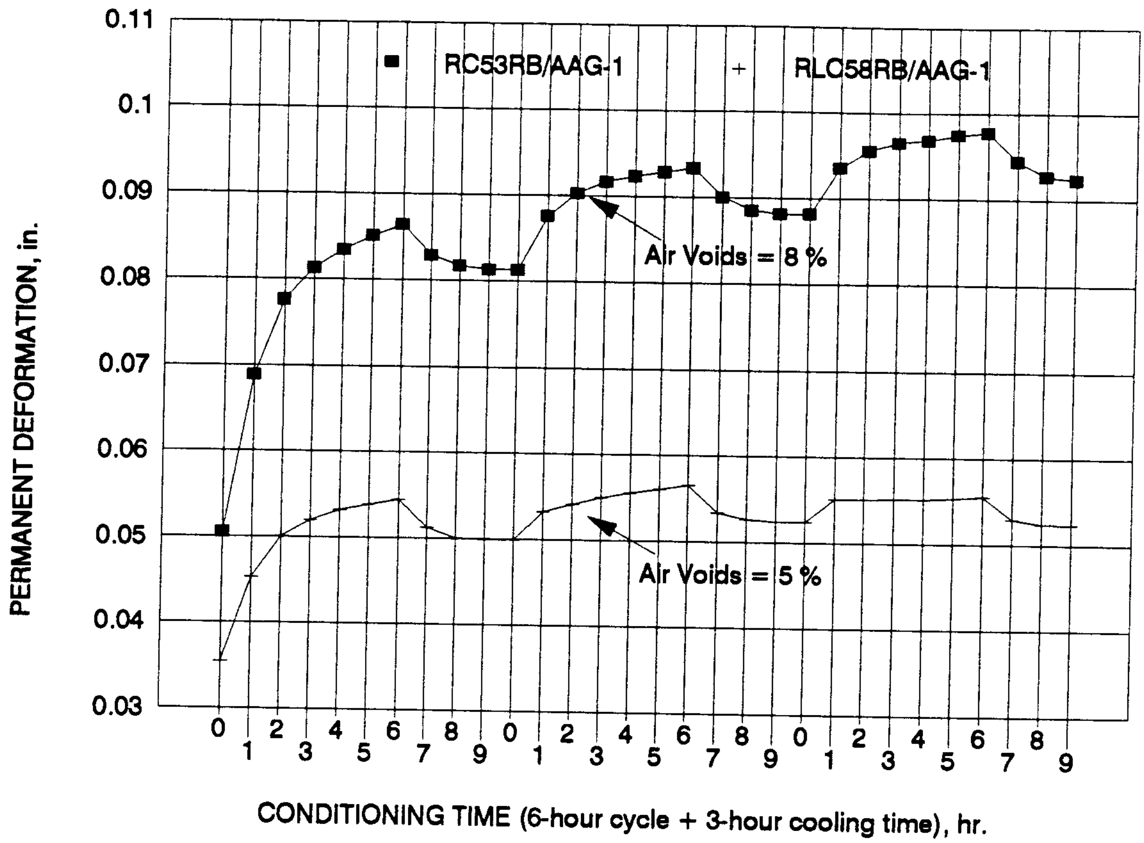


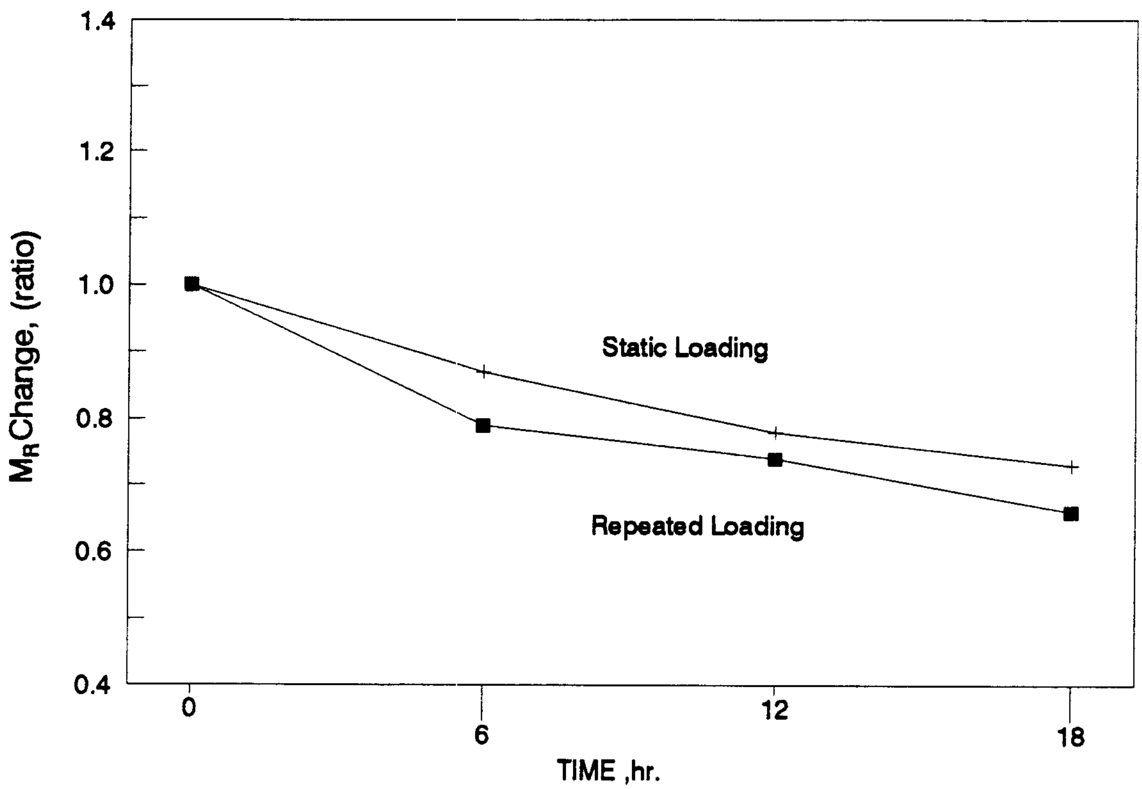
Figure 4.8 Effect of Hot Wet Conditioning and Repeated Loading on Permanent Deformation

The two sets are No. 20 for static loading, and No. 3 for repeated loading, as shown in Table 3.8. Figure 4.9 shows retained M_R versus conditioning cycle-time and the effect of the repeated loading is noticeable. In addition, stripping rates were reported for the two specimens in Table 3.8 ; 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 strength response, which indicates that repeated loading has more effect on adhesion. Finally, it was concluded that repeated loading during water conditioning is a very important variable to be included in water conditioning protocols. Therefore, a repeated 200 lb. load was adopted for the ECS procedure as a repeated loading, although other loads may be evaluated as time permits.

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.

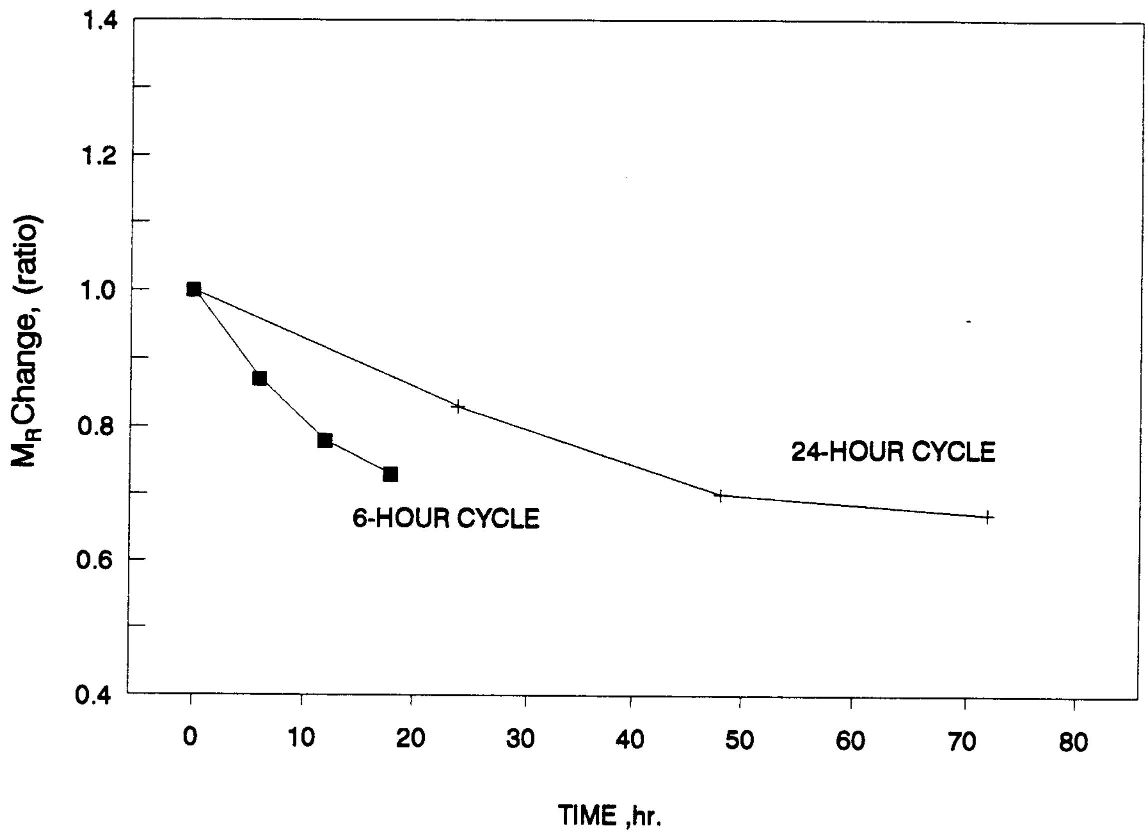
In terms of cycle length, the typical cycle length specified by previous studies and by AASHTO T-283 was 40-hours (16-hour freeze and 24-hour hot). To examine the



(Static loading VS Repeated Loading Throughout Conditioning Cycles)

Figure 4.9 Effect of Continuous Repeated Loading on Resilient Modulus Change effect of cycle length, two similar sets of specimens were subjected to the same conditioning code (code C, Fig. 2.1). One set (No. 20) was conditioned for 6-hour cycles and the second set (No. 23, Table 3.8) was conditioned for 24-hour cycles. The data of the two sets were plotted in Figure 4.10 and shows only slight difference between the two cycle lengths after completing 3 cycles. Since the cycling process contributes more to damage than cycle length, a 6-hour cycle was established for the ECS water conditioning, either freeze or hot conditioning.

In terms of the number of cycles, it is known that the more the cycles, the closer the simulation to the field cycling conditions,where the number of cycles representes day-night and summer-winter cycles. After establishing the cycle length of 6 hours, three cycles for hot conditioning were proposed, because this is a practical test duration with considering the expected freezing cycles, which is discussed later. So, after proposing 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 hot cycles at the end of the first cycle, and the same thing applies 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 + second cycles, and first + second + 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 thing applies with the third cycle.



(Hot Saturated Conditioning With Static Loading)

Figure 4.10 Effect of Conditioning Time on Resilient Modulus Change

In order to answer the two 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 shown in Table 4.12 (the original data were extracted from Table 3.8).

In order to see if there is a significant difference between the three cycles, the M_R ratios were analyzed. The GLM was performed 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 showed 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 the more conditioning cycles the more the deterioration.

In order to analyze the differences between the three deterioration trends (slopes, which was the second question), linear regression analyses were performed to calculate the three 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 the 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 and/or the

Table 4.12 Slopes of M_R ratios, (Extracted from Table A−1)

Spec. and Test ID	Time (hr)	M_R (ksi)	M_R (Ratio)	Slopes of M_R ratios: First Cycle	First+second Cycles	First+second + third Cycles
RC53RL/AAK	0	699	1.00	0.038	0.019	0.015
RC53RL/AAK	6	537	0.77			
RC53RL/AAK	12	541	0.77			
RC53RL/AAK	18	497	0.71			
RC201RL/AAK	0	660	1.00	0.033	0.025	0.020
RC201RL/AAK	6	530	0.80			
RC201RL/AAK	12	460	0.70			
RC201RL/AAK	18	420	0.64			
RC209RL/AAK	0	420	1.00	0.030	0.020	0.020
RC209RL/AAK	6	345	0.82			
RC209RL/AAK	12	320	0.76			
RC209RL/AAK	18	250	0.60			
RC56RL/AAG	0	1310	1.00	0.047	0.026	0.021
RC56RL/AAG	6	942	0.72			
RC56RL/AAG	12	910	0.69			
RC56RL/AAG	18	776	0.59			
RC79RL/AAG	0	808	1.00	0.028	0.005	0.010
RC79RL/AAG	6	672	0.83			
RC79RL/AAG	12	757	0.94			
RC79RL/AAG	18	615	0.76			
RC103RB/AAK	0	290	1.00	0.017	0.006	0.008
RC103RB/AAK	6	260	0.90			
RC103RB/AAK	12	270	0.93			
RC103RB/AAK	18	240	0.83			
RC104RB/AAK	0	400	1.00	0.003	0.021	0.015
RC104RB/AAK	6	320	0.80			
RC104RB/AAK	12	299	0.75			
RC104RB/AAK	18	285	0.71			
RC61RB/AAG	0	779	1.00	0.007	0.010	0.009
RC61RB/AAG	6	750	0.96			
RC61RB/AAG	12	689	0.88			
RC61RB/AAG	18	664	0.85			
RC105RB/AAG	0	716	1.00	0.020	0.013	0.011
RC105RB/AAG	6	628	0.88			
RC105RB/AAG	12	610	0.85			
RC105RB/AAG	18	562	0.78			
RC106RB/AAG	0	703	1.00	0.020	0.019	0.014
RC106RB/AAG	6	620	0.88			
RC106RB/AAG	12	539	0.77			
RC106RB/AAG	18	534	0.76			
RC113RB/AAG	0	701	1.00	0.015	0.016	0.012
RC113RB/AAG	6	640	0.91			
RC113RB/AAG	12	571	0.81			
RC113RB/AAG	18	554	0.79			

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	DF	Sum of Squares	Mean Square	F Value	P=0.05 F Crit
Model	2	0.001	0.001	3.19	3.32
Error	30	0.002	0.0001		
Corrected Total	32	0.003			

Table 4.14 Ranking Differences Between M_R Ratios After Three Hot-Wet Conditioning Cycles

Alpha= 0.2 df= 30 MSE= 0.000082
Least Significant Difference= 0.0051
Means with the same letter are not significantly different.

T Grouping	Mean	N	TIME
A	0.02345	11	6
B	0.01636	11	12
C	0.01409	11	18

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	DF	Sum of Squares	Mean Square	F Value	P=0.05 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 the Slopes of M_R Ratios After Three Hot-Wet Conditioning Cycles

Alpha= 0.2 df= 6 MSE= 0.001722
Least Significant Difference= 0.0488
Means with the same letter are not significantly different.

T Grouping	Mean	N	TIME
A	0.7967	3	6
B	0.7433	3	12
C	0.6500	3	18

third cycle from the effect of the first cycle or cycles, within an acceptable confidence level. In addition to the above reasoning for the need to perform the three cycles, performing the three cycles increases the confidence level of the test. Although it does 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 approuch to developing the ECS water conditioning procedure.

4.3 Visual Evaluation

Direct observation can provide insight as to the nature and extent of stripping. The primary disadvantage of visual evaluation of stripping is the subjective nature of the results. Sometimes, in an attempt to limit the subjectivity of the visual evaluation, rating patterns are compared to actual specimens to aid the rater and help in establishing 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

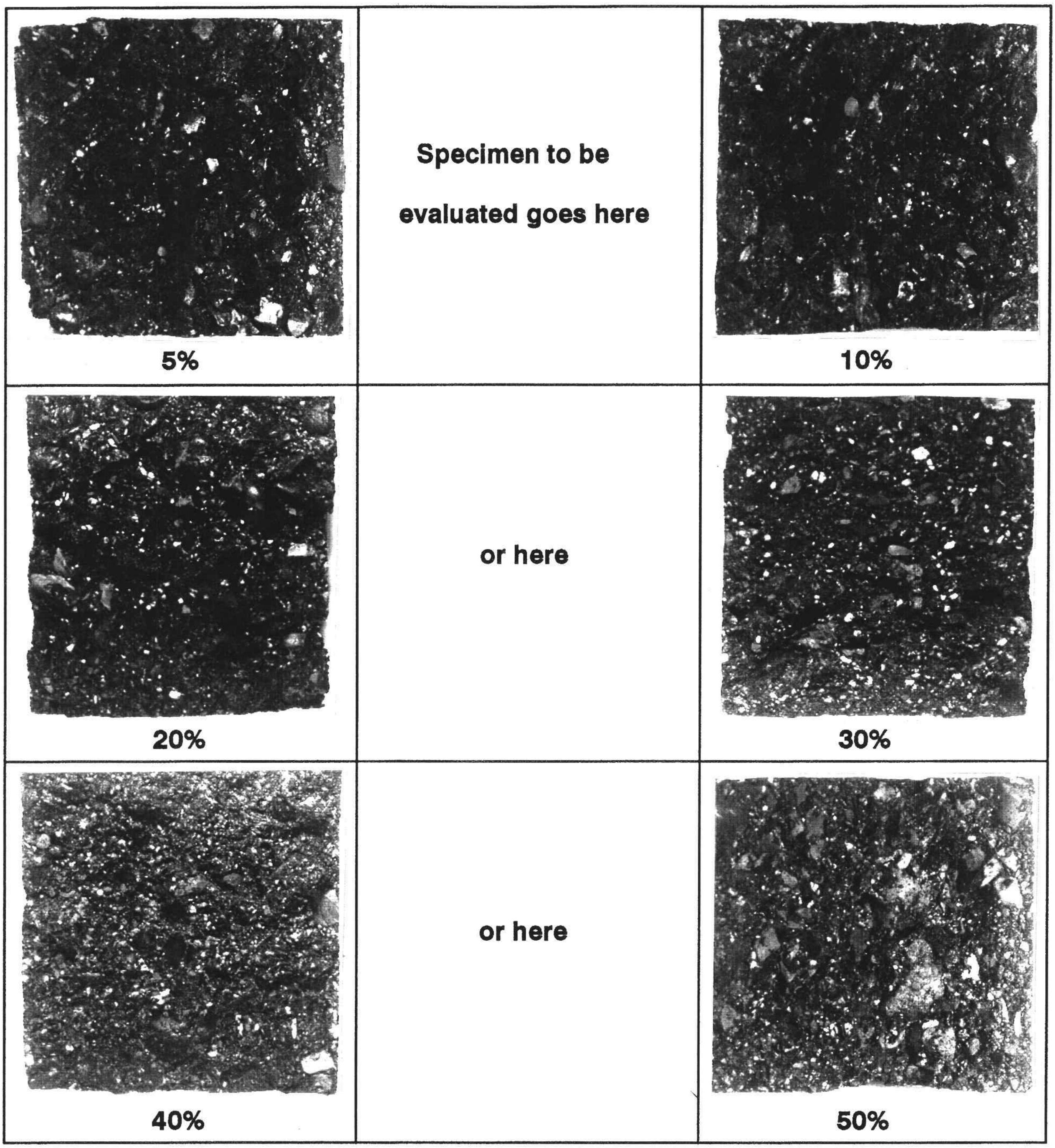


Figure 4.11 Stripping Rate Standards (Calibrated by Trial and Error of Water Conditioning)

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 (3 × 3) rectangular openings as shown in Figure 4.11. The three empty slots are used for the tested specimens which are to be rated.

This new technique has been used on all the ECS conditioned specimens to date. Following the final resilient modulus test, the specimen was split apart and the stripping rate was determined. This study was aimed at how engineers might utilize the visual evaluation and retained mechanical properties (M_R) after water conditioning. Due to space limitations, only one asphalt-aggregate combination, RB/AAG-1, will be discussed here as an illustration of the procedure.

Five specimens were prepared from the same asphalt-aggregate combination RB/AAG-1 and compacted to the same air voids level, 8 percent ± 1. 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 as 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, which

Table 4.17 Summary of Water Conditioning Test Results

Spec. No.	Conditioning Factors	Time (hr.)	M_R (ksi)	Ret. M_R Ratio	Perm. XE-9 cm/s	Ret. Per. (ratio)	Stripping Rate (%)
1	**Freeze** moist with static loading	0 6 12 18	707 680 651 652	1.00 0.96 0.92 0.92	10.38 15.16 19.23 14.32	1.00 1.46 1.85 1.38	5
2	**Freeze** saturated with static loading	0 6 12 18	610 577 510 521	1.00 0.95 0.84 0.85	3.09 2.79 2.19 2.08	1.00 0.90 0.71 0.67	10
3	**Hot** moist with repeated loading	0 6 12 18	770 667 656 587	1.00 0.87 0.85 0.76	1.34 1.07 0.43 0.24	1.00 0.80 0.32 0.18	10
4	**Hot** saturated with static loading	0 6 12 18	845 757 652 568	1.00 0.90 0.77 0.67	2.50 1.89 1.93 1.77	1.00 0.76 0.77 0.71	30
5	**Hot** saturated with repeat-ed loading	0 6 12 18	1278 800 878 747	1.00 0.63 0.69 0.58	1.11 1.36 1.45 1.03	1.00 1.23 1.31 0.93	40

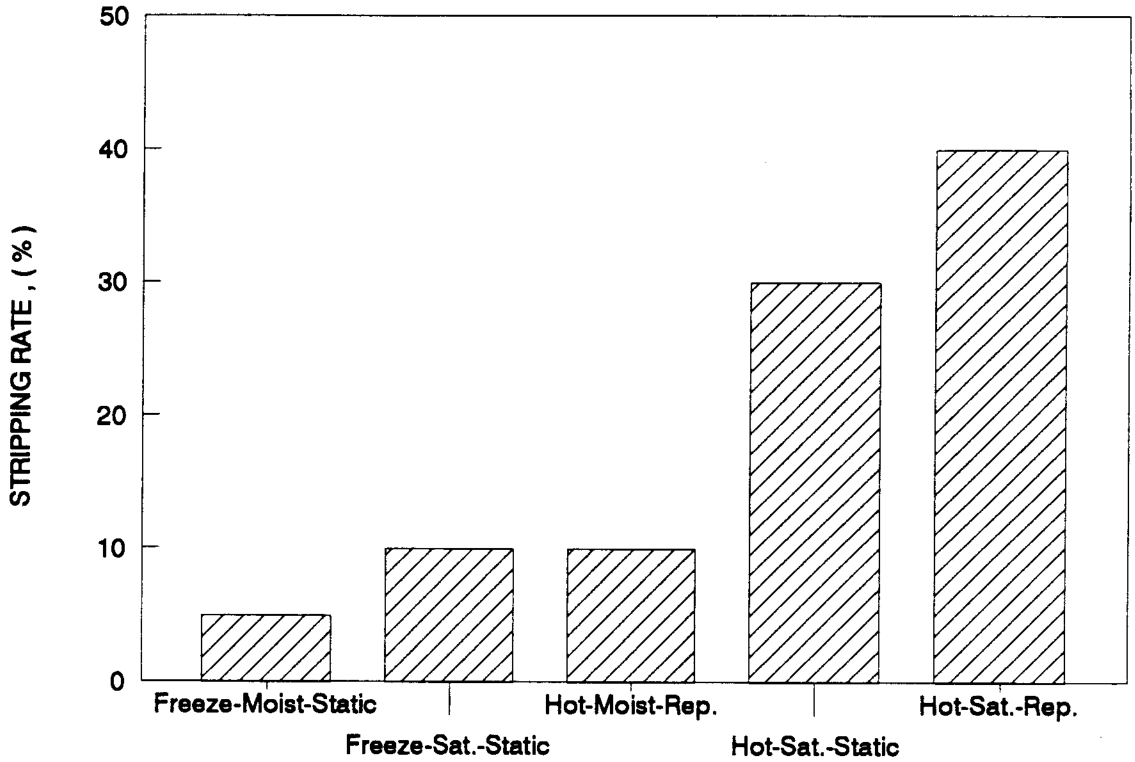


Figure 4.12 Effect of Conditioning Factors on Stripping Rate

was three cycles of hot-saturated 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 10 in. Hg during the conditioning cycle without repeated axial loading) (Specimen 1) induced the lowest stripping rate.

As explained earlier, this part of this study attempts 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 the 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 to as that determined by visual stripping.

Figure 4.13 shows that hot-saturated 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

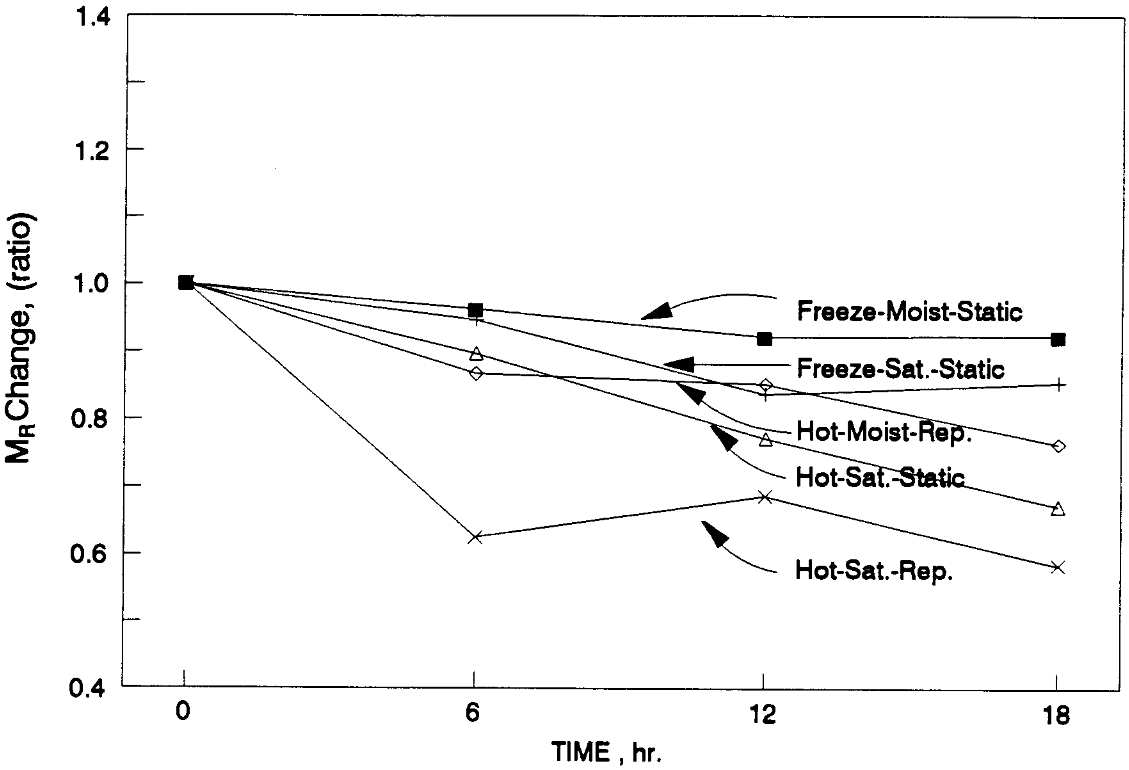


Figure 4.13 Effect of Conditioning Factors on Resilient Modulus Change

several points of view within the SHRP program. Adsorption/desorption of asphalt on aggregate surfaces (see the final report of 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 (see the study of Void Structure by SHRP, 1992). Still other ideas include the loss of (dissolving of) aggregate surface minerals as a source or cause of asphalt stripping. It is expected that the other studies ,i.e., SHRP, will contribute to the understanding of stripping and needs to be incorporated with this procedure.

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 voids data shown in Table 3.9 is displayed in Figure 4.14. Figure 4.14 shows that the relationship between permeability and air voids is not a proportional relationship, especially when the data is obtained from different asphalt-aggregate combinations. This finding is contrary to customary conceptions. Early investigators Ellis and Schmidt, 1961, were concerned with

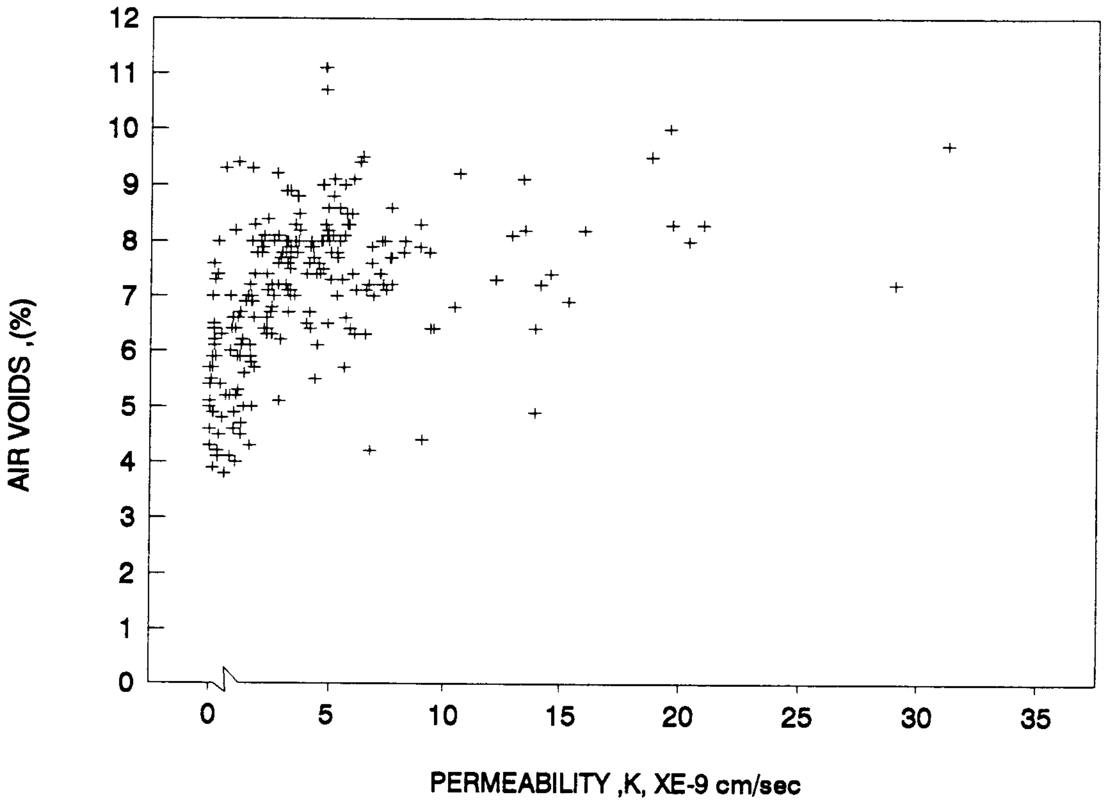


Figure 4.14 Permeability-Air Voids Relationship

obtaining permeabilities low enough to prevent liquid water from entering the base but at the same time 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 in a previous section. In this section, the discussion covers the capability of the permeability test to monitor the internal structure change during the water conditioning process, then addresses the possibility of using that change (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 voids structure during the water conditioning cycle, as with the resilient modulus test. In order to measure the sensitivity of the permeability test in detecting the change of the internal air voids structure of the asphalt concrete, four specimens from two asphalt-aggregate combinations, RB/AAK-1 and RL/AAK-1, were placed inside the environmental cabinet and connected with the rest of the ECS. The permeability test using air was performed at the four temperature levels, -18, 0, 25, and 60°C, and the data are shown in Figure 4.15. Figure 4.15 shows the permeability test to be sensitive in detecting slight changes such as specimen contraction and expansion due to temperature changes.

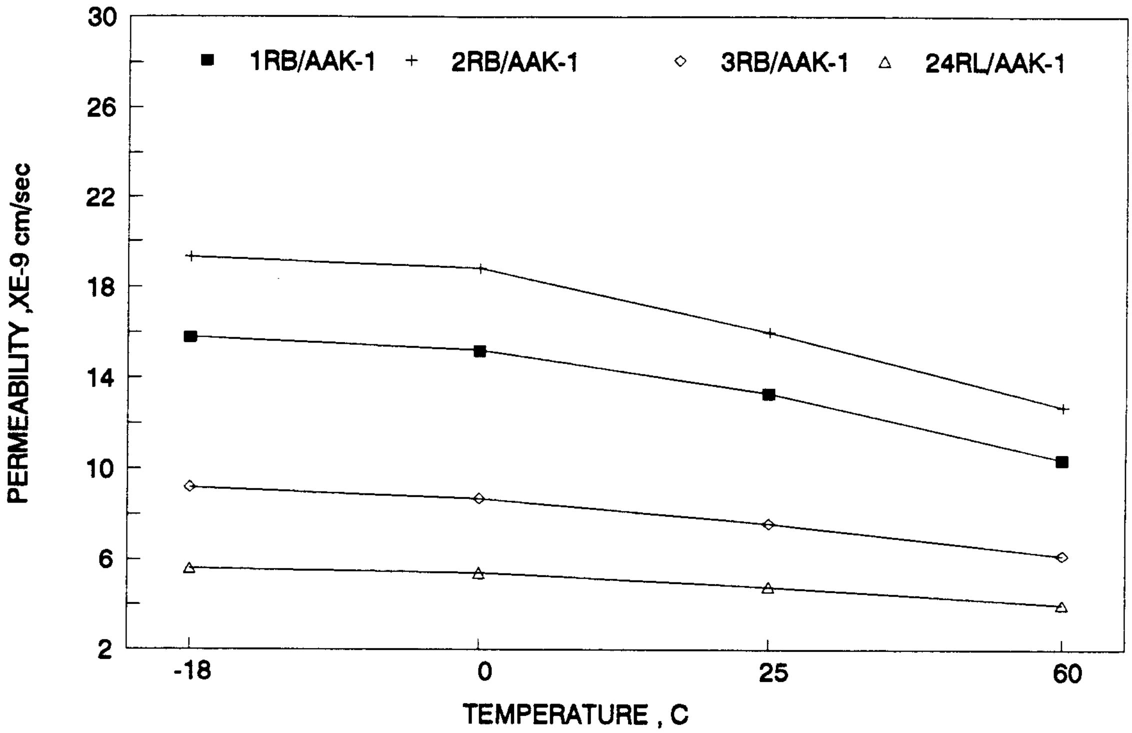


Figure 4.15 Permeability-Temperature Relationship

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.

In order to provide a water flow with voids fully saturated with water, a very high pressure is required. Vallerga and Hicks, 1968, tested water permeability with 50 psi back pressure. The vacuum level used for the ECS procedure is 20-in. Hg, which is equivalent to only 10 psi. 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.

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 prior to water conditioning and again after each 6-hour conditioning cycle. The retained permeability versus conditioning cycles are plotted for five specimens listed in Table 4.17 and shown in Figure 4.16. The data show considerable variation in the general trends, especially since all the specimens were prepared from the same materials combination.

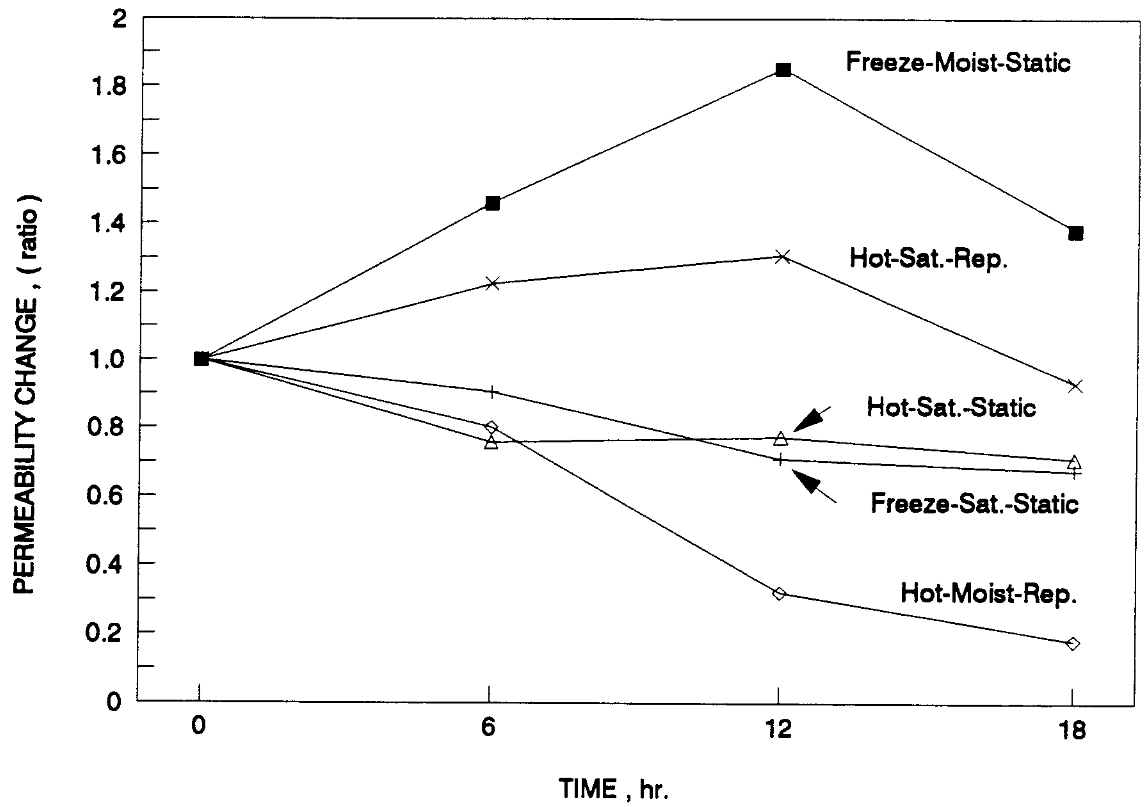


Figure 4.16 Effect of Conditioning Factors on Permeability Change

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 respect to the retained M_R (see Figure 4.13). It appears that measuring permeability of partially saturated mixtures is a major source of the variability.

4.5 Confirmation of Hypothesis

As explained in the previous section, the hypothesis of the pessimum voids concept 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 voids such as 4 percent, where the mixture is almost impermeable to water, are essentially not affected by water. Mixtures with air voids 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 for very long. Between these two extremes of impermeable and free draining mixtures is a range of air voids which is accessible to water, but lacking free drainage and thus tends to retain water. This range experiences the highest water damage.

It was necessary to prove the above analogy of the pessimum voids concept in the laboratory, but the ECS laboratory experiment plan was not appropriate to be used directly for this purpose. The ECS experiment was designed to simulate field service conditions in such a way as to accelerate the service conditions by retaining the water inside the specimen under the effect of vacuum during the conditioning cycles. Free drainage is not provided in this experiment, which 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 concept by providing free drainage. A separate conditioning set-up was constructed to permit this conditioning to simulate the action of free drainage following wetting. Three 2-specimen sets of mixtures were prepared from the same asphalt-aggregate combination (RL/AAK) and compacted at three air void contents; low at 4 percent, pessimum range at 8 percent and free drainage at 30 percent. The diametral resilient modulus, M_R, was then determined for each specimen. The six specimens were placed in a vacuum container and a partial vacuum of 22 in. Hg was applied for 10 minutes. Then, the vacuum was removed and the specimens were left submerged in the water for 30 minutes. 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 degrees of saturation of 99 and 38 percent, respectively, as shown in Table 4.18.

The relationship between air voids and level of saturation implies that specimens with high air voids are totally accessible to water, and in specimens with very low air voids they 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, then 5 hours at 25°C 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 instead of 60°C 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 4-inch diametral cylindrical membrane during condition cycles to assist them in retaining their original geometry.

Table 4.18 Permeability, Air Voids and Degree of Saturation Data

Spec.	Thick. In.	Permeability E-9 (cm/s)	AV. (%)	Degree of Sat. (%)
1H	4.660	5.71 E-07	32.60	97
2H	4.450	3.04 E-07	30.00	98
1M	4.380	6.88 E-09	8.40	68
2M	4.230	5.57 E-09	8.90	70
1L	4.200	Impermeable	5.50	35
2L	4.180	Impermeable	4.20	41

This conditioning process (partial saturation, 6 hours at 50°C, then 5 hours at 25°C) was repeated 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 range, shows significant water damage. In order to show the behavior trend, each set is represented by a regression formula (as shown in Figure 4.17). Specimens with 8 percent air voids are expressed by the regression formula $y = 0.8x^{-0.18}$, which gives $R^2 = 0.89$. Open graded mixture ratios are expressed by $y = 0.8x^{-0.01}$ with $R^2 = 0.11$. Specimens with 4 percent air voids are expressed by a linear regression, $y = 1.0 + x$, and because it is almost a horizontal line, R^2 is not applicable, but one can see the low variation around the line.

In order to display the test results in a format similar to that used earlier to introduce the pessimum voids concept, M_R change - air void plots Figure 4.17 was prepared for selected cycles (from number 1 to number 5 and number 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 less voids.

Table 4.19 Resilient Modulus Test Data

CYCLE NO.	L-MR Avg, ksi	L-MR Ratio	M-MR Avg, ksi	M-MR Ratio	H-MR Avg, ksi	H-MR Ratio
D	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

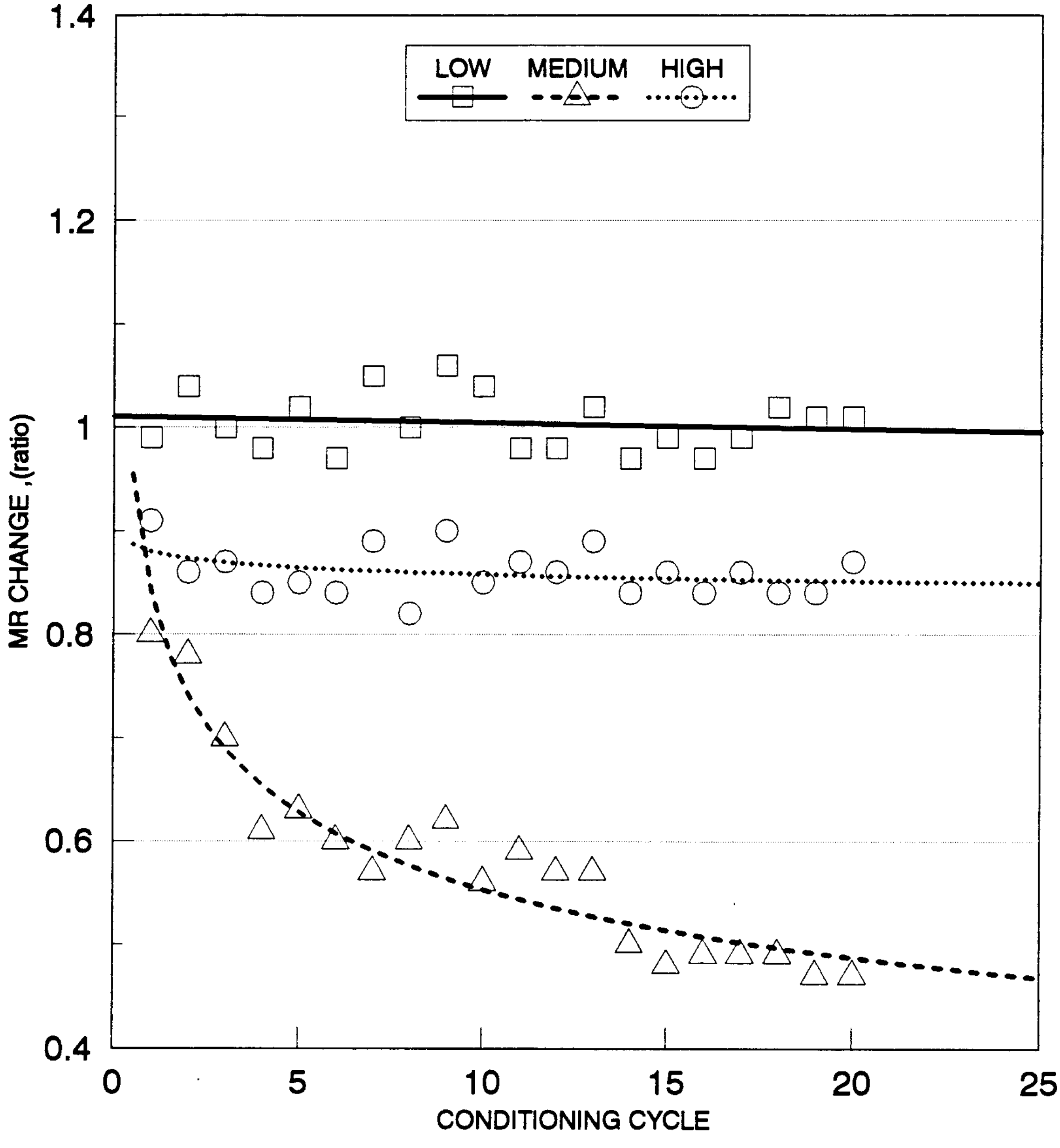
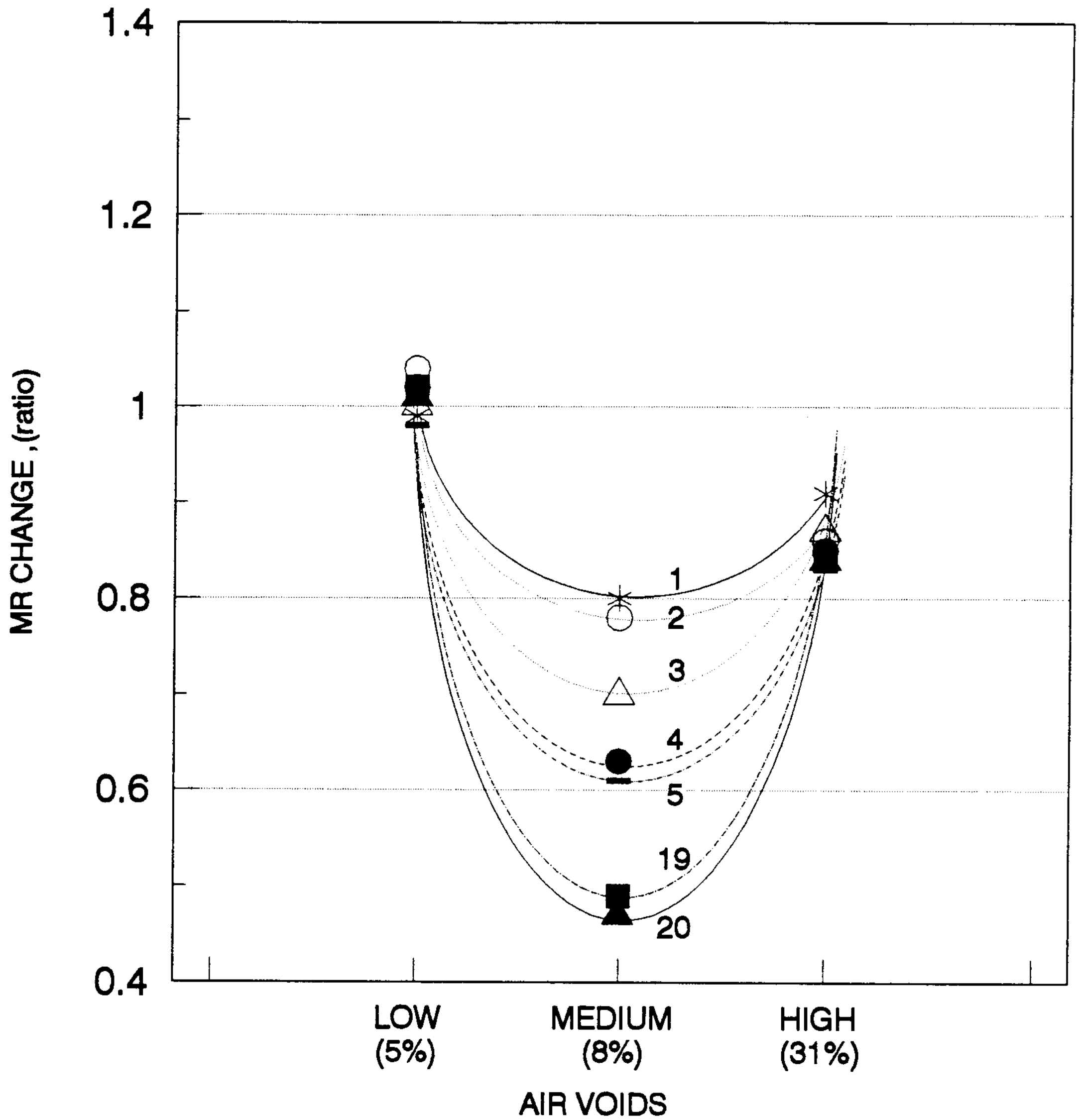


Figure 4.17 Resilient Modulus Change After Free Drainage Water Conditioning



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 Resilient Modulus Change - Air void content Relationship After Free Drainage Water Conditioning

4.6 Repeatability of the ECS

In the preceding section it has been shown that the test procedure was subjected to a screening process in order to establish the proper degree of control and field simulation over the conditioning factors. This has been accomplished 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 as a test system and as a test procedure.

Repeatability is a term used to refer 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 at the same time, where all the tests are performed on the same conditioning setup. As a result of this integration, a test determination may be described as :

1) value obtained at the end of the ECS-M_R test to reflect the repeatability of the test system, and

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

The repeatability of each value is explained in the following paragraphs.

Test System Repeatability

Although the repeatability of ECS-M_R with different test settings is discussed in a previous section, 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 herein because it is simple and statistical terms are avoided to the greatest extent. Coefficient of Variation expresses the standard variation (s) as a percentage of data mean (x), CV = 100 (s/x), (Mandel, 1964).

Two dry specimens were tested for ECS-M_R, for one test setting and repeating the test seven times, i.e., 7 test replicates. The test results as shown in Table 4.20 are very repeatable with Coefficients of Variation (CV) for the two specimens of 0.9 and 0.6. Such low CVs show the high consistency of the ECS. Since the 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 above conclusion.

Since the ECS is an automated control, close loop system, the variation indicated by this analysis expresses only the variation of the test system performance

Table 4.20 M_R Test Results of Two Specimens Tested Seven Times at The Same Test Setting

Test No.	Resilient Moduluis, ksi	
	Spec. No. 1	Spec. No. 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

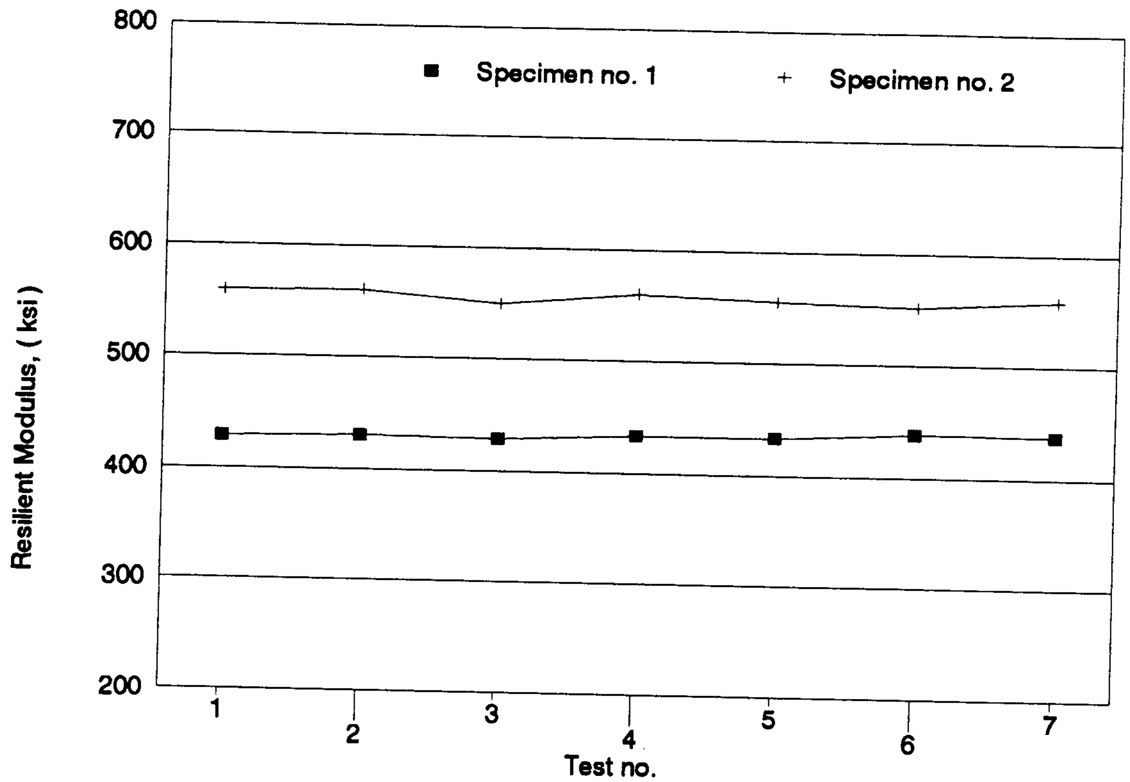


Figure 4.19 Repeatability of ECS-M_R Test

and excludes the variation associated with the conditioning variables and specimen properties such as air voids and strength.

Repeatability of Water Conditioning Procedure

This section is intended to provide a preliminary overview for the repeatability of the conditioning evaluation procedure. Although this technique evaluates an asphalt aggregate mixture response to a water conditioning procedure by using 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 which is not as applicable with the conventional statistical methods. Also, the repeatability of permeability change will be discussed in the validation report where more data is available. The repeatability of the test system which was discussed earlier, by analyzing M_R test results 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 developing program. Fewer replicates were used, because the ECS development 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:

. Effect of conditioning time,

. Mixture properties, i.e. air voids, strength, and permeability,

. Effect of water by introducing a hydrostatic pressure,

. Temperature cycling,

. Conditioning variables, i.e. repeated loading.

Because of the wide range of variables, a compromise was made in order to decrease the sources of variability. So the repeatability was analyzed for the M_R ratio after each conditioning cycle rather than representing the whole conditioning procedure by one M_R ratio value. 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 was extracted from the experiment test plan (Table 3.9) and RL/AAK-1 and RB/AAG-1 combinations were tested for three and four specimen replicates, respectively. Coefficient of Variation was calculated for each cycle for the same asphalt/aggregate combination, as shown in Table 4.21. The data exhibit very good repeatability where CVs were less than 10 percent for the two combinations with

Table 4.21 Coefficient of Variation of M_R Ratios

Spec. no.	Asph./Agg. Type	Resilient Moduluis Ratio		
		Cycle No. 1	Cycle No. 2	Cycle No. 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 (CV)		**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 (CV)		**4.2**	**5.8**	**4.9**

each cycle. It was preferred to express the repeatability of the conditioning by one CV value. But since it is not possible to pool coefficients of variation 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. In order to display M_R ratios, Figure 4.20 was prepared for the two asphalt/aggregate combinations and confirms the above conclusion where the variation of MR ratios for each conditioning is quite reasonable. Interestingly, one can see from CV analysis and Figure 4.20, that the test variation is not dependant on the number of conditioning cycles. In other words, CV increases with increasing cycles for the RL/AAK combination (3.2, 5.1 and 8.6, in Table 4.21), while no trend can be drawn for RB/AAG 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. In order to obtain a quantitative estimate of repeatability, the standard deviation was 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 :

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

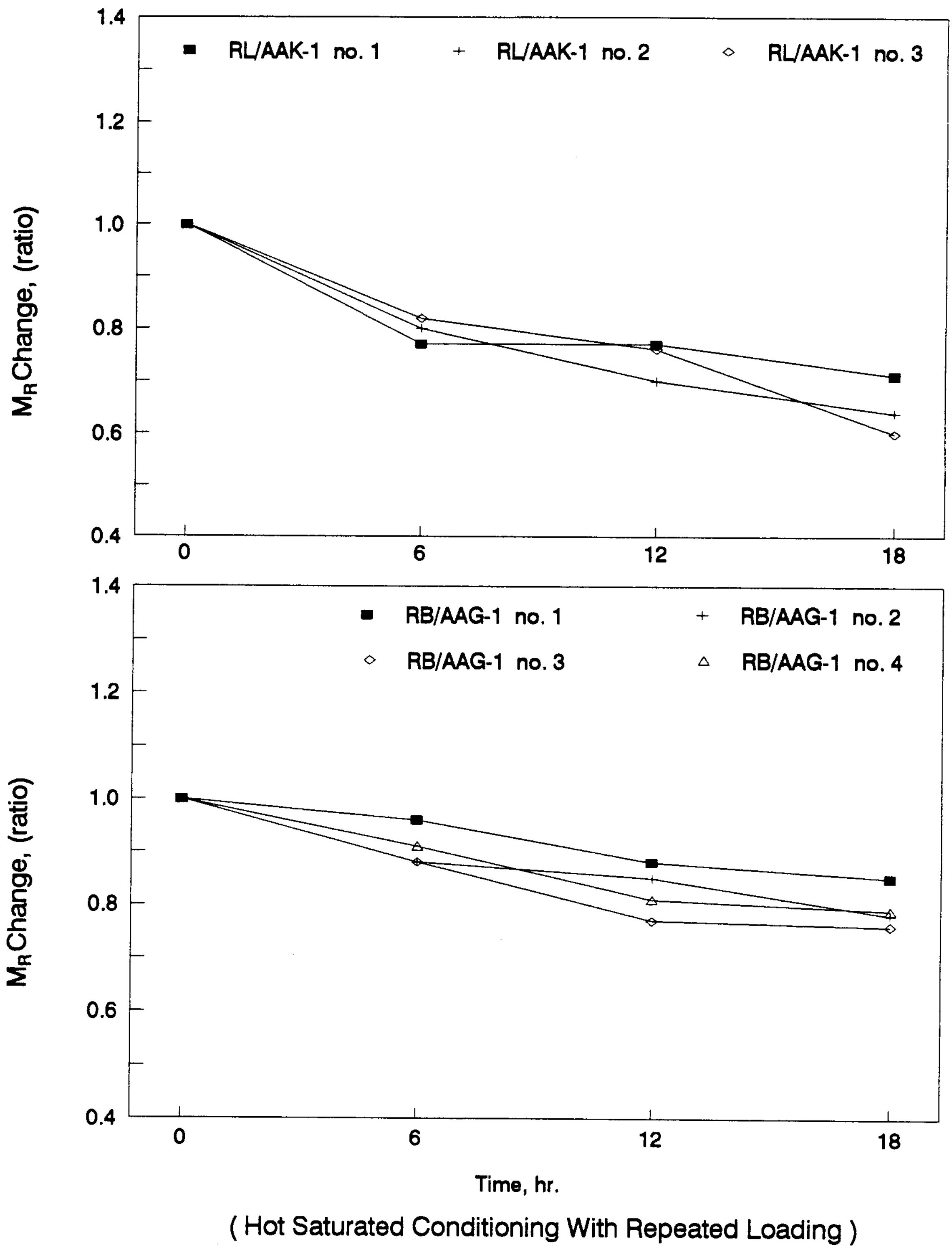


Figure 4.20 Repeatability of Water Conditioning Procedure

Table 4.22 Variance and Repeatability of M_R ratios

Asph./Agg Type	Spec. no.	Original M_R ratio	Cycle no.1 M_R ratio	Cycle no.2 M_R ratio	Cycle no. 3 M_R ratio
RL/AAK	1	1.00	0.77	0.77	0.71
RL/AAK	2	1.00	0.80	0.70	0.64
RL/AAK	3	1.00	0.82	0.76	0.60
Av. M_R ratios			0.80	0.74	0.65
RB/AAG	1	1.00	0.96	0.88	0.85
RB/AAG	2	1.00	0.88	0.85	0.78
RB/AAG	3	1.00	0.88	0.77	0.76
RB/AAG	4	1.00	0.91	0.81	0.79
Av. M_R ratios			0.91	0.83	0.80
Variance Samples (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% conf.level)			0.14	0.12	0.19

NA: Not Applicable

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

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

$$**:\ Measurement\ Variance\ (s_2) = \frac{7(0.77^2+0.80^2+0.82^2+0.96^2+0.88^2+0.88^2\sim}{\sim}$$

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

Where:

s_i : represents the sample component of variance for assessing repeatability for each source of variability included within 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 result 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 variance samples, and

s_2 : estimates the measurement variance.

Based on the data shown in Table 4.22, the estimated repeatability for cycle no. 1 is:

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

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 that was derived from the Coefficient of Variation analysis, above.

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." Ninety percent repeatability limit is approximated by 1.65 $\sqrt{2}\, s_r$, (ASTM E 456). It is essential to base this formula on the estimate that the standard deviation s_r derived from a normal distribution.

Accordingly: the 95% repeatability limit = $1.65\sqrt{2}\, s_r = 1.65\sqrt{2}\; 0.061 = 0.14$

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 than the one has been concluded earlier 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) on evaluating the variation between the test results.

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

In addition to the repeatability, further studies and applications will help in establishing the reproducibility of the new conditioning procedure by using data from different laboratories. Reproducibility means test result variability associated with specifically defined components of variance obtained both from 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:

- Conditioning temperature; hot conditioning, 60°C; freeze conditioning, -18°C.
- Vacuum level; 20 in. Hg for wetting stage and 10 in. Hg during the conditioning process.
- Cycle length; 6 hours
- Conditioning fluid: distilled water
- 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 200 lb.

During the development of the ECS conditioning procedure, three aspects were carefully considered: simulation of service conditions, repeatability and reproducibility of the test results, and practicality of the test procedure. Service conditions were established in this test procedure after a detailed investigation of the effect of each variable, as discussed earlier. The repeatability and reproducibility was determined after performing a statistical analysis of the test results, and is discussed in the preceding section. The practicality of the test procedure was one of the major aspects in the mind of the researcher during the development process, which is discussed in this section. 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 to be sufficient to account for the modest effect of cold climate, as discussed earlier, 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 conditioning cycles; 2) cold climate conditioning procedure which would include hot conditioning cycles and one freeze cycle.

In order 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 should be moderate.
2) There is 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 freezing cycles is not significant, which satisfies the first requirement. The second requirement was investigated by conducting two cycles of 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 target, 8 percent. The four specimens were divided into two sets, and each

a: Hot-Freeze Sequence

CONDITIONING FACTOR	CONDITIONING STAGE		
	WETTING *	CYCLE-1	CYCLE-2
Vacuum Level (in. Hg) :	20	10	10
Repeated Loading	NO	YS	NO
Ambient Temp.(C) **	25	60	-18
Duration (hr.)	0.5	6	6

b: Freeze-Hot Sequence

CONDITIONING FACTOR	CONDITIONING STAGE		
	WETTING *	CYCLE-1	CYCLE-2
Vacuum Level (in. Hg) :	20	10	10
Repeated Loading	NO	NO	YS
Ambient Temp.(C) **	25	-18	60
Duration (hr.)	0.5	6	6

* WETTING : Wetting the Specimen Prior to Conditioning Cycles
** Inside the Environmental Cabinet

Figure 4.21 Conditioning Information Charts for Climate Sequence Investigation set was conditioned in 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 not significant. This 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 freezing cycle at the end of the hot conditioning procedure. This 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 performing the hot conditioning procedure.

In the previous section, it was found statistically that the more hot cycles, the more water damage, and also it was found that the difference between the slope combinations of three hot cycles (first cycle, first + second cycle, and first + second + third cycles) is statistically 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 thing with 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 necessary to investigate the possibility of shorter conditioning procedure and retaining 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

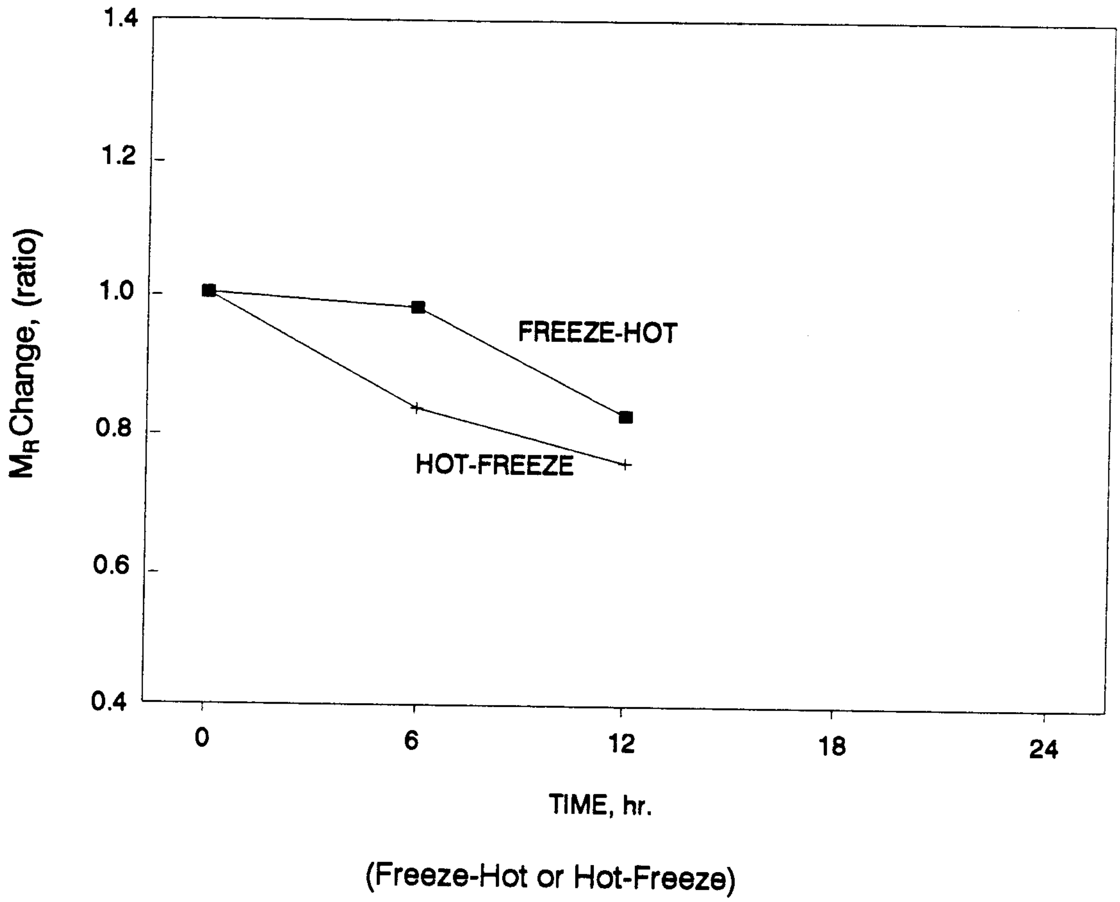


Figure 4.22 Effect of conditioning sequence on Resilient Modulus change

a: 1 Hot + 1 Freeze

CONDITIONING FACTOR	CONDITIONING STAGE		
	WETTING*	CYCLE-1	CYCLE-2
Vacuum Level (in. Hg) :	20	10	10
Repeated Loading	NO	YS	NO
Ambient Temp.(C) **	25	60	-18
Duration (hr.)	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	YS	YS	NO
Ambient Temp.(C) **	25	60	60	-18
Duration (hr.)	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	YS	YS	YS	NO
Ambient Temp.(C) **	25	60	60	60	-18
Duration (hr.)	0.5	6	6	6	6

* WETTING : Wetting the Specimen Prior to Conditioning Cycles
**Inside the Environmental Cabinet

Figure 4.23 Conditioning Information Charts for Water Conditioning Procedure Investigation 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 for 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 procedures and each of the two hot cycle and one hot cycle procedures. In other words, the three hot cycle and one freeze cycle conditioning procedure cannot be substituted by the one hot cycle, nor by the two hot cycle and one freeze cycle procedure. Therefore, it is concluded that three hot-wet cycles with continuous repeated loading is an appropriate water conditioning procedure for hot climates, and three hot-wet cycles with continuous repeated loading plus one freeze-wet cycle is an appropriate conditioning procedure for cold climates. The ECS conditioning protocol is described in detail in Appendix B.

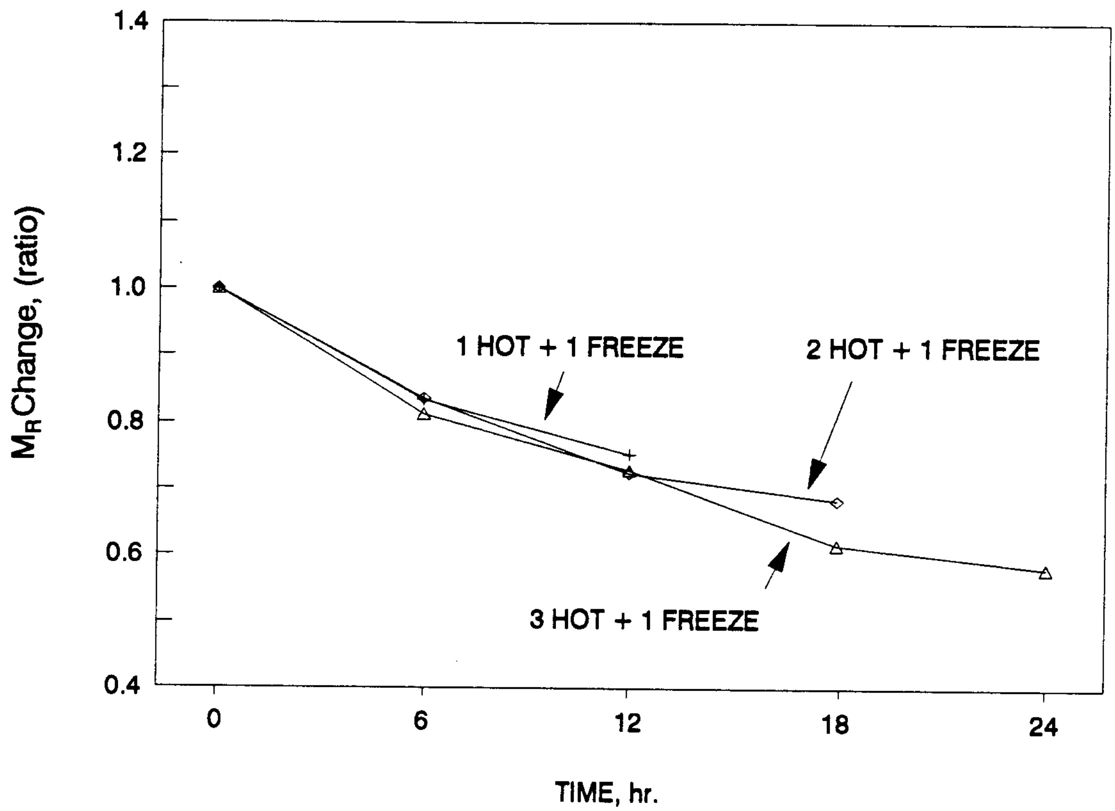


Figure 4.24 Effect of Number of Hot Cycles on Resilient Modulus change

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

Several different tests are used to determine the moisture sensitivity of an asphalt mixture. AASHTO T-283, including its various improvements is the best known test procedure among the highway agencies. AASHTO T-283 was used in this study as a benchmark for comparison. More than one hundred specimens were prepared and tested for evaluation. For each test, six specimens were divided into two sets (dry and conditioned sets). Internal water pressure in the conditioned specimens was produced by vacuum saturation followed by a freeze and thaw cycle. Two numerical indices of retained resilient modulus (M_R) and indirect tensile strength (TS) are obtained by comparing the retained indirect tensile strength and resilient modulus of conditioned laboratory specimens with the similar tests of 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, such as that one combination (RB/AK-1) showed M_R ratios varying between 0.60 and 1.12 (Table 4.23), which is unexpectedly high. Likewise, retained ST results after water conditioning are shown in Figure 4.26. Also, ST ratios

Table 4.23 Summary of AASHTO T 283 Water Conditioning Test Results

Test No.	Asph/Agg Combination	ST * Ratio	M_R * Ratio
1	RL/AAK1	0.54	0.74
2	RL/AAK1	0.6	0.82
3	RL/AAK1	0.83	0.62
4	RL/AAK1	0.53	0.53
5	RL/AAK1	0.93	0.68
6	RL/AAK1	0.3	0.26
Coefficient of Variation		**36.5**	**32.5**
1	RL/AAG1	0.49	0.40
2	RL/AAG1	0.3	0.40
3	RL/AAG1	0.57	0.63
4	RL/AAG1	0.61	0.47
5	RL/AAG1	0.53	0.60
6	RL/AAG1	0.4	0.38
7	RL/AAG1	0.43	0.69
Coefficient of Variation		**16**	**24.5**
1	RB/AAK1	0.64	0.60
2	RB/AAK1	0.65	0.61
3	RB/AAK1	0.81	0.72
4	RB/AAK1	0.67	1.12
5	RB/AAK1	0.79	0.93
Coefficient of Variation		**11.4**	**28.2**
1	RB/AAG1	1.24	0.62
2	RB/AAG1	1.16	0.83
3	RB/AAG1	0.58	0.77
4	RB/AAG1	0.51	0.62
5	RB/AAG1	0.77	0.55
Coefficient of Variation		**39.1**	**17.2**

*: Each ST ratio or M_R ratio is an average of three test replicates resulting from dividing M_R or ST results of three conditioned specimens by dry M_R or ST results of three dry specimens (See Table 3.2 for More Details)

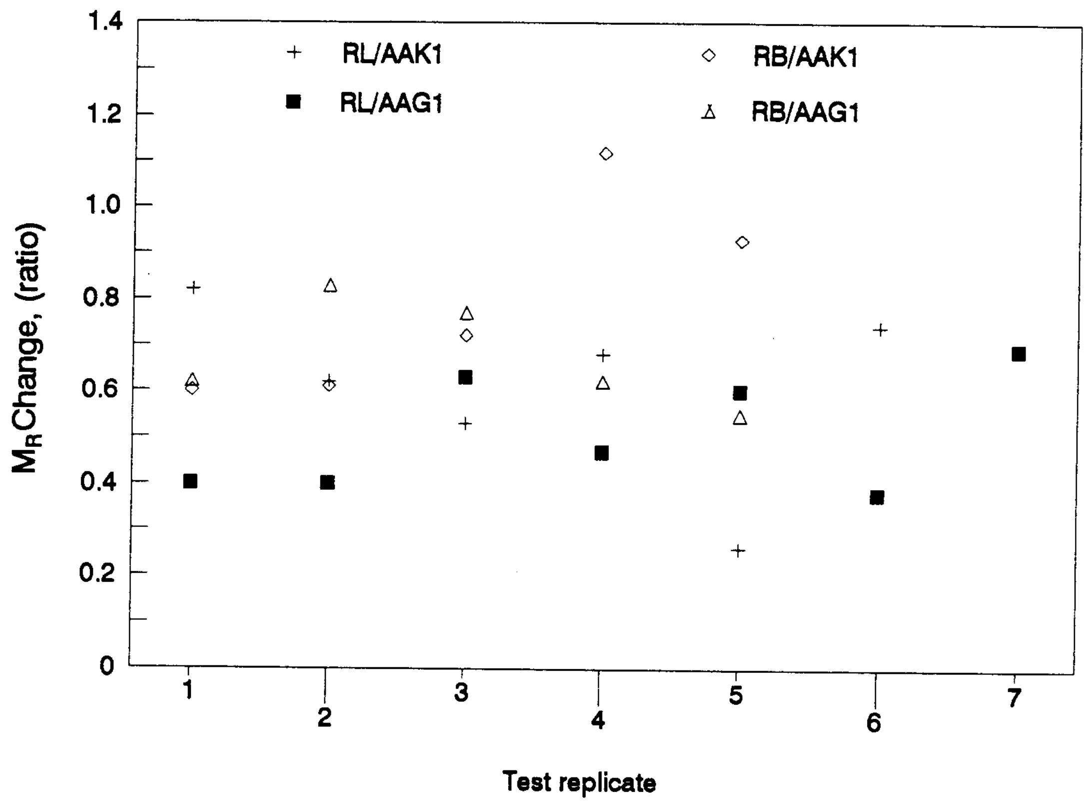


Figure 4.25 Resilient Modulus Change After AASHTO T 283 Test

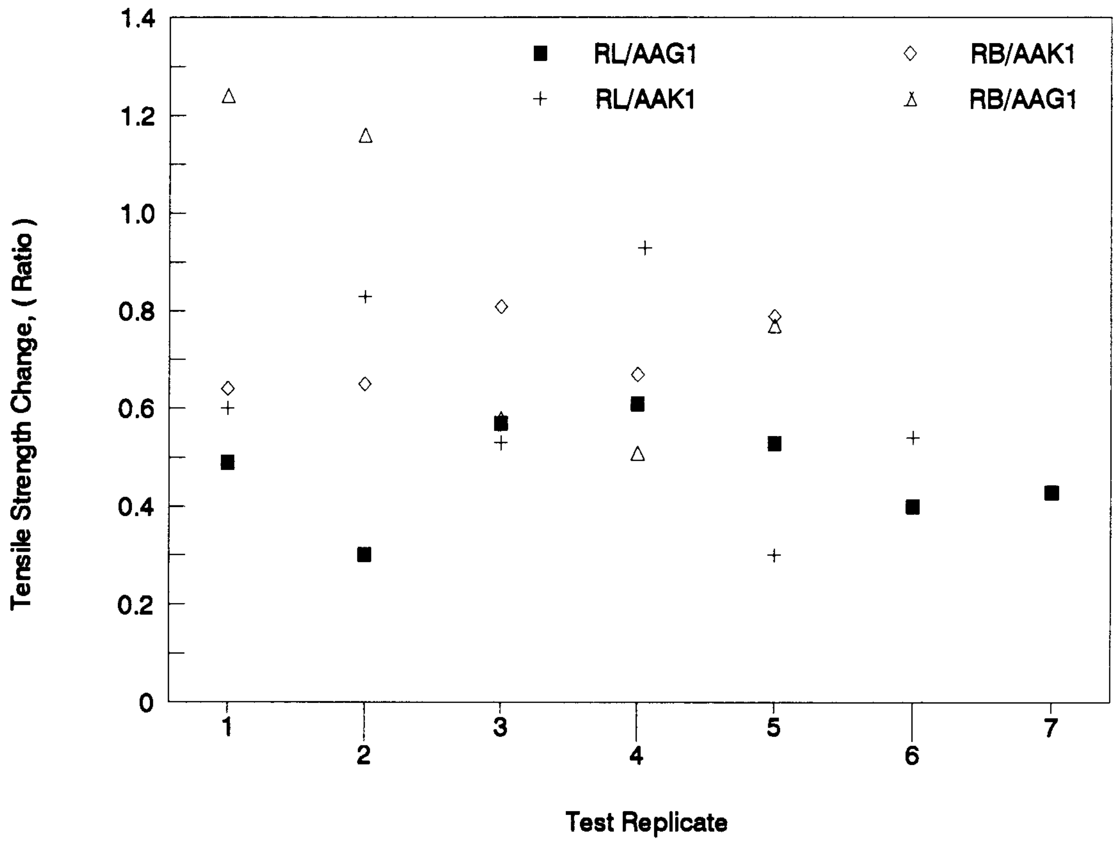


Figure 4.26 Retained Tensile Strength After AASHTO T 283 Test

showed a significant variation within each combination, particularly RB/AAG-1 which showed ST ratios between 0.50 and 1.24.

Since the variation associated with M_R and ST indices questions the repeatability of the test, the Coefficient of Variation (CV) was calculated for M_R and ST ratios for each asphalt-aggregate combination shown in Table 4.23. CV varied between 11 and 39 percent, where the correspondent CV of ECS procedure (this is discussed in more detail in following section) did not exceed 10 percent with the four asphalt-aggregate combinations.

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

Using the GLM in this way 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 giving 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

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	DF	Sum of Squares	Mean Square	F Value	P=0.10 F Crit
Model	3	0.252	0.084	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 ST Ratios After AASHTO T 283 Conditioning for the Four Asphalt-Aggregate Combinations

Source	DF	Sum of Squares	Mean 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			

conditioning. Table 4.26 shows LSD ranking results based on the retained M_R. LSD results showed that AASHTO T 283 test ranks the four combinations according to the aggregate type at the 90 percent confidence level with a least significant difference 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 ST ratios. Although, M_R and ST ratios in Table 4.23 seemed different, LSD based on ST 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.

Since 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 the current practice, the comparison between the two techniques is addressed below.

Although AASHTO T-283 ranked the four combinations statistically according to their known durability, the number of the tested specimens used for the statistical analysis is significantly higher than the corresponding number used for the ECS. Each M_R and ST ratio in Table 4.23 is resulted from averaging the test results of six

Table 4.26 Asphalt/Aggregate Ranking by M_R

Alpha= 0.10 df= 19 MSE= 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

Table 4.27 Asphalt/Aggregate Ranking by LSD

Alpha= 0.10 df= 19 MSE= 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

specimens (three dry and three wet), so the total specimens used for this comparison were 22X6= 132 specimens. On the other hand, only 11 specimens (hot wet-saturated conditioning) were used for the statistical analysis to rank the four combinations according to ECS-M_R ratios, as discussed earlier. The major difference between the two techniques is that for AASHTO T-283 six specimens are needed in order to get one M_R ratio (or ST ratio). In contrast to AASHTO T-283, with ECS technique three M_R ratios are obtained by testing one specimen (and the fourth one after a freeze cycle).

For AASHTO T-283, the variation of M_R and ST ratios with the same asphalt-aggregate combination, which is expressed by high Coefficient of Variation compared to those from the ECS procedure, and by present M_R and ST ratios more than 1.0, questions the repeatability of AASHTO T-283 and indicates that using this test as a water sensitivity test needs more development.

The significant difference between AASHTO T-283 results in terms of the repeatability confirms what has been discussed in proceeding sections about the role of simulating the mechanisms of asphalt-aggregate interaction in the presence of water in improving the repeatability of the test. Also, ECS test results show that using one conditioning and testing device to perform all the tests on the same test setup and one specimen orientation decreases the variability of the test results and reduces the error sources associated with specimen handling and testing different specimen orientations which is associated with AASHTO T-283.

Finally, from this comparison it has been concluded that AASHTO T 283, with its current procedure, is a good moisture conditioning protocol to predict asphalt concrete response to the change in mixture and conditioning variables of a water conditioning protocol.

5. CONCLUSIONS

The following conclusions are based on the test results obtained in this laboratory research and their analysis as presented. Conclusions that appear warranted are as follows:

1. Comparisons between LVDTs and strain gages showed no significant difference on dry specimens. However, the use of strain gages presented problems regarding practicality during actual testing. That is, the strain gages wrinkled under the effect of repeated loading with hot water conditioning. Therefore, the use of LVDTs was adopted for strain measurement during the resilient modulus tests.

2. Although the use of strain gages for the ECS was abandoned, tests on the type of glue used to bond the gages to the specimens showed no significant

difference between glue types. The manufacturer recommended a super glue, however.

3. The modulus tests on specimens having an L/D ratio of 5/4 showed essentially the same very low variability and the same magnitude as those on specimens with L/D ratios of 7/4. Backed by these results and the fact that the 4-in. high by 4-in. diameter specimen is more representative of actual pavement lift thicknesses, it was concluded that a specimen size of 4 in. diam. by 4 in. high is more suitable than the conventional 4 in. by 2.5 in. high specimen.

4. Tests investigating and evaluating the difference between the 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. So, the perforated disks are used rather than solid disks to provide openings for air and water flow.

5. Regarding permeability measurement, 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 - the two methods indicate no significant difference.

6. Permeability is an appropriate measure of the void system in a mixture.

7. Retained M_R, permeability (k), and stripping rate are suitable measures of mixture behavior following various conditioning treatments such as degree of wetting, temperature, and amount of air voids.

8. Three 6-hour temperature cycles are adequate to evaluate the effect of conditioning. Longer (24-hour) cycles do not increase one's ability to discern differences among mixtures.

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

10. Tests investigating the effect of continuous repeated loading during hot-wet cycling was (within the 200 lb. repeated load level) modest on M_R, while it was significant on the stripping rate. That is, repeated loading has more detrimental effect on adhesion.

11. Specimens with voids higher or lower than the pessimum range resist water damage more than specimens within the pessimum range.

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 performing a mix design.

13. The ECS as a test system is utilizing today's technology, which provides continuous development in terms of test precision and convenient data acquisition.

14. The ECS as a test method provides a number of parameters from the tested specimen, i.e., retained M_R, retained permeability, stripping rate, and more,

such as stress-strain information at different temperatures during the conditioning procedure, which is available through the data acquisition capability of the system. These data and capabilities will provide a better understanding about asphalt-aggregate interaction and establish a reliable base for a continuous education process.

15. Finally, regarding evaluation of the overall system, it was shown that the system is sufficiently sensitive to detect the level of damage due to water in terms of saturation level, conditioning temperature, and air voids level. In short, the ECS has been demonstrated to be suitable for and capable of determining the effect of water damage for a range of asphalt concrete mixture.

6. RECOMMENDATIONS

6.1 Implementation

The overall goal of this research was to relate asphalt mixture properties to performance of mixtures. The Environmental Conditioning System (ECS) was developed and fabricated 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 as accomplished in this water sensitivity study. These recommendations are development of a testing equipment and development of water conditioning techniques, which are discussed in the following sections.

Testing Equipment

The ECS was devised and fabricated for water sensitivity testing and evaluation. This device has been used for more than two years at different environmental conditioning levels by including or excluding variability of related variables with different treatment levels such as permeability, time of conditioning, rate of wetting,

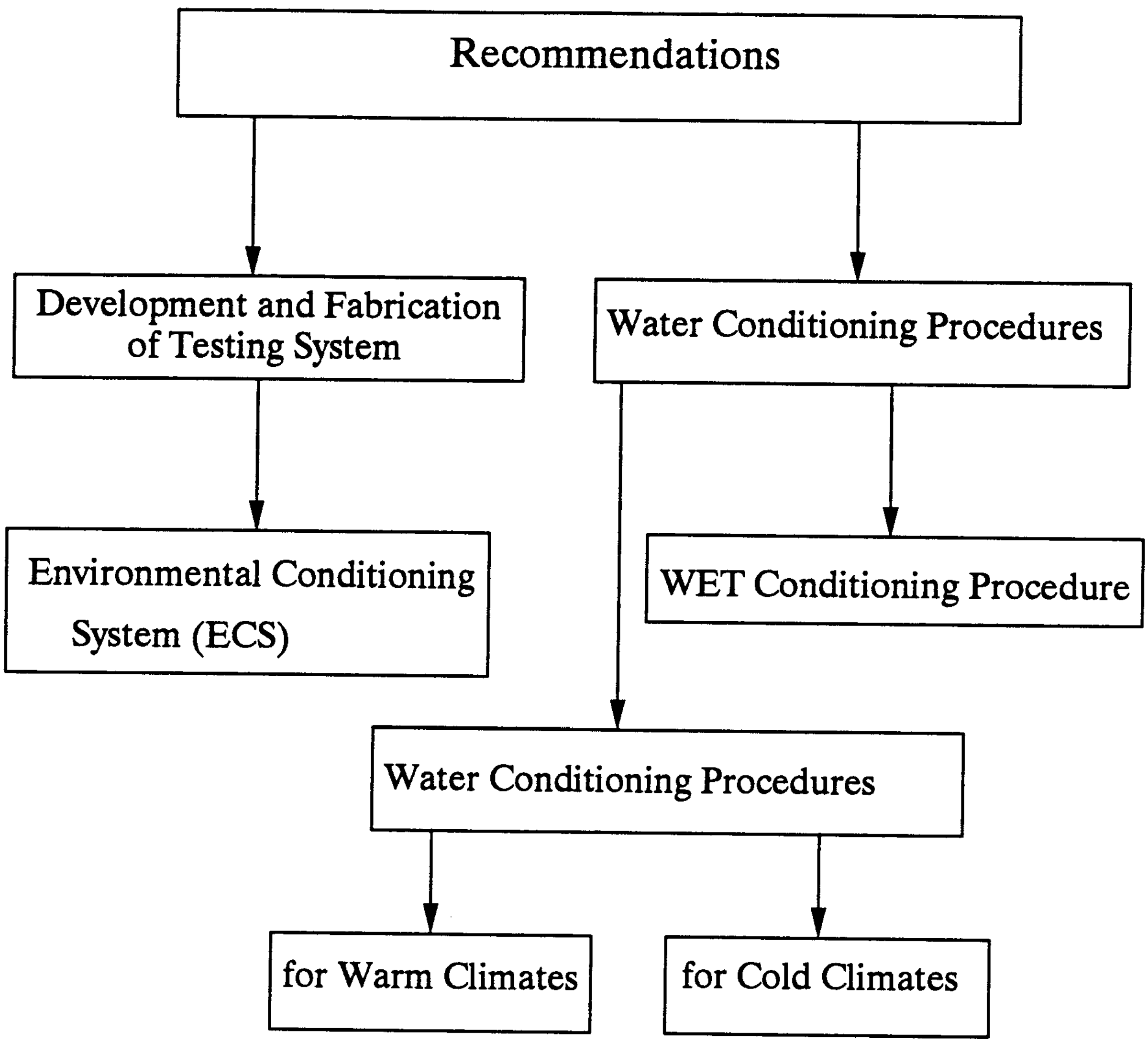


Figure 6.1 Recommendation Chart as Accomplished in this Water Sensitivity Study

aging, loading, air voids, etc. The ECS shows a wide capability for environmental conditioning and testing compacted asphalt mixtures. Although precision of tests has not yet been developed, the ECS has a greater capability for simulating field conditions to which the asphalt concrete is exposed better than previous methods. Correspondingly, the ECS is a reliable testing device for water sensitivity and its apparent advantages over previous methods are summarized in the following points:

1. The ECS monitors the permeability of the specimens after each conditioning cycle, either thawing or freezing.
2. Eliminates leaking and specimen deformation during the test.
3. Decreases the variability of resilient modulus since only one specimen setup is required.
4. 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, instead of following a complete conditioning cycle (freezing and thawing together).
6. The ECS conditions and tests compacted asphalt specimens with any percent of air voids.
7. The ECS applies repeated loads throughout the duration of 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 design using the ECS is less than the required specimens for the same purpose using AASHTO T-283.

Water Conditioning Techniques

A series of tests were performed on four different MRL materials according to an experiment plan which was established after selection to include the most important related variables. Figure 6.2 shows the two recommended conditioning procedures. These are summarized as follows:

Water Conditioning Procedure

In order 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. An analysis was conducted on the test results to show asphalt mixtures behavior in several ways:

- Saturation vs. moisture
- Wet vs. dry
- Water vs. vapor
- Water vs. air
- Permeability vs. air void content

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	YS	YS	YS	NO
Ambient Temp.(C) **	25	60	60	60	-18
Duration (hr.)	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 : Wetting the Specimen Prior Conditioning Cycles
** Inside the Environmental Cabinet

Figure 6.2 Conditioning Charts for Hot and Cold Climates

- Freeze vs. hot
- Volume change effect
- Conditioning time, such as cycle length
- Dynamic loading vs. static loading
- Stripping

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

- Resilient modulus
- Permeability
- Stripping rate

From the analysis of the above variables, two water conditioning procedures were recommended to give optimum simulation for asphalt mixture variables and give practical 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: includes three wet-hot cycles of 6-hour duration at 60°C with continuous repeated loading.
2. Water conditioning for cold climate: includes three wet-hot cycles of 6-hour duration at 60°C with continuous repeated loading (as the hot climate), plus one wet-freeze cycle of the same duration as the hot cycle with static loading at - 18°C.

Repeated loading is performed during the hot cycles for the two procedures. Figure 6.2 shows the conditioning charts for the two procedures, and the details are shown in Appendices B and C.

Wet Conditioning Procedure

Wet conditioning is identified by the term "Wetting" in Figure 6.2. Wet conditioning is a wetting process by running water (under vacuum) through compacted asphalt concrete specimens at ambient 25 °C temperature for 30 minutes. Wet conditioning is recommended to be performed prior to testing in fatigue, rutting, and low temperature cracking. The wet conditioning procedure, including specimen setup recommendations for cylindrical and beam specimens, is shown in Appendix C.

6.2 Future Research

Additional research of moisture damage in asphalt concrete is recommended. The following suggested research is not covered by any known previous study or by this study:

1. Although the visual evaluation rating standard 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 very good evaluation method for water damage, because it is related to the adhesion bond, there is a need for developing an objective stripping rate standard test. Using an electronic scanner technique could be the key for the required development. Although a scanner includes the broken aggregate as a stripped aggregate, this problem can be controlled by coloring the broken aggregates with a black color, or by scanning a similar unconditioned specimen, then subtracting the result of the stripping rate of the unconditioned specimen from the stripping rate of the conditioned one.

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

7. REFERENCES

Al-Ohaly, A.A. and Terrel, R. L.(1989). "Effects of microwave heating on adhesion and moisture damage of asphalt mixtures, " TRR 1171, Transportation Research Board.

AASHTO, "Resistance of Computed Bituminous Mixtures to Moisture Induced Damage," AASHTO T283-85.

AASHTO, "Effect of Water on Cohesion of Compacted Bituminous Mixtures," AASHTO T165-82.

AASHTO, "Coating and Stripping of Bituminous-Aggregate Mixtures," AASHTO T182-82.

AASHTO, "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus," AASHTO T245-82.

Al-Swailmi, S., and Terrel, R.L. (1992). " Evaluation of Water Damage of Asphalt Concrete Mixtures Using the Environmental Conditioning System (ECS)," Journal of the Association of Asphalt Paving Technologists, Charleston, South Carolina, 1992.

Al-Swailmi, S., Scholz, T.V., and Terrel, R.L. (1992). " The Development and Evaluation of a Test System to Induce and Monitor Moisture Damage to Asphalt Concrete Mixtures," Transportation Research Board Meeting, Washington, DC.

ASTM, "Test for Effect of Water on Bituminous Coated Aggregate," ASTM D 3625-77.

ASTM, "Effect of Water on Cohesion of Compacted Bituminous Mixtures," ASTM D 1075-81.

ASTM, "Coating and Stripping of Bituminous-Aggregate Mixtures," ASTM D1664-80.

ASTM, "The Standard Test Method for Dynamic Modulus of Asphalt Mixtures," ASTM D3497.

ASTM, "The Standard Method of Indirect Tension Test for Resilient Modulus of Bituminous Mixtures," ASTM D4123.

ASTM, "The Standard Capping Method," ASTM C617.

ASTM, "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens," ASTM D1188.

ASTM, "Bulk Specific Gravity of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimen," ASTM D2726.

ASTM, "Standard Terminology for Statistical Methods," ASTM E 456.

ASTM, "Standard Practice for Conducting an Inter Laboratory Test Program to Determine the Precision of Test Methods for Construction Materials," ASTM C 802.

ASTM, "Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods," ASTM E 177.

Blight, G.E. (1977),"A falling head air permeameter for testing asphalt," Die Sivielle Ingenieur in Suid-Afrika.

Curtis, W.C., Ensley, K., and Epps, J., Draft Final Report on Fundamental Properties of Asphalt-Aggregate Interactions Including Adhesion and Absorption, Strategic Highway Research Program, National Research Council, Washington, DC, 1992.

Curtis, C., Terrel, R.L., Perry, L.M., Al-Swailmi, S., and Brannon, E.J., "Asphalt-Aggregate Interactions," Journal Association of Asphalt Paving Technologists, 1991.

Del Valle, H. (1985). "Procedure-Bulk specific gravity of compacted bituminous mixtures using parafilm-coated specimens," Chevron Research Company, Richmond, California.

Ellis, W.H. and Schmidt, R. J.,(1960) "A Method for measuring the air permeability of asphalt concrete pavements," ASTM Special Technichal Publication No. 294.

Eriksen, K., (1991), Quarterly Report on Microscopical Analysis of Asphalt-Aggregate Mixtures Related to Pavement Performance, Strategic Highway Research Program, National Research Council, Washington, DC, September, 1991.

Field, F. and Phang, W.A. (1986). "Stripping in asphaltic concrete mixes: observations and test procedures," Proceedings, 12th Annual Conference of the Canadian Technical Asphalt Association, Halifax.

Goode, J.F. and Lutsey, L.A. (1965). "Voids, Permeability, Film Thickness vs. Asphalt Hardening", Proceedings, Association of Asphalt Paving Technologists, 34, 430-462.

Graf, P.E. (1986). Discussion of "Factors affecting moisture susceptibility of asphalt concrete mixes", Proceedings, Association of Asphalt Paving Technologists, 55, 175-212.

Hein, T.C. and Schmidt, R.J. (1961). "Air Permeability of Asphalt Concrete", American Society for Testing and Materials, ASTM Special Technichal Publication No. 309.

Kennedy, T.W., Roberts, F.L., and Lee, K.W., (1982) "Evaluation of Moisture Susceptibility of Asphalt Mixtures Using the Texas Freeze-Thaw Pedestal Test," Proceedings, Assoc. Asphalt Paving Technol., 51.

Kennedy, T.W., Roberts, F.L., Lee, K.W. (1983). "Evaluation of moisture effects on asphalt concrete mixtures," TRR 911, Transportation Research Board. Washington, DC.

Kumar, A. and Goetz, W.H. (1977). "Asphalt hardening as affected by film thickness, voids, and permeability in asphaltic mixtures," Proceedings, Association of Asphalt Paving Technologists, San Antonio.

Kumar, A. and Goetz, W.H. (1977). "Laboratory measurement of permeability of compacted asphalt mixtures," TRR 659, Transportation Research Board. Washington, DC.

Lottman, R.P. (1971). "The moisture mechanism that causes asphalt stripping in asphaltic pavement mixtures," Department of Civil Engineering, University of Idaho, Final Report.

Lottman, R.P. (1978). "Predicting moisture-induced damage to asphaltic concrete," NCHRP 192, Transportation Research Board. Washington, DC.

Lottman, R.P. (1982). "Prediction moisture-induced damage to asphaltic concrete - field evaluation," NCHRP 246, Transportation Research Board.

Majidzadeh, K. and Brovold, F.N. (1968). "State of the art: effect of water on bitumen-aggregate mixtures," Highway Research Board, Special Report 98.

Mandel, J.,(1964),"The Statistical Analysis of Experiment Data," John Wiley & Sons, New York.

Parker, F. and Gharaybeh, F. (1987). "Evaluation of indirect tensile tests for assessing stripping of Alabama asphalt concrete mixtures," TRR 1115, Transportation Research Board, 113-124. Washington, DC.

Parker, F., and Wilson, M.S. (1986). "Evaluation of boiling and stress pedestal tests for assessing stripping potential of Alabama asphalt concrete mixtures," TRR 1096, Transportation Research Board, 90-99.

Podoll, R. T., (1991), Monthly Progress Report on Surface Analysis By Laser Ionization of the Asphalt-Aggregate Bond, Strategic Highway Research Program, National Research Council, Washington, DC., June, 1991.

Rensel, Paul (1965). "Simplified quality control of asphalt concrete", Proceedings, Northwest Roads and Streets Conference, University of Washington, Seattle.

Schmidt, R.J. and Graf, P.D. (1972). "The effect of water on the resilient modulus of asphalt treated mixes," Proceedings, Association of Asphalt Paving Technologists, 41, 118-162.

Shute, J.W., R.G. Hicks, J.E. Wilson, and L.G. Scholl (1989). "Effectiveness of antistripping additives," Vols. I and II, Oregon DOT, May 1989.

Stuart, K.D. (1986). "Evaluation of procedures used to predict moisture damage in asphalt mixtures," FHWA/RD-86/091.

Terrel, R.L. and J.W. Shute (1989). "Summary report on water sensitivity," SHRP-A/IR-89-003, Strategic Highway Research Program.

Terrel, R.L. (1990). "Water sensitivity of asphalt concrete," Proceedings, New Mexico Paving and Transportation Conference.

Tunnicliff, D.G., and Root, R.E. (1984). "Use of antistripping additives in asphaltic concrete mixtures," NCHRP 274, Transportation Research Board.

Vallerga, B.A. and Hicks, R.G. (1968). "Water permeability of asphalt concrete specimens using back-pressure saturation," Journal of Materials, 3(1). Washington, DC.

8. APPENDICES

APPENDIX A

ORIGINAL TEST RESULTS OF ECS

In order to make it convenient for conducting different studies which may not be included in this research, this appendix includes the whole ECS conditioning data. Two groups of data are included in Appendix A:

1- Table A-1: the original data of the ECS tests results from 4 in.-high specimens, which are included in section 3 (Table 3.8) after averaging the replicates,

2- Table A-2 : the original data of the ECS results from 2.5 inch-high specimens which are not discussed in this report because of the high variability associated with M_R, but still could be used for further analysis for the variability of the M_R test or some other studies related to the other reported data (i.e., air voids, permeability etc.).

Table A–1 Summary of ECS Test Results

Specimen ID	Air Voids (%)	Air Perm. E–9 (cm/s)	Time (hr.)	ECS–M_R (ksi)	Ret. ECS–M_R (Ratio)	Water Perm. E–9 (cm/s)	Ret. Water Perm. (Ratio)	Stripping Rate (%)
RLC204RL/AAK	5	1.8	0	500	1.00	0.95	1.00	
			6	420	0.84	0.99	1.04	
10–16–91			12	419	0.84	0.76	0.80	
			18	370	0.74	0.69	0.73	20
RLC91RL/AAK	4.5	1.3	0	500	1.00	0.56	1.00	
			6	460	0.92	0.68	1.21	
10–18–91			12	433	0.87	0.51	0.91	
			18	395	0.79	0.44	0.79	20
RLC58RB/AAG	4	1.11	0	1102	1.00	0.31	1.00	
			6	869	0.79	0.24	0.77	
10–5–90			12	953	0.86	0.18	0.58	
			18	964	0.87	0.13	0.42	10
RLC118RB/AAG	4.3	1.7	0	929	1.00	0.29	1.00	
			6	846	0.91	0.27	0.93	
02–08–91			12	750	0.81	0.18	0.62	
			18	680	0.80	0.16	0.55	10
RC53RL/AAK	7.1	7.48	0	699	1.00	1.74	1.00	
			6	537	0.77	1.48	0.85	
10–03–90			12	541	0.77	0.98	0.56	
			18	497	0.71	0.65	0.37	40
RC201RL/AAK	7	3.4	0	660	1.00	2.08	1.00	
			6	530	0.80	1.97	0.95	
10–12–91			12	460	0.70	1.99	0.96	
			18	420	0.64	1.49	0.72	50
RC209RL/AAK	7.1	3.4	0	420	1.00	1.91	1.00	
			6	345	0.82	1.84	0.96	
10–27–91			12	320	0.76	1.61	0.84	
			18	250	0.60	1.62	0.85	50
RC56RL/AAG	7.2	29.0	0	1310	1.00	6.87	1.00	
			6	942	0.72	2.22	0.32	
14–03–90			12	910	0.69	3.08	0.45	
			18	776	0.59	4.15	0.60	40
RC79RL/AAG	6.9	1.83	0	808	1.00	1.85	1.00	
			6	672	0.83	0.51	0.28	
03–18–91			12	757	0.94	0.26	0.14	
			18	615	0.76	0.21	0.11	20

Table A−1 (continued)

Specimen ID	Air Voids (%)	Air Perm. E−9 (cm/s)	Time (hr.)	ECS−M_R (ksi)	Ret. ECS−M_R (Ratio)	Water Perm. E−9 (cm/s)	Ret. Water Perm. (Ratio)	Stripping Rate (%)
RC103RB/AAK	8	7.3	0	290	1.00	2.61	1.00	
			6	260	0.90	1.53	0.59	
10−22−91			12	270	0.93	1.14	0.44	
			18	240	0.83	0.81	0.31	30
RC104RB/AAK	8.1	2.3	0	400	1.00	2.18	1.00	
			6	320	0.80	1.42	0.65	
10−29−91			12	299	0.75	0.52	0.24	
			18	285	0.71	0.21	0.10	30
RC61RB/AAG	8.2	13.3	0	779	1.00	1.58	1.00	
			6	750	0.96	1.18	0.75	
10−17−90			12	689	0.88	1.26	0.80	
			18	664	0.85	0.79	0.50	30
RC105RB/AAG	7.9	8.92	0	716	1.00	1.65	1.00	
			6	628	0.88	1.51	0.92	
01−24−91			12	610	0.85	0.8	0.48	
			18	562	0.78	0.35	0.21	30
RC106RB/AAG	8.2	5.02	0	703	1.00	1.76	1.00	
			6	620	0.88	1.3	0.74	
02−04−91			12	539	0.77	0.33	0.19	
			18	534	0.76	0.164	0.09	30
RC113RB/AAG	7.7	7.7	0	701	1.00	1.25	1.00	
			6	640	0.91	0.43	0.34	
02−02−91			12	571	0.81	0.876	0.70	
			18	554	0.79	0.296	0.24	30
SLI111RL/AAK	3.9	0.14	0	1140	1.00	0.09	1.00	
			6	1032	0.91	0.06	0.67	
04−26−91			12	1129	0.99	0.07	0.78	
			18	989	0.87	.	.	5
SLI81RL/AAG	4.9	1.03	0	926	1.00	0.35	1.00	
			6	889	0.96	0.33	0.94	
05−04−91			12	855	0.92	0.29	0.83	
			18	811	0.88	.	.	5
SLI65RL/AAG	4.1	0.32	0	1058	1.00	0.09	1.00	
			6	976	0.92	0.07	0.78	
04−13−91			12	976	0.92	.	.	
			18	929	0.88	.	.	5

Table A–1 (continued)

Specimen ID	Air Voids (%)	Air Perm. E–9 (cm/s)	Time (hr.)	ECS–M_R (ksi)	Ret. ECS–M_R (Ratio)	Water Perm. E–9 (cm/s)	Ret. Water Perm. (Ratio)	Stripping Rate (%)
SLI71RB/AAK	4.6	0.99	0	581	1.00	0.15	1.00	
			6	506	0.87	0.14	0.93	
04–26–91			12	518	0.89	0.12	0.80	
			18	460	0.79	0.12	0.80	5
SLI66RB/AAK	4.1	0.86	0	591	1.00	0.29	1.00	
			6	580	0.98	0.27	0.93	
04–29–91			12	570	0.97	0.16	0.55	
			18	561	0.95	0.21	0.72	5
SLI115RB/AAG	4.5	0.39	0	888	1.00	0.18	1.00	
			6	847	0.95	0.17	0.94	
02–10–91			12	825	0.93	0.10	0.58	
			18	699	0.79	0.09	0.50	5
SLI168RB/AAG	5.2	1.13	0	685	1.00	0.33	1.00	
			6	660	0.96	0.31	0.94	
10–26–91			12	623	0.91	0.2	0.61	
			18	649	0.95	0.24	0.73	5
SI61RL/AAK	7.7	5.42	0	454	1.00	2.44	1.00	
			6	424	0.93	3.51	1.44	
11–14–90			12	414	0.91	3.63	1.49	
			18	392	0.86	3.02	1.24	5
SI101RL/AAK	7.9	2.24	0	557	1.00	2.22	1.00	
			6	516	0.93	1.91	0.86	
02–26–91			12	468	0.84	1.7	0.77	
			18	471	0.85	1.63	0.73	10
SI59RL/AAG	7	1.63	0	1100	1.00	5.07	1.00	
			6	969	0.88	1.99	0.39	
12–10–90			12	907	0.82	3.95	0.78	
			18	960	0.87	2.85	0.56	10
SI55RB/AAK	6.8	10.4	0	276	1.00	2.25	1.00	
			6	275	1.00	1.80	0.80	
11–10–90			12	308	1.12	3.52	1.56	
			18	297	1.08	3.31	1.47	5
SI57RB/AAK	6.4	9.4	0	596	1.00	1	1.00	
			6	553	0.93	0.91	0.91	
03–04–91			12	503	0.84	1.22	1.22	
			18	439	0.74	0.66	0.66	5

Table A–1 (continued)

Specimen ID	Air Voids (%)	Air Perm. E–9 (cm/s)	Time (hr.)	ECS–M_R (ksi)	Ret. ECS–M_R (Ratio)	Water Perm. E–9 (cm/s)	Ret. Water Perm. (Ratio)	Stripping Rate (%)
SI63RB/AAG	8.3	20.9	0	610	1.00	3.09	1.00	
			6	577	0.95	2.79	0.90	
10–22–90			12	510	0.84	2.19	0.71	
			18	521	0.85	2.08	0.67	10
SI85RB/AAG	7	1.76	0	1099	1.00	2.02	1.00	
			6	1024	0.93	2.11	1.04	
03–06–91			12	923	0.84	2.18	1.08	
			18	853	0.78	1.7	0.84	10
SI161RB/AAG	7.8	2.21	0	710	1.00	2.59	1.00	
			6	660	0.93	2.29	0.88	
10–24–91			12	650	0.92	2.25	0.87	
			18	675	0.95	1.58	0.61	5
RB205RL/AAK	7.9	4.37	0	530	1.00	1.5	1.00	
			6	460	0.87	1.09	0.73	
10–15–91			12	450	0.85	0.45	0.30	
			18	420	0.79	0.45	0.30	20
RB206RL/AAK	9.1	5.26	0	338	1.00	1.22	1.00	
			6	293	0.87	0.76	0.62	
10–22–91			12	270	0.80	0.71	0.58	
			18	260	0.77	0.82	0.67	20
SH214RL/AAK	8.5	3.79	0	330	1.00	2.62	1.00	
			6	320	0.97	2.31	0.88	
11–09–91			12	299	0.91	2.1	0.80	
			18	320	0.97	2.13	0.81	5
SH62RB/AAG	8.2	3.81	0	707	1.00	10.38	1.00	
			6	680	0.96	15.16	1.46	
10–29–90			12	651	0.92	19.23	1.85	
			18	652	0.92	14.32	1.38	5
SH108RB/AAG	7.3	5.62	0	894	1.00	1.2	1.00	
			6	889	0.99	1.05	0.88	
02–06–91			12	737	0.82	0.70	0.58	
			18	712	0.80	0.60	0.50	5
SLH99RL/AAK	3.8	0.64	0	690	1.00	.	.	
			6	631	0.91	.	.	
02–12–91			12	697	1.01	.	.	
			18	571	0.83	.	.	10

Table A−1 (continued)

Specimen ID	Air Voids (%)	Air Perm. E−9 (cm/s)	Time (hr.)	ECS−M_R (ksi)	Ret. ECS−M_R (Ratio)	Water Perm. E−9 (cm/s)	Ret. Water Perm. (Ratio)	Stripping Rate (%)
RF208RL/AAK	8	4.71	0	325	1.00	1.54	1.00	
			6	293	0.90	1.28	0.83	
10−28−91			12	246	0.76	0.78	0.51	
			18	240	0.74	0.45	0.29	5
RF209RL/AAK	8.9	3.25	0	383	1.00	2.28	1.00	
			6	340	0.89	2.17	0.95	
10−28−91			12	325	0.85	2.19	0.96	
			18	320	0.84	1.69	0.74	5
SC207RL/AAK	8.8	5.21	0	250	1.00	1.58	1.00	
			6	215	0.86	1.28	0.81	
10−27−91			12	195	0.78	1.26	0.80	
			18	188	0.75	0.79	0.50	30
SC208RL/AAK	8	4.78	0	570	1.00	1.79	1.00	
			6	500	0.88	1.49	0.83	
10−30−91			12	447	0.78	1.47	0.82	
			18	410	0.72	1.01	0.56	30
VC47RL/AAK	6.8	2.61	0	594	1.00	8.95	1.00	
			6	656	1.10	7.5	0.84	
07−29−90			12	635	1.07	7.77	0.87	
			18	604	1.02	8.44	0.94	5
A31RL/AAK	9	5.7	0	394	1.00	5.7	1.00	
			6	459	1.16	5	0.88	
07−03−90			12	527	1.34	5.1	0.89	
			18	508	1.29	5.1	0.89	
SC214RL/AAK	8.4	2.46	0	280	1.00	3.2	1.00	
			24	226	0.81	2.1	0.66	
10−20−91			48	195	0.70	1.1	0.34	
			72	188	0.67	0.9	0.28	40

Table A-2 Summary of Water Conditioning Test Results
(This Table Includes Only 2.5 in High Specimens, For 4.0 in. High Specimens See Table A-1)

Specimen No./Date	Time (hr.)	M_R (ksi)	Ret. M_R ratio	Per. XE 9 c	Ret. Per. (ratio)	Stripping Rate (%)
A31RL/AAK-1 7-3-90	0 24 48 72	394 459 527 508	1.00 1.16 1.34 1.29	5.7 5 5.1 5.1	1.00 0.88 0.89 0.89	
B26RL/AAK-1 6-690	0 24 48 72	394 330 302 285	1.00 0.84 0.77 0.72			50
C13RL/AAK-1 5-14-90	0 24	434 320	1.00 0.74	2.8 1.4	1.00 0.50	10
C17RL/AAK-1 5-8-90	0 24	374 357	1.00 0.95	3.8 0.6	1.00 0.16	
C11RL/AAK-1 5-6-90	0 24	240 236	1.00 0.98	4.9 1.4	1.00 0.29	
C20RL/AAK-1 5-22-90	0 6 12 18 24	305 265 243 235 206	1.00 0.87 0.80 0.77 0.68			
C20RL/AAK-1 5-18-90	0 6 12 18 24 30 36	474 337 360 330 346 301 324	1.00 0.71 0.76 0.70 0.73 0.64 0.68			40
C23RL/AAK-1 6-1-90	0 24 48 72	397 389 266 237	1.00 0.98 0.67 0.60	1.6 1.1 0.5 0.4	1.00 0.69 0.31 0.25	

Table A-2 (continued)

Specimen No./Date	Time (hr.)	M_R (ksi)	Ret. M_R ratio	Per. XE 9 c	Ret. Per. (ratio)	Stripping Rate (%)
F25RL/AAK-1 6-3-90	0	297	1.00	4.7	1.00	10
	24	247	0.83	3.1	0.66	
	48	279	0.94	3.1	0.66	
	72	200	0.67	3.3	0.70	
F29RL/AAK-1 6-19-90	0	394	1.00	3.4	1.00	
	24	260	0.66	1	0.29	
	38	270	0.69	0.9	0.26	
	72	300	0.76	0.4	0.12	
H28RL/AAK-1 6-15-90	0	340	1.00	2.3	1.00	20
	24	329	0.97	0	0.00	
	48	244	0.72	0	0.00	
	72	245	0.72	0	0.00	
127RL/AAK-1 6-10-90	0	218	1.00	3.10	1.00	10
	24	248	1.14	0	0.00	
	48	218	1.00	0	0.00	
	72	242	1.11		0.00	
132RL/AAK-1 7-7-90	0	312	1.00	2.4	1.00	
	24	215	0.69	2.7	1.13	
	48	228	0.723	7.8	3.25	
	72	210	0.67	9.7	4.04	
L12RL/AAK-1 5-17-90	0	331	1.00	6.1	1.00	
	24	191	0.58	0.9	0.15	
AG19RL/AAK-1 5-25-90	0	266	1.00	5	1.00	0.0
	3	332	1.25	5.4	1.08	
	6	354	1.33	5.4	1.08	
	9	350	1.32	5.6	1.12	
	12	365	1.37	5.4	1.08	
	18	401	1.51	5.6	1.12	

Table A-2 (continued)

Specimen No./Date	Time (hr.)	M_R (ksi)	Ret. M_R ratio	Per. XE 9 c	Ret. Per. (ratio)	Stripping Rate (%)
AG22RL/AAK-1	0	248	1.00	5.5	1.00	0.0
5-27-90	6	311	1.25	5.6	1.02	
	12	368	1.48	5.8	1.05	
	18	309	1.25	5.9	1.07	
	24	303	1.22	5.8	1.05	
	30	402	1.62	5.8	1.05	
	36	492	1.98	6	1.09	
W10RL/AAK-1	0	368	1.00			
5-7-90	0.5	379				
	0.5	299	1.02			
	2.5	254	0.87			
	5.5	220	0.75			
	7	224	0.77			
W7RL/AAK-1	0	292	1.00			
5-8-90	0.5	301	1.03			
	0.5	299	1.02			
	2.5	254	0.87			
	5.5	2209	0.75			
	7	224	0.77			
W3RL/AAK-1	0	257	1.00			
4-29-90	0.5	253	0.98			
W2RL/AAK-1	0	301	1.00			
4-28-90	0.5	289	0.96			
VLC47RL/AAK-1	0	594	1.00	0.69	1.00	
7-29-90	6	656	1.10	0.62	0.90	
	12	635	1.07	0.63	0.91	
	18	604	1.02	0.64	0.93	
VC33RL/AAK-1	0	427	1.00	8.95	1.00	5
8-1-90	6	601	1.41	7.5	0.84	
	12	558	1.31	7.77	0.87	
	18	519	1.22	8.44	0.94	

APPENDIX B

STANDARD METHOD OF TEST FOR DETERMINING MOISTURE SENSITIVITY CHARACTERISTICS OF COMPACTED BITUMINOUS MIXTURES SUBJECTED TO HOT AND COLD CLIMATE CONDITIONS

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

1. SCOPE

1.1 This method describes conditioning procedures intended to determine the moisture sensitivity or stripping characteristics of a compacted bituminous mixture in the laboratory under hot and cold climatic conditions. Environmental variables such as temperature, moisture and load are used in the procedure.

2. APPLICABLE DOCUMENTS

2.1 *AASHTO Test Methods:*

T247-80 Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor

T167-84 Compressive strength of Bituminous Mixtures

2.2 *ASTM Test Methods:*

D 1561-81a Preparation of Bituminous Mixture Test Specimens by Means of California Kneading Compactor

D 3497-79 Standard Test Method for Dynamic Modulus of Asphalt Mixtures

D 3549-83 Thickness or Height of Compacted Bituminous Paving Mixture Specimens

D 4013-81 Standard Practice for Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor

3. APPARATUS

3.1 *Test System* - A Environmental Conditioning System (ECS) capable of simulating a hot or cold climatic regime to condition a compacted bituminous mixture specimen. Periodic measurements of the modulus (defined as the ECS modulus or ECS-M_R) of the specimen will be made throughout the test. In addition, air permeability of the specimen is measured before the conditioning begins.

The ECS-M_R is similar to the dynamic modulus defined in ASTM D3497-79. However, there are 2 important differences; 1) the height of the specimen is 4 in. instead of 8 in., and 2) the specimen is encapsulated in a rubber membrane throughout the test.

Figures 1 and 2 present diagrams of a test system which is capable of performing the required testing. Figure 1 is an illustration of the test setup with a specimen ready for testing and Figure 2 is a schematic drawing of the ECS setup. After the specimen has been prepared, it is placed in the ECS and the initial (dry) ECS-M_R and air permeability determined. The specimen then undergoes a wetting procedure at 25°C where a vacuum equivalent to 20 in. of mercury (Hg) is used to pull distilled water through the specimen for 30 minutes. At the end of 30 minutes (wetting stage), the water permeability is measured.

Before the conditioning begins, the vacuum is reduced from 20 in. to 10 in. of Hg, and the water flow is adjusted to a maximum flow of 5 cc/min. This is to maintain water replacement for the air bubbles coming out from the specimen during the hot conditioning cycles as well as the cooling and thawing periods. For the hot conditioning cycle, the temperature of the environmental cabinet (ambient temperature) is set to 60°C. After 6 hours, the temperature is changed back to the testing temperature of 25°C ± 0.5°C. After 2 additional hours (i.e. a total of 8 hours), the ECS-M_R and water permeability are measured. Throughout the hot conditioning cycle, a repeated load (haversine, 0.1s on, 0.9s off, with a magnitude of 30 lbs static and 200 lbs dynamic load) is applied.

For hot climate conditioning, the hot 6-hour cycle is repeated for a total of 3 cycles (total of 24 hours) for each specimen. If the bituminous mixture is to be used in a cold climate, the three hot 6-hour cycles are followed by one cold 6-hour cycle. The cold cycle is similar to the hot cycle; however, the temperature is changed to -18°C (instead of 60°C), and no repeated loading is applied. Distilled water continues to be pulled through the specimen at a vacuum of 10 in. of Hg . After 6 hours at -18°C, the temperature is brought to 25°C for 2 hours, and the ECS-M_R and water permeability is measured again at the end of the conditioning cycle. The ECS-M_R and water permeability measurements are made at the end of each 6-hour conditioning cycle. Figure 3 illustrates the conditioning procedures for both hot and cold climates.

As a minimum, the test system should meet the following requirements:

<u>Load Measurement</u>

Range:	0 to 1000 lb_f tension
Resolution:	≤ 0.5 lb_f
Accuracy:	± 1% Full Scale

<u>Deformation</u>

Range:	0 to 0.25 inch
Resolution:	≤ 5 x 10^{-6} inch
Accuracy:	± 5 x 10^{-6} inch

Temperature

Range:	-20°C to 100°C
Resolution:	≤ 0.5°C
Accuracy:	± 0.5°C

Vacuum

Range:	0 to 25 in. Hg
Resolution:	≤ 1.0 in. Hg
Accuracy:	± 0.5 in. Hg

Air Flow

Range:	20 cc/min to 40 scfh
Resolution:	≤ 20 cc/min
Accuracy:	± 10 cc/min

Water Flow

Range:	0 to 40 gph
Resolution:	≤ 1 cc/min
Accuracy:	± 0.5 cc/min

3.2 *Testing Machine* - A mechanical or hydraulic testing machine that meets the requirements of AASHTO T167-84.

3.3 *Specimen Holder* - A specimen holder capable of holding a 4 in. diameter by 4 in. high bituminous specimen is required for the sealing process. See Figure 4.

3.4 *End Platens* - Two 4 in. diameter by 2 in. thick aluminum platens. One side of the platens will have a drainage hole as well as a pattern of grooves as shown in Figure 5. Platens shall also have a one-sixteenth (1/16th) in. diameter O-ring groove.

3.5 *Miscellaneous Apparatus:*

- Metal tape or ruler/set of calipers
- Source of compressed air
- 1.5 and 6 in. lengths of rubber membrane (4 in. diameter)
- 2 Linear Variable Differential Transformers (LVDTs)
- Clear silicone cement
- Vacuum source

- 10 gallons of distilled water

4. TEST SPECIMENS

4.1 *Compacted Bituminous Concrete Specimens* - Specimens shall be cored from a slab prepared with the use of a rolling wheel compactor or as molded if prepared by kneading or gyratory compaction. It is *not* recommended that the Marshall method of compaction be used (AASHTO T245-82 or ASTM D 1559-89). If specimens are cored, the top and bottom of the specimen shall *not* be cut. Specimens shall be 4.0 ± 0.15 inches high and 4.0 ± 0.15 inches in diameter.

4.2 *Measurement of Specimen Size* - Measure the specimen at four locations, at approximately quarter points and record the average measurement as the thickness of the specimen within ± 0.15 cm. Measure the diameter of the specimen in the same fashion. Determine the specimen cross sectional area as described in Section 6.1.

4.3 *Sealing the Specimen* - Place the specimen on the specimen holder and apply silicone cement in the middle of the specimen wall. Apply a large enough bead such that a surface 1.5 inches wide is uniformly covered. Place a cylindrical rubber membrane 1.5 inches wide over the bead of cement and mold the encapsulated cement to uniform thickness using your fingers. Cure the specimen overnight at room temperature. See Figure 4 for an illustration of this procedure.

5. TEST PROCEDURES

5.1 *Test Set-Up* - Figure 1 illustrates a specimen completely set-up, ready for testing.

Place the specimen in the load frame apparatus and complete all electrical connections i.e. LVDTs and load cells. Envelope the specimen with a cylindrical rubber membrane long enough to cover the specimen base platen, the upper and lower porous teflon disks, and the specimen top platen. Seal the membrane using rubber O-rings at each end i.e. at the top and bottom platens.

Attach the vacuum outlet to the differential pressure gage and vacuum pump, and to the inlet of the flowmeter. Close the flowmeter until it reads 20 inches of Hg by adjusting the vacuum level with the vacuum regulator. Observe the manometer reading to see if the reading decreases; if none occurs, the system is airtight and the test may proceed.

5.2 *Air Permeability test* - A pressure differential is applied across the specimen by connecting the specimen setup to a vacuum pump. Attach the differential pressure gage and vacuum pump to the inlet of the flowmeter. Open the air flow meter and valve and apply the desired pressure (use the lowest differential pressure possible) by adjusting the vacuum regulator. Read the air flow reading through the specimen from the air flow meter. Repeat for four different pressures and calculate the pressure differential. The temperature of the environmental chamber should be at 25°C. The air permeability calculations are described in Section 6.2.

5.3 *Initial ECS-M_R measurement* - An axial, compressive and repeated load (haversine wave, 0.1s on, 0.9 s off with a magnitude of 60 lbs static, 600 lbs dynamic) is applied to the specimen at a temperature of 25°C. The initial or dry ECS-M_R is determined by averaging the 40th to 50th cycles. The calculations for determining the modulus are described in Section 6.6.

5.4 *Wetting the Specimen* - After the measurement of the air permeability and initial ECS-M_R, the specimen undergoes the wetting procedure. Distilled water is pulled through the specimen using a vacuum of 20 in. Hg for 30 minutes at 25°C. The water permeability of the specimen is then determined at the end of this wetting procedure.

5.4 *Hot Climate Conditioning* - After completion of the wetting process, begin the conditioning procedure. Reduce the vacuum to 10 in. of Hg, and reduce the water flow to between 2 and 5 cc/min. Change the temperature of the environmental chamber to the conditioning temperature of 60°C, and maintain this setting for 6 hours. At the end of 6 hours, the setting is decreased to 25°C for an additional 2 hours. Throughout the test, a repeated axial compressive load of 200 lbs is applied (haversine wave, 0.1s on. 0.9s off). At the end of the 8 hour cycle, re-measure the ECS-M_R and water permeability. See Section 6.3 for the water permeability calculations.

The conditioning process includes a total of three 6 hour cycles as described in the preceding paragraph. After the ECS-M_R has been measured at the end of the first cycle, the temperature is changed to 60°C for 6 hours, then to 25°C for 2 more hours. The ECS-M_R and water permeability are measured again and this completes the second cycle. The third cycle is a duplicate of the first and second. A total of 24 hours is required for the entire hot climate conditioning process. At the conclusion of 24 hours, the specimen may be removed from the ECS setup. The permeability and modulus ratios are determined as described in Sections 6.5 and 6.6, respectively.

5.5 *Cold Climate Conditioning* - If the bituminous mixture is to be tested for cold climates, additional conditioning is required. The procedures described in Sections 5.1 through 5.4 are first performed. At the end of the third hot conditioning cycle (end of Section 5.4), the temperature of the environmental chamber is then changed to -18°C for cold climate conditioning. This temperature is maintained for 6 hours. At the end of the 6 hours, the temperature is changed to 25°C for another two hours. At the end of this cycle, the ECS-M_R and water permeability are determined as described in Sections 6.6 and 6.3, respectively. The total time required for the cold climate conditioning is 32 hours (24 hours of hot conditioning, then 8 hours of cold conditioning). At the conclusion of 32 hours, the specimen may be removed from the ECS setup.

Occasionally monitor the test outputs (environmental cabinet temperature, elapsed time, vacuum, and load) as the test progresses to ensure all instrumentation is functioning correctly and a valid test is being conducted.

5.6 *Stripping Rate* - At the conclusion of the last conditioning cycle, remove the specimen from the ECS and place it between two bearing plates of a loading jack on a mechanical or hydraulic testing machine (AASHTO T167-84). Care must be taken to ensure that the load will be applied to along the diameter of the specimen. Apply the load to the specimens by means of a constant rate of movement and continue loading until a vertical crack appears. Remove the specimen from the testing machine and pull the two halves apart. Inspect the interior surface of the specimen for stripping and record your observations. See Section 6.7 for the procedure to determine the stripping rate.

6. CALCULATIONS

6.1 Determine the *cross-sectional area* of the specimen as follows:

$$A = \pi(D^2/4)$$

where: A = cross sectional area, cm^2
D = average diameter of specimen, cm

6.2 Determine the *air permeability* of the specimen as follows:

$$K = \frac{Q\mu L}{A(P_1 - P_2)}$$

where: K = permeability, cm/s
Q = volume rate of flow of air, cm^3/s
μ = viscosity of air, poises
A = cross sectional area of specimen, cm^2
L = length (or height) of specimen, cm
P_1-P_2 = pressure difference, $dynes/cm^2$

For specimens 4 in. diameter and with the viscosity of air = 1.853×10^{-4} poises at room temperature (25° ± 3°C), the above formula is reduced to:

$$K = 1.53 \times 10^{-11} (F/P)L$$

where: F = rate of air flow, cc/min
P = pressure differential, in. of water
L = length (or height) of specimen, cm

By plotting the rate of air flow (F) against the pressure differential (P), this reduces the above formula to :

$$K = 1.53 \times 10^{-11} SL$$

where: S = slope of the straight line portion of rate of air flow (F) versus differential pressure (P).

6.3 Determine the *water permeability* of the specimen as follows:

$$K = 0.738 \times 10^{-9} SL$$

This assumes a water viscosity of 0.8937×10^{-2} poises at a room temperature of 25° ± 3°C. The following conversion factors are used:

1 gallons/hr = 63.09 cm^3/min
1 ft^3/hr = 471.9 cm^3/min
1 mm Hg = 1.868 in. of water
1 dyne/cm^2 = 33.455 x 10^{-6} ft of water
1 Pa.s = 10 poises

6.4 *Example of permeability calculations*

Length or height of specimen (L) = 10.5 cm
Differential pressure readings (P, in. of water) = 203.2, 186.3, 159.8, 112.4
Corresponding water flow rates (Q, cm^3/min) = 113.6, 100.9, 78.9, 31.5

Plot Q (y -axis) vs P (x-axis). Draw a straight line through the points and determine the slope of the line. This results in S = 0.91 cm^3/min/in. of water.

Therefore;

$$K = 0.738 \times 10^{-9}\ SL$$

$$K = (0.738 \times 10^{-9})\ (0.91 cm^3/min/in.\ of\ water) \times (10.5\ cm)$$

$$K = 7.06 \times 10^{-9}\ cm/sec$$

6.5 Determine the *permeability ratio* - the permeability ratio is determined at the end of each conditioning cycle as follows:

$$Permeability\ ratio = \frac{Water\ permeability\ @\ end\ of\ conditioning\ cycle}{Initial\ Water\ permeability\ (after\ pre\text{-}wetting\ stage)}$$

6.6 Calculate the *ECS-M_R and modulus ratio* as follows:

Measure the average amplitude of the load with the electronic load cell and the strain with the LVDTs over the 40th to the 50th loading cycles. Calculate the ECS-M_R as follows:

$$ECS\text{-}M_R = \frac{Axial\ loading\ stress}{Recoverable\ axial\ strain}$$

Calculate the modulus ratio as follows:

$$\textit{Modulus Ratio} = \frac{(ECS\text{-}M_R \text{ @ end of each cycle})}{(\text{Initial (dry) } ECS\text{-}M_R)}$$

6.7 Determine the *stripping rate* - Estimate the stripping rate at the end of each conditioning procedure as a relative ratio to the standard pattern (5%, 10%, 20%, 30%, 40% and 50% or more) as shown in Figure 6.

7. REPORT

7.1 The test report shall include the following information:

7.1.1 *Bituminous Mixture Description* - bitumen type, bitumen content, aggregate type, aggregate gradation, and air void percentage.
7.1.2 *Cross-Sectional Area of Specimen*
7.1.3 *Air Permeability* of specimen before pre-wetting
7.1.4 *Water Permeability* of specimen before conditioning
7.1.5 *Water Permeability* of specimen after each 6-hour cycle
7.1.6 *Water Permeability* ratio at the end of each 6-hour cycle
7.1.7 *Initial (dry) ECS-*M_R of specimen before conditioning
7.1.8 *ECS-*M_R at the end of each 6-hour cycle
7.1.9 *ECS-*M_R modulus ratio at the end of each 6-hour cycle
7.1.10 *Stripping rate*

8. PRECISION

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

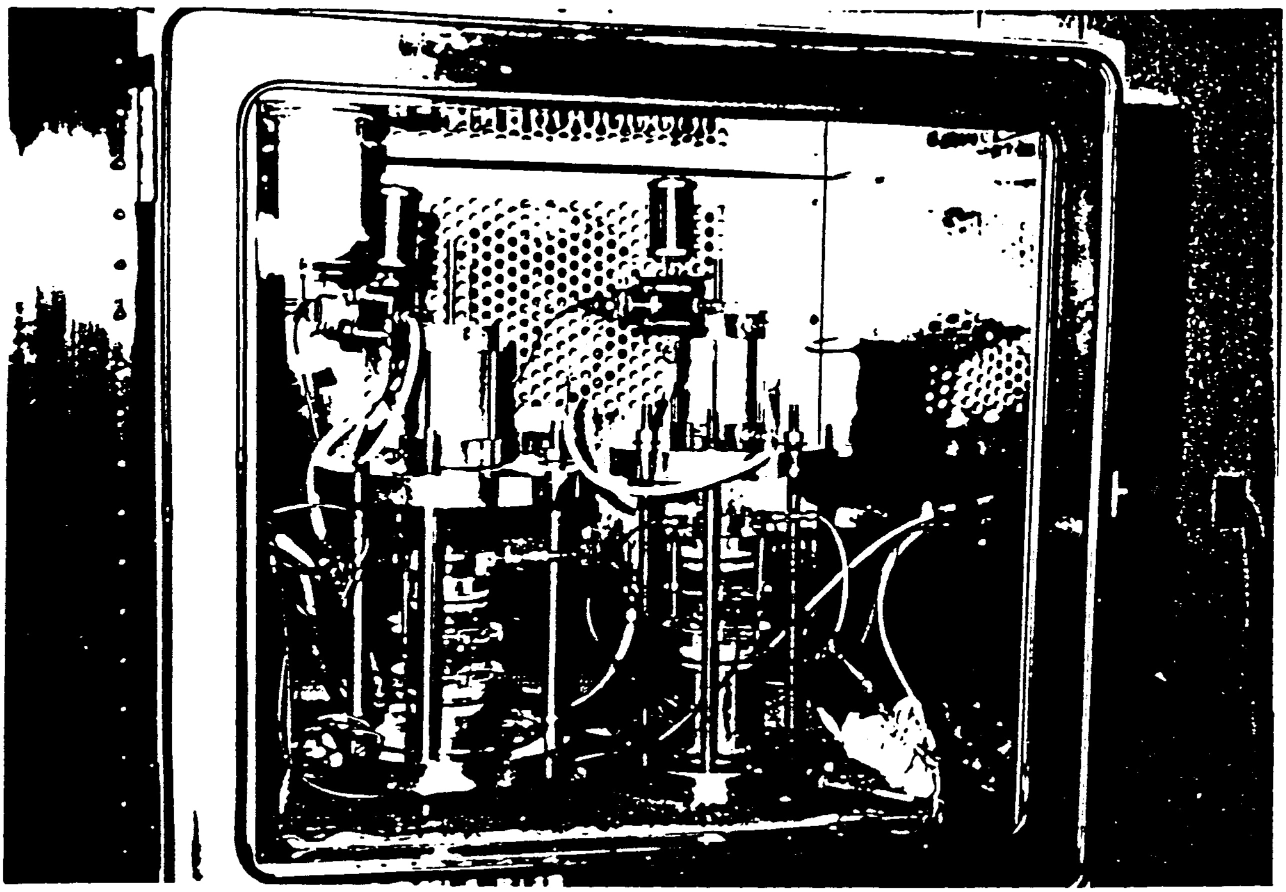


Figure B-1 Environmental Conditioning System (ECS) Setup

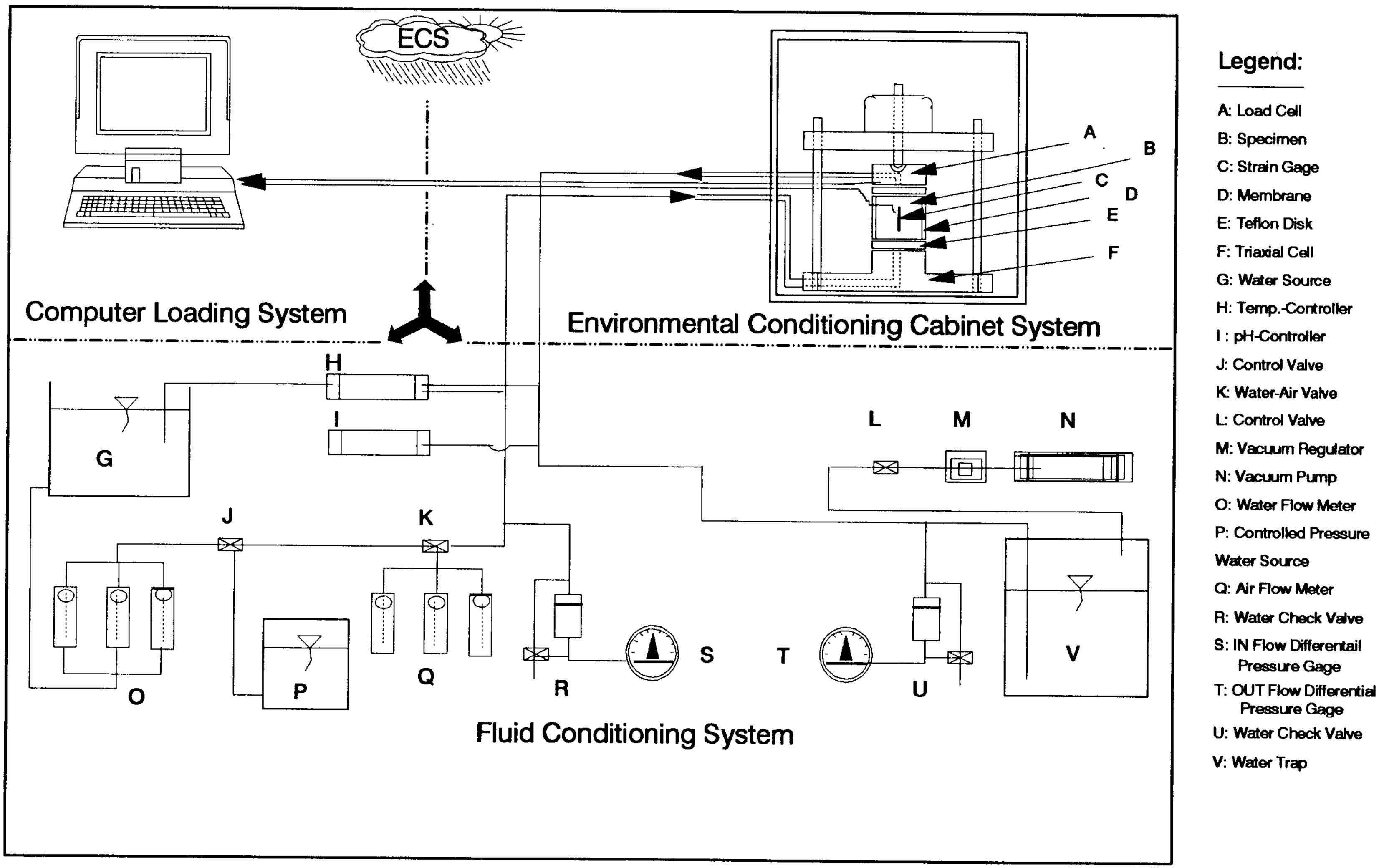


Figure B-2 Schematic Drawing of Environmental Conditioning System (ECS)

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	YS	YS	YS	NO
Ambient Temp.(C) **	25	60	60	60	-18
Duration (hr.)	0.5	6	6	6	6

Conditioning Procedure for Hot Climate (WETTING through CYCLE-3)

Conditioning Procedure for Cold Climate (WETTING through CYCLE-4)

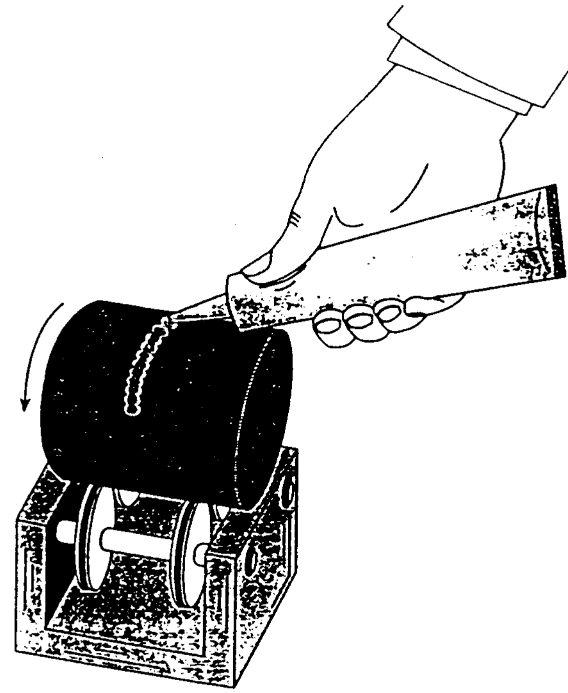
* WETTING : Wetting the Specimen Prior Conditioning Cycles

** Inside the Environmental Cabinet

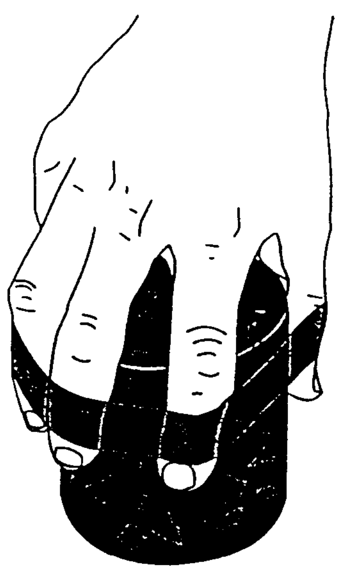
a: Conditioning Proceduref for Hot Climate : Wet then 3 hot cycles

b: Conditioning Procedure for Cold Climate : Wet then 3 hot cycles plus one cold cycle

Figure B-3 Conditioning Information Chart for Warm and Cold Climates

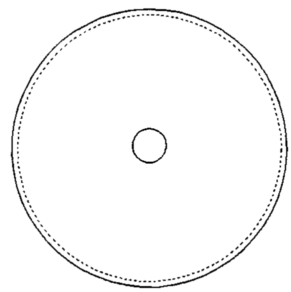


a) Specimen sealing for 1.5" of the middle

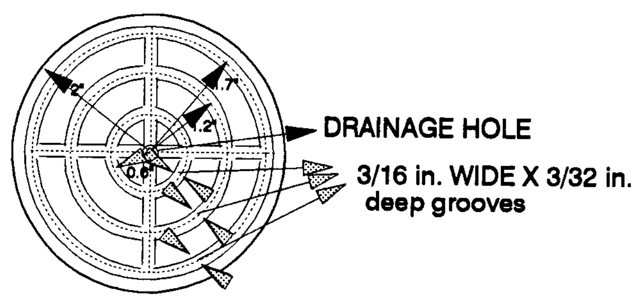


b) Rubber membrane fastening to specimen

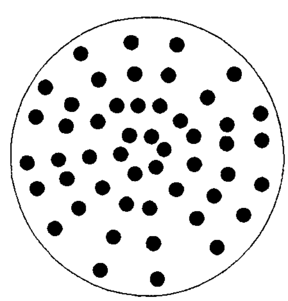
Figure B-4 Specimen Sealing Process



(a) TOP VIEW OF TOP CAP



(b) GROOVE PATTERN FOR BOTTTOM OF
TOP CAP AND TOP OF THE BASE



(c) PERFORATION PATTERN FOR TEFLON DISK

(2/16" HOLE DIAMETER)

Figure B-5 Specimen End Platens and Teflon Disk Perforation Pattern

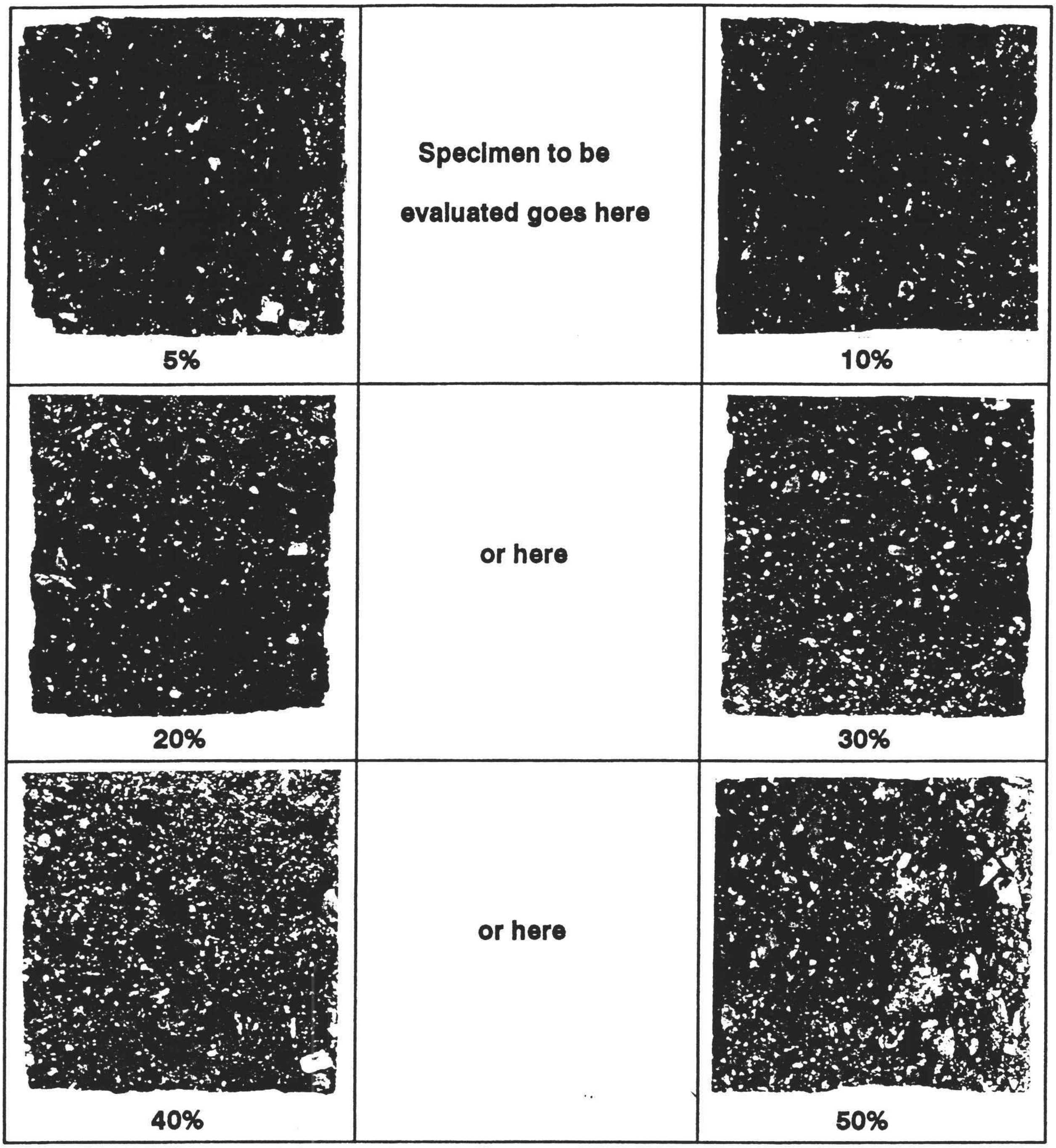


Figure B-6 Stripping Rate Standards

APPENDIX C

WET CONDITIONING PROTOCOL

Scope

This conditioning procedure covers assembly set-ups, as well as wetting conditioning of compacted bituminous mixtures. Wet conditioning a specimen is defined as "pulling" water through the specimen at 20 in. Hg of vacuum for 30 minutes. Ambient room temperature is acceptable for both water and specimen.

Applicable Documents

AASHTO Standards:
- T 166 Bulk Specific Gravity of Compacted Bituminous Mixtures
- T 167 Compressive Strength of Bituminous Mixtures
- T 168 Sampling Bituminous Mixtures
- T 209 Maximum Specific Gravity of Bituminous Paving Mixtures
- T 247 Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor or Gyratory Compactor
- T 269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

Significance and Use

As noted in the scope, this method is intended to accelerate water conditioning of compacted bituminous mixtures in the laboratory. This method can be used to (a) test bituminous mixtures in conjunction with mixture design testing, or (b) test asphalt concrete cores and beams obtained from in-service pavements.

test bituminous mixtures in conjunction with mixture design testing, or (b) test asphalt concrete cores and beams obtained from in-service pavements.

Apparatus

According to the geometry of the test specimens there are two types of mold-specimen assembly setups. Figure C-1 shows the recommended mold-specimen assembly setup for cylindrical specimens, such as those prepared by Hveem kneading compactor.

Figure C-2 shows a suggested universal mold-specimen assembly setup for a beam specimen which is adjustable to fit a range of expected beam sizes. Figure C-3 shows another option for mold-specimen assembly set-up for a beam specimen. Figure C-4 is a schematic sketch of a simplified wet conditioning system to be used with any of the specimen holders.

Preparation of Laboratory Test Specimens

See Apendix D.

Evaluation of Test Specimens and Grouping

See Appendix D.

Sealing the Test Specimen

As proposed earlier, this conditioning procedure is applicable for the two types of specimen geometries, cylindrical and beam specimens.

Leakage of water or air through the surface void system of cylindrical specimen (along the cylindrical surface of the specimen) when flow is being measured would give erroneous results. Using a single seal at the mid-point was adequate.

To seal the cylindrical specimen use the following steps:

1. Place the specimen on specimen holder and apply silicon cement in the middle of the specimen wall. Apply a large enough bead of silicone cement such that a surface 1.5 in. high is uniformly covered. Place a cylindrical rubber membrane of the same width (1.5 inches) over the

bead and mold the encapsulated cement to uniform thickness. Carefully smooth the seal using fingers, and, cure the specimen overnight.

2. Assemble the specimen with the mold-specimen setup as shown in Figure C-4, and enclose the specimen with a cylindrical rubber membrane long enough to envelope the sample base, upper and lower porous teflon disks, and sample top cap. Seal the membrane using a rubber O-ring at each end (at the base and top cap).

   To seal beam specimens use the following procedure:

   1. Apply silicone to the vertical surface of the beam (as positioned for testing, such as fatigue) for a height equal to about 2/3 of the specimen height.

      Immediately place a strip or band of rubber membrane on the silicone to spread it and provide a smooth, uniform surface. Cure overnight.

   2. Place the specimen on the screen basket as shown in Figure C-2.

   3. Loosen the adjustable side brackets to accommodate the specimen. Insert the specimen. Adjust the sides sufficiently and with enough pressure to close the gap all around. Sufficient silicone should have been applied at the corners to allow it to be squeezed into the corners of the holder. As added insurance, a small amount of silicone could be applied at the four bottom corners.

   4. Cover the vacuum box and connect the inlet and outlet to the appropriate ends in the conditioning device (Figure C-4).

Checking for Leakage

1. To check for leaks, close the water source valve and open the vacuum control valve (Figure C-4). Adjust the vacuum level (with the vacuum regulator) to 20 in. of Hg (inflow manometer) and close the vacuum control valve.

2. Wait until the two manometers read the same vacuum level (20 in.

Hg). Monitor the vacuum level for 5 minutes. If the manometer reading does not decrease, the system is air tight and ready for testing.

3. Open vacuum control valve and release the vacuum through the vacuum regulator.

WET Conditioning Procedure

As shown on the conditioning chart, Figure B-3 (Appendix B), the "WET" conditioning is the water preconditioning stage for the specimen. For performing WET conditioning, use the following procedure:

1. Close water source valve as shown in Figure C-4, and open vacuum control valve. Apply vacuum of 20 in. Hg for 10 minutes to remove any voids from the specimen and the system as well.

2. Open the water source valve and at the same time adjust the vacuum regulator to maintain a constant 20 in. Hg inflow vacuum level.

3. Keep water flow running for 30 minutes, then close water source valve and release the vacuum through the regulator.

4. Remove the specimen from its setup and remove silicone sealing from the specimen.

5. Cover the vacuum saturated specimen tightly with plastic film (Saran Wrap or parafilm).

6. Make cut holes in the plastic wrap as necessary for specimen instrumentation and testing.

7. Proceed with testing in the usual manner without adding water or otherwise re-wetting the specimen.

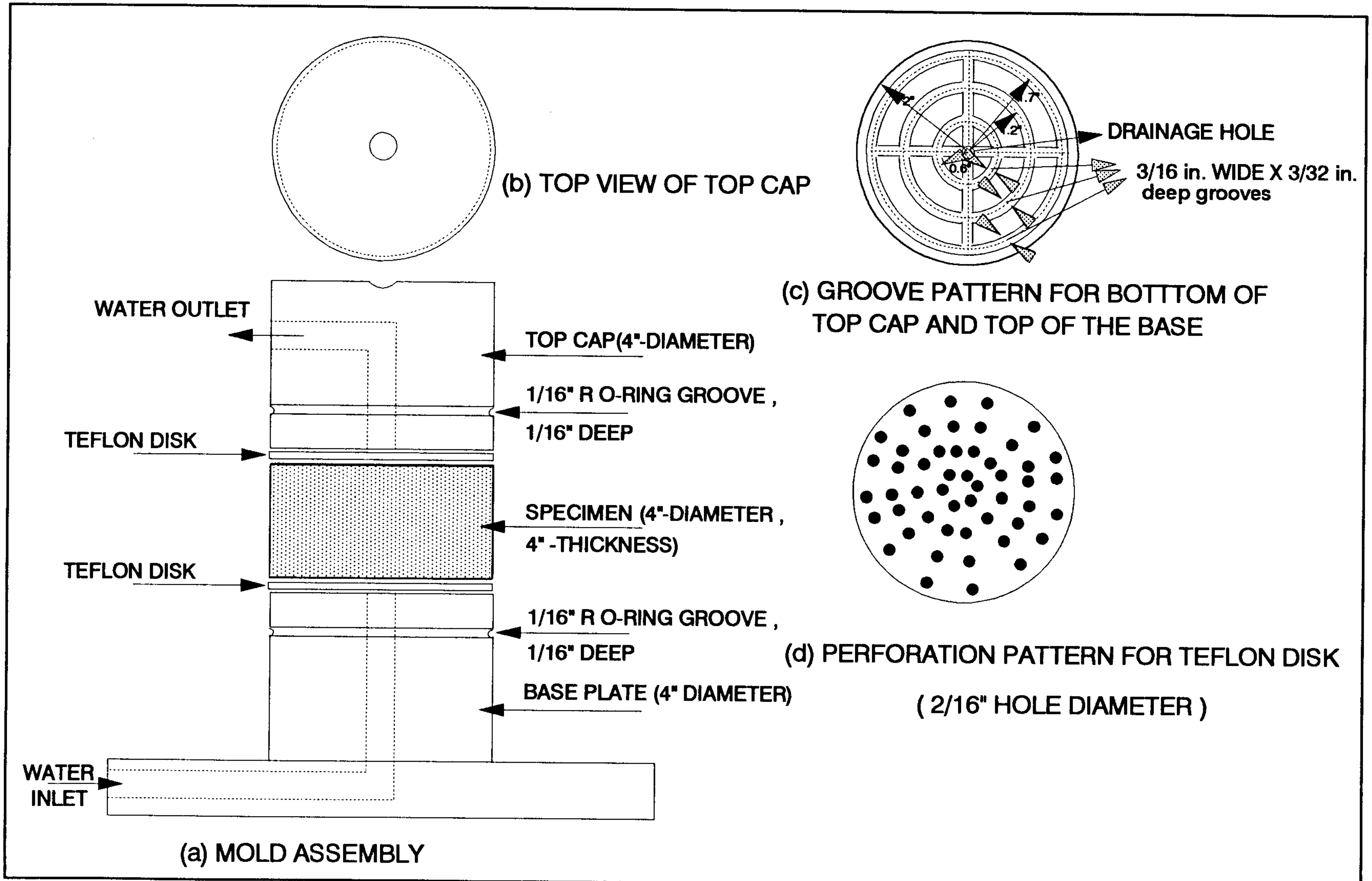


Figure C-1 Water Conditioning Setup for Cylindrical Specimen

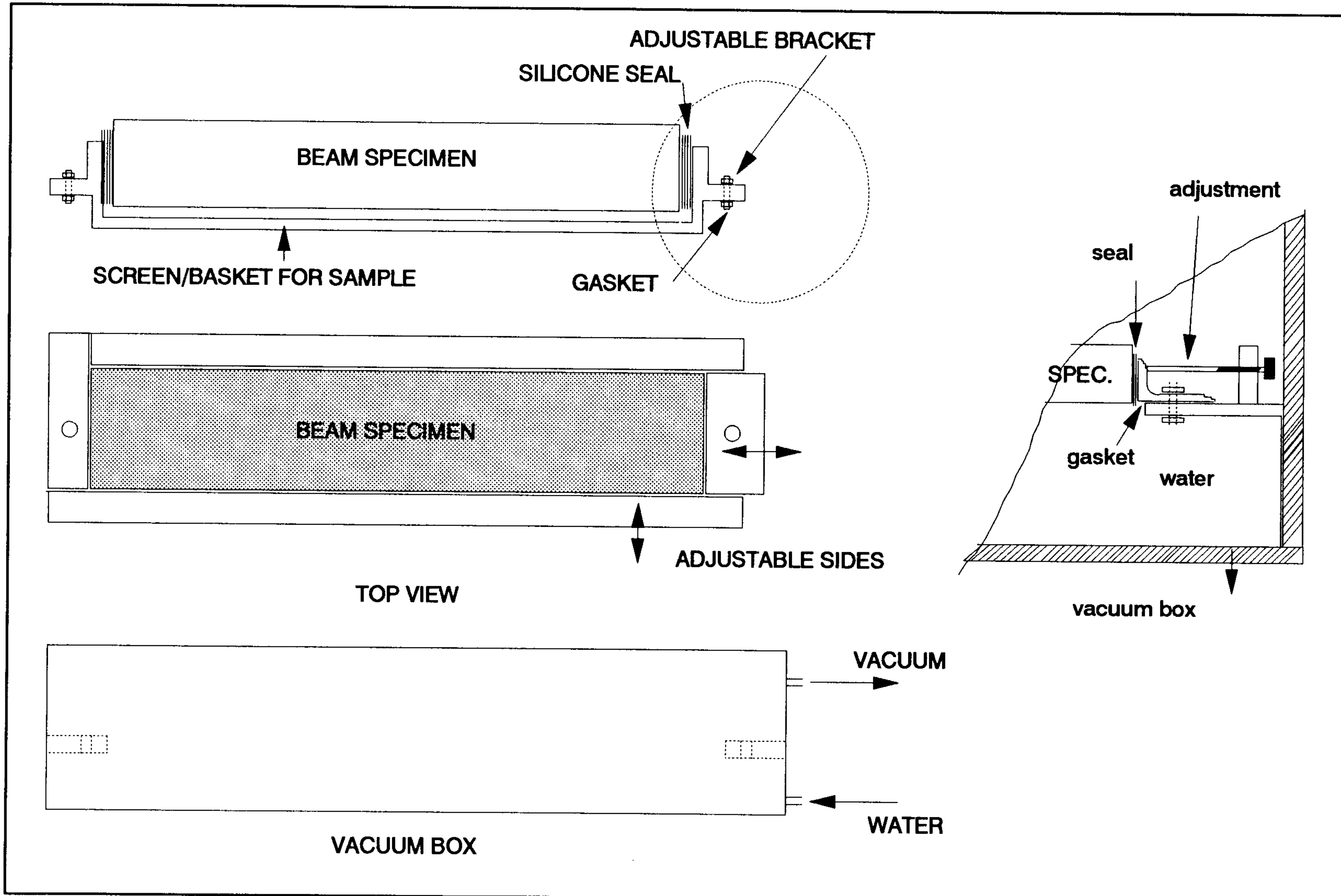


Figure C-2 Recommended Universal Mold-Specimen Assembly Setup for Beam Specimen

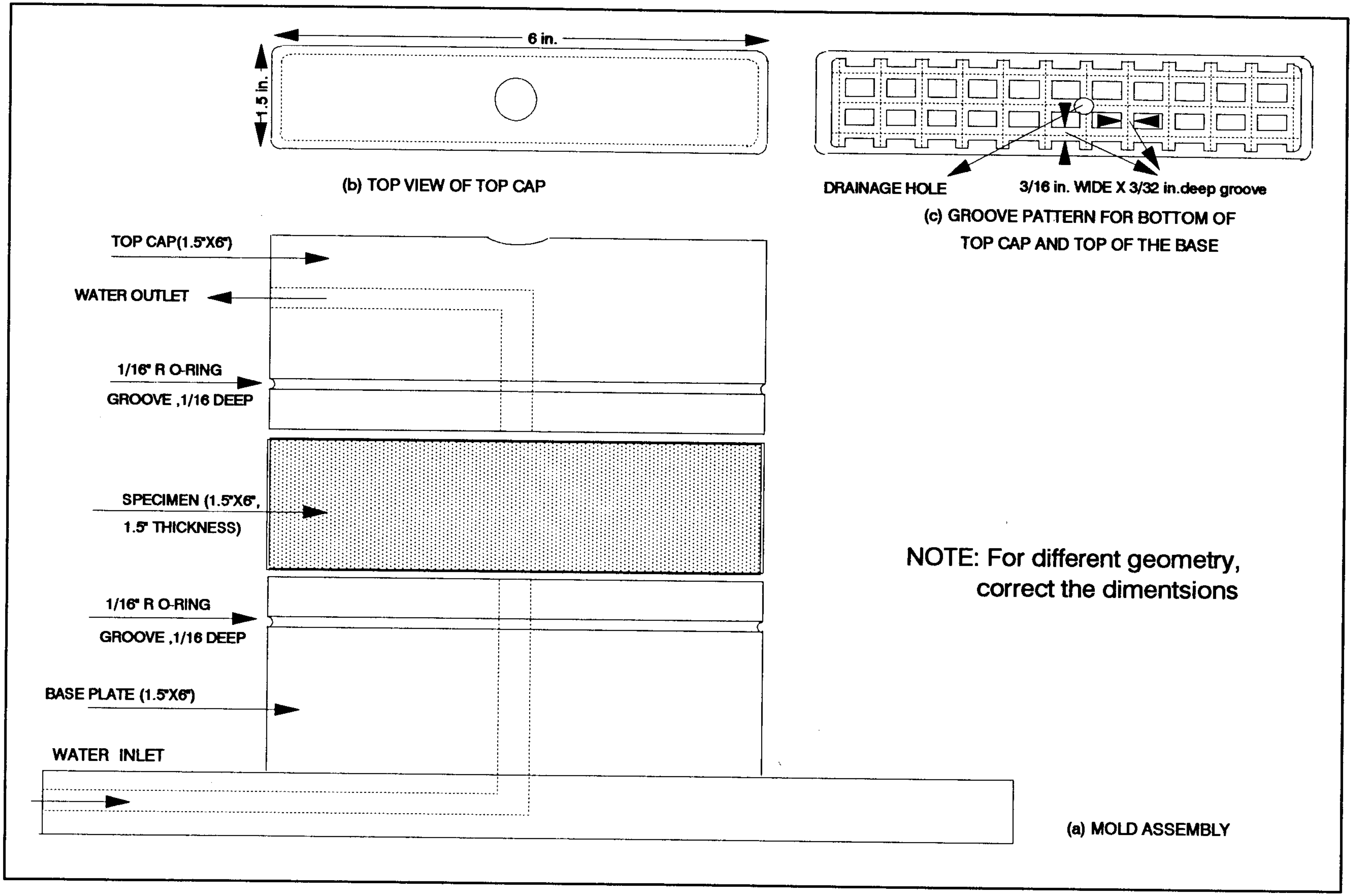


Figure C-3 Water Conditioning Setup for Beam Specimen 1.5X6in , 1.5in. Thickness

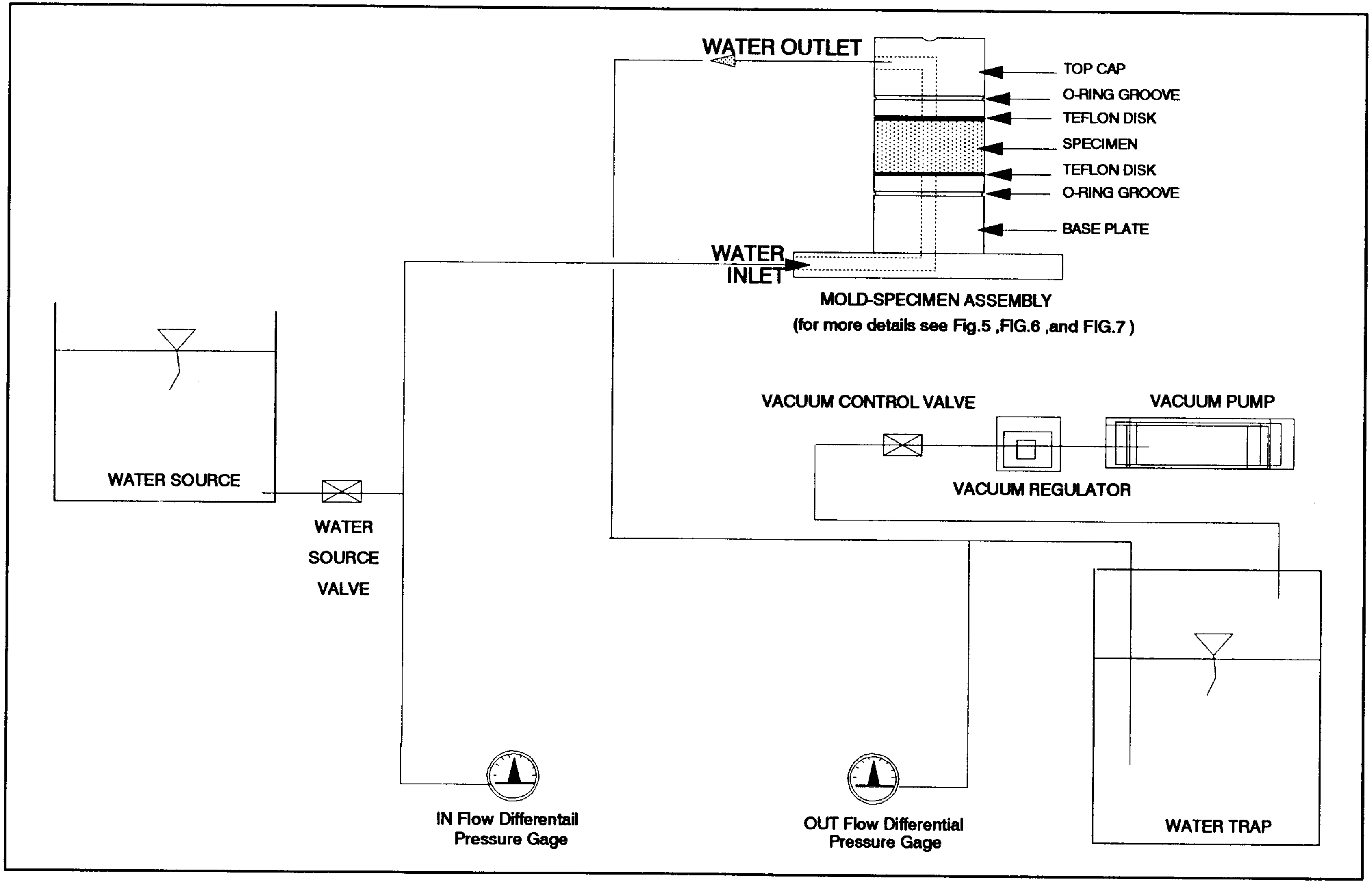


Figure C-4 Schematic Drawing for Water Conditioning Device

APPENDIX D

SAMPLE PREPARATION PROTOCOL

Preparation of Laboratory Test Specimens

1. Specimens 4-in. (102 mm) in diameter and 4-in. (63.5 mm) high are normally used. Specimens of larger dimensions may be used if desired and should be used if aggregate larger than 1-in. (25.4 mm) is present in the mixture and/or is not permitted to be scalped out.

2. After mixing, the mixture shall be placed in an aluminum pan having a surface area of 75-100 square inches in the bottom and a depth of approximately 1-in. (25.4 mm) and cooled at room temperature for 2 ± 0.5 hours. Then the mixture shall be placed in a 140°F (60°C) oven for 16 hours for curing. The pans should be placed on spacers to allow air circulation under the pan if the shelves are not perforated.

3. After curing, place the mixture in an oven at 275°F (135°C) for 2 hours prior to compaction. The mixture shall be compacted in two lifts. Desired air void level can be obtained by adjusting the foot pressure, number of tamps, levelling load, or some combination in AASHTO T247; or number of revolutions in ASTM D 3387. The exact procedure must be determined experimentally for each mixture before compacting the specimens for each set.

4. After extraction from the molds, the test specimens shall be stored for 72 to 96 hours at room temperature.

Evaluation of Test Specimens and Grouping

1. Determine theoretical maximum specific gravity of the mixture by AASHTO T-209.

2. Determine specimen thickness by ASTM D 3549.

3. Determine bulk specific gravity by ASTM D 2726 and ASTM D 1188. The determination of the bulk specific gravity of compacted asphalt concrete specimens is to be done according to ASTM D 1188 (replacing paraffin coating by parafilm wrapping). According to the comparative study at OSU, for calculating air voids by the regular method ASTM D 2726 (based on the weight of saturated surface-dry specimen in air) and using parafilm for ASTM D 1188, there is a difference between the two methods; where the results (air voids) by parafilm are about 1.5% higher than those results without parafilm (ASTM D 2726), according to aggregate type. In order to insure consistency in determination of bulk specific gravity by different laboratories involved with the SHRP A-003A project, bulk specific gravity will be determined by both methods: one by using the parafilm with ASTM D 1188 and the second by using regular method ASTM D 2726.

4. Calculate air voids by AASHTO T-289. Percent air void levels 4, 8, and 20%, will be based on the bulk specific gravity calculated by ASTM D 1188.

Sealing the Test Specimen

1. Place the specimen on specimen holder and apply silicone cement in the middle of the specimen wall. Apply a large enough bead of cement such that a surface 1.5 inches high is uniformly covered. Place a cylindrical rubber membrane of the same width (1.5 inches) over the bead of cement and mold the encapsulated cement to uniform thickness using your fingers. Cure the specimen overnight.

2. Place the specimen in the triaxial apparatus and complete all electrical connections (i.e., LVDs and load cell.) Envelope the specimen with

a cylindrical rubber membrane long enough to envelope the sample base, the upper and lower porous teflon disks, and the sample top cap. Seal the membrane using rubber O-rings at each end (at the base and top cap.)

3. Attach the vacuum outlet to the manometer and vacuum pump, and to the inlet of the flowmeter.

APPENDIX E

RESISTANCE OF COMPACTED BITUMINOUS MIXTURE TO MOISTURE INDUCED DAMAGE

AASHTO DESIGNATION: T 283-85
Modified for use at OSU under SHRP contract A-003A

1.1 Scope

This method covers preparation of specimens and measurement of the change of diametral tensile strength and diametral resilient modulus resulting from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures. Internal water pressures in the compacted specimens are produced by vacuum saturation followed by a freeze and thaw cycle. Two numerical indices of retained indirect tensile strength and resilient modulus are obtained by comparing the values before and after conditioning.

Applicable Documents

AASHTO Standards:

T 166 Bulk Specific Gravity of Compacted Bituminous Mixtures
T 167 Compressive Strength of Bituminous Mixtures
T 168 Sampling Bituminous Paving Mixtures
T 209 Maximum Specific Gravity of Bituminous Paving Mixtures
T 245 Resistance to Plastic Flow of Bituminous Mixtures Using

T 245 Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus
T 246 Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus
T 247 Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
T 269 Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures
M 156 Requirements for Mixing Plants for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures

ASTM Standards:

D 3387 Test for Compaction and Shear Properties of Bituminous Mixtures by Means of the U.S. Corps of Engineers Gyratory Testing Machine (GTM)
D 3549 Test for Thickness or Height of Compacted Bituminous Paving Mixture Specimens
D 4123 Indirect Tension Test for Resilient Modulus of Bituminous Mixtures

Significance and Use

As noted in the scope, this method is intended to evaluate the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in the laboratory. This method can be used (a) to test bituminous mixtures in conjunction with mixture design testing, (b) to test bituminous mixtures produced at mixing plants, and (c) to test the bituminous concrete cores obtained from completed pavements of any age.

Numerical indices of retained indirect tensile properties are obtained by comparing the retained indirect properties of saturated, accelerated water-conditioned laboratory specimens with the similar properties of dry specimens.

Summary of Method

Six test specimens for each set of mix conditions, such as plain asphalt, asphalt with antistripping agent, and aggregate treated with lime, are tested (Note 1). Each set of specimens is divided into and tested in a dry condition for resilient modulus. The

---

1 - It is recommended to prepare two additional specimens for the set. These specimens can then be used to establish the vacuum saturation technique.

other set is subjected to vacuum saturation followed by a freeze and warm-water soaking cycle and then tested for resilient modulus and tensile strength. Two numerical indices of retained resilient modulus and tensile strength are computed from the test data obtained on the two subsets: dry and conditioned.

Apparatus

Equipment for preparing and compacting specimens from one of the following AASHTO Methods: T 245 and T 247, or ASTM Method D 3387.

Vacuum Container, preferably Type D, from ASTM Method D 2041 and vacuum pump or water aspirator from ASTM D 2041 including manometer or vacuum gauge.

Balance and water bath from AASHTO T 166.

Water bath capable of maintaining a temperature of 140° ± 1.8°F (60 ± 1°C).

Freezer maintained at 0 ± 5°F (-18° ± 3°C).

A supply of plastic film for wrapping, heavy-duty leak proof plastic bags to enclose the saturated specimens and masking tape.

10 ml graduated cylinder.

Aluminum pans having a surface area of 75-100 square inches in the bottom and a depth of approximately 1 inch.

Forced air draft oven capable of maintaining a temperature of 140° ± 1.8°F (60° ± 1°C).

Apparatus as listed in ASTM D 4123.

Preparation of Laboratory Test Specimens

Specimens 4 inches (102 mm) in diameter and 2.5 inches (63.5 mm) high are usually used. Specimens of larger dimensions may be used if desired and should be used if aggregate larger than 1 inch (25.4 mm) is present in the mixture and/or is not permitted to be scalped out.

After mixing, the mixture shall be placed in an aluminum pan having a surface area of 75-100 square inches in the bottom and a depth of approximately 1 inch (25.4 mm) and cooled at room temperature for 2 ± 0.5 hours. Then the mixture shall be placed in a 140°F (60°C) oven for 16 hours for curing. The pans should be placed on spacers to allow air circulation under the pan if the shelves are not perforated.

After curing, place the mixture in an oven at 275°F (135°C) for 2 hours prior to compaction. The mixture shall be compacted to 7 ± 1.0 percent air voids or a void level expected in the field. This level of voids can be obtained by adjusted the number of blows in AASHTO T 245; adjusting foot pressure, number of tamps, levelling load, or some combination in AASHTO T 247; and adjusting the number of revolutions in ASTM D 3387. The exact procedure must be determined experimentally for each mixture before compacting the specimens for each set.

After extraction from the molds, the test specimens shall be stored for 72 to 96 hours at room temperature.

Preparation of Core Test Specimens

Select locations on the completed pavement to be sampled, and obtain cores. The number of cores shall be at least 6 for each set of mix conditions.

Separate core layers as necessary by sawing or other suitable means, and store layers to be tested at room temperature.

Evaluation of Test Specimens and Grouping

Determine theoretical maximum specific gravity by mixture by AASHTO T 209.

Determine specimen thickness by ASTM D 3549.

Determine bulk specific gravity by D 2726 and D 1188. In order to ensure consistency in determination of bulk specific gravity by different laboratories involved with the SHRP A003A project, bulk specific gravity will be determined by the two methods. One by using the parafilm with D 1188, only for air voids determination for dry specimens, and the second by using regular method D 2726, for all the three circumstances (dry, saturated, and water-conditioned specimens). Continuously drain water, which makes it very difficult to wrap the specimen with parafilm within the required short time period.

Calculate air voids by AASHTO T 269. Target air voids (6 - 8%) will be based on the bulk specific gravity calculated by D 2726.

Sort specimens into two subsets of three specimens each so that average air voids of the two subsets are approximately equal.

Preconditioning of Test Specimens

At least six specimens shall be made for each test, three to be tested dry and three to be tested after saturation and water conditioning. The average air voids of the two subsets are approximately equal.

Specimens 4 inches in diameter and 2.5 inches high are used. Specimens of greater dimensions may be used if desired and should be used if aggregate larger than 1 inch is present.

The dry subset will be tested as follows:

1. Determine the permeability as described in Appendix F

2. For bringing dry specimens to tensile strength and resilient modulus test temperatures without water intrusion into the dry specimens in the water bath, we need to enclose the dry specimens in heavy duty leak - proof plastic bags or we can use metal jars of at least 4 inches in diameter and at least 6 inches high. In this study we use controlled temperature cabinet.

3. If only low-to-moderate stresses are applied to the specimens in the diametral resilient modulus test, this test can be considered nondestructive and the same specimens can be used for the diametral tensile strength test. Since they will be used for the two subsets, specimens should be maintained at test temperature either to be enclosed in the controlled temperature cabinet for dry specimen or to be re-immersed in the water bath, for conditioned specimens, at selected test temperature 77 °F (25 °C) for 1 to 2 hours after diametral resilient modulus testing and prior to the diametral tensile strength testing.

4. The second subset shall be conditioned as follows:

   - Place the specimens in the vacuum container. The specimens will be supported above the container bottom by a spacer. Fill the container with distilled water at room temperature so that the specimens have at least 1 inch of water above their surface. Apply partial vacuum by either attaching a vacuum hose from vacuum pump or a water aspirator as was used at OSU. Apply the partial vacuum, such as 20 inches Hg, for a short time, such as five minutes. The level of vacuum and time duration appear to be different for different mixtures, but the vacuum level is more effective in changing the degree of saturation than the time duration. Remove the vacuum and leave the specimens submerged in water for 30 minutes.

- Remove each of the specimens from the vacuum container, surface dry the specimen by blotting quickly with a damp towel (regardless of the water draining from specimen) and weigh immediately in air. This is the saturated surface dry weight for saturated specimen. Then weigh the specimen submerged in distilled water bath at 77°F (25°C) to get weight in water for saturated specimen. Immediately after weighing each submerged specimen, return the specimens to the water-filled vacuum container and submerge each specimen temporarily under the water at atmospheric pressure.

- Determine specimen thickness by Method D 3549.

- Calculate volume of absorbed water by subtracting the air dry weight of the specimen found in section 8.3.

- Determine the degree of saturation by dividing the volume of absorbed water by the volume of air voids and express the result as a percentage. If this percentage is between 55 and 80, proceed the test. If it is more than 80 percent the specimen has been damaged and is discarded. If calculated percentage is less than 55 percent, repeat the procedure beginning with new specimen using a slightly higher partial vacuum.

- Determine the ratio of volume change (in most circumstances, this will be swell) of saturated specimens by dividing the change in specimen volume found in saturated specimen and dry specimen volume by the dry specimen volume.

- Cover the vacuum saturated specimens tightly with plastic film (saran wrap or equivalent). Place each wrapped specimen in a plastic bag containing 10 ml of distilled water and seal the bag.

- Place the plastic bag containing specimen in a freezer at 0° +5° (-18° + 3°) for 16 hours.

- After 16 hours, take the specimens from the freezer and remove plastic bag containing 10 ml of distilled water and seal the bag.

- Place the plastic bag containing specimen in a freezer at 0° +5° (-18° + 3°) for 16 hours.

- After 16 hours, take the specimens from the freezer and remove the plastic bag and film from the specimens. Place each specimen in heavy - duty, leak proof plastic bag containing enough distilled water to cover the specimen. This treatment is to conserve the distilled water consumption so tap water can be used in the water bath.

- Place the heavy-duty leak proof plastic bags which containing the specimens into a 140°± 1.8°F (60°± 1°C) water bath for 24 hours.

- After 24 hours in the 140°F (60°C) water bath, take the plastic bags from the water bath and remove the specimens from the plastic bags, and place them in water bath already at 77°± 1°F (25°± .5°C) for 2 hours. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 77°F (25°C).

- After 2 hours in the 77°F (25°C) water bath, determine water absorption and degree of saturation for water - conditioned specimens. Saturation exceeding 80 percent is acceptable in this step.

- Measure the thickness for water - conditioned specimens by ASTM D 3549.

- Determine the ratio of volume change of water - conditioned specimens by dividing the change in specimen volume found in the water - conditioned specimen by the dry specimen volume.

Mechanical Testing and Numerical Indices

- Diameteral Resilient Modulus

- Place the transducers of the resilient modulus apparatus on the specimen and proceed rapidly with diametral loading at .1 - sec. load duration time. Record load and horizontal deformation. Rotate the specimen 90° and repeat.

- Calculate the specimen's diametral modulus for each of the two 90° rotations as follows:

$$M_R = \frac{P(v + 0.2734)}{t\Delta}$$

M_R = diametral resilient modulus, Ksi
P = max. load in lbs
v = Poisson's ratio (0.35)
Δ = horizontal deformation, in.
t = thickness of specimen, in.

- Repeat procedure and calculation which is described above for the two subsets (dry and water - conditioned subsets).

- Calculate diametral resilient modulus index of the effect of vacuum saturation and accelerated water conditioning as the ratio of the diametral resilient modulus of the water - conditioned subset to the diametral resilient modulus of the dry subset as follows:

$$M_R R = \frac{M_{R_c}}{M_{R_d}}$$

M_R R = diametral resilient modulus ratio index of water-conditioned subset

M_{RC} = average diametral resilient modulus of water-conditioned specimen subset, Ksi

M_{Rd} = average diametral resilient modulus of dry specimen subset, Ksi

- Diametral tensile strength.

- Apply diametral load in accordance with method D 4123 at 2.0 inches per minute until the maximum load is reached and record the maximum load.

- Continue loading until specimen fractures. Slowly pull apart the two sides of the specimen at the crack. The internal surface may then be observed for stripping.

- Calculate tensile strength as follows:

$$S_t = \frac{2P}{\Pi t D}$$

S_t = tensile strength, psi
P = maximum load, lb
t = Thickness of specimen immediately before tensile test, in.
D = specimen diameter, in.

- Repeat procedure and calculation described in section 10.2.3 for the two subsets (dry and water - condition subsets).

- Calculate diametral tensile strength ratio index of the effect of vacuum saturation and accelerated water conditioning as the ratio of the diametral tensile strength of dry subset as follows:

$$TSR = (S_{tm} / S_{td})\ 100$$

TSR: diametral tensile strength ratio index
S_{tm}: average tensile strength of water-conditioned subset, psi
S_{td}: average tensile strength of dry subset, psi

Test Results

Original test results of AASHTO T 283 are included here for the convenience of researchers in the subject area, who may conduct more research work. Table E-1 contains details of laboratory test results and related information from AASHTO T 283.

Table E-1 AASHTO T 283 Test Results

Agg. Type: RL Mix Date: 8-4-90 Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAG1 Cond. Date: 8-11-90 Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ -9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T21RL/AAG1	2.680	2.455	5.10	1242.1	696.1	1243.	2.280	7.3	194.3	79.6		
T22RL/AAG1	2.647	2.455	1.71	1240.5	702.4	1242.	2.310	6.1	255.7	130.4		
T23RL/AAG1	2.651	2.455	2.30	1243.6	702.3	1245.	2.300	6.4	331.4	158.3		
T24RL/AAG1	2.683	2.455		1243.3	708.1	1247.	2.310	6.1			2.68	727.1
T25RL/AAG1	2.705	2.455		1243.2	705.4	1248	2.290	6.7			2.7	726.4
T26RL/AAG1	2.682	2.455		1242.7	709.2	1246.	2.310	5.8			2.68	727.7

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1267.7	74.2	0.241	2.694	730.8	1286.7	133.10	1.010	181.2	0.490	72.6	0.40	
1270.7	76.0	0.313	2.731	725.8	1285.6	118.20	1.210	107.3	0.490	43.8	0.40	
1265.9	74.6	0.168	2.702	729.7	1282.7	129.50	0.880	120.4	0.490	58.7	0.40	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water-conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/ S_{td}) or (23) = (22)/(10)

% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E-1 (Continued)

Agg. Type: RL   Mix Date: 5-13-90   Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi
Asph. Type: AAG1   Cond. Date: 8-15-90   Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ -9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T29RL/AAG1	2.663	2.475	0.16	1238.6	696.7	1240.	2.287	7.6	427.7	181.7		
T33RL/AAG1	2.651	2.475	0.20	1244.5	708.1	1246.	2.321	6.2	543.9	210.7		
T31RL/AAG1	2.660	2.475	0.24	1241.6	700.0	1243.	2.293	7.3	464.4	173.9		
T32RL/AAG1	2.656	2.475		1243.8	715.3	1279.	2.328	5.9			2.658	730.2
T30RL/AAG1	2.637	2.475		1237.4	706.6	1245.	2.297	7.2			2.648	726
T34RL/AAG1	2.697	2.475		1239.9	706.8	1241.	2.319	6.3			2.701	726.9

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1264.5	65.4	0.019	2.669	733.7	1281.0	118.80	1.097	146.3	0.300	91.3	0.40	
1262.6	65.0	-0.390	2.653	729.1	1279.8	111.10	1.093	147.2	0.300	65.7	0.40	
1265.3	75.3	0.692	2.716	730.7	1283.5	129.60	0.994	167.8	0.300	76.0	0.40	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water-conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E−1 (Continued)

Agg. Type: RL — Mix Date: 5−31−90 — Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAK1 — Cond. Date: 6−1−90 — Target Air Voids: 8% +/− 1%

1 ID	2 Thick. (in.)	3 G_{mm}	4 Permeability 10^ −9 cm/sec	5 W_a Dry	6 W_w	7 W_{ssd}	8 G_{mb}	9 Air Voids (%)	10 Tens. St. (S_{sd}), psi	11 M_R (M_{Rd}), ksi	12 Thick. (in).	13 (W_w)
T36RL/AAK1	2.650	2.456	0.22	1241.9	705.7	1244.0	2.307	6.1	122.8			
T37RL/AAK1	2.687	2.456	0.19	1245.0	705.0	1247.3	2.296	6.5	121.1	166.8		
T35RL/AAK1	2.707	2.456		1244.2	694.1	1247.6	2.280	7.2			2.71	724.4
T38RL/AAK1	2.693	2.456		1246.3	703.2	1246.2	2.287	6.9			2.69	728.5

14 W_{ssd}	15 % of Sturation	16 % Change of Volume	17 Thikness (in.)	18 W_w	19 W_{ssd}	20 % of Sat.	21 % Change of Volume	22 Tens. St. S_{tm}	23 Tens. St. Rat. (TSR)	24 Cond. M_R (M_{Rc}), ksi	25 M_R Ratio (M_RR)	26 Observed Stripping
1270.8	67.1	−1.300	2.713	726.0	1277.0	0.83	−0.670	72.0	0.542	162.6	0.74	
1272.3	69.6	0.100	2.693	730.8	1284.1	1.01	0.130	60.3	0.542	84.4	0.74	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)−(18)−(7)+(6))/((7)−(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E−1 (Continued)

Agg. Type: RB   Mix Date: 10−28−90   Compaction Effort: 20 blows @ 200 psi and 150 blows @ 200 psi

Asph. Type: AAG1   Cond. Date: 11−17−90   Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T116RB/AAG1	2.622	2.570	5.01	1251.9	707.8	1255.6	2.303	10.4	493.5	215.1		
T119RB/AAG1	2.580	2.570	20.44	1253.6	708.5	1257.2	2.301	10.4	498.3	213.7		
T121RB/AAG1	2.650	2.570	10.50	1250.5	709.6	1254.4	2.314	10.0	503.4	190.6		
T117RB/AAG1	2.674	2.570	9.90	1253.4	734.1	1260.3	2.382	7.3			2.62	751.7
T118RB/AAG1	2.657	2.570	21.47	1254.0	729.9	1261.3	2.360	8.2			2.67	751.4
T120RB/AAG1	2.650	2.570	11.66	1250.2	711.6	1252.2	2.313	10.0			2.65	745.3

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1277.2	61.8	−0.133	2.626	755.3	1286.7	87.70	1.194	433.7	0.771	136.8	0.58	
1281.6	63.5	−0.226	2.669	754.8	1293.1	91.20	1.164	339.0	0.771	116.0	0.58	
1286.3	66.7	−0.074	2.653	751.7	1301.6	95.30	0.446	282.1	0.771	100.6	0.58	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E−1 (Continued)

Agg. Type: RL | Mix Date: 8−17−90 | Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAG1 | Cond. Date: 8−22−90 | Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T38RL/AAG1	2.667	2.456	1.27	1237.6	692.8	1239.5	2.273	7.5	543.1	187.4		
T39RL/AAG1	2.643	2.456	4.21	1240.3	698.0	1242.1	2.288	6.8	541.8	181.7		
T41RL/AAG1	2.651	2.456	0.56	1242.7	703.0	1244.4	2.303	6.2	583.1	206.7		
T36RL/AAG1	2.642	2.456		1238.3	707.7	1243.3	2.312	5.9			2.665	724.7
T40RL/AAG1	2.667	2.456		1243.7	713.1	1247.6	2.327	5.3			2.646	728.3
T42RL/AAG1	2.674	2.456		1240.6	710.9	1244.9	2.323	5.4			2.667	726.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1260.5	70.7	0.037	2.676	727.6	1276.6	123.10	0.980	316.1	0.570	106.3	0.63	
1262.3	66.2	−0.094	2.651	730.9	1276.4	117.20	0.641	325.3	0.570	124.8	0.63	
1260.2	67.9	0.037	2.671	728.9	1277.0	127.10	0.850	365.5	0.570	133.2	0.63	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water−conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19)−(18)−(7)+(6))/((7)−(6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E-1 (Continued)

Agg. Type: RL — Mix Date: 8-21-90 — Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAG1 — Cond. Date: 8-31-90 — Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^-9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T44RL/AAG1	2.656	2.463	6.20	1240.3	698.2	1242.1	2.289	7.1	556.2	229.1		
T46RL/AAG1	2.641	2.463	0.12	1238.8	697.6	1240.3	2.290	7.0	517.6	210.2		
T48RL/AAG1	2.653	2.463	2.17	1238.8	692.0	1240.3	2.266	8.0	509.0	225.3		
T45RL/AAG1	2.692	2.463	0.43	1238.9	712.1	1244.0	2.329	5.4			2.664	725.4
T47RL/AAG1	2.664	2.463	0.97	1242.3	706.5	1246.5	2.301	6.6			2.697	726.1
T49RL/AAG1	2.706	2.463	1.26	1244.2	707.9	1249.3	2.298	6.7			2.71	728.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1260.5	75.4	0.639	2.663	727.8	1271.0	112.20	1.614	413.6	0.614	145.6	0.47	
1269.6	76.7	0.648	2.703	727.6	1282.9	114.90	1.437	216.7	0.614	94.8	0.47	
1273.0	79.5	0.665	2.732	730.0	1288.8	124.20	1.622	235.9	0.614	67.7	0.47	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water-conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E-1 (Continued)

Agg. Type: RL　　Mix Date: 8-23-90　　Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi
Asph. Type: AAK1　　Cond. Date: 8-25-90　　Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ -9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T51RL/AAK1	2.666	2.455	12.83	1239.7	690.1	1241.7	2.257	8.1	415.1	208.2		
T54RL/AAK1	2.675	2.455	4.25	1241.4	701.0	1243.1	2.298	6.4	569.8			
T55RL/AAK1	2.626	2.455	3.59	1239.0	696.6	1241.7	2.283	7.0	520.4	241.1		
T52RL/AAK1	2.668	2.455	13.85	1238.8	703.9	1242.8	2.299	6.4			2.63	694.9
T53RL/AAK1	2.696	2.455	9.53	1240.3	703.3	1243.3	2.297	6.4			2.68	721.1
T56RL/AAK1	2.693	2.455	1.27	1244.6	708.3	1247.2	2.310	5.9			2.69	728.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1260.5	63.3	4.955	2.633	728.0	1278.2	115.70	5.739	370.8	0.600	104.0	0.82	
1266.2	74.5	0.944	2.681	730.6	1285.6	131.00	1.508	282.8	0.600	85.6	0.82	
1267.8	72.6	0.167	2.725	732.0	1285.1	127.40	0.653	385.7	0.600	105.7	0.82	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water-conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E−1 (Continued)

Agg. Type: RL　　Mix Date: 8−27−90　　Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAK1　　Cond. Date: 8−30−90　　Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T61RL/AAK1	2.697	2.447	2.46	1240.7	695.0	1242.1	2.274	7.1	368.0	155.6		
T62RL/AAK1	2.721	2.447	0.87	1244.7	697.9	1245.5	2.277	7.0	369.6	167.4		
T63RL/AAK1	2.683	2.447	7.40	1245.7	692.5	1247.0	2.252	8.0	363.8	165.1		
T58RL/AAK1	2.710	2.447	2.99	1243.3	707.7	1249.6	2.294	6.2			2.70	726.0
T59RL/AAK1	2.684	2.447	4.56	1243.5	707.0	1248.4	2.297	6.1			2.71	726.0
T60RL/AAK1	2.687	2.447	1.74	1240.8	704.6	1243.6	2.302	5.9			2.70	724.5

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1267.2	70.7	−0.129	2.701	728.2	1280.9	112.50	1.046	310.8	0.825	104.7	0.62	
1267.2	71.3	−0.037	2.707	728.0	1278.4	106.00	0.876	294.5	0.825	98.6	0.62	
1263.6	71.4	0.019	2.692	727.3	1275.3	108.60	0.541	276.9	0.825	105.7	0.62	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_m/ S_{td}) or (23) = (22)/(10)

% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E–1 (Continued)

Agg. Type: RL　　Mix Date: 9–3–90　　Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAK1　　Cond. Date: 9–5–90　　Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ –9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T68RL/AAK1	2.659	2.449	1.86	1245.3	700.7	1246.5	2.287	6.6	330.5	168.6		
T69RL/AAK1	2.673	2.449	14.50	1242.0	693.9	1243.5	2.267	7.4	375.0	159.1		
T70RL/AAK1	2.690	2.449	4.21	1245.4	700.2	1246.5	2.285	6.7	411.4	153.4		
T65RL/AAK1	2.668	2.449	1.75	1230.6	700.4	1233.7	2.308	5.8			2.65	720.0
T66RL/AAK1	2.675	2.449	1.89	1239.9	705.9	1242.9	2.309	5.7			2.67	725.4
T67RL/AAK1	2.665	2.449	5.71	1240.0	705.7	1242.5	2.310	5.7			2.67	726.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1253.8	75.3	0.094	2.670	724.4	1268.2	122.80	0.679	223.1	0.530	79.3	0.53	
1262.6	73.9	0.037	2.683	729.5	1279.1	128.40	0.599	194.1	0.530	82.2	0.53	
1263.2	76.1	0.075	2.676	730.5	1278.7	127.60	0.543	216.5	0.530	86.4	0.53	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (S_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)–(18)–(7)+(6))/((7)–(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

Table E−1 (Continued)

Agg. Type: RL | Mix Date: 8−13−90 | Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAK1 | Cond. Date: 9−17−90 | Target Air Voids: 8% +/− 1%

1 ID	2 Thick. (in.)	3 G_{mm}	4 Permeability 10 ^ −9 cm/sec	5 W_a Dry	6 W_w	7 W_{ssd}	8 G_{mb}	9 Air Voids (%)	10 Tens. St. (S_{sd}), psi	11 M_R (M_{Rd}), ksi	12 Thick. (in).	13 (W_w)
T72RL/AAK1	2.664	2.440	0.92	1241.6	698.0	1242.9	2.285					
T73RL/AAK1	2.656	2.440	2.94	1236.5	702.6	1238.0	2.317					
T75RL/AAK1	2.619	2.440	0.17	1242.5	699.1	1243.9	2.287					
T74RL/AAK1	2.650	2.440	13.85	1242.8	712.4	1248.2	2.320				2.67	725.4
T76RL/AAK1	2.662	2.440	9.03	1243.0	714.3	1247.2	2.333				2.65	726.2
T78RL/AAK1	2.655	2.440	1.33	1243.7	713.1	1247.8	2.326				2.66	727.7

14 W_{ssd}	15 % of Sturation	16 % Change of Volume	17 Thikness (in.)	18 W_w	19 W_{ssd}	20 % of Sat.	21 % Change of Volume	22 Tens. St. S_{tm}	23 Tens. St. Rat. (TSR)	24 Cond. M_R (M_{Rc}), ksi	25 M_R Ratio (M_RR)	26 Observed Stripping
1262.5	74.5	0.243					1.263					
1259.7	71.1	0.113					0.908					
1262.5	75.2	0.019					0.792					

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)−(18)−(7)+(6))/((7)−(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E–1 (Continued)

Agg. Type: RB — Mix Date: 10–30–89 — Compaction Effort: 25 blows @ 250 psi and 150 blows @ 350 psi

Asph. Type: AAG1 — Cond. Date: 11–4–89 — Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ –9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T207RB/AAG1	2.598	2.578		1253.1	737.8	1256.6	2.420	6.3			2.61	752.0
T208RB/AAG1	2.591	2.578		1254.3	739.3	1257.7	2.420	6.1			2.60	753.1
T209RB/AAG1	2.543	2.578		1238.7	732.2	1241.8	2.430	5.7			2.54	745.8
T210RB/AAG1	2.584	2.578	3.34	1247.4	735.9	1254.4	2.410	6.7	131.4	404.0		
T211RB/AAG1	2.568	2.578	0.10	1247.2	737.4	1250.4	2.430	5.7	143.4	143.4		
T212RB/AAG1	2.578	2.578	0.25	1253.8	740.0	1256.8	2.430	5.9	137.2	137.2		

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1271.6	56.5	0.150	2.600	758.0	1282.5	89.84	1.100	102.4	0.770	158.0	0.62	
1274.4	63.1	0.560	2.600	758.5	1284.1	93.53	1.390	103.8	0.770	204.0	0.62	
1258.6	38.4	0.630	2.600	749.9	1266.3	94.81	1.330	111.4	0.770	225.0	0.62	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/ S_{td}) or (23) = (22)/(10)

% of volume change = (((19)–(18)–(7)+(6))/((7)–(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

Table E−1 (Continued)

Agg. Type: RB — Mix Date: 9−21−90 — Compaction Effort: 20 blows @ 250 psi and 150 blows @ 250 psi

Asph. Type: AAK1 — Cond. Date: 10−10−91 — Target Air Voids: 8% +/− 1%

1 ID	2 Thick. (in.)	3 G_{mm}	4 Permeability 10 ^ −9 cm/sec	5 W_a Dry	6 W_w	7 W_{ssd}	8 G_{mb}	9 Air Voids (%)	10 Tens. St. (S_{sd}), psi	11 M_R (M_{Rd}), ksi	12 Thick. (in).	13 (W_w)
T82RB/AAK1	2.589	2.568	18.77	1253.8	714.1	1255.6	2.324	9.5	351.9	148.4		
T84RB/AAK1	2.572	2.568	0.33	1252.5	725.8	1254.0	2.379	7.4	401.8	167.4		
T85RB/AAK1	2.586	2.568	0.36	1252.5	722.4	1253.6	2.363	8.0	365.0	165.1		
T80RB/AAK1	2.601	2.568	5.00	1252.0	734.2	1255.7	2.401	6.5			2.59	753.5
T81RB/AAK1	2.633	2.568	5.39	1252.1	731.6	1255.6	2.390	7.0			2.61	752.7
T83RB/AAK1	2.578	2.568	0.51	1253.5	734.9	1255.9	2.406	6.3			2.58	754.4

14 W_{ssd}	15 % of Sturation	16 % Change of Volume	17 Thikness (in.)	18 W_w	19 W_{ssd}	20 % of Sat.	21 % Change of Volume	22 Tens. St. S_{tm}	23 Tens. St. Rat. (TSR)	24 Cond. M_R (M_{Rc}), ksi	25 M_R Ratio (M_RR)	26 Observed Stripping
1273.6	63.6	−0.268	2.599	757.7	1285.8	100.20	0.444	237.9	0.635	98.6	0.60	
1276.3	66.4	−0.076	2.616	757.4	1287.4	97.60	0.596	248.8	0.635	96.6	0.60	
1274.7	61.5	−0.136	2.615	758.3	1285.7	98.40	0.328	270.6	0.635	104.7	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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

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% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E−1 (Continued)

Agg. Type: RB Mix Date: 7−5−90 Compaction Effort: 20 blows @ 250 psi and 150 blows @ 250 psi

Asph. Type: AAK1 Cond. Date: 10−12−90 Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T89RB/AAK1	2.671	2.550	31.23	1258.2	712.1	1258.0	2.304	9.7	396.0	139.9		
T90RB/AAK1	2.566	2.550	1.37	1252.8	724.5	1253.6	2.372	6.2	380.4	174.7		
T91RB/AAK1	2.584	2.550	0.00	1255.3	732.7	1256.1	2.402	5.0	462.8	183.1		
T87RB/AAK1	2.636	2.550	5.75	1257.7	738.2	1266.2	2.382	6.6			2.67	754.2
T88RB/AAK1	2.686	2.550	15.26	1255.1	734.7	1263.2	2.375	6.9			2.64	751.5
T92RB/AAK1	2.587	2.550	0.02	1254.8	740.1	1258.5	2.421	4.3			2.59	753.8

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1281.1	67.3	−0.208	2.675	759.4	1291.7	99.30	1.424	285.9	0.646	106.4	0.61	
1279.5	67.2	−0.095	2.644	757.1	1290.5	99.00	1.460	258.5	0.646	92.8	0.61	
1271.2	73.8	−0.193	2.625	758.4	1283.0	127.70	0.525	365.8	0.646	130.1	0.61	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

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% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E−1 (Continued)

Agg. Type: RB | Mix Date: 9−4−90 | Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAG1 | Cond. Date: 9−10−90 | Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T93RB/AAG1	2.558	2.570	2.40	1248.4	728.1	1249.1	2.400	6.6	477.2	261.5		
T94RB/AAG1	2.518	2.570	3.29	1249.9	726.2	1251.5	2.387	7.1	478.2	241.6		
T95RB/AAG1	2.566	2.570	0.00	1249.8	735.4	1251.1	2.430	5.4	526.2	269.0		
T96RB/AAG1	2.555	2.570	0.08	1253.5	742.2	1258.2	2.429	5.5			2.56	757.8
T97RB/AAG1	2.257	2.570	1.44	1248.6	741.4	1253.0	2.441	5.0			2.56	758.0
T98RB/AAG1	2.531	2.570	0.00	1253.2	744.2	1255.6	2.451	4.6			2.54	760.1

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1274.6	74.7	0.155	2.563	759.1	1280.9	97.90	1.076	660.4	1.240	136.1	0.62	
1269.8	82.3	0.039	2.559	759.1	1275.1	103.80	0.907	585.0	1.240	171.0	0.62	
1273.1	83.7	0.313	2.540	762.1	1279.9	112.80	0.786	666.2	1.240	166.7	0.62	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{m}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E−1 (Continued)

Agg. Type: RB Mix Date: 7−31−90 Compaction Effort: 20 blows @ 200 psi and 150 blows @ 200 psi
Asph. Type: AAK1 Cond. Date: 10−29−90 Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T99RB/AAK1	2.616	2.606	0.66	1251.6	722.1	1251.8	2.364	9.3	388.8	157.8		
T100RB/AAK1	2.629	2.606	6.36	1252.3	721.8	1252.8	2.360	9.4	411.7	178.0		
T101RB/AAK1	2.604	2.606	19.53	1255.7	720.2	1256.2	2.345	10.0	421.8	168.1		
T102RB/AAK1	2.616	2.606	2.88	1259.2	742.3	1265.0	2.409	7.6			2.56	758.4
T103RB/AAK1	2.600	2.606	4.99	1251.8	735.2	1258.0	2.394	8.1			2.56	752.6
T104RB/AAK1	2.611	2.606	1.79	1253.9	736.2	1259.2	2.398	8.0			2.54	754.7

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1280.7	54.4	−0.077	2.624	762.9	1287.9	73.50	1.045	353.5	0.811	122.0	0.62	
1275.0	54.7	−0.077	2.626	756.4	1283.0	74.40	1.123	322.2	0.811	115.2	0.62	
1276.7	54.5	−0.191	2.617	759.0	1284.9	74.80	0.831	373.1	0.811	134.6	0.62	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water−conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/ S_{td}) or (23) = (22)/(10)
% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E–1 (Continued)

Agg. Type: RB   Mix Date: 10–10–90   Compaction Effort: 20 blows @ 200 psi and 150 blows @ 200 psi

Asph. Type: AAG1   Cond. Date: 10–17–90   Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ –9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T110RB/AAG1	2.592	2.570	3.74	1250.3	721.5	1251.9	2.365	8.0	434.5	225.1		
T112RB/AAG1	2.575	2.570	2.88	1251.1	721.2	1252.1	2.362	8.1	505.6	222.5		
T114RB/AAG1	2.535	2.570	1.71	1252.2	726.8	1253.1	2.384	7.2	520.0	231.6		
T109RB/AAG1	2.542	2.570	1.33	1247.1	733.2	1249.9	2.414	6.1			2.59	751.3
T111RB/AAG1	2.594	2.570	0.00	1249.3	738.9	1251.3	2.438	5.1			2.54	753.2
T113RB/AAG1	2.615	2.570	4.09	1255.5	739.2	1261.6	2.403	6.5			2.61	754.8

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1266.9	63.0	–0.213	2.593	755.4	1277.3	96.60	0.331	537.1	1.161	186.6	0.83	
1264.7	58.6	–0.176	2.593	756.2	1272.6	89.00	0.216	653.8	1.161	233.3	0.83	
1276.4	61.7	–0.153	2.613	757.8	1285.5	89.60	1.027	523.1	1.161	147.0	0.83	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19) – (18) – (7) + (6))/((7) – (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

Table E−1 (Continued)

Agg. Type: RL   Mix Date: 7−10−90   Compaction Effort: 20 blows @ 250 psi and 150 blows @ 250 psi

Asph. Type: AAK1   Cond. Date: 10−10−90   Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T123RL/AAK1	2.680	2.442	2.58	1248.3	700.6	1249.1	2.280	6.7	452.3	184.5		
T124RL/AAK1	2.671	2.442	1.75	1246.8	698.4	1247.5	2.274	6.9	429.5	165.0		
T128RL/AAK1	2.696	2.442	0.89	1249.6	703.5	1250.3	2.289	6.0	434.6		2.68	725.1
T125RL/AAK1	2.671	2.442	1.47	1245.3	706.8	1248.5	2.299	5.6			2.67	725.1
T126RL/AAK1	2.684	2.442	1.20	1245.1	707.2	1247.5	2.304	5.3			2.67	724.1
T127RL/AAK1	2.669	2.442	4.48	1242.2	706.5	1246.4	2.301	5.5				

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1266.8	71.5	0.000	2.694	731.3	1279.4	114.10	0.594	407.8	0.928	125.5	0.68	
1265.1	69.6	−0.056	2.682	730.9	1278.3	116.00	0.390	394.4	0.928	114.1	0.68	
1264.5	75.5	−0.019	2.683	730.1	1277.6	120.70	0.765	342.6	0.928	109.4	0.68	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/ S_{td}) or (23) = (22)/(10)

% of volume change = (((19)−(18)−(7)+(6))/((7)−(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E-1 (Continued)

Agg. Type: RL Mix Date: 11-21-89 Compaction Effort: 25 blows @ 250 psi and 150 blows @ 350 psi
Asph. Type: AAG1 Cond. Date: 12-18-89 Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^-9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T141RL/AAG1	2.700	2.453	6.94	1241.4	699.3	1242.1	2.280	7.0	109.0	210.0		
T142RL/AAG1	2.717	2.453	7.66	1237.5	692.7	1240.3	2.260	7.7	107.0	203.0		
T143RL/AAG1	2.729	2.453	7.33	1238.9	697.1	1240.3	2.280	7.2	117.0	231.0		
T144RL/AAG1	2.718	2.453		1236.0	690.9	1244.0	2.260	7.8			2.7	716.9
T145RL/AAG1	2.720	2.453		1238.7	694.0	1246.5	2.270	7.6			2.7	720.9
T146RL/AAG1	2.690	2.453		1245.3	699.2	1249.3	2.280	7.1			2.7	724.6

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1265.7	69.8	0.440	2.800	720.4	1279.1	112.20	2.250	59.0	0.530	120.0	0.60	
1269.0	73.0	0.290	2.800	723.5	1282.5	114.90	2.290	54.0	0.530	127.0	0.60	
1272.0	70.7	0.290	2.800	729.8	1274.6	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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water-conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E−1 (Continued)

Agg. Type: RL Mix Date: 11−28−89 Compaction Effort: 20 blows @ 250 psi and 150 blows @ 350 psi

Asph. Type: AAG1 Cond. Date: 12−24−89 Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T147RL/AAG1	2.730	2.457	8.30	1242.7	1244.8	1244.8	2.260	8.0	111.0	254.0		
T148RL/AAG1	2.696	2.457	6.72	1238.7		1241.3	2.280	7.2	125.0	285.0		
T149RL/AAG1	2.724	2.457	8.22	1245.2		1246.5	2.270	7.8	120.0	265.0		
T150RL/AAG1	2.706	2.457		1242.6		1244.6	2.280	7.3			2.71	726.9
T151RL/AAG1	2.719	2.457		1246.5		1247.7	2.280	7.2			2.71	726.5
T152RL/AAG1	2.737	2.457		1246.2		1248.1	2.270	7.8			2.73	728.4

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1273.8	77.9	0.200	2.700	730.5	1287.6	112.33	2.070	46.0	0.400	98.0	0.38	
1274.9	72.3	0.330	2.700	732.5	1288.2	106.18	1.660	52.0	0.400	113.0	0.38	
1279.4	77.4	0.160	2.700	730.7	1291.2	104.90	1.890	46.0	0.400	96.0	0.38	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water−conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)−(18)−(7)+(6))/((7)−(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E-1 (Continued)

Agg. Type: RL Mix Date: 11-28-89 Compaction Effort: 20 blows @ 250 psi and 150 blows @ 450 psi

Asph. Type: AAG1 Cond. Date: 12-24-89 Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^-9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T153RL/AAG1	2.723	2.410		1241.0	699.8	1244.7	2.280	5.5				
T154RL/AAG1	2.705	2.410		1234.9	697.0	1238.2	2.280	5.3				
T155RL/AAG1	2.749	2.410		1244.7	701.6	1247.7	2.280	5.4				
T156RL/AAG1	2.751	2.410		1245.6	690.6	1250.6	2.220	7.7	136.8	186.0		
T157RL/AAG1	2.771	2.410		1250.5	686.5	1250.5	2.220	8.0	100.4	225.0		
T158RL/AAG1	2.754	2.410		1246.5	691.4	1250.9	2.230	7.6	113.2	205.0		

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1269.5	95.1							50.0	0.430	141.0	0.69	
1265.2	105.2							51.8	0.430	167.0	0.69	
1272.9	95.2							50.0	0.430	119.0	0.69	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water-conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E−1 (Continued)

Agg. Type: RL　　Mix Date: 11−21−89　　Compaction Effort: 25 blows @ 250 psi and 150 blows @ 360 psi
Asph. Type: AAK1　　Cond. Date: 12−26−89　　Target Air Voids: 8% +/− 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ −9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T161RL/AAK1	2.692	2.466	7.20	1238.1	698.4	1240.7	2.280	7.4	145.0	292.0		
T162RL/AAK1	2.694	2.466	6.49	1235.5	693.3	1234.4	2.280	7.4	153.0	336.0		
T163RL/AAK1	2.691	2.466	6.86	1238.5	696.0	1239.4	2.280	7.6	145.0	300.0		
T164RL/AAK1	2.688	2.466		1240.5	698.9	1241.3	2.290	7.3			2.69	723.5
T165RL/AAK1	2.690	2.466		1238.3	695.0	1239.2	2.280	7.7			2.70	723.1
T166RL/AAK1	2.706	2.466		1238.6	695.8	1241.0	2.270	7.9			2.71	723.3

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1269.8	74.4	0.720	2.700	728.6	1289.9	125.51	3.480	45.3	0.300	82.0	0.26	
1270.5	76.6	0.590	2.700	726.8	1290.9	125.09	3.660	45.3	0.300	80.0	0.26	
1272.3	78.5	0.700	2.700	728.0	1296.2	134.17	4.220	40.8	0.300	83.0	0.26	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water−conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19) − (18) − (7) + (6))/((7) − (6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC−30

Table E–1 (Continued)

Agg. Type: RL　　Mix Date: 9–25–89　　Compaction Effort: 20 blows @ 250 psi and 150 blows @ 200 psi

Asph. Type: AAK1　　Cond. Date: 10–5–89　　Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^–9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T167RL/AAK1	2.760	2.461	4.77	1240.8	691.1	1244.9	2.240	9.0	90.2	318.0		
T168RL/AAK1	2.700	2.461	5.11	1242.4	697.9	1245.7	2.270	7.8	115.4	310.0		
T169RL/AAK1	2.740	2.461	3.73	1243.0	693.4	1247.0	2.250	8.8	99.2	262.0		
T170RL/AAK1	2.690	2.461		1246.3	690.8	1250.9	2.230	9.6			2.71	728.4
T171RL/AAK1	2.720	2.461		1242.3	685.2	1247.1	2.210	10.2			2.75	728.4
T172RL/AAK1	2.560	2.461		1248.8	694.2	1253.5	2.230	9.3			2.72	727.5

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1283.5	69.3	–0.890										
1279.4	65.0	–1.840										
1282.3	64.6	–0.800										

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19) – (18) – (7) + (6))/((7) – (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

Table E–1 (Continued)

Agg. Type: RB
Asph. Type: AAK1
Mix Date: 11–22–89
Cond. Date: 12–24–89
Compaction Effort: 25 blows @ 250 psi and 150 blows @ 275 psi
Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ –9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T181RB/AAK1	2.597	2.584		1244.7	733.0	1248.9	2.410	6.6			2.58	750.2
T182RB/AAK1	2.694	2.584		1245.9	734.6	1251.6	2.410	6.7			2.57	754.0
T183RB/AAK1	2.600	2.584		1249.7	731.3	1252.1	2.400	7.1			2.61	755.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1267.9	67.8	0.350	2.700	756.9	1278.5	98.82	1.100	117.0		279.0		
1272.8	77.2	0.350	2.700	758.1	1282.0	103.61	1.330	104.0		256.0		
1276.2	71.3	0.080	2.700	758.9	1286.6	99.27	1.320	103.0		206.0		

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data
W_a is the weight of the dry sample in air.
W_w is the weight of the sample in distilled water at 25 deg C.
W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.
S_{td} stands for the tensile strength of dry sample in psi.
S_{tm} stands for the tensile strength of water–conditioned sample in psi.
There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen
M_{Rd} : diametral resilient modulus of dry specimen in ksi.
M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.
M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)
TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)
% of volume change = (((19)–(18)–(7)+(6))/((7)–(6)))*100
Asphalt contents of the samples are at optimum
Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)
RB= Watsonville Granite, RL=Texas Chert
AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

Table E–1 (Continued)

Agg. Type: RB　　Mix Date: 12–5–89　　Compaction Effort: 25 blows @ 250 psi and 150 blows @ 300 psi

Asph. Type: AAK1　　Cond. Date: 12–18–89　　Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10 ^ –9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T184RB/AAK1	2.572	2.578	6.14	1242.9	732.6	1247.0	2.420	6.3	161.0	278.0		
T185RB/AAK1	2.564	2.578	6.59	1239.4	730.2	1243.5	2.410	6.3	170.0	292.0		
T186RB/AAK1	2.585	2.578	5.96	1245.7	733.3	1249.6	2.410	6.4	148.0	289.0		
T187RB/AAK1	2.416	2.578		1245.0	729.4	1247.4	2.400	6.8			2.60	749.4
T188RB/AAK1	2.601	2.578		1246.0	733.5	1252.2	2.400	6.8			2.60	751.5
T189RB/AAK1	2.588	2.578		1252.8	737.0	1254.9	2.420	6.2			2.60	755.3

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1268.8	67.9	0.270	2.600	753.3	1278.3	94.96	1.350	108.0	0.670	361.0	1.12	
1272.8	75.7	0.500	2.700	769.9	1282.7	103.73	–1.140	98.0	0.670	322.0	1.12	
1278.6	80.8	1.040	2.600	774.0	1288.8	112.70	–0.600	116.0	0.670	277.0	1.12	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19) – (18) – (7) + (6))/((7) – (6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite,　RL=Texas Chert

AAK1 = California Vally AR 400,　AAG1 = Boscan AC–30

Table E-1 (Continued)

Agg. Type: RB Mix Date: 9-25-89 Compaction Effort: 25 blows @ 250 psi and 150 blows @ 200 psi

Asph. Type: AAK1 Cond. Date: 10-5-89 Target Air Voids: 8% +/- 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^-9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T190RB/AAK1	2.610	2.603		1246.2	718.8	1250.6	2.340	10.0			2.60	754.1
T191RB/AAK1	2.610	2.603		1245.9	715.1	1250.3	2.330	10.6			2.60	753.3
T192RB/AAK1	2.560	2.603		1256.8	725.0	1261.2	2.340	10.0			2.61	760.8
T193RB/AAK1	2.630	2.603	1.19	1249.9	724.8	1254.6	2.360	9.4	133.8	275.0		
T194RB/AAK1	2.630	2.603	4.90	1245.3	714.0	1249.8	2.320	10.7	113.0	227.0		
T195RB/AAK1	2.630	2.603	4.86	1242.9	710.4	1247.5	2.310	11.1	114.2	281.0		

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1272.7	50.0	-2.480						98.0	0.790	286.0	0.93	
1273.5	48.8	-2.800						86.0	0.790	225.0	0.93	
1284.0	51.0	-2.420						100.0	0.790	215.0	0.93	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water-conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (S_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)-(18)-(7)+(6))/((7)-(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC-30

Table E–1 (Continued)

Agg. Type: RB   Mix Date: 11–21–89   Compaction Effort: 25 blows @ 250 psi and 150 blows @ 175 psi

Asph. Type: AAG1   Cond. Date: 12–26–89   Target Air Voids: 8% +/– 1%

1	2	3	4	5	6	7	8	9	10	11	12	13
ID	Thick. (in.)	G_{mm}	Permeability 10^–9 cm/sec	W_a Dry	W_w	W_{ssd}	G_{mb}	Air Voids (%)	Tens. St. (S_{sd}), psi	M_R (M_{Rd}), ksi	Thick. (in).	(W_w)
T201RB/AAG1	2.626	2.574	4.65	1251.8	731.5	1256.6	2.380	7.4	165.0	256.0		
T202RB/AAG1	2.652	2.574	9.32	1253.9	732.6	1261.1	2.370	7.8	111.0	211.0		
T203RB/AAG1	2.619	2.574	6.05	1251.8	729.9	1255.2	2.380	7.4	162.0	255.0		
T204RB/AAG1	2.613	2.574		1251.1	733.9	1257.0	2.390	7.1			2.61	751.0
T205RB/AAG1	2.594	2.574		1237.2	720.6	1240.7	2.380	7.6			2.59	746.1
T206RB/AAG1	2.610	2.574		1246.4	729.4	1250.7	2.390	7.1			2.60	751.0

14	15	16	17	18	19	20	21	22	23	24	25	26
W_{ssd}	% of Sturation	% Change of Volume	Thikness (in.)	W_w	W_{ssd}	% 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
1276.5	68.6	0.460	2.600	755.9	1286.2	94.74	1.380	75.8	0.510	148.0	0.62	
1266.2	73.5	0.000	2.600	747.7	1274.7	95.06	1.330	64.4	0.510	154.0	0.62	
1272.7	70.9	0.080	2.600	753.8	1282.2	96.57	1.360	81.3	0.510	144.0	0.62	

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 sample data. Columns 12 through 16 are partially saturated. Columns 17 through 26 are fully saturated sample data

W_a is the weight of the dry sample in air.

W_w is the weight of the sample in distilled water at 25 deg C.

W_{ssd} is the weight of the sample "Saturated Surface Dry" where the sample is blotted and weight in air.

S_{td} stands for the tensile strength of dry sample in psi.

S_{tm} stands for the tensile strength of water–conditioned sample in psi.

There are 3 average columns representing each stage of conditioning for tracking the volume change of the specimen

M_{Rd} : diametral resilient modulus of dry specimen in ksi.

M_{Rc} : diametral resilient modulus of conditioned specimen in ksi.

M_RR (Resilient Modulus Ratio) = (M_{Rc}/M_{Rd}), or (25) = (11)/(24)

TSR (Tensile Strength Ratio) = (St_{tm}/S_{td}) or (23) = (22)/(10)

% of volume change = (((19)–(18)–(7)+(6))/((7)–(6)))*100

Asphalt contents of the samples are at optimum

Sample ID's inducate (ASHTO T 283) (Sample no.) (Agg./Asph.)

RB= Watsonville Granite, RL=Texas Chert

AAK1 = California Vally AR 400, AAG1 = Boscan AC–30

APPENDIX F

PERMEABILITY PROTOCOL

Scope

This test method is for laboratory measurement of permeability of compacted bituminous mixtures. This method measures the rate at which air can be drawn (vacuum system) through bituminous mixtures.

This procedure takes advantage of previous experience, providing accuracy and simplicity, and reducing the possibility of asphalt contamination, specimen deformation, and the other deficiencies often found with other methods. In this procedure, the middle one-third of the specimen's circumference is coated with silicone and then enveloped with a cylindrical rubber membrane 1.5 inches high to provide a smooth surface, then cured overnight. A pressure differential is applied across the specimen by connecting the specimen setup to a vacuum pump. For different vacuum readings, the rate of air flow through the specimen is reported. Permeability is determined by calculating the rate of air flow and pressure differential.

Referenced Documents

ASTM Standards: D 3637 Permeability of Bituminous Mixtures

Definitions

Permeability as defined by Wyckoff, et al 1933: Permeability (K) 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)

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

Summary of Method

From the permeability definition, air permeability can be measured by creating a known pressure differential through the specimen by measuring the rate of air flow for a known period of time.

In order for the air flow to pass only through the specimen, 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 disadvantage of this method is that deformation of the specimen may be caused by the air pressure in the membrane.

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

The OSU procedure is simple and eliminates the above problems while still preventing leakage. The procedure is outlined in the following sections.

Significance and Use

This method can be used only for a laboratory test for mix design purposes.

The following ideal test conditions are prerequisites for the laminar flow of air through porous medium under constant-head conditions:

- Continuity of flow with no volume change during a test.
- Flow with the voids fully saturated with the air.
- Flow in the steady state with no changes in pressure gradient, and
- Direct proportionality of velocity of flow with pressure gradients below certain values, at which turbulent flow starts.

Apparatus

Figure F-1 shows the equipment set-up. The set-up is capable of accommodating a range of specimen sizes.

Test Specimens

Since this test is part of the Moisture Induced Damage Study, the dry subset for AASHTO T 283 will be tested for permeability.

Procedure

Place the specimen on specimen holder and seal the middle (Fig. F-2) specimen wall by applying silicone to the middle 1.5 inch, and enveloping the silicone seal with a cylindrical rubber membrane for the same width (1.5 inches). Cure the specimen overnight.

Place the specimen in the triaxial apparatus and envelope the specimen with a cylindrical rubber membrane, long enough to envelope the sample base, upper and lower porous teflon, and sample cap, then tie the assembly using rubber bands at each end.

Attach the vacuum outlet to the manometer and vacuum pump, and to the inlet to the flowmeter. To check for leaks, open valve (a) in Figure B-2 (Appendix B) and close the flowmeter until the manometer reads more than 250 mm Hg, by adjusting the vacuum level with the vacuum regulator.

Close valve (a) in Figure B-2 and watch the manometer reading. If manometer reading does not decrease, the system is air tight and ready for testing.

Open the flow meter and valve (a), apply the desired pressure difference (manometer reading) by adjusting the vacuum regulator, then take the rate of air flow, reading through the specimen from the air flow meter. Repeat for several different pressures and calculate the pressure differential.

Calculation

The permeability of a porous medium defined in fundamental units, is:

$$K = \frac{\mu Q L}{A(P_1 - P_2)}$$

where:

K = permeability in centimeters per second.
μ = viscosity of fluid in poises,
Q = rate of flow, cubic centimeters per second.
L = height of sample, centimeters
A = area of sample in square centimeters
$P_1 - P_2$ = pressure difference, dynes per square centimeter.

The above formula was modified by Kumar and Goetz as shown below:

For specimen 4 inch (10.16 cm) in diameter, a test temperature of 20°C (68°F) and a value for μ at 20°C (68°F) of 1.813×10^{-4} poises, the above formula reduces to:

$$K = (3.812 \times 10^{-11} \times R \times H)/\Delta P$$

where:

R = rate of airflow in ml per minute
H = height of specimen in centimeters, and
ΔP = pressure differential in centimeters of water

By using the slope (S) of the straight line portion of the curve obtained from the plot of rate of airflow (R) (y axis) versus pressure differential (ΔP) (x axis), this reduces the above formula to:

$$K = 3.812 \times 10^{-11} \times S \times H$$

Since the pressure difference is measured in millimeters of mercury (mm Hg) and the rate of airflow in cubic foot per hour (ft^3/hr) the following conversion factors are used:

$1.0\ ft^3/hr = 471.9\ cm^3/min.$

1.0 mm HG = 1.868 inch of water

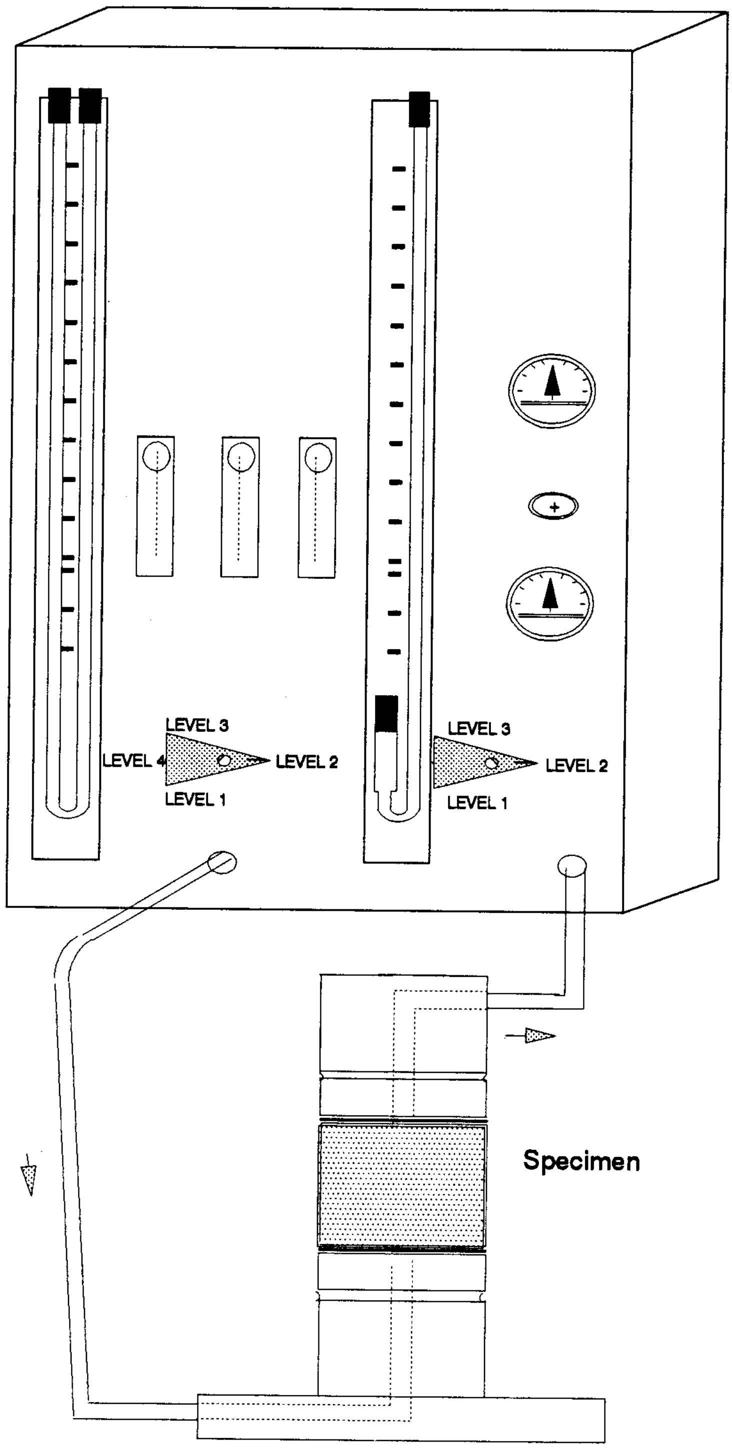
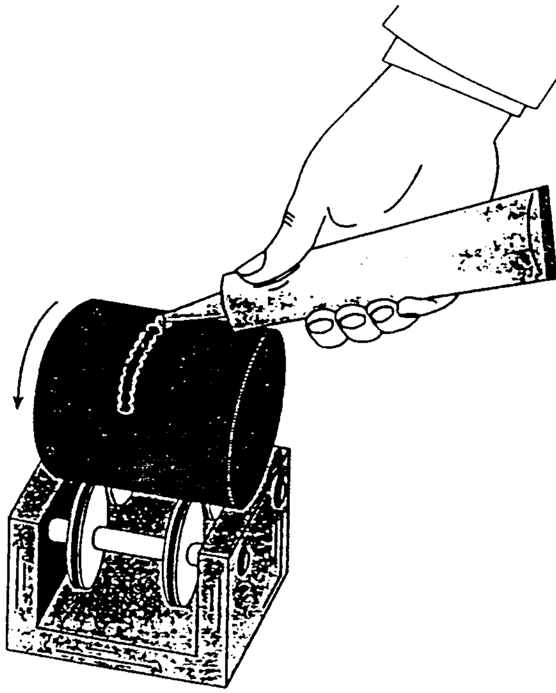
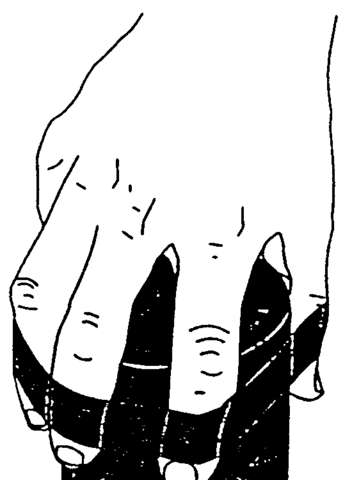


Figure F-1 Schematic Diagram of Permeability Apparatus



a) Specimen sealing for 1.5" of the middle



b) Rubber membrane fastening to specimen

Figure F-2 Permeability Sealing of Compacted Asphalt Mixtures

APPENDIX G

STANDARD TEST METHOD FOR DYNAMIC MODULUS OF ASPHALT MIXTURES ASTM D 3497

Scope

This test method covers procedures for preparing and testing asphalt mixtures to determine dynamic modulus values. The procedure described covers a range of both temperatures and loading frequencies. The minimum recommended test series consists of testing at 41, 77, and 104°F (5, 25, and 40°C) at loading frequencies of 1, 4, and 15 Hz for each temperature.

This method is applicable to asphalt paving mixtures similar to mixes 3A, 4A, 5A, 6A, and 7A, as defined by Specification D 3515.

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

Referenced Documents

ASTM Standards:

C 617 Practice for Capping Cylindrical Concrete Specimens
D 3496 Method for Preparation of Bituminous Mixture

Specimens for Dynamic Modulus Testing

D 3515 Specifications for Hot-Mixed, Hot-Laid Bituminous

Paving Mixtures

Definitions

Dynamic modulus - the absolute value of the complex modulus that defines the elastic properties of a linear viscoelastic material subjected to a sinusoidal loading, $|E^*|$.

Complex modulus - a complex number that defines the relationship between stress and strain for a linear viscoelastic material, E^*.

Linear material - a material whose stress to strain ratio is independent of the loading stress applied.

Summary of Method

A sinusoidal (haversine) axial compression stress is applied to a specimen of asphalt concrete at a given temperature and loading frequency. The resulting recoverable axial strain response of the specimen is measured and used to calculate dynamic modulus.

Significance and Use

The values of dynamic modulus can be used for both asphalt paving mixture design and asphalt pavement thickness design.

Apparatus

Testing Machine - An electro-hydraulic testing machine with a function generator capable of producing a haversine wave form has proven to be most suitable for use in dynamic modulus testing. The testing machine should have the capability of applying the loads over a range of frequencies from 0.1 to 20 Hz and stress levels up to 100 psi (690 kPa).

Temperature-Control System - The temperature-control system should be capable of a temperature range from 32 to 120 ± 1°F (0 to 50 ± 0.5°C). The temperature chamber should be large enough to hold six specimens.

Measurement System - The measurement system consists of a two-channel recorder, stress- and strain-measuring devices, suitable signal amplification, and excitation equipment. The measurement system should have the capability for determining loading up to 3000 lbf (13.3 kN) from a recording with a minimum sensitivity of 2% of the test load per millimetre of chart paper. This system should also be capable for use in determining strains over a range of full-scale recorder outputs from 300 to 5000 micro units of strain. At the highest sensitivity setting, the system should be able to display 4 micro strain units or less per millimetre on the recorded chart.

Recorder - The recorder amplitude should be independent of frequency for tests conducted up to 20 Hz.

Strain Measurement - The values of axial strain are measured by bonding two wire strain gages at mid-height opposite each other on the specimens. The gages are wired in a Wheatstone Bridge circuit with two active gages on the test specimen and two temperature-compensating gages on an unstressed specimen exposed to the same environment as the test specimen. The temperature-compensating gages should be at the same position on the specimen as the active gages. The sensitivity and type of measurement device should be selected to provide the strain readout required in 6.3.

Load Measurements - Loads are measured with an electronic load cell meeting requirements for load and stress measurements in 6.3.

Hardened Steel Disk - A hardened steel disk with a diameter equal to that of the test specimen is required to transfer the load from the testing machine to the specimen.

Test Specimens

Laboratory Molded Specimens - Prepare the laboratory molded specimens in accordance with Method D 3496. The specimens should have a height-to-diameter ratio of 2 to 1, a minimum diameter of 4 in. (101.6 mm) and a diameter four or more times the maximum nominal size of aggregate particles. A minimum of three specimens is required for testing.

Pavement Cores - A minimum of six cores from an in-service pavement is required for testing. Obtain cores having a minimum height-to-diameter ratio of 2 to 1 and with diameters not less than two times the maximum nominal size of an aggregate particle. Select cores to provide a representative sample of the pavement section being studied.

Specimen Preparation - Cap all specimens with a sulfur mortar in accordance with the requirements of Method C 617 prior to testing. Bond the strain gages with epoxy cement to the sides of the specimen near mid-height in position to measure axial strains (Note 1). Wire the strain gages as required in 6.3.2 and attach suitable lead wires and connectors.

NOTE 1 - On specimens with large-size aggregate, care must be taken so that the gages are attached over areas between the aggregate faces.

Procedure

Place the specimen in a controlled temperature cabinet and bring them to the specified test temperature.

NOTE 2 - A dummy specimen with a thermocouple in the center can be used to determine when the desired test temperature is reached.

Place the specimen into the loading apparatus and connect the strain gage wires to the measurement system. Put the hardened steel disk on top of the specimen and center both under the loading apparatus. Adjust and balance the electronic measuring system as necessary.

Apply haversine loading to the specimen without impact and with loads varying between 0 and 35 psi (241 kPa) for each load application for a minimum of 30 s and not exceeding 45 s at temperatures of 41, 77, and 104°F (5, 25, and 40°C) and at loading frequencies of 1, 4, and 16 Hz for each temperature.

NOTE 3 - If excessive deformation (greater than 2500 micro units of strain) occurs, reduce the maximum loading stress level to 17.5 psi.

For pavement-cored specimens, test six specimens at each temperature and frequency condition once. Start at the lowest temperature and run the three frequencies from fastest to slowest. Bring specimens to specified temperature before each test. Repeat for next highest temperature.

For laboratory-molded specimens, test three specimens at each temperature and frequency condition twice. Conduct tests in same order as pavement cores (8.4). Run the replicate tests before the temperature is changed for the three frequencies. Bring the specimens to the specified test temperature before each test.

Monitor both the loading stress and axial strain during the test. Increase the recorder chart speed such that 1 cycle covers 10 to 20 mm of chart paper for five to ten repetitions before the end of the test.

Complete the loading for the test within 2 min from the time specimens are removed from the temperature-control cabinet.

NOTE 4 - The 2-min testing time limit may be waived if loading is conducted within a temperature-control cabinet meeting requirements in 6.2.

Calculations

Measure the average amplitude of the load and the strain over the last three loading cycles to the nearest 0.5 mm (see Fig. F-1).

Calculate the loading stress, σ_o, as follows:

$$\sigma_o = (H_1 \text{ X } L)/(H_2 \text{ X } A)$$

where:

H_1 = measured height of load, in. (or mm) (see Fig. F-1),
H_2 = measured chart height, in. (or mm) see Fig. F-1),
L = full-scale load amplitude determined by settings on the recording equipment, lbf (or N), and
A = cross-sectional area of the test specimen, in. ^{2} (or m^2).

Calculate the recoverable axial strain, ϵ_o, as follows:

$$\epsilon_o = (H_3 \text{ X } S)/H_4$$

where:

H_3 = measured height of recoverable strain, in. (or mm) (see Fig. F-1),
H_4 = measured chart height, in. (or mm) see Fig. F-1), and
S = full-scale strain amplitude determined by settings on the recording equipment, in./in. (or m/m).

Calculate dynamic modulus, $|E^*|$; as follows:

$$\text{Dynamic modulus} = \sigma_o/\epsilon_o$$

where:

σ_o = axial loading stress, psi (or kPa), and
ϵ_o = recoverable axial strain, in./in. (or m/m).

Report

Report the average dynamic modulus at temperatures or 41, 77, and 104°F (5, 25, and 40°C) for 1, 4, and 16-Hz loading frequencies at each temperature.

Precision

11.1 This test method shall not be used for Specification purposes.

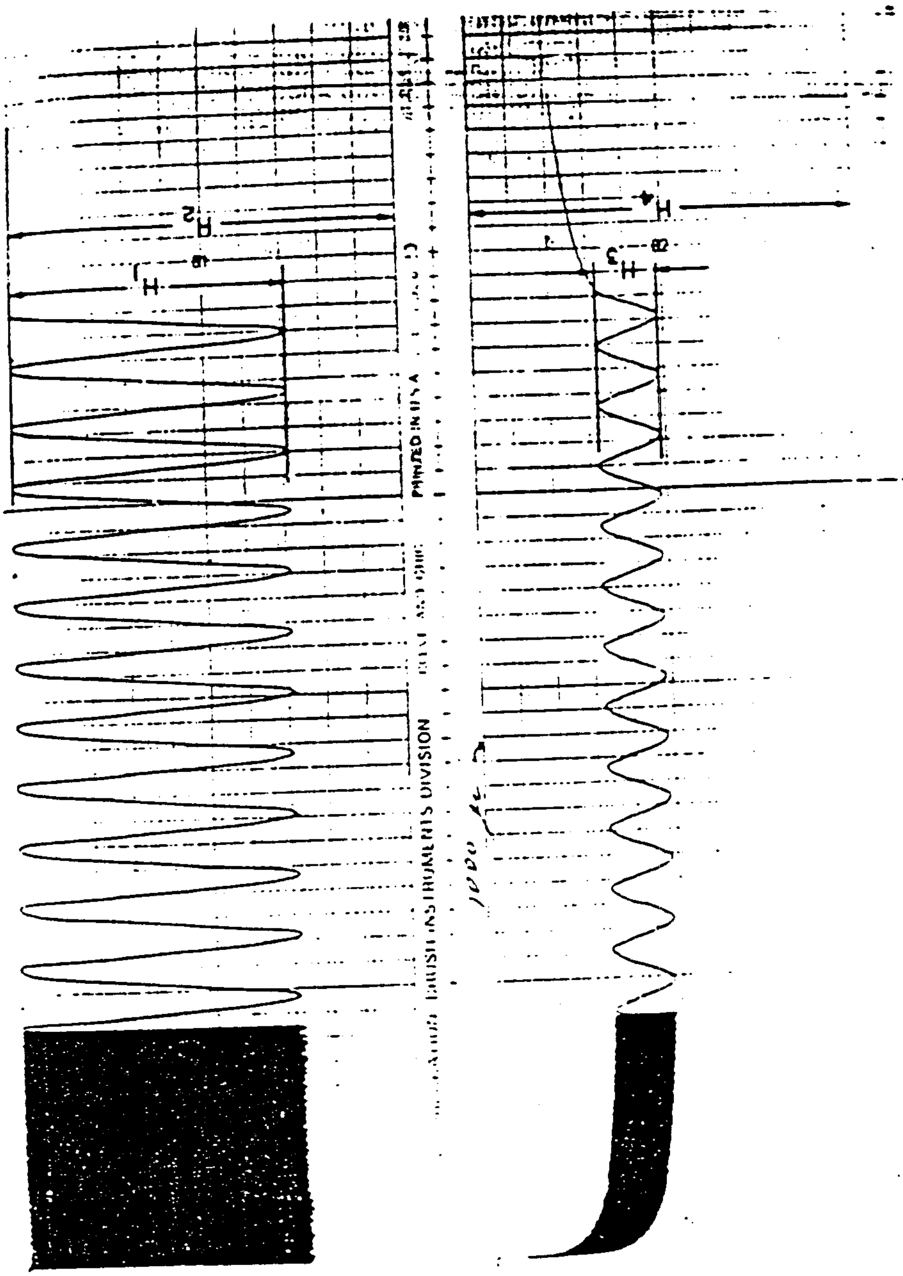


Figure G-1 Recording of Load and Strain