AN ABSTRACT OF THE THESIS OF

Richard L. Boudreau for the degree of Master of Science in Civil Engineering presented on March 7, 1989.

Title: Test Method to Determine the Degree of Asphalt Stripping from Aggregates

Abstract Approved: _____
R. G. Hicks

Moisture damage has long been recognized as one of the most critical factors influencing the performance of asphalt concrete (AC) pavements. This moisture-induced damage occurs from either the physical separation of the asphalt film from the aggregate or the softening of the asphalt binder within the AC mixture in the presence of water. This phenomenon is often termed stripping.

Although many test procedures have been developed over the years to identify stripping potential of AC mixtures, none have received wide acceptance by the engineering profession. The purpose of this research was to develop a standard test procedure that will allow for a quantitative means of predicting moisture susceptibility of AC mixtures and provide for an assessment on the effectiveness of antistripping additives.

The measure of response made in this study was the resilient modulus obtained from a pneumatic repeated-load test system. Dense-graded, laboratory-compacted test specimens fabricated from two

aggregate sources in the state of Oregon were evaluated in this research.

The test procedure and specimen preparation developed was implemented with a saturation and freeze-thaw moisture condition cycling. Results indicate that the procedure can significantly differentiate between a proven stripping aggregate and a proven non-stripping aggregate. The comparison can be made following full saturation plus one freeze-thaw cycle. Results also indicate that caution must be used when comparing mixes of different air void contents. The results of the procedure developed appear to over predict moisture susceptibility of low air void groups (<6.5%) and under predict moisture susceptibilty of high air void groups (>8.5%). The procedure also has a strong potential to assess the effectiveness of antistripping additives, although some of the additives evaluated in this study generally did not improve the mixtures sensitivity to moisture damage.

Test Method to Determine the Degree of Asphalt Stripping from Aggregates

by

Richard L. Boudreau

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Completed March 7, 1989

Commencement June 1990

APPROVED:

Redacted for Privacy

Professor of Civil Engineering in Charge of Major

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Date Thesis is Presented March 7,1989

Typed by researcher for Richard L. Boudreau

ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to his project advisor, Dr. Gary Hicks, for his guidance, patience, encouragement, and criticism over the long haul.

A special thank you is extended to Bud Furber, Andy Brickman, and Todd Scholz for technical input and needed support.

The author is also grateful to Professor David Faulkenberry, Dr. Chris Bell, and Dr. Bob Leichti for their active participation on the graduate committee.

Joanne Heddlesten deserves special recognition for her excellent organization of tables included in this document.

Finally, I must thank my conscience, my strong will to achieve, my patience,..... my wife Mimi, who possesses more of these characteristics than me. She should be as proud of this thesis as I.

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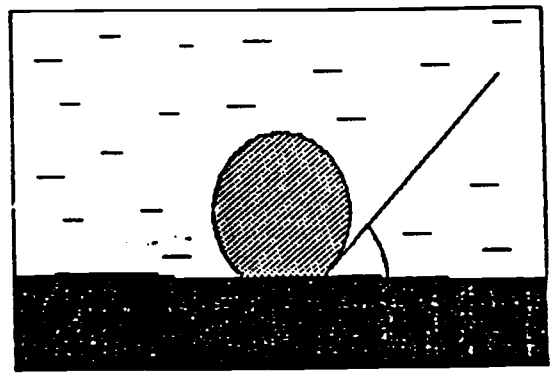
1 INTRODUCTION

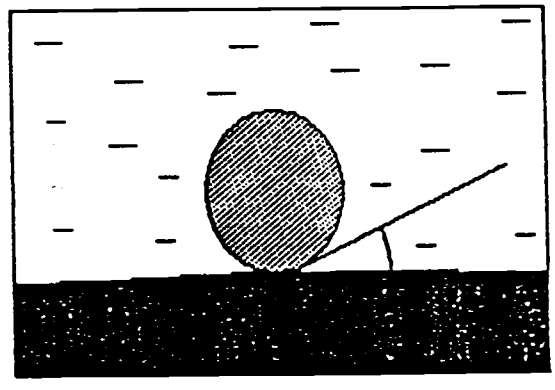
1.1 Problem Statement

The durability of an asphalt concrete (AC) pavement depends to a great degree on the adhesion between the asphalt cement and the aggregate. Although construction methods, traffic, environmental conditions and mix properties contribute to the deterioration of an AC pavement, the presence of water or water vapor (moisture) often is one of the most critical factors affecting the durability of asphalt concrete mixtures (Lottman, 1982).

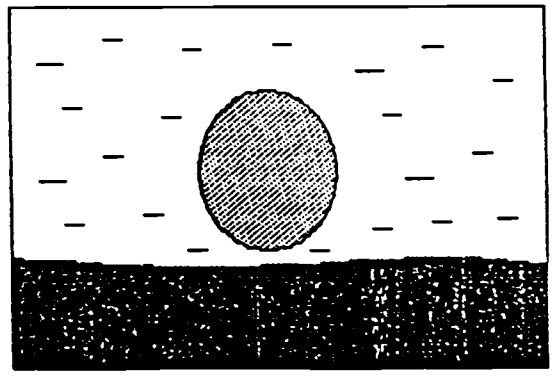
Water or moisture damage in AC pavements may be associated with two mechanisms (Kennedy et al., 1983). First, aggregates generally have a greater affinity for water than asphalt. Water can get between the asphalt and aggregate and "strip" the asphalt film away. This mechanism for loss of adhesion may be viewed in terms of a reduction in the contact angle between the asphalt and aggregate surface, as shown in Figure 1.1. The rate at which adhesion stripping takes place is a function of temperature, type of aggregate and viscosity and composition of the asphalt (Tyler, 1938). This theory suggests that "bare" aggregates at the extreme may be the result of adhesion loss. The second probable mechanism identified is the interaction of water with the asphalt cement (or emulsification) which causes a reduction in cohesion with a severe reduction in integrity and strength of the



(a) The moment at which the aggregate, with the drop of bitumen, is immersed in water. The contact angle is less than 90°.



(b) The water begins to remove the bitumen drop from the aggregate surface and the contact angle decreases.



(c) Finally, the stage is reached where the contact angle is 0° and the bitumen loses contact with the aggregate surface.

FIGURE 1.1 – Schematic of the Stripping Process (after Tyler, 1938).

mixture (White, 1987). This type of stripping is not as visible to the human eye as the loss of adhesion mechanism. Graf (1986) reports that the cohesive failure theory can further be divided into two distinctly different types of failure. The first involves a softening of the AC in the presence of water which will lead to failure within the asphalt film of the aggregate matix. The other involves the softening of the AC which weakens the bond between the AC and the aggregate, causing a seperation of the film from the aggregate. Therefore an adhesion failure may be thought of as a combination of cohesion loss and adhesion loss.

1.2 Study Objective

A wide variety of test procedures have been developed to predict the moisture susceptibility of asphalt concrete pavements. Although many of the test procedures have produced good results in localized regions of the country, a common test procedure has not been developed that is widely accepted by the engineering profession. This study is concerned with the development of a standard test procedure to be used to determine the stripping potential of a compacted AC mixture by means of a Repeated-Load Diametral Test System.

The overall goal of this study is to develop an improved test method to quantify the susceptibility of an asphalt concrete mixture to stripping which allows a quantitative assessment of the effectiveness of antistripping additives. Specific objectives include:

1. Selection of test conditions that will discriminate between material characteristics (ie: air voids, asphalt type and content, aggregate type, etc.) while yielding repeatable results.
2. Selection of a laboratory compaction method that results in a high degree of replication in air void contents and repeatability in resilient modulus.
3. Implementation and evaluation of a moisture-conditioning process and test method that will meet the overall goals of this study as mentioned above.

1.3 Scope of Study

A detailed discussion of the Repeated-Load Diametral Test equipment and procedure is presented in Chapter 2. Also presented in Chapter 2 is a description of the materials used to prepare the laboratory compacted specimens and the moisture-conditioning process to initiate stripping.

The Parametric Study presented in Chapter 3 is a quantitative study of controlled laboratory compacted AC specimen subjected to a series of variable resilient modulus test conditions. The variable conditions include temperature, load duration and frequency, and induced strain level desired to perform the test. The resilient modulus at each combination of test conditions is recorded and evaluated. The conclusions derived in this portion of the study are intended to meet the criteria of specific objective number one listed previously.

The presentation of the Compaction Study in Chapter 4 is intended to aid in the development of sample preparation. Four methods of compaction and two curing procedures are evaluated for specimen consistency including air void contents and resulting resilient modulus values. The method of compaction and curing which result in the highest degree of repeatability will be used as the method of compaction for the proposed improved test method.

The Factorial Study presented in Chapter 5 is a concentrated laboratory testing effort using the testing conditions and compaction method developed in Chapters 3 and 4. In this study, the test method incorporates an accelerated moisture-conditioning process on mixtures containing two separate aggregate types, two asphalt types and two antistripping agents. The results of the resilient modulus tests are analyzed and evaluated for additive effectiveness, and the ability of the improved test method to be sensitive to moisture damage.

Finally, the conclusions and recommendations resulting from this study are given in Chapter 6.

2 MATERIALS AND TEST METHODS

A number of test methods have been developed over the years to identify the susceptibility of an AC mixture to moisture. The number of tests have recently increased with greater concern for stripping and evaluation of antistripping agents. Available tests range from a qualitative inspection of coated aggregates in a loose mixture submerged in water at ambient or elevated temperatures to more quantitative mechanical responses to moisture of compacted AC mixtures. A summary of some of the available tests are listed in Table 2.1 (after Taylor and Khosla, 1983).

This paper presents an evaluation of a repeated-load diametral test procedure to detect the susceptibility of AC mixtures to moisture damage. The repeated-load diametral procedure to determine the resilient modulus (M_r) was selected over the methods briefly outlined in Table 2.1 because the test is non-destructive. The non-destructive nature of the test allows measurement of strength loss over repetitive cycles of conditioning on the same sample. This will decrease the number of samples required for testing over the destructive testing alternatives, and variations in strength loss should only be attributed to the conditioning of the samples, and not slight differences in replication of samples (i.e., by testing the same sets of sample => exact replication!).

The M_r concept provides support for the more recent acceptance the M_r incorporated in the new AASHTO pavement design guide (AASHTO, 1986). The M_r of a compacted AC mixture is believed to be a measure of

TABLE 2.1 - Summary of Laboratory Procedures to Determine Water Sensitivity of Asphalt Concrete (modified after Taylor and Khosla, 1983)

Dynamic Immersion Tests
- Nicholson Test
- Dow or Tyler Wash Test

Technique

Static Immersion Tests
- ASTM D-1664
- Lee Test
- Holmes Water Displacement
- Oberbach Test
- German U-37 Test

Boiling Tests
- ASTM D-3625
- Riedel and Weber Test

Chemical Immersion Tests
- Riedel and Weber Test

Abrasion Tests
- Cold Water Abrasion Test
- Abrasion-Displacement Test
- Surface Water Abrasion Test

Simulated Traffic Tests
- English Trafficking Tests
- Test Tracks

Quantitative Coating Evaluation Tests
- Dye Absorption Test
- Mechanical Integration Method
- Radioactive Isotope Tracer

- Tracer-Salt with Flame Photometer Analysis
- Light-Reflection Method

Nondestructive Tests
- Sonic Test
- Resilient Modulus Test

Immersion-Mechanical Tests
- Marshall Immersion Test
- Moisture Vapor Susceptibility Test
- Water Susceptibility Test
- Indirect Tension (Diametral Compression) Test
- Immersion-Compression Test ASTM D-1075 or AASHTO T-165

Miscellaneous Tests
- Detachment Tests
- Briquet Soaking Test
- Stripping Coefficient Measurement
- Peeling Test
- Texas Freeze-Thaw Pedestal Test

the elastic response of a pavement under conditions which simulate repeated traffic loads. Therefore, the M_r has been employed in the mechanistic design procedure for asphalt concrete pavements.

The following sections describe the equipment used to determine the M_r of compacted AC mixtures. Also a discussion of the M_r test procedure and the moisture-conditioning process employed to initiate stripping is presented. Lastly, presented in this chapter is a description of the materials used to prepare laboratory test specimens for the 1) Parametric Study, 2) Compaction Study and 3) Factorial Study. The materials used include aggregates, asphalt and antistripping additives.

2.1 Diametral Modulus Testing Apparatus

The M_r used to identify the stripping potential and effectiveness of antistripping additives for this study were determined with a Repeated-Load Diametral Test System (ASTM, 1987a). The Repeated-Load System consists of three basic units: (1) the load system, (2) testing accessories, and (3) recording devices. Each of these units are described below.

2.1.1 The Load System

The load system is shown in Figure 2.1. It includes an air-powered testing apparatus and a control cabinet from which dynamic and static load can be controlled. Figure 2.2 shows the electropneumatic system used to apply loads. It consists of a Bellofram air cylinder, a shuttle valve and a MAC valve. Operation of the MAC valve requires

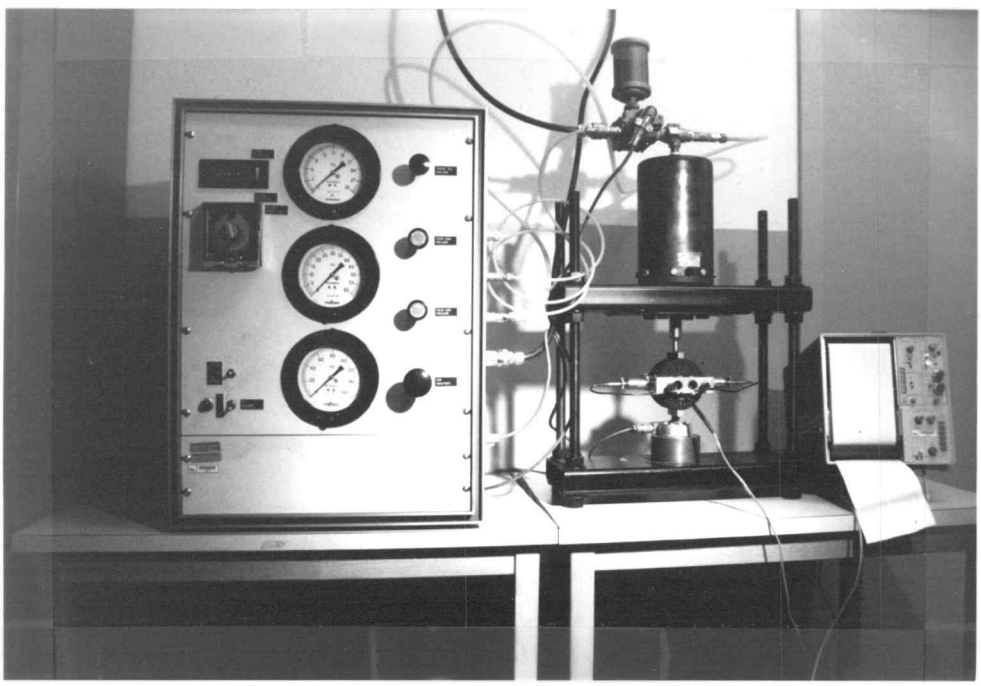


FIGURE 2.1 – Repeated-Load Diametral Test System

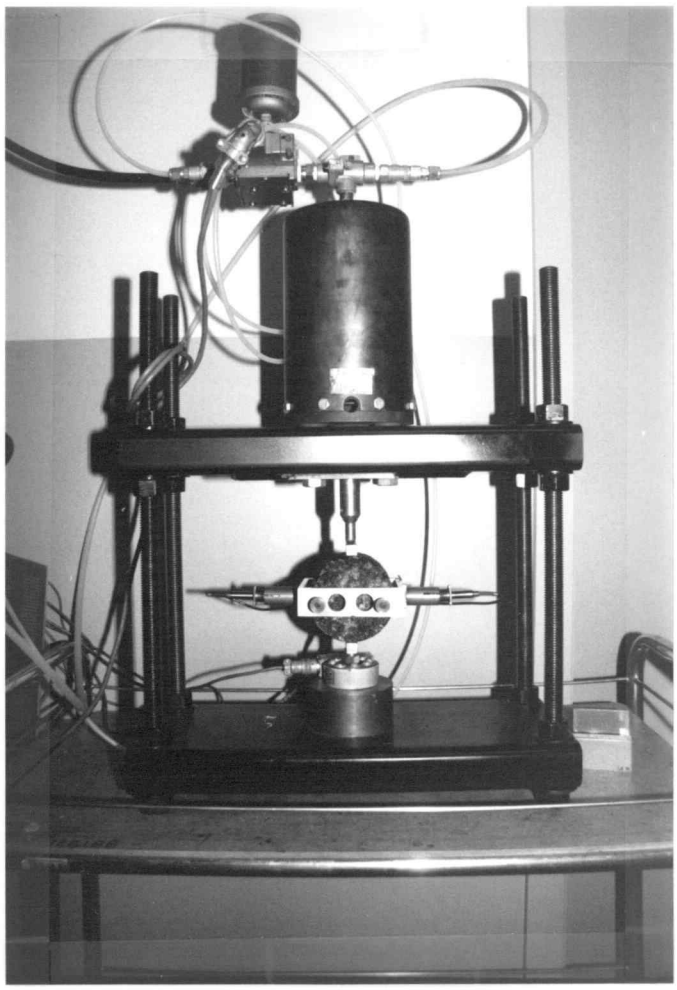


FIGURE 2.2 – Load Frame with Loading Components

a 110 volt power supply, a pilot air supply, and a main air supply (100–125 psi air pressure). The Bellofram air cylinder can be activated either by the MAC valve line or the static load line. The shuttle valve regulates airflow to the Bellofram air cylinder and is designed to allow the line of highest pressure to flow into the air cylinder. Because the MAC valve is normally closed, the static load line is connected to the Bellofram air cylinder when the MAC valve is not activated by an electrical signal. If the MAC valve is activated, the shuttle valve closes the static load line and opens the MAC valve line to the Bellofram air cylinder. Static and dynamic load pressure lines, and electrical signals to the MAC valve are monitored from the control cabinet.

The control cabinet, shown in Figure 2.3, contains a pneumatic system able to supply air to the Bellofram cylinder and an electrical system designed primarily to monitor the MAC valve. Precision air regulators and pressure gauges control the static and dynamic air pressure lines. A dual timer controls the electrical signal to the MAC valve (pulse interval and pulse duration) and a counter to record the number of load pulses.

2.1.2 Testing Accessories

A diametral yoke (Figure 2.4) is required to conduct repeated load diametral tests. The yoke is used to mount LVDT's (Sangamo Linear Variable Differential Transformers [LVDT's], model no. AG/2.5) which measure the horizontal deformation of cylindrical samples subjected to dynamic vertical load. The sample horizontal deformation

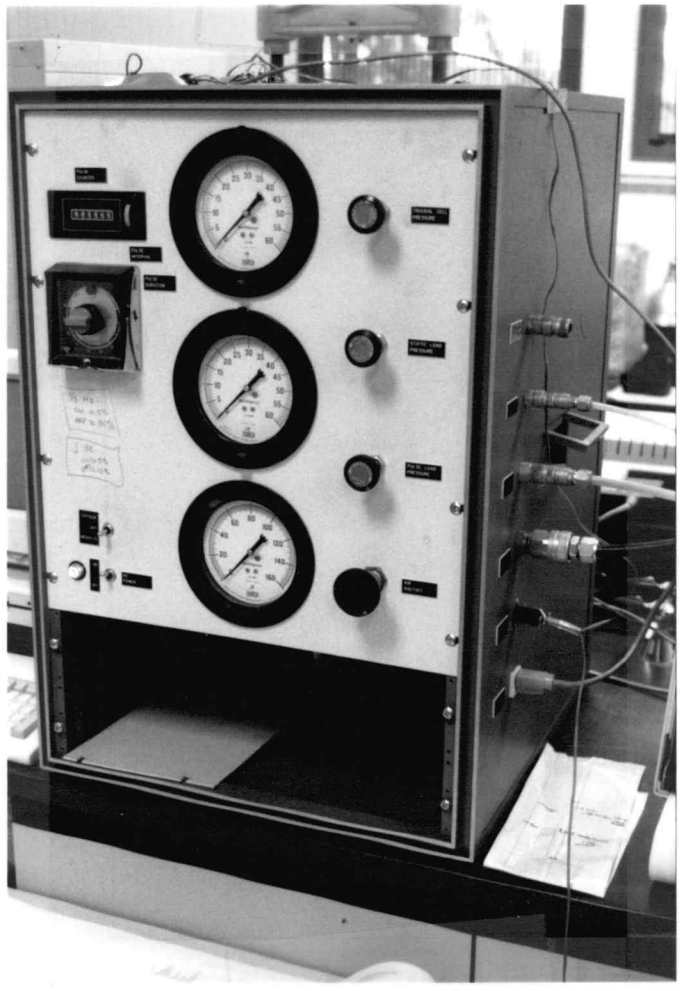


FIGURE 2.3 – Air Control Cabinet

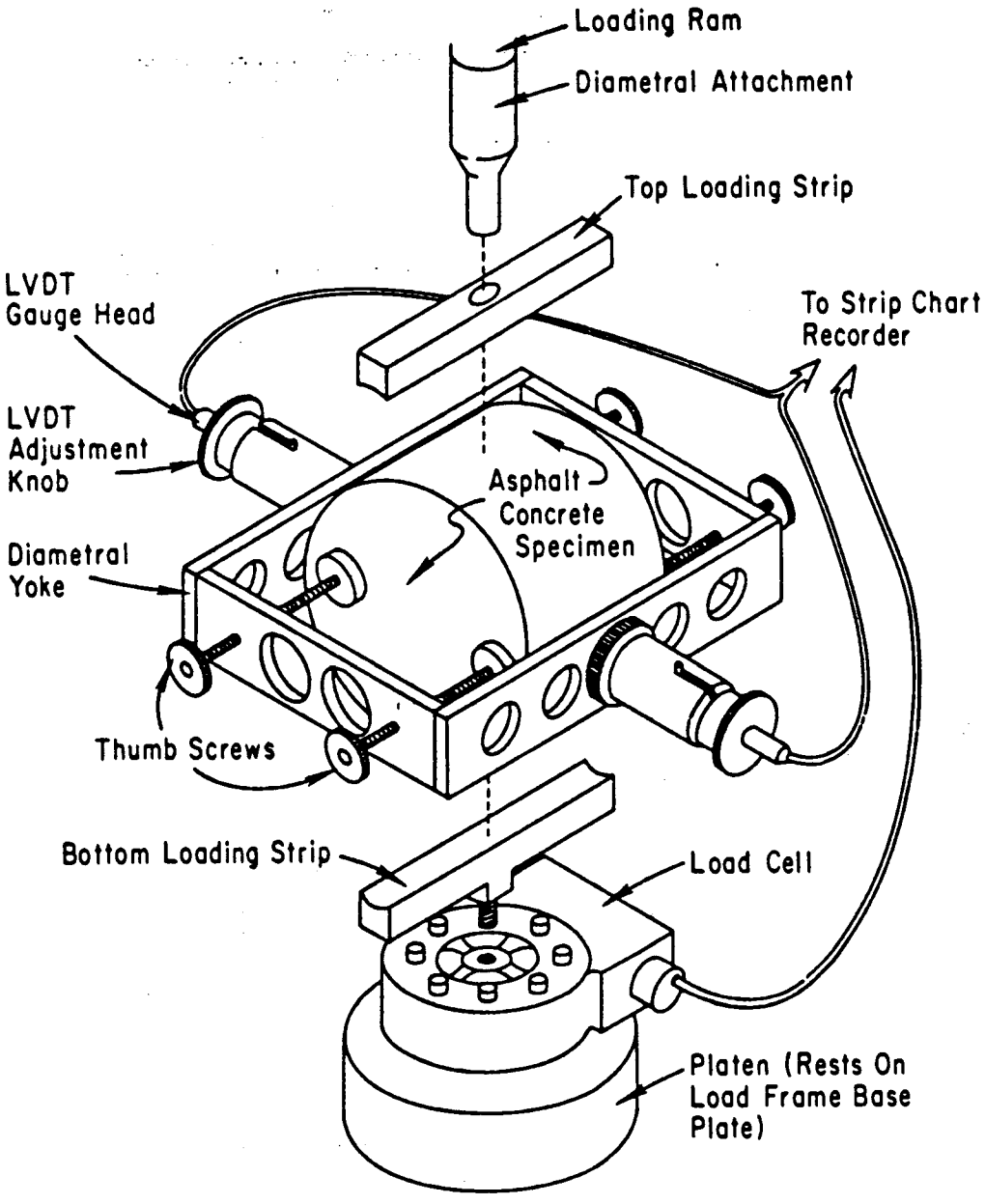


FIGURE 2.4 – Test Specimen with Diametral Yoke and Loading Ram

is measured by the LVDT's. The dynamic load is measured using a flat load cell (Strainsert Universal Load Cell, model no. FL2.5 U2SGKT, 2.5 kip capacity).

2.1.3 Recording Device

A two channel oscillographic strip-chart recorder (Figure 2.5), with A/C carrier preamplifiers, is used for the diametral test transducer LVDT's and the load cell. Detailed information on both the oscillographic recorder and the A/C preamplifiers is presented in the operating and service manuals supplied by the manufacturer (e.g., Hewlett-Packard, Gould, etc.).

2.2 Test Procedures

The following sections describe the test procedure used to determine the M_r of compacted AC mix specimen, and the moisture-conditioning process used to simulate field moisture conditions. The moisture-conditioning process was only used for the Primary Factorial Study presented in Chapter 5.

2.2.1 Repeated-Load Diametral Test

The test procedure used in this study to determine the M_r was done in accordance with ASTM D4123 (1987a). In this procedure, a nominal 4-inch diameter cylindrical specimen undergoes a repeated load along its vertical diametral plane. The load and the horizontal elastic deformation are measured with a calibrated signal conditioner (i.e., a two-channel oscillographic strip-chart recorder) after a

FIGURE 2.5 – Signal Conditioning Device (Hewlett Packard 2–channel Strip Chart Recorder)

series of pre-conditioning loads. The purpose of pre-conditioning a specimen is to eliminate early plastic flow and achieve good contact between the specimen and the platen. This should result in a stable deformation readout, and typically takes 50 - 100 load pulses at room temperature. Fewer pre-conditioning load pulses are required for low temperature testing (less plastic), and more may be required for higher temperatures (more plastic).

The load and deflection data obtained from an individual test is used to calculate the M_r using equation 2.1:

$$M_r = P(\nu+0.27)/Ht \quad \ldots\ldots\ldots\ldots\ldots (2.1)$$

where M_r = Resilient modulus, psi.
t = specimen thickness, in.
P = dynamic pulse load, lbs.
H = horizontal elastic deformation, in.
ν = Poisson's Ratio

The tensile strain at the center of the specimen is given by:

$$\epsilon_t = [(0.16+0.48\nu)/(0.27+\nu)] \times H \quad \ldots\ldots\ldots\ldots\ldots (2.2)$$

Equations 2.1 and 2.2 are supported by work done by Hadley et al.(1970). A typical value of Poisson's ratio for asphaltic concrete is 0.35 (Yoder and Witczak, 1975); therefore equations 2.1 and 2.2 can be reduced to:

$$M_r = 0.62\ (P/Ht) \quad \ldots\ldots\ldots\ldots\ldots (2.3)$$

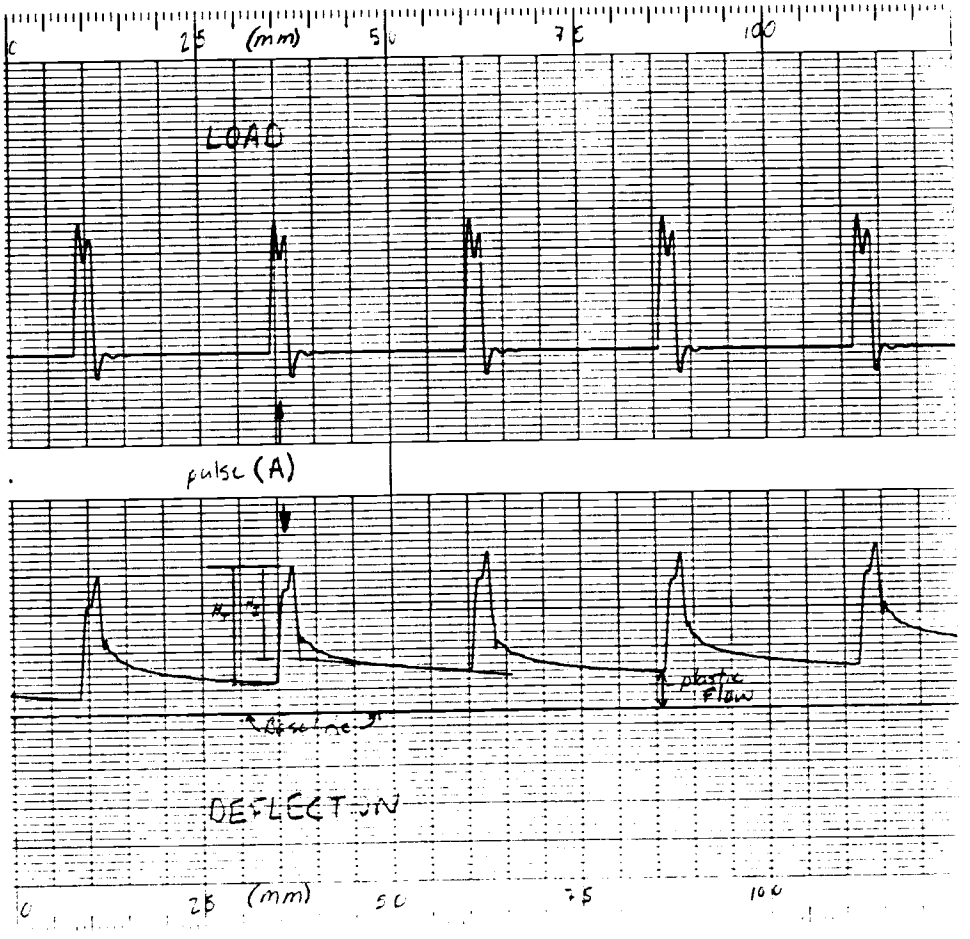
$$\epsilon_t = 0.52H \quad \ldots\ldots\ldots\ldots\ldots (2.4)$$

The testing operator can control the magnitude of the applied pulse load by using the pulse load regulator on the front panel of the control cabinet. By adjusting the load, the operator can target the

horizontal elastic deformation required to achieve a pre-determined strain level (eq 2.4). Note that the load reading and the horizontal deformation occur simultaneously on the two-channel strip-chart recorder (Figure 2.6). The M_r test mobilizes small strains in the specimen. Under small strains the material approaches the elastic range of its stress-strain response (Heinicke and Vinson, 1988). Further, it is desirable to test at small strain levels as this condition will avoid damage to the specimen, hence making the test non-destructive. A microstrain level of 50 - 150 (1 microstrain = $1x10^{-6}$ in/in) was determined to satisfy this case (ASTM, 1987a).

The horizontal displacement that the test specimen undergoes as a result of an applied vertical load may be measured either upon load application or release. The former measurement leads to determination of the so-called total M_r while the latter is used to determine the so-called instantaneous M_r (ASTM, 1987a). A typical load and displacement response trace from a 2-channel strip-chart recorder is shown in Figure 2.6.

It is somewhat simpler to measure the total displacement (H_T) than it is to measure the instantaneous (H_I) as the instantaneous displacement is smaller and strain relaxation must be accounted for in determining the measurement. The instantaneous M_r is preferred from a theoretical viewpoint, because it represents the elastic response and should be more sensitive to the degree adhesion (and loss of cohesion) than is the total M_r, which is influenced by plastic strain that occurs at load application (Kelley et al., 1986). Both measurements were made in the Parametric Study. Results were analyzed to determine



Sample Calculation for pulse (A):

Specimen thickness, t = 2.5 in.

1. Load Pen Displacement = 17 mm

   Load Calibration = 10 lb/mm =>Load (P)=170 lbs.

2. Instantaneous Deflection
   Pen Displacement = 12mm

   Defl. Calibration = 9 μin/mm => H_I = 108 μin.

3. Total Deflection
   Pen Displacement = 15 mm

   Defl. Calibration = 9 μin/mm => H_T = 135 μin

Diametral Strain $\epsilon_t = 0.52\ H_T = 0.52\ (135\ \mu in) = 70.2$ microstrain

Instantaneous $M_r = 0.62\ [P/(H_I)(t)] = 0.62\ [170 lb/(135 \times 10^{-6}\ in)(2.5\ in)] = 390{,}370$ psi

Total $M_r = 0.62\ [P/(H_T)(t)] = 0.62\ [170 lb./(108 \times 10^{-6}\ in)(2.5 in)] = 312{,}296$ psi

FIGURE 2.6 – Typical Load-Deflection Response Trace

which measurement is most sensitive to material changes while yielding reliable results. Because the instantaneous M_r better characterizes the elastic response of the asphalt concrete mixture it should be used in instances where the test data is to be used for evaluation of structural performance of pavements.

Testing temperatures of 40, 73 and 100° F were selected for M_r testing for the Parametric Study. The range of temperatures was selected in order to analyze the effects of temperature on the M_r as well as to determine the testing temperature that produces repeatable results within similar material groups. Test temperatures can be controlled by performing the tests inside a control cabinet. A refrigerator with temperature control was used (Figure 2.7). Test temperatures of 55 and 73°F for derived E-modulus values from the indirect tensile strength test were studied in the development of the Lottman procedure. The 55°F test temperature was found to give a stronger indication of moisture susceptibility for E-modulus ratios (Lottman, 1982).

The advantage of the non-destructive testing is that the M_r can be calculated from test specimen response to low strain levels. This is significant because the same test specimen can be tested throughout the conditioning cycles described in the following section, reducing the number of specimens required in the moisture-susceptibility test procedures developed by Lottman. This is also significant in the fact that errors associated with testing so-called "replicated" groups is minimized.

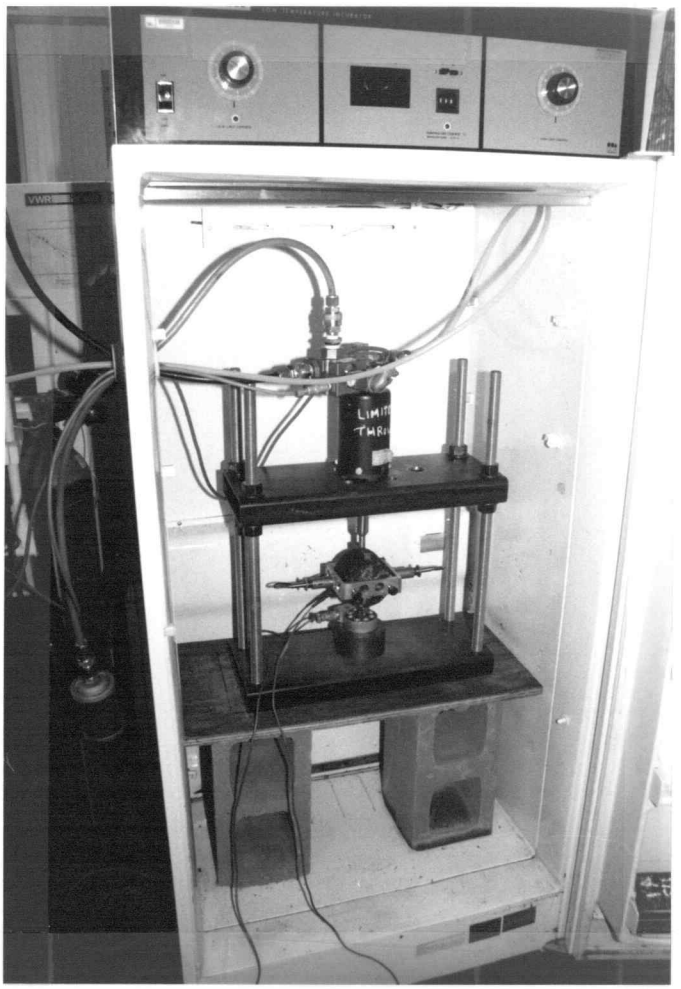


FIGURE 2.7 – Temperature Control Cabinet

2.2.2 Moisture Conditioning

The laboratory specimens used in this study were moisture conditioned following the procedure set forth in the National Cooperative Highways Research Program (NCHRP) Report Number 192 (Lottman, 1978). This procedure was used in NCHRP 192 with the indirect tensile strength test as the tool for strength loss measurement due to moisture damage. This study incorporates the moisture process and evaluates the use of the M_r as a viable tool to measure moisture induced strength loss. A recommendation for saturation level made in NCHRP 274 (Tunnicliff and Root, 1984) is also incorporated into the moisture conditioning process, and appropriate comparisons are made. Figure 2.8 shows the steps taken to moisture condition the compacted specimen used in this study.

In the Lottman procedure, a compacted specimen is first measured for response (M_r in this study) in its original dry state at the appropriate testing temperature. This measurement is recorded as $M_r$base, the reference base that all strength ratios are computed from. The strength ratio, termed the Index of Retained Resilient Modulus (IRM_r), is given by equation 2.5:

$$IRM_r = M_r \text{ conditioned}/M_r \text{ base} \quad \ldots\ldots\ldots \quad (2.5)$$

The first moisture treatment is intended to achieve a partially saturated condition. This was recommended by Tunnicliff and Root (1984) to avoid damage to the specimen that is not stripping. The procedure involves vacuum saturation in distilled water using a

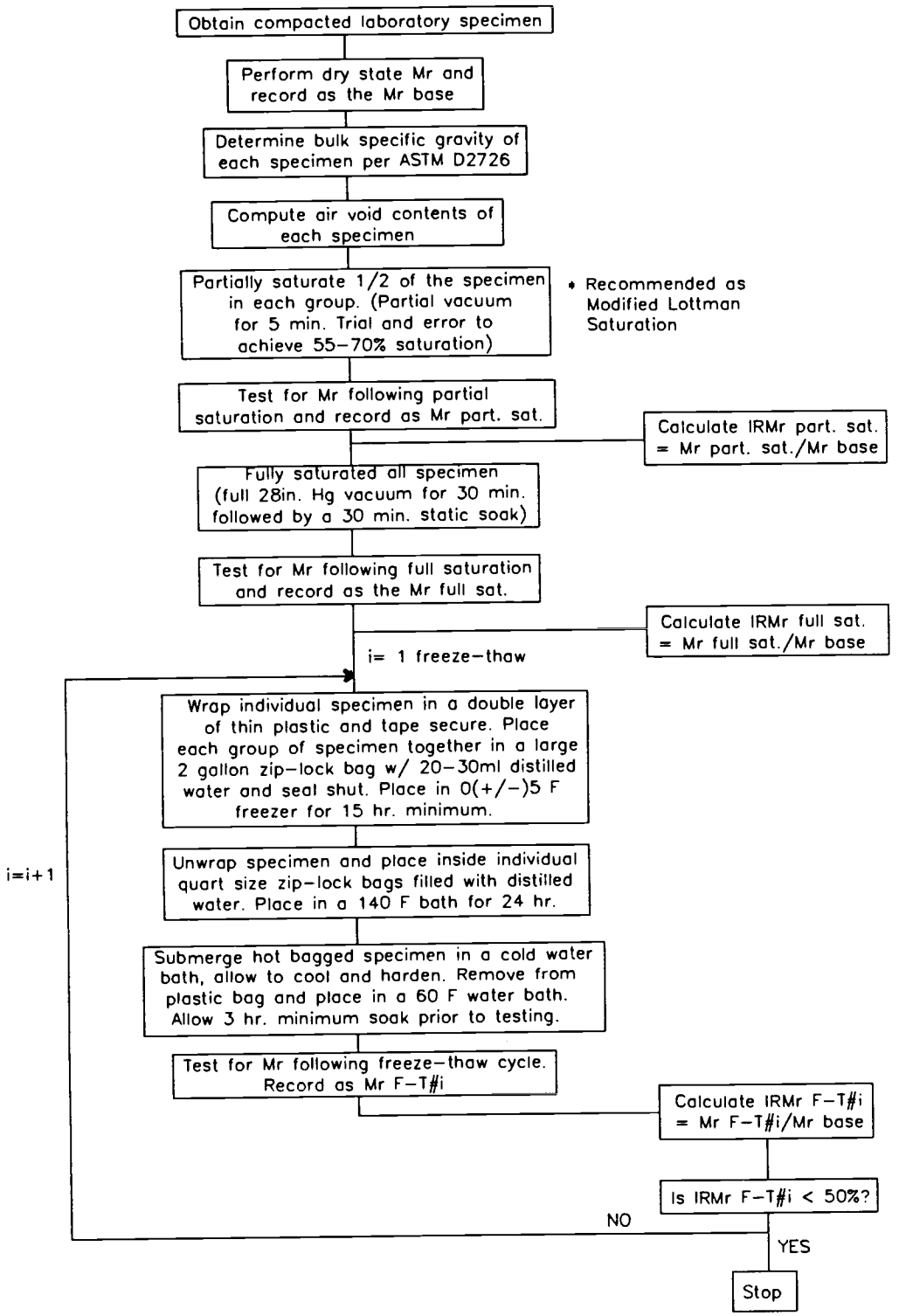
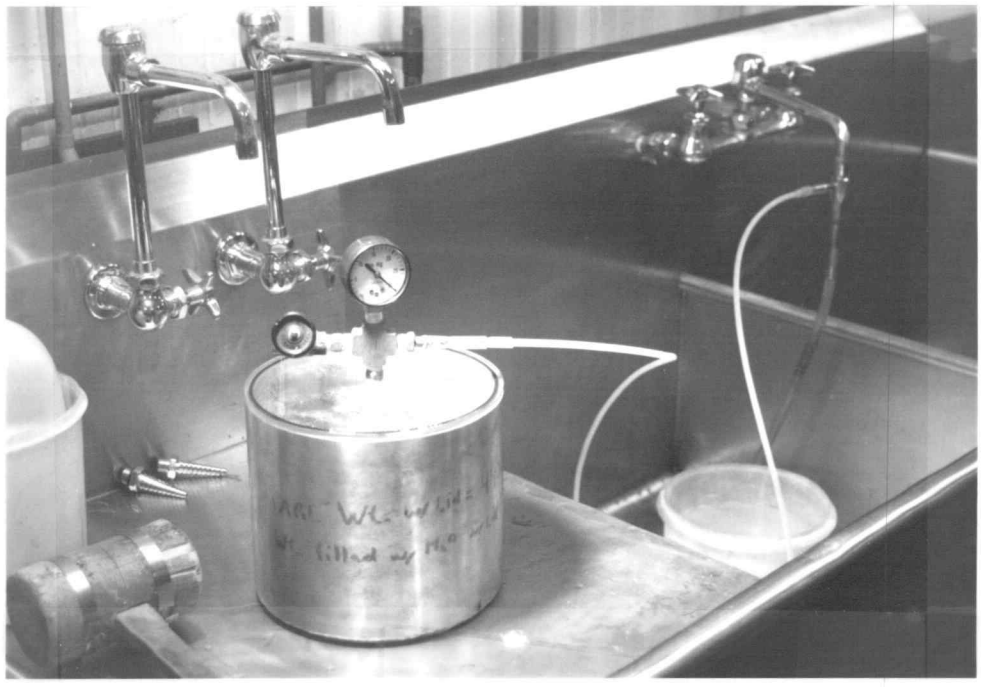


FIGURE 2.8 – Moisture Conditioning Process

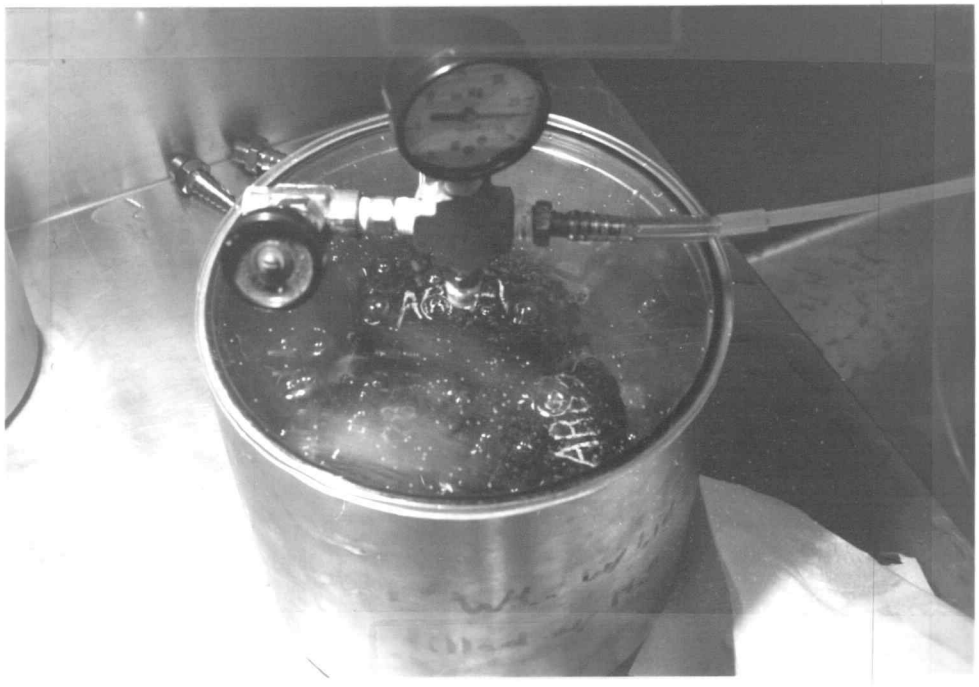
partial vacuum (15–20 in. Hg.) for 5 minutes. The saturation process used is shown in Figure 2.9. By trial and error, one can achieve the recommended degree of saturation (55–70% for air voids greater than 6.5% and 70–80% for air voids less than 6.5%). The degree of saturation is defined as the volume of water permeating the specimen as a percentage of the volume of air voids in the specimen. When the desired saturation is achieved, the specimen is sealed in plastic and placed in a constant temperature water bath (at the appropriate testing temperature) for 3 hours prior to testing for M_r. The M_r was recorded as $M_r$part.sat. and the ratio IRM_rpart.sat. was computed and labeled.

The second moisture treatment is intended to achieve full saturation, and requires the specimen to be subjected to a 26–inch vacuum in distilled water for 30 minutes, followed by a 30 minute static soak at ambient pressure (Lottman, 1978). At the conclusion, the specimen is transferred to the constant water bath for 3 hours, then tested for resilient modulus. The M_r is recorded as $M_r$full sat. and the ratio IRM_r full sat. is computed. It should be noted that specimen partially saturated were tested for M_r then fully saturated.

The following cycles are successive freeze plus thaw conditionings that are intended to induce substantial volume changes which in turn lead to displacement, detachment and other stripping mechanisms. Some consider this moisture conditioning to be too severe (Tunnicliff and Root, 1984; Dukatz, 1987). However, Lottman presents considerable evidence demonstrating a good match between the microstructure of conditioned specimens and that of field



a) Water Asperator Apparatus



b) Vacuum Pot Close-up

FIGURE 2.9 – Vacuum Saturation Apparatus

specimens (Lottman, 1978). The procedure involves wrapping a fully saturated specimen in a double layer of thin plastic and sealing closed by tape. The wrap is intended to hold the pore moisture in place and prevent drying (evaporation) of the specimen during the freeze cycle. The wrapped specimen then is placed in a plastic bag with an additional 10 milliliters of distilled water and sealed shut. This is intended to further reduce evaporation of the specimen while freezing. The specimen is then placed in a $0^{\circ} \pm 3.6^{\circ}$ F freezer for a minimum of 15 hours. Following the freeze, the specimen is transferred to a $140^{\circ} \pm 1^{\circ}$ F distilled water bath. The specimen is unwrapped after 3 minutes of immersion in the hot bath and allowed to soak for 24 hours. The specimen is then carefully transferred to the constant water bath for 3 hours prior to testing for M_r. Following M_r testing, the specimen is wrapped as before and subjected to additional freeze-thaw conditionings. The M_r obtained following each successive freeze-thaw cycle is recorded and the ratio IRM_r is computed.

Coplantz (1987) reported that vacuum saturation without freeze-thaw cycling was is not severe enough to cause a loss of cohesive strength of AC mixtures, and concluded that vacuum saturation alone does not seem to initiate a stripping mechanism.

An IRM_r of less than 70% represents a substantial strength loss that is interpreted to indicate stripping susceptibility (Hicks et al., 1985).

2.3 Materials

Preparation of the laboratory compacted test specimens occurred over a period of two years, January 1986 to January 1988. Because of this time spread, it was not possible to use the same materials for each aspect of the research. Therefore, this section is divided to correspond to the three studies: 1) Parametric, 2) Compaction and 3) Factorial.

2.3.1 Parametric Study

Aggregates. Two aggregate sources were used for the Parametic Study: Ross Island Sand and Gravel (a known non-stripper from Portland, Oregon) referred to as Aggregate A, and Tigard Sand and Gravel (a known stripper from Tigard, Oregon) referred to as Aggregate B. These aggregates were separated into 7 stockpiles and recombined to match mix design gradation recommendations supplied by the Oregon Department of Transportation (ODOT, 1984). Mix designs (gradation and optimum asphalt content) for the dense graded C-mix were determined by the Hveem Method of Mix Design at ODOT (TAI, 1984). The mix designs are shown in Table 2.2.

In addition, the following properties were measured by ODOT for each aggregate:

1. L.A. Rattler (ASTM C131)
2. Sodium Sulfate (ASTM C88)
3. Oregon Air Degradation (OSHD 208)
4. Friable Particles (ASTM C142)

These results are given in Table 2.3.

TABLE 2.2 - ODOT Mix Designs for Dense Graded C-Mix - Parametric Study

Seive Size	Percent Passing Percentages of Total Aggregate (by weight) Aggregate A	Aggregate B	ODOT Specifications
3/4"	100	100	100
1/2"	98	99	95 - 100
3/8"	81	87	
1/4"	65	66	60 - 80
#10	32	33	26 - 46
#40	12	16	9 - 25
#200	5.0	4.8	3 - 8
Optimum Asphalt Content*	6.0	6.7	4 - 8

*Percent of total mix by weight

TABLE 2.3 - Summary of Aggregate Properties - Parametric Study

Aggregate Source Properties	Aggregate A Course	Fine	Aggregate B Course	Fine
L A Rattler, %	14.0		22.8	
Sodium Sulfate, %	0.7	3.7	3.8	5.2
Degredation				
height, in.	0.5	0.6	0.8	0.7
P20, %	10.9	12.7	12.0	13.0
Friable Particles, %		0.1	0.4	0.6

Asphalt Cement. One asphalt cement was used in the Parametric Study, an AR-4000W supplied by Chevron USA, Wilbridge Refinery in Portland,Oregon. The asphalt cement was tested for its physical properties and chemical composition, and the results are summarized in Table 2.4 and Table 2.5 respectively. The asphalt, sampled at the refinery on January 20, 1986, was batched with each aggregate per the following ODOT recommendation:

1. Aggregate A mixes - 6.0% AC (% by wt. of total mix).
2. Aggregate B mixes - 6.7 % AC (% by wt. of total mix).

Antistripping Additives. One additive was used in the parametric study, a hydrated lime supplied by Ash Grove Cement West, Portland, Oregon. Typical properties of the hydrated lime are shown in Table 2.6.

2.3.2 Compaction Study

Aggregates. The aggregate sources used in the Parametric Study were also used in the Compaction Study. However, these sources were sampled at nearly 1 1/2 years later than those used in the Parametric Study. As a result, mix designs supplied by ODOT differed slightly. The updated mix design gradations and asphalt contents that were used for batching in this study are shown in Table 2.7.

The following properties were measured for each aggregate source:

1. L.A. Rattler (ASTM C131)
2. Sodium Sulfate (ASTM C88)
3. Oregon Air Degradation (OSHD 208)
4. Friable Particles (ASTM C142)

These results are given in Table 2.8

TABLE 2.4 - Physical Properties of AR-4000W - Parametric Study and Compaction Study

Original Asphalt	Actual Value	Specification (ASTM D-3387)
Absolute Vis @ 140°F, Poises (ASTM D-2171)	1465	
Kinematic Vis (ASTM D2170), Cs	268	
Penetration (ASTM D-5)	84	
Flash Point, COC, (ASTM D-92), °F	580	
Solubility (ASTM D-2042), %	99.8	99% min.
Residue from RTFC		
Absolute Vis @ 140°F, Poises	3497	4000 ± 1000
Kinematic Vis @ 275°F, Cs	406	275 min.
Penetration @ 77°F, dmm	48	25 min.
Percent of original penetration	57.1	45 min.
Ductility at 145°F (ASTM D-113)	13.8	

TABLE 2.5 - Chemical Composition of AR-4000W - Parametric Study and Compaction Study

(a) Rostler Analysis (ASTM D-2006)

Composition	Percent
Asphaltenes	20.4
Polar Compounds (nitrogen bases)	33.1
First acidaffins	16.7
Second acidaffins	19.6
Paraffins (saturates)	10.2 (waxy)

(b) Clay - Gel (ASTM D-2007)

Asphaltenes	14.95
Polar Aromatics	44.37
Napthene Aromatics	30.55
Saturates	9.65
Total Analysis	99.52

TABLE 2.6 - Properties of Ash Grove "Kemilime" Hydrated Lime*

Available Calcium Hydroxide	$Cal(OH)_2$		96.50%
Equivalent to Calcium Oxide	CaO		73.10%
Magnesium Hydroxide	$Mg(OH)_2$		00.31%
Calcium Sulphate	$CaSO_4$		00.04%
Calcium Carbonate	$CaCO_3$		01.04%
Silicon Dioxide	SiO_2		00.40%
Ferric Oxide	Fe_2O_3		00.07%
Aluminum Oxide	Al_2O_3		00.27%
Sulphur Trioxide	SO_3		00.12%
Carbon Dioxide	CO_2		00.95%
Mechanical Moisture	H_2O		00.60%
Chemically Combined Water	H_2O		23.53%
Arsenic	As	Less than	2 p.p.m.
Fluorine	F	Less than	250 p.p.m.
Lead	Pb	Less than	5 p.p.m.

Specific Gravity	2.3 to 2.4
Specific Heat	0.30
Solubility	0.07(100°C)
Settling Rate	2.67 mm per minute
Bulk Density	28-30 lbs./cu.ft.
Basicity Factor	0.736
Fineness:	
Passing 400 mesh screen	99.6%
Passing 200 mesh screen	99.8%

*Results supplied by Ash Grove Cement West, Inc.

TABLE 2.7 - ODOT Mix Designs for Dense Graded C-mix - Compaction and Factorical Studies

Sieve Size	Percent Passing Percentages of Total Aggregate (by weight) Aggregate A	Aggregate B	ODOT Specifications
3/4"	100	100	100
1/2"	99	99	95 - 100
3/8"	83	87	
1/4"	66	66	60 - 80
#10	33	33	26 - 46
#40	14	16	9 - 25
#200	5.0	4.8	3 - 8
Optimum Asphalt Content*	5.9	6.6	4 - 8

*Percent of total mix by weight

TABLE 2.8 - Summary of Aggregate Properties - Compaction and Factorial Studies

Aggregate Source	Aggregate A		Aggregate B	
Properties	Course	Fine	Course	Fine
L A Rattler, %	22.0		18.6	
Sodium Sulfate, %	1.0	2.7	9.4	3.6
Degredation				
height, in.	0.5	0.6	1.2	0.8
P20, %	13.6	13.0	26.6	16.1
Friable Particles, %	0.2	0.0	0.3	0.1

Asphalt Cement. The same AR-4000W asphalt cement used for the Parametric Study was also used for the Compaction Study (see Section 2.3.1 and Tables 2.5 and 2.6). However, recommended asphalt content supplied by ODOT for each aggregate was updated as follows:

1. Aggregate A mixes - 5.9% AC (% by wt. of total mix).
2. Aggregate B mixes - 6.6 % AC (% by wt. of total mix).

These slight changes in asphalt content are best explained by the small changes in gradation of each aggregate due to the difference in time of sampling and performing mix designs.

Antistripping Additives. Antistripping additives were not used for this study. The Compaction Study is intended to examine the effects of different compaction methods on the resilient modulus. Stripping and the effectiveness of antistripping additives were not concerns in this phase of the laboratory study.

Specimen Preparation. Specimen preparation for 4 compaction methods evaluated are discussed in detail in Chapter 4. All specimens were prepared to approximately 8% air voids, so the effects of differing resilient modulus values should only be attributed to the differing methods of compaction, not changes in the materials.

2.3.3 Factorial Study

Aggregates. The same two aggregates that were used in the Compaction study were also used in the Factorial Study. These aggregates were batched to the same proportions used in the Compaction Study (Table 2.7).

Asphalt Cement. Two asphalt cements were used in batching the test specimen for this study. An AR-4000W from Chevron USA, Wilbridge Refinery in Portland, Oregon was drawn on October 30, 1987. The asphalt cement was tested for both its physical and chemical properties and the results are summarized in Tables 2.9 and 2.10 respectively. An AC-20R rubberized asphalt from Asphalt Services and Supplies in Vancouver, Washington was used as the second asphalt. The AC-20R is a latex modified AR-4000 grade asphalt cement. Properties of the AC-20R are summarized in Table 2.11. Both asphalts were batched with each aggregate per recommendations supplied by ODOT:

1. Aggregate A mixes - 5.9% AC (% by wt. of total sample)
2. Aggregate B mixes - 6.6% AC (% by wt. of total sample)

Antistripping Additives. Two antistripping additives were used with the Tigard aggregate as a treatment with the AR-4000W asphalt cement. The hydrated lime used in the Parametric Study was also used in the Factorial Study. Typical properties of the hydrated lime were given in Table 2.6. The lime was added to the aggregate in a slurry at a rate of 1.0 percent lime by dry weight of aggregate, and the slurry composition was 35% lime in 65% water. The slurried aggregate was allowed to cure in a moist state at room temperature for 24 hours, then dried and heated at mixing temperature to a dry constant weight prior to mixing and compacting. This type of treatment is a pretreatment of the aggregate. The theory involves the replacement of the aggregate surface ions with calcium cations which seeks to promote a stronger bond between the asphalt and aggregate (Schmidt and Graf, 1972). It is believed that the lime produces a sharp decrease in the

TABLE 2.9 - Physical Properties of AR-4000W - Factorial Study

Original Asphalt	Actual Value	Specification (ASTM D-3387)
Absolute Vis @ 140°F, Poises (ASTM D-2171)	1215	
Kinematic Vis (ASTM D2170), Cs		
Penetration (ASTM D-5)	92	
Flash Point, COC, (ASTM D-92), °F	545	
Solubility (ASTM D-2042), %	99.7	99% min.
Residue from RTFC		
Absolute Vis @ 140°F, Poises	3309	4000 ± 1000
Kinematic Vis @ 275°F, Cs		275 min.
Penetration @ 77°F, dmm	49	25 min.
Percent of original penetration	53	45 min.
Ductility at 145°F (ASTM D-113)	13.5	

TABLE 2.10 - Chemical Composition of AR-4000W - Factorial Study

(a) Rostler Analysis (ASTM D-2006)

Composition	Percent
Asphaltenes	20.5
Polar Compounds (nitrogen bases)	25.5
First acidaffins	21.0
Second acidaffins	22.7
Paraffins (saturates)	10.3

(b) Clay - Gel (ASTM D-2007)

Asphaltenes	19.7
Polar Aromatics	28.4
Napthene Aromatics	40.4
Saturates	11.5
Total Analysis	100.0

TABLE 2.11 - Properties of AC-20R - Factorial Study

Specification Property	ASTM No	Result	Min.	Max.
Viscosity @ 140°F., Poises	D2171	1783	1600	2400
Viscosity @ 275°F., CSt	D2170	660	325	
Ductility @ 39.2°F., (5cm/min)cm	D113	85.5	50	
Rolling thin film circulating				
Oven test	D2872*			
Tests on residue:				
Viscosity @ 140°F., Poise	D2171	5864		8000
Ductility @ 39.2°F., (5cm/min)cm	D113	25.5	25	

*TFOT ASTM D 1754 may be used. Rolling Thin Film Circulating oven shall be the preferred method.

interfacial tension between the asphalt cement and water, thus resulting in stronger adhesive forces.

Also used as an additive was PaveBond Special. The PaveBond Special was added to the asphalt as 0.5% by weight of the total asphalt content. The PaveBond-treated asphalt was then added to the heated aggregate at the proportions given above. The PaveBond Special additive is a surface active agent (surfactant). This agent is supplied in liquid form containing amines, which are strongly basic compounds derived from amonia (Majizadeh and Brovold, 1968). The theory of surfactants as an asphalt treatment involves the reduction of the surface tension of the asphalt and make it better able to "wet" the aggregate (Tunnicliff and Root, 1984).

3 PARAMETRIC STUDY

This chapter presents results of a laboratory study along with a statistical summary in order to aid in the selection of Repeated-Load Diametral Test parameters to be used as the standard test conditions in the subsequent studies. The purpose of this study is to determine test conditions that yield M_r values with the highest degree of sensitivity to material changes while minimizing testing error. By meeting this objective, one can be relatively confident that the procedure will also be sensitive to the degree of M_r loss associated with moisture damage. The results obtained in this study will be adapted as the standard test parameters to be used in the proposed test procedure.

3.1 Experimental Design

In order to evaluate the objective of this phase of the research, several variables were used in the Parametric Study. These test variables can be divided into two general groups: 1) material variables and 2) procedural variables. These groups of variables are summarized in Table 3.1 and are described in more detail below.

The experimental design used to analyze the test results was a completely randomized design (CRD) and a two-way analysis of variance (ANOVA) was selected as the statistical tool to aid in the evaluation of the results (Devore and Peck, 1986a). For this design the procedural variables or settings were assigned as Factor A, and the material variables, or simply materials, were assigned as Factor B.

TABLE 3.1 - Procedural and Material Variables

a) Procedural Variables (Settings)

Load Duration (s.)	Load Frequency (hz)	Microstrain Level ($x10^{-6}$ in/in)	Temperature (°F)
0.1	0.33	50	40
0.2	0.50	75	73
0.4	1.00	100	100

b) Material Variables (Materials)

Aggregate Type	Asphalt	Additive	Air Voids, %
Ross Island - A	AR-4000W	None	4
Tigard - B		1% lime	10

Therefore 13 levels of Factor A, 4 levels of Factor B and 52 total treatments (AxB interactions) could be evaluated.

An assumption of ANOVA is that experimental errors are random, independent and normally distributed about zero mean with common variance (Devore and Peck, 1986a). The F-ratio, a statistic computed from the ANOVA error terms, is the ratio of two independent estimates of the same variance. Where the F-ratio is used, a null hypothesis of equal factor means is assumed. In general terms, the ratio represents a comparison between a biased estimated variance (mean square for factors, MSA, MSB, or MSAB) of the experiment and an unbiased estimate of variance (mean square for error, MSE) of the experiment. The hypothesis of equal means is rejected in favor of unequal means if the computed F-ratio is larger than critical F-ratios for any combination of degrees of freedom and significance levels associated with a given experiment. Critical F-ratios are tabularized in most statistics text books.

Because the total and instantaneous M_r were measured, two ANOVA tables were generated similar to the one shown in Table 3.2. A comparison of precision between the two measurements can be made using the coefficient of variation, CV (Peterson, 1985a). The CV is defined by equation 3.1:

$$CV=[(MSE)^{1/2}/x)*100\% \qquad \text{.....(3.1)}$$

3.1.1. Material Variables

The specimens tested in this study were laboratory Marshall-compacted AC specimen (ASTM, 1987b) composed of materials stated in

TABLE 3.2 - Experimental Design ANOVA

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Settings (Factor A)	k-1	SSA	MSA	F_A
Materials (Factor B)	l-1	SSB	MSB	F_B
Treatments (A x B)	(k-1)(l-1)	SSAB	MSAB	F_{AB}
Error	kl(m-1)	SSE	MSE	
Total	klm-1	SSTot		

Variable definitions:

k = No. of levels of settings = 13
l = No. of levels of materials = 4
kl = No. of treatments (each one a combination of settings level and materials level) = 52
m = No. of observations on each treatment = 3 replicates

Calculations:

CT = Correction term = $klmx^2_{..}$ where $x_{..}$ = Grand mean of all observations

$SSA = ml\Sigma A^2_k - CT$

$SSB = mk\Sigma B^2_l - CT$

$SSAB = m\Sigma\Sigma AB^2_{kl} - SSA - SSB - CT$

$SSTot = \Sigma\Sigma\Sigma x^2_{klm} - CT$

$SSE = SSTot - SSA - SSB - SSAB$

Mean squares are determined by dividing the sum of squares by their associated degrees of freedom.

F-ratios are determined by dividing the mean squares by the mean square for error.

Section 2.3.1. Each specimen was wrapped in plastic and stored at room temperature for 1 1/2 years. These specimens were used as controls in work done in the Phase I portion of this study (Kelly et al., 1986).

The variables of the test specimen were air void content and aggregate type. The air void contents were determined by the standard procedure given in ASTM D3203 (1987c), "Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures", and reported as a percent of total specimen volume. Bulk specific gravities were determined using ASTM D2726 (1987d), "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens". Two air void contents, 4 and 10%, were used in this study. The purpose of using varying air void contents for the test program was to detect if the test procedure will be sensitive enough to differentiate between M_r values of varying voids. The expected trend is a decrease in M_r with an increase in air voids (Hicks et al., 1985; Dukatz, 1987).

3.1.2 Procedural Variables

The Repeated-Load Diametral Test System was described and illustrated in Section 2.1. As noted in that section, the test operator can control a fairly wide range of values for the load duration, frequency and amplitude, along with the testing temperature. Each test specimen, therefore, was subjected to a series of tests over a range of controlled variables, as shown in Table 3.3. The range was selected in order to investigate the full range of variables specified by ASTM (1987a). The table shows that 13 test combinations out of a

Table 3.3 – Test Conditions for Parametric Study

Duration, s.	Frequency, hz.	Temperature, °F / Microstrain	40			73			100		
			50	75	100	50	75	100	50	75	100
0.1	0.33						X				
	0.5		X	X	X	X	X	X	X	X	X
	1.0						X				
0.2	0.33										
	0.5						X				
	1.0										
0.4	0.33										
	0.5						X				
	1.0										

81 total test combinations were selected for the evaluation. The selection of the 13 test conditions was made with the assumption that trends of M_r with respect to duration, frequency and strain level are the same for any given material at any temperature. Therefore the effects of duration, frequency and strain level were only observed at 73°F, and the most typical combination which includes 0.1 second load duration, 0.5 hertz load frequency was observed at all temperatures, and the effects of strain level were observed. If this assumption is correct, the F-ratio for the AxB interaction should not be significant.

3.2 Specimen Preparation

Specimens from each aggregate source were batched and compacted to 4 and 10% air voids with pre-determined variable blows using the Marshall Compaction Method. Triplicates were used for testing at each air void content for both aggregate sources. Specimen constituents were given in Table 2.2. The specimens were labeled for identification by aggregate type as follows:

1. A - Aggregate A, and
2. B - Aggregate B.

Further, the B specimens batched and compacted to 4% air voids contain 1% lime (sample group BL-4). There is not a significance of the lime additive in this phase of the study as it pertains to the effectiveness to prevent stripping. A summary of bulk specific gravities and actual air void contents of the compacted specimens are shown in Table 3.4.

TABLE 3.4 - Summary of Specific Gravities and Air Void Contents - Parametric Study

Aggregate A - Ross Island Sand and Gravel

Specimen ID	Bulk Specific Gravity ASTM D-2726	Maximum Specific Gravity ASTM D-2041	Air Voids,% ASTM D-3203
A4 - 1	2.411		2.74
A4 - 3	2.417	2.479	2.50
A4 - 7	2.406		2.95
			Avg. = 2.73
A10 - 1	2.214		10.73
A10 - 4	2.222	2.480	10.40
A10 - 6	2.227		10.20
			Avg. = 10.44

Aggregate B - Tigard Sand and Gravel

Specimen ID	Bulk Specific Gravity ASTM D-2726	Maximum Specific Gravity ASTM D-2041	Air Voids,% ASTM D-3203
BL4 - 2	2.301		5.35
BL4 - 6	2.327	2.431	4.28
BL4 - 7	2.333		4.03
			Avg. = 4.55
B10 - 5*	2.224		9.63
B10 - 6*	2.227	2.461	9.51
B10 - 7*	2.228		9.47
			Avg. = 9.54

* Not lime treated.

3.3 Test Results

M_r tests were performed on each test specimen (4 groups x 3 replicates/group = 12 total specimens) using the Repeated Load Test System. The specimens were tested at each of the 13 test conditions identified in Table 3.3, and corresponding total and instantaneous M_r values were recorded. The values were averaged for the three replicated specimens in each group (ie. A4, A10, BL4, and B10) and the results are presented in Tables 3.5 - 3.16. The right side of these tables show summary statistics for the three replicated specimens tested at each combination of procedural variable conditions.

By general observation of these tables, it appears that the total M_r measurement may be more accurate than the instantaneous measurement based on the relative ranking of the cv columns. This was expected in that the interpretation of the instantaneous measurement deflection is more judgemental than the total measurement of deflection, as illustrated in section 2.2.1, leaving more chance for error when obtaining instantaneous M_r results.

As previously stated, M_r values are expected to vary with varying air void contents. One might also expect to observe M_r differences in aggregate type (ie. surface texture, percent fracture, etc.) for a given level of air voids, asphalt type and content (Akhter and Witczak, 1985).

It should be noted that tests performed at 100°F were only marginally successful for the 4% air void samples and could not be performed for the 10% air void samples. This temperature was found to be too warm, and all samples exhibited flow (excessive permanent

TABLE 3.5 – Effects of Temperature on M_r Group A4 at 50, 75 and 100 μstrain. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
40	0.1	0.5	49.86	2.13	4.27	2085.31	51.22	2.46	1801.10	85.13	4.73
40	0.1	0.5	73.79	0.67	0.91	2082.59	32.12	1.54	1801.30	76.45	4.24
40	0.1	0.5	96.07	1.49	1.55	2121.07	117.69	5.55	1840.05	91.79	4.99
73	0.1	0.5	48.15	3.47	7.21	1282.71	85.52	6.67	409.82	50.26	12.26
73	0.1	0.5	74.01	1.83	2.47	947.81	104.96	11.07	396.31	6.98	1.76
73	0.1	0.5	98.61	3.07	3.11	934.52	64.12	6.86	409.28	9.61	2.35
100	0.1	0.5	52.70	0.47	0.89	113.15	55.25	48.83	97.32	41.97	43.13
100	0.1	0.5	77.96	1.29	1.65	138.69	17.12	12.34	95.18	8.60	9.04
100	0.1	0.5	103.01	4.61	4.48	191.77	23.79	12.41	92.44	6.34	6.86

TABLE 3.6 – Effects of Load Duration on M_r Group A4 at 75 μstrain, 0.5 hz., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.5	74.01	1.83	2.47	947.81	104.96	11.07	396.31	6.98	1.76
73	0.2	0.5	73.94	1.23	1.66	784.92	34.52	4.40	255.64	6.29	2.46
73	0.4	0.5	74.83	2.88	3.85	581.97	27.46	4.72	182.95	27.63	15.10

TABLE 3.7 – Effects of Load Frequency on M_r Group A4 at 75 μstrain, 0.1 sec., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.3	71.55	6.15	8.60	1109.30	266.88	24.06	397.96	95.64	24.03
73	0.1	0.5	74.01	1.83	2.47	947.81	104.96	11.07	396.31	6.98	1.76
73	0.1	1.0	78.04	2.91	3.73	866.35	75.11	8.67	392.17	23.33	5.95

TABLE 3.8 – Effects of Temperature on M_r Group A10 at 50, 75 and 100 μstrain. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
40	0.1	0.5	50.01	2.88	5.76	1336.42	336.00	25.14	1063.44	197.80	18.60
40	0.1	0.5	73.94	3.85	5.21	1222.51	33.75	2.76	1032.75	37.05	3.59
40	0.1	0.5	94.66	4.20	4.44	1283.65	11.87	0.92	1016.81	22.79	2.24
73	0.1	0.5	51.58	2.46	4.77	502.94	67.25	13.37	187.36	13.73	7.33
73	0.1	0.5	76.25	0.39	0.51	671.63	90.93	13.54	192.31	21.42	11.14
73	0.1	0.5	103.68	7.08	6.83	738.12	134.70	18.25	210.64	19.46	9.24
100	0.1	0.5	*			*			*		
100	0.1	0.5	*			*			*		
100	0.1	0.5	*			*			*		

* Test performed on these samples at 100 F exhibited excessive plastic flow with only a ten pound static load.

TABLE 3.9 – Effects of Load Duration on M_r Group A10 at 75 μstrain, 0.5 hz., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.5	76.25	0.39	0.51	671.63	90.93	13.54	192.31	21.42	11.14
73	0.2	0.5	74.01	2.54	3.43	280.72	72.31	25.76	108.06	17.78	16.45
73	0.4	0.5	73.94	6.61	8.94	198.61	12.96	6.53	74.47	10.94	14.69

TABLE 3.10 – Effects of Load Frequency on M_r Group A10 at 75 μstrain, 0.1 sec., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.3	74.01	2.91	3.93	576.09	90.57	15.72	175.44	20.06	11.43
73	0.1	0.5	76.25	0.39	0.51	671.63	90.93	13.54	192.31	21.42	11.14
73	0.1	1.0	76.55	2.80	3.66	819.90	211.58	25.81	231.08	15.85	6.86

TABLE 3.11 – Effects of Temperature on M_r Group BL4 at 50, 75 and 100 μstrain. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
40	0.1	0.5	50.38	2.24	4.45	1742.54	51.71	2.97	1641.68	89.34	5.44
40	0.1	0.5	74.16	1.27	1.71	1758.93	143.47	8.16	1610.34	128.94	8.01
40	0.1	0.5	97.79	3.64	3.72	1571.43	199.24	12.68	1405.73	202.91	14.43
73	0.1	0.5	51.43	1.77	3.44	1125.13	221.50	19.69	432.54	23.05	5.33
73	0.1	0.5	74.31	2.51	3.38	1032.72	90.10	8.72	428.53	13.12	3.06
73	0.1	0.5	99.73	3.29	3.30	928.24	231.48	24.94	408.87	23.76	5.81
100	0.1	0.5	50.68	5.74	11.33	176.58	21.40	12.12	143.21	12.77	8.92
100	0.1	0.5	76.55	1.27	1.66	211.03	13.30	6.30	121.24	1.76	1.45
100	0.1	0.5	105.32	0.81	0.77	299.65	20.55	6.86	114.94	4.51	3.92

TABLE 3.12 – Effects of Load Duration on M_r Group BL4 at 75 μstrain, 0.5 hz., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.5	74.31	2.51	3.38	1032.72	90.10	8.72	428.53	13.12	3.06
73	0.2	0.5	75.20	3.42	4.55	713.93	86.60	12.13	283.39	30.96	10.92
73	0.4	0.5	72.37	1.74	2.40	725.82	57.20	7.88	268.06	11.69	4.36

TABLE 3.13 – Effects of Load Frequency on M_r Group BL4 at 75 μstrain, 0.1 sec., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.3	72.30	3.57	4.94	867.00	145.51	16.78	503.99	92.75	18.40
73	0.1	0.5	74.31	2.51	3.38	1032.72	90.10	8.72	428.53	13.12	3.06
73	0.1	1.0	73.71	4.81	6.53	920.71	122.98	13.36	435.81	11.43	2.62

TABLE 3.14 – Effects of Temperature on M_r Group B10 at 50, 75 and 100 μstrain. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
40	0.1	0.5	51.65	1.47	2.85	1327.37	161.78	12.19	1224.09	161.59	13.20
40	0.1	0.5	74.38	1.81	2.43	1435.25	166.79	11.62	1259.06	105.26	8.36
40	0.1	0.5	99.13	3.77	3.80	1361.68	125.46	9.21	1211.08	131.62	10.87
73	0.1	0.5	53.29	0.93	1.75	745.88	88.17	11.82	300.47	88.44	29.43
73	0.1	0.5	75.87	2.02	2.66	667.96	155.90	23.34	307.53	74.77	24.31
73	0.1	0.5	100.10	3.05	3.05	699.25	32.62	4.66	310.30	38.14	12.29
100	0.1	0.5	*			*			*		
100	0.1	0.5	*			*			*		
100	0.1	0.5	*			*			*		

* Tests performed on these samples at 100 F exhibited excessive plastic flow with only a ten pound static load.

TABLE 3.15 – Effects of Load Duration on M_r Group B10 at 75 μstrain, 0.5 hz., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.5	75.87	2.02	2.66	667.96	155.90	23.34	307.53	74.77	24.31
73	0.2	0.5	73.86	2.85	3.86	624.27	7.78	1.25	214.22	28.41	13.26
73	0.4	0.5	75.13	4.26	5.67	489.73	51.86	10.59	172.96	4.52	2.61

TABLE 3.16 – Effects of Load Frequency on M_r Group B10 at 75 μstrain, 0.1 sec., and 73°F. (n=3)

Temp. F	Load Duration sec.	Load Frequency hz.	Total Strain Ave.	Total Strain Stnd Dev.	Total Strain C.V.	Instantaneous Mr (ksi) Ave.	Instantaneous Mr (ksi) Stnd Dev.	Instantaneous Mr (ksi) C.V.	Total Mr (ksi) Ave.	Total Mr (ksi) Stnd Dev.	Total Mr (ksi) C.V.
73	0.1	0.3	72.89	2.68	3.68	758.68	62.68	8.26	352.80	27.15	7.70
73	0.1	0.5	75.87	2.02	2.66	667.96	155.90	23.34	307.53	74.77	24.31
73	0.1	1.0	75.80	0.81	1.07	771.97	38.28	4.96	344.09	28.22	8.20

deformation) with only a 10 pound static seating load. Therefore, the 100°F test temperature was removed from consideration as a practical temperature, and the ANOVA table presented in Table 3.2 was adjusted accordingly.

3.4 Analysis of Results

The specific objectives of the testing and analysis of the results are:

1. Determine which measurement, total or instantaneous M_r, is most sensitive to material changes (material variables) while minimizing overall testing error.
2. Determine which combination of test conditions (procedural variables) will result in the strongest differentiation in test results among material changes.
3. Explore the need for additional testing.

The overall goal, as stated previously, is to select one test temperature, load duration and frequency, and one microstrain level to meet the standards presented in the above objectives.

Two ANOVA tables were generated at the conclusion of the M_r testing. Table 3.17 contains a summary of the analysis for the instantaneous measurement. Similarly, Table 3.18 represents the total measurement. These tables show a highly significant interaction (shown as a significant F_{AB}), suggesting that Factors A and B do not act independently of each other. Therefore, the results can be summarized in a two-way table of AB means as shown in Tables 3.19 and 3.20 for the instantaneous and total measurements respectively.

TABLE 3.17 – Summary of Analysis of Variance – Instantaneous M_r

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Settings (Factor A)	9	19,808,201	2,200,911	135.7
Materials (Factor B)	3	4,956,958	1,652,319	101.9
Treatments (A x B)	27	1,738,808	64,400	3.97**
Error	80	1,297,769	16,222	
Total	119	27,801,736		

** significant at the $\alpha = 0.01$ level

Grand mean, x.. = 1017.4 ksi

CV = $[(16{,}222)^{1/2}/1017.4] * 100\% = 12.5\%$

TABLE 3.18 – Summary of Analysis of Variance – Total M_r

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Settings (Factor A)	9	31,487,797	3,498,644	611.8
Materials (Factor B)	3	2,454,355	818,118	143.1
Treatments (A x B)	27	1,404,254	52,009	9.1**
Error	80	457,486	5,719	
Total	119	35,803,892		

** significant at the $\alpha = 0.01$ level

Grand mean, $x.. = 632.3$ ksi

$CV = [(5,719)^{1/2}/632.3] * 100\% = 11.9\%$

TABLE 3.19 – Mean Instantaneous M_r of Four Types of Materials Under Different Levels of Settings

Instantaneous Resilient Modulus, ksi (n=3)

	SETTINGS*									
	1	2	3	4	5	6	7	8	9	10
Temp.	40°F			73°F						
Freq.(hz)	0.5			0.5	0.33	0.5			1.0	0.5
duration (sec.)	0.1			0.1	0.1	0.1	0.2	0.4	0.1	0.1
microstrain	50	75	100	50	75					100
MATERIALS**										
A4	2085	2083	2121	1283	1109	948	785	582	866	935
BL4	1743	1759	1571	1125	867	1033	714	726	921	928
A10	1336	1223	1284	503	576	672	281	199	820	738
B10	1327	1435	1362	746	759	668	624	490	772	699
mean	1623	1625	1585	914	828	830	601	499	845	825

* Settings are combinations of temperature, load frequency and duration, and microstrain level.

** Materials are combinations of aggregate type, air void content and additive type

TABLE 3.20 – Mean Total M_r of Four Types of Materials Under Different Levels of Settings

Total Resilient Modulus, ksi (n=3)

	SETTINGS*									
	1	2	3	4	5	6	7	8	9	10
Temp.	40 F			73 F						
Freq.(hz)	0.5			0.5	0.33	0.5			1.0	0.5
duration (sec.)	0.1			0.1	0.1	0.1	0.2	0.4	0.1	0.1
microstrain	50	75	100	50	75					100
MATERIALS**										
A4	1801	1801	1840	410	398	396	256	183	392	409
BL4	1642	1610	1406	433	504	429	283	268	436	409
A10	1063	1033	1017	187	175	192	108	74	231	211
B10	1224	1259	1211	300	353	308	214	173	344	310
mean	1433	1426	1369	333	358	331	215	175	351	335

* Settings are combinations of temperature, load frequency and duration, and microstrain level.

** Materials are combinations of aggregate type, air void content and additive type

At the onset of the experiment, both measurements were expected to detect significant differences between material groups at any setting. Differences between material groups at any level of setting combinations can be made using the t-test statistic. The t-test tests the hypothesis that means are equal against the alternative that the means are different (Devore and Peck, 1986b). The t-statistic is computed as follows:

$$t = (x_{ij} - x_{i'j'})/(2MSE/m)^{1/2} \quad \text{.....(5.2)}$$

where x_{ij} = mean M_r at the ith level of material and the jth level of settings.
$x_{i'j'}$ = mean M_r at the ith' level of material and the jth' level of settings. $x_{ij} = x_{i'j'}$.
$(2MSE/m)^{1/2}$ = standard error for differences between AB means.
MSE = mean square for error of the appropriate experiment.
m = number of replications at each AB level

The computed t-statistic is compared to a tabularized critical t-value at the appropriate level of significance and associated degrees of freedom. These critical t-values can be found in most statistics text books. Differences of material means at each level of setting combinations were compared in Tables 3.19 and 3.20, and the means that were not significantly different were marked as shown. These comparisons were made at the 0.05 α-level. The tables illustrate that differences between material groups are most apparent at the 40°F test temperature. It is also apparent from these tables that the total M_r measurement differentiates between material changes more than the instantaneous M_r measurement at the lower temperature. Also, the computed CV of the total M_r experiment was 11.9% as compared to the

12.5% CV computed from the instantaneous experiment, suggesting that the total measurement is relatively more precise.

The full range of frequency, duration and microstrain levels were only observed at the 73°F testing temperature. Because the ANOVA presented in Table 3.18 showed that materials and settings did not act independently on the total M_r, conclusions on settings at 40°F are limited to the settings investigated at this temperature.

The conclusions based on the analysis of variance strongly suggest 40°F as the preferred testing temperature. The conclusion is supported by the fact that at this temperature, the test procedure yields M_r values that differ significantly between material changes. The test procedure does not give a strong differentiation of M_r results at 73°F.

The 40°F test procedure requires special conditions, namely a cold environment to work in. The closer the test temperature is to ambient temperature, the more practical the test will be. If the test temperature is significantly different than ambient, heat loss or gain becomes a problem and an individual test will take an unrealistic amount of time. Therefore, a temperature between 40° and 73°F needed to be explored as a practical alternative.

This was done with samples compacted to 4% and 8% air voids for each aggregate type. Four replicates were compacted and tested for total M_r at temperatures of 40, 50, 60, and 73°F. A summary of the results is shown in the ANOVA Table 3.21. The analysis was done by partitioning the temperatures as blocks in a randomized block design

Table 3.21 - Supplemental Temperature Study - Total M_r

Total Resilient Modulus, ksi

Treatments	Blocks of Temperature 1 40 F	2 50 F	3 60 F	4 73 F
A4	2595.1	1881.5	1270.5	495.5
B4	2717.3	2213.2	1685.6	771.0
A8	1768.1	1188.9	724.8	208.3
B8	1831.2	1420.6	959.9	321.5
block mean=	2228	1676	1160	449
SS(Tr)j=	743135	633310	517904	180039
MS(Tr)j=	247712	211103	172635	60013
F(Tr)j=	13.53	11.53	9.43	3.28

ANALYSIS OF VARIANCE TABLE

Source of variation	degrees of freedom	sum of squares	mean square	F-ratio
Treatments	3	1909595	636532	34.76**
Blocks	3	6886178	2295393	125.36**
Error	9	164793	18310	
Total	15			

** significant at the 0.01 level

(RBD) and selecting the 4 material groups as treatments (Peterson, 1985b). This table shows that there exists highly significant differences between treatment means, and blocking was successful in removing one source of variation from the experimental error (shown as significant F-ratios).

The primary concern in this supplemental temperature study was to determine if some intermediate temperature between 40 and 73°F would lead to M_r values which strongly differentiate between treatment means. This was done by computing the individual contribution of variability amoung blocks (MST_{b1}) to the overall variability of the experiment (MSE), shown as a partial F-ratio in Row (1) of Table 3.21. This analysis suggests choosing the largest F-ratio amoung blocks, which implies the largest contribution to the overall experimental variability, or in other words, the block (temperature) which results in M_r values most different with respect to material groups.

The 40°F temperature again leads to the most discriminate M_r values, shown as a high F-ratio in Table 3.21, Row(1). However, by elevating the test temperature to 50 and 60°F, the results still appear to highly discriminate between material groups, but at 73°F, this generalization does not seem warranted. The relationship between 40 and 73° with respect to material sensitivity are consistent with those found earlier.

3.5 Conclusions and Recommendations

From this study, the following conclusions can be made:

1. M_r results obtained showed a high degree of material sensitivity at 40°F and a low degree of sensitivity at 73°F.
2. The total measurement led to results with a higher degree of material sensitivity than did the instantaneous measurement. The total measurement is also comparitively more precise than the instantaneous measurement.
3. There is no significant change in the ability of the test procedure to differentiate between material changes when testing total M_r at 40, 50, or 60°F. This is shown in Row(1) of Table 3.21.
4. There is insufficient evidence that indicates differentiation between material changes at 73°F testing temperature, shown as a low F-ratio in Row(1) of Table 3.21.

Based on the evaluation of these study results, it is recommended that the test conditions of 0.1 second load duration, 0.33 hertz load frequency, between 50 and 75 microstrain at 60°F be employed as the standard test procedure to be used with the Repeated-Load Test System and the M_r reported as a total M_r.

4 COMPACTION STUDY

This chapter presents an evaluation on the effects of compaction methods on the total M_r. Four methods of compaction are studied together with two types of pre-compaction mixture conditionings. The overall goal of this study is to determine which combination of compaction and conditioning will tend to yield the most consistent M_r values within a group of replicated specimens.

Of secondary concern is the ability of the M_r test procedure to be sensitive enough to discriminate between M_r values of the conditioning treatments for the method of compaction selected. By meeting the overall goal of this study, a method of sample preparation can be applied with the proposed test method which will lead to the highest potential of exact replication. The selection will tend to reduce errors associated with sample sets that are "non-replicated". This inturn will maximize the potential of the test method to detect differences in M_r values associated with changes in mechanical properties due to the randomness of the AC sample matrix (i.e., maximize changes in M_r values due soley to moisture damage, which is evaluated in the following chapter).

4.1 Experimental Design

A three-factor factorial analysis of variance (Peterson, 1985c) was performed on the M_r data collected in this study. Factor A represents the 2 aggregate types, factor B represents the 2 curing procedures, and factor C represents the 4 methods of compaction.

Therefore, sixteen treatments (factor A x factor B x factor C = 2 x 2 x 4 = 16) where analyzed in this factorial design. The ANOVA table used for the evaluation is given in Table 4.1.

The objective of this evaluation is to determine if any of the three factors act independently on the M_r, or if the interaction of any three factors affect the M_r. By performing this type of analysis, one can compare treatment means by testing the significance of differences between means with their associated standard errors.

The test program followed for this study is shown in Figure 4.1. The following sections describe the preparation of the specimens tested with a detailed description of the following methods of compaction evaluated in this study:

1. Static Compaction (ASTM D1074)
2. Marshall Compaction (ASTM D1559)
3. Kneading Compaction (ASTM D1561)
4. Gyratory-shear Compaction (ASTM D4013)

4.2 Mixing and Curing

The specimens were batched individually to mix design recommendations supplied by the Oregon Department of Transportation, previously identified in Table 2.7.

Mixing time was 2 minutes at 305°F, using a heated, mechanical mixer. Four samples for each aggregate type and each compaction method were compacted after mixing (noted "no cure"). The remaining

TABLE 4.1 - Experimental Design ANOVA - Compaction Study

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Total	rabc-1	SSTot		
A	a-1	SSA	MSA	F_A
B	b-1	SSB	MSB	F_B
AxB	(a-1)(b-1)	SSAB	MSAB	F_{AB}
C	c-1	SSC	MSC	F_C
AxC	(a-1)(c-1)	SSAC	MSAC	F_{AC}
BxC	(b-1)(c-1)	SSBC	MSBC	F_{BC}
AxBxC	(a-1)(b-1)(c-1)	SSABC	MSABC	F_{ABC}
Error	(r-1)(abc)	SSE	MSE	

$CV = [(MSE)^{1/2}/x..] * 100\%$

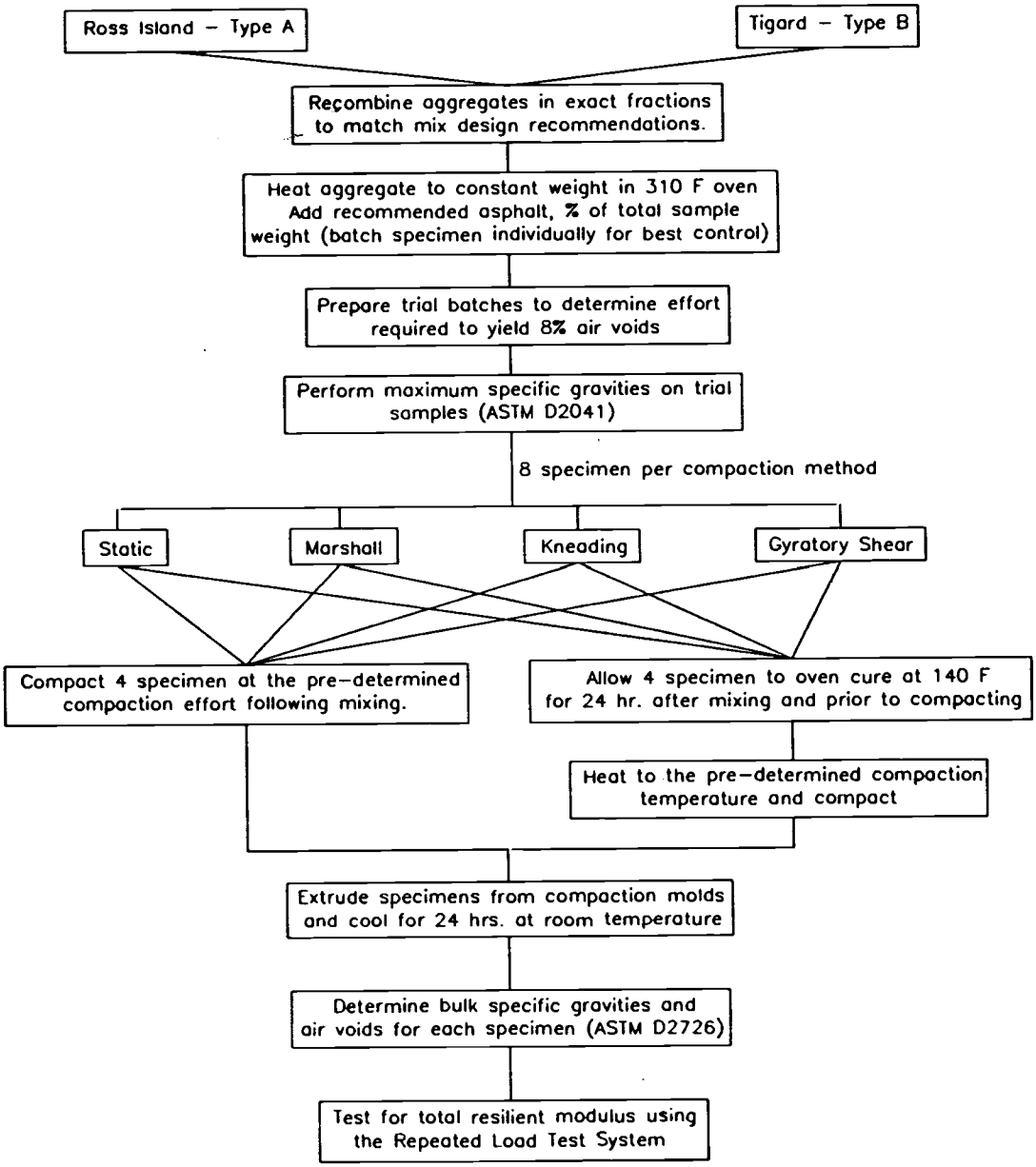


FIGURE 4.1 – Laboratory Program – Compaction Study

four specimen in each set were oven cured for 24 hours at 140°F after mixing. Prior to compaction, the cured samples were heated to a predetermined temperature and compacted (noted "24 hour cure").

4.3 Compaction Methods

Four methods of compaction and 2 curing procedures were used in this study. Each compaction method was broken into 2 subsets, oven cured and no cure, as previously stated. In each subset, 4 replicate specimens were compacted to 8% air voids. Air voids were determine in accordance with ASTM D3203 (1987c). Bulk specific gravities were determined using ASTM D2726 (1987d).

The following sections describe the standard compaction methods used, and the deviations from those standards to achieve 8% air voids.

4.3.1 Static Compaction (ASTM D1074)

The standard test procedure followed for static compaction was in general accordance with ASTM D1074 (1987e), "Compressive Strength of Bituminous Mixtures". This procedure recommends a compaction temperature of 255°F. The compaction is done by a double plunger, static compressive load. The loose mix is first allowed to cool to 255°F in a 4-inch diameter mold. A Marshall mold and collar were used. The mix is first subjected to a 150 psi (1,885 lb for 4-in. diam.) seating load, followed by a 3,000 psi (37,700 lb) double plunge load applied at a rate of 0.05 inch per minute per inch of sample height, or 0.125 inch per minute for a 2.5 inch sample. The compressive stress of 3,000 psi is held for 2 minutes and then released. The

sample is allowed to cool, then extracted from the mold. A Tinius-/Olsen Super "L" compression machine was used (capacity = 400,000lbs) to apply the static load at the recommended rate (see Figure 4.2).

No deviations from this procedure were needed to achieve approximately 8% air voids. A summary of the air voids achieved are:

	ave.	s.dev.	cv
Aggregate A (no cure)	7.36	0.07	1.0%
Aggregate A (24 hr. cure)	6.94	0.35	5.0%
Aggregate B (no cure)	8.00	0.16	2.0%
Aggregate B (24 hr. cure)	7.60	0.16	2.1%

(statistics based on 4 specimen/group)

4.3.2 Marshall Compaction (ASTM D1559)

The standard test procedure followed for Marshall Compaction was in general accordance with ASTM D1559 (1987b), "Resistance to Plastic Flow of Bituminous Mixtures Using the Marshall Apparatus".

In this procedure, a 10 pound hammer with a 3 7/8 inch diameter face is dropped 18 inches, and this is termed a blow. The equipment used is shown in Figure 4.3. The recommended compaction is 50 blows/face at a compaction temperature equal to the temperature required to obtain an asphalt viscosity of 280±30 centistokes. For the AR-4000W asphalt used for this study, the compaction temperature was 275°F.

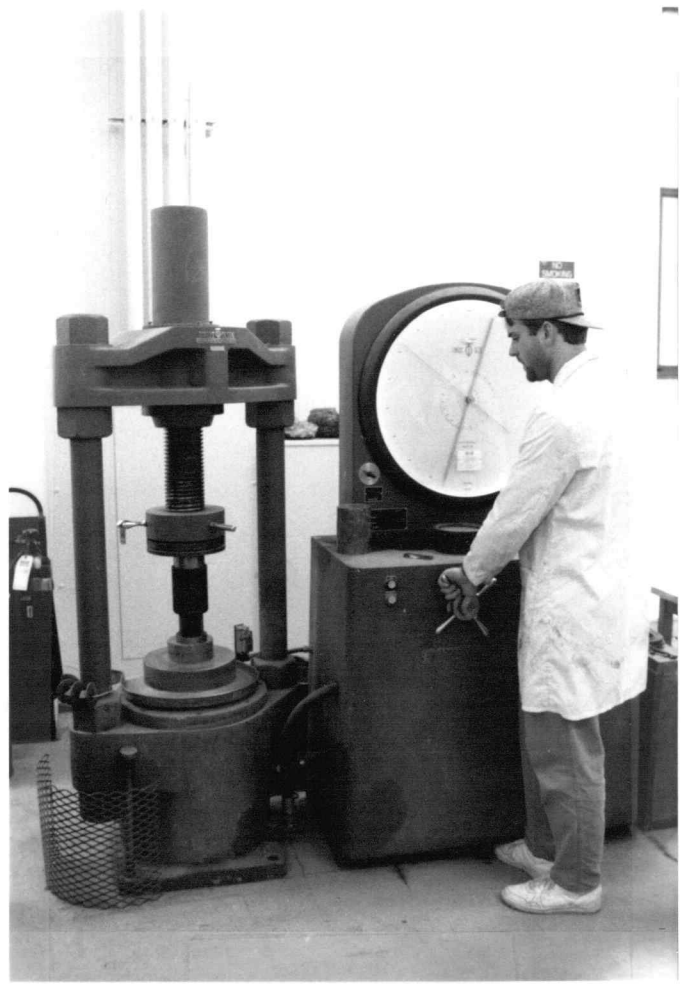


FIGURE 4.2 – Static Compaction Equipment (ASTM D1074)

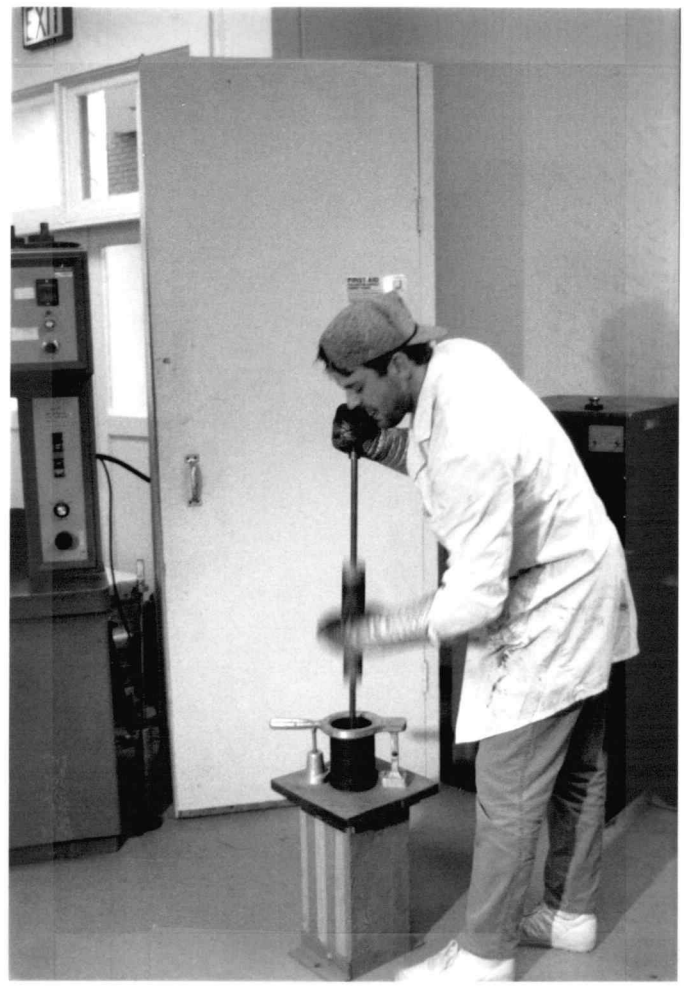


FIGURE 4.3 – Marshall Compaction Equipment (ASTM D1559)

By trial, the required effort for aggregate A was 18 blows/face and for aggregate B was 23 blows/face to yield approximately 8% air voids. A summary of the air voids achieved are:

	ave.	s.dev.	cv
Aggregate A (no cure)	9.37	0.34	3.6%
Aggregate A (24 hr cure)	9.10	0.32	3.5%
Aggregate B (no cure)	8.32	0.37	4.5%
Aggregate B (24 hr cure)	8.17	0.41	5.0%

(statistics based on 4 specimen/group)

4.3.3 Kneading Compaction (ASTM D1561)

The standard test procedure followed for preparation of AC mix specimens by the Kneading Compactor was in general accordance with ASTM D1561 (1987f), "Preparation of Bituminous Mixture Test Specimen by Means of the California Kneading Compactor".

In this procedure, a 3.1 $in.^2$ compactor foot is applied to the mix surface in a 4-inch diameter mold by a hydraulic ram. A Cox CS-1000 California Kneading Compactor was used for compaction (see Figure 4.4). The standard ASTM procedure recommends compaction of the asphalt-aggregate mix at 230°F. A precompaction effort of 20 tamping blows at 250 psi is required prior to the full compaction of 150 tamping blows at 500 psi. The precompaction effort is recommended to "form the mixture into a semi-compacted condition so that it will not be unduly disturbed by the full pressure..."(ASTM, 1987f). Following the precompaction, the compaction mold is allowed to move side-to-side 1/8 inch during the full compaction effort. This allows the kneading

FIGURE 4.4 – Kneading Compaction Equipment (ASTM D1561)

action. The base and sample mold unit are rotated 50° between tamping blows to assure equal coverages per sample surface. At the conclusion of the full compaction, the specimen and mold together are placed in a constant temperature oven at 140°F for 90 minutes. Following the constant temperature conditioning, the faces of the molded specimen are "leveled" by means of a double plunge static load of 12,000 pounds applied at a rate of 0.25 inch per minute. The specimen is allowed to cool prior to extruding from its compaction mold.

In order to achieve the desired 8% air voids, deviations from these standards were necessary. By trial, the required effort for aggregate A was 20 tamping blows precompaction and 50 tamping blows full compaction, and for aggregate B was 20 and 100. A summary of the air voids achieved are:

	ave.	s.dev.	cv
Aggregate A (no cure)	7.09	0.27	3.8%
Aggregate A (24 hr cure)	7.07	0.13	1.8%
Aggregate B (no cure)	8.40	0.28	3.3%
Aggregate B (24 hr cure)	8.19	0.29	3.5%

(statistics based on 4 specimen/group)

4.3.4 Gyratory-shear Compaction (ASTM D4013)

The Gyratory-shear specimen were compacted in general accordance with the specifications presented as ASTM D4013 (1987g), "Preparation of Test Specimens of Bituminous Mixtures by Means of Gyratory Shear Compactor" (see Figure 4.5).

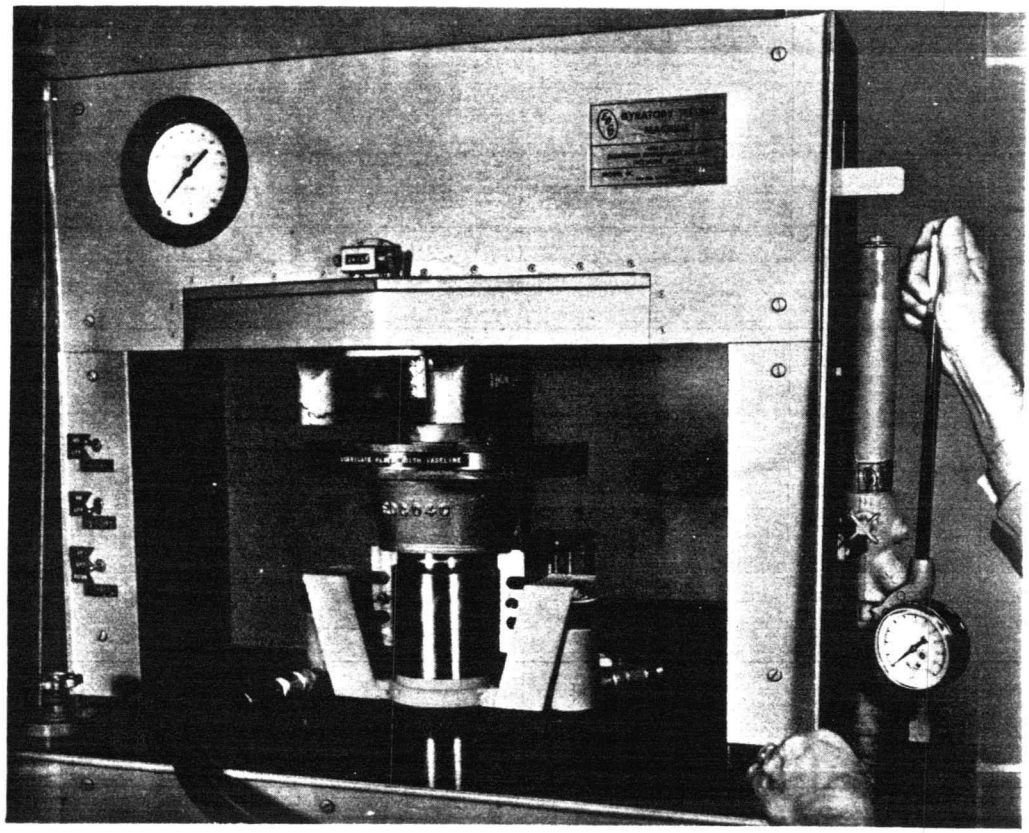


FIGURE 4.5 – Gyratory-shear Compaction Equipment (ASTM D4013)

The loose mix is first cured in an oven at 140±10°F to a constant weight, then transferred to a heated mold and base plate beneath the ram of the press. The ram is pumped down into the center of the 4-inch diameter mold until the 3.985-inch diameter face of the ram makes contact with the surface of the mixture. Pumping is continued until the low pressure gage reaches the pregyration stress point of 31.8 psi (400 lbf.). The mold is immediately tilted to a specified angle of gyration (up to 12°). The mold is then gyrated 3 times, stopped, and squared back to a 0° tilt. One full stroke of the metering pump is applied. By observation of the low pressure gage, when an end point stress of 95.3 psi (1,200 lbf.) is obtained after one full stroke, the gyratory-shear compaction is completed. If the end point stress is not achieved, the method is repeated.

After completion of the gyratory-shear compaction, at approximately one stroke per second, the pressure is pumped up to 1590 psi (20,000 lbf.) for consolidating the mix. The specimen is allowed to cool in the mold, then extruded.

In order to compact the specimen to 8% air voids, a 1° angle of gyration was used at a compaction temperature of 275°F. An end point stress of 100 psi was also used. A summary of the air voids achieved are:

	ave.	s.dev.	cv
Aggregate A (no cure)	8.07	0.26	3.2%
Aggregate A (24 hr cure)	7.83	0.22	2.8%
Aggregate B (no cure)	7.95	0.25	3.1%
Aggregate B (24 hr cure)	7.97	0.26	3.3%

(statistics based on 4 specimen/group)

4.4 Analysis and Results

M_r tests were performed on each sample using the Repeated-Load Test System. Both the 40°F and 73°F test temperatures were evaluated, and the standard test conditions of 0.1 second load duration, 0.33 hertz load frequency and a microstrain level between 50 and 60 were also used.

The assumption of consistent replicated specimens is nearly met in that the cv of air voids for any combination of compaction and curing shown in the previous pages does not exceed 5% .

Results of the testing are given in Table 4.2. This table shows the computed means of each treatment combination with the associated standard deviations (s.dev.) and coefficients of variation (cv) based on 4 specimens per group.

The analysis of the 40°F test results are presented in Table 4.3. Similarly, Table 4.4 presents analysis of the 73°F test results. Both resulted in a highly significant (at the 0.01 α-level) F-ratio of the second order (AxBxC) interaction, suggesting that none of the three factors act independently on the resilient modulus, and that differences between interactive treatment means exist.

Once again, the lower temperature leads to greater precision than the higher temperature. This is supported by the comparison of the CV between the two experiments. This finding further supports the conclusion made in the Parametric Study that lower testing temperatures lead to more precise M_r values. Thus the 73°F results were dropped from the remaining analysis.

A summary of the results at 40°F are shown in Table 4.5. The treatment groups means and standard error of means are given, as well

TABLE 4.2 - Total M_r Test Results - Compaction Study (n=4)

Group	Total M_r @ 73°F (ksi) ave.	s.dev.	cv	Total M_r @ 40°F (ksi) ave.	s.dev.	cv
A-M-NC	218.8	20.69	9.46	1856.6	35.7	1.92
A-M-OC	407.3	10.77	2.64	2202.9	62.0	2.81
A-S-NC	300.4	14.95	4.98	2052.2	45.2	2.20
A-S-OC	392.9	13.05	3.32	2199.9	62.2	2.83
A-K-NC	208.3	18.60	8.93	1768.1	121.6	6.88
A-K-OC	371.9	46.60	12.53	2082.8	259.4	12.45
A-G-NC	299.3	52.30	17.47	1862.7	174.8	9.38
A-G-OC	502.7	68.20	13.57	2169.6	78.7	3.63
B-M-NC	431.9	30.81	7.13	2483.2	165.5	6.66
B-M-OC	517.6	31.80	6.14	2364.0	115.0	4.86
B-S-NC	335.8	14.11	4.20	1771.5	80.5	4.54
B-S-OC	454.3	41.30	9.09	2039.5	111.0	5.44
B-K-NC	321.5	28.20	8.77	1831.2	60.7	3.31
B-K-OC	664.2	8.13	1.22	2266.6	76.5	3.38
B-G-NC	390.4	46.77	11.98	1914.7	181.4	9.47
B-G-OC	812.5	25.60	3.15	2329.7	107.2	4.60

Group Key:

A = Ross Island Aggregate
B = Tigard Aggregate
M = Marshall Compaction
S = Static Compaction
K = Kneading Compaction
G = Gyratory-shear Compaction
NC = No curing
OC = Oven cured @ 140°F for 24 hours

TABLE 4.3 – ANOVA for Total M_r at 40°F

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Total	63	3,715,108		
A	1	162,812	162,812	11.4**
B	1	1,118,306	1,118,306	78.5**
AxB	1	3,423	3,423	0.2
C	3	547,129	182,376	12.8**
AxC	3	756,605	252,202	17.7**
BxC	3	190,063	63,354	4.4**
AxBxC	3	253,266	84,422	5.9**
Error	48	683,504	14,240	

** Significant at the $\alpha = 0.01$ level CV = 5.8%

TABLE 4.4 – ANOVA for Total M_r at 73°F

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Total	63	1,518,169		
A	1	376,076	376,076	342.3**
B	1	653,672	653,672	595.0**
AxB	1	25,760	25,760	23.4**
C	3	167,044	55,681	50.7**
AxC	3	63,168	21,056	19.2**
BxC	3	114,348	38,116	34.7**
AxBxC	3	65,371	21,790	19.8**
Error	48	52,730	1,099	

** Significant at the α = 0.01 level CV = 8.0%

TABLE 4.5 - Summary of Modulus Means, Standard Errors, and Significant Differences at 40°F

Group	Total Resilient Modulus @ 40°F (ksi) (statistics of four replicates) Mean (ksi)	Standard Error of Mean (ksi)
A-M-NC	1856.6	$(MSE/r)^{\frac{1}{2}} = (14,987/4)^{\frac{1}{2}} = 61.2$
A-M-OC	2202.9	
A-S-NC	2052.2	
A-S-OC	2199.9	
A-K-NC	1768.1	
A-K-OC	2082.8	
A-G-NC	1862.7	
A-G-OC	2169.6	
B-M-NC	2483.2	
B-M-OC	2364.0	
B-S-NC	1771.5	
B-S-OC	2039.5	
B-K-NC	1831.2	
B-K-OC	2266.6	
B-G-NC	1914.7	
B-G-OC	2329.7	

Equal Compaction Methods*

Equal Curing Methods*

*Standard Error for Differences:
$SE = (2MSE/r)^{\frac{1}{2}} = 86.6$ ksi

Group Key:

A = Ross Island Aggregate
B = Tigard Aggregate
M = Marshall Compaction
S = Static Compaction
K = Kneading Compaction
G = Gyratory-shear Compaction
NC = No curing
OC = Oven cured @ 140°F for 24 hours

as links of equal means as governed by the t-statistic of interactive treatment mean differences [standard error for differences = $(2MSE/r)^{1/2}$, where r = no. of replicated specimens = 4] at the 0.05 α-level.

In general, all methods of compaction yield similar M_r results, as shown on the left side of the means column in Table 4.5. However, the following exceptions to this generalization exist. The Static method yielded M_r values distinctly different from the other 3 methods for Aggregate A with no oven curing. Similarly, the Marshall method yielded different M_r values for Aggregate B with no oven curing, and the Static method yielded different M_r values for Aggregate B with the oven curing treatment. The comparisons were made using a t-test between means.

Also of interest are the differences in M_r values between curing procedures at each level of aggregate type and compaction method. From Table 4.5, as shown on the right side of the means column, the Static method did not yield significantly different M_r values between curing procedures for Aggregate A, and the Marshall method for Aggregate B.

From the previous discussion, choosing either the Kneading or the Gyratory-shear methods of compaction appears warranted. The selection between the two can be made by observing the cv column shown in Table 4.2. This method of selection suggests choosing the compaction method that results in the lowest cv (implying the best accuracy in M_r results). By observation, it would appear that the Kneading compaction method without the oven cure precompaction conditioning may

be the best. However, it could be reasonably argued that any method of compaction could meet this requirement.

Further, the Kneading method or the Gyratory-shear method of compaction are leading candidates for laboratory compaction based on the acceptible ability to simulate field compaction with respect to material properties (Consuegra et al., 1989).

4.5 Conclusions and Recommendations

Based on the evaluation of these study results, the following conclusions appear warranted:

1. For any of the 4 methods of compaction, the 2 methods that result in the highest differences between modulus values of 2 methods of preconditioning are the Kneading compaction and the Gyratory-shear compaction.
2. The desired method of compaction and conditioning based on repeatable modulus values is the Kneading compaction without the oven cure preconditioning.

From the conclusions made, the recommended compaction method to be used for the improved test method to determine the degree of asphalt stripping from aggregates is the Kneading compaction (ASTM, 1987f).

5 PRIMARY FACTORIAL STUDY

This chapter presents results of a concentrated laboratory study to evaluate the effects of asphalts, air voids and antistripping additives on stripping. The following sections provide a format for the analysis of results with specific questions of interest to be answered. The preparation of the test specimen is described, followed by a presentation of test results and discussion of the results. Finally, conclusions and recommendations are summarized for the work effort.

5.1 Objectives

Six replicate specimens were prepared for each factorial combination of treatments identified in the following section. This number was selected to increase the likelihood of obtaining significant discrimination between treatment groups without doing an excessive quantity of testing. The selection is supported by work done by Kim et al. (1989).

The overall goal of this phase of the study is to evaluate the sensitivity of the test method to detect moisture damage in AC specimens. Of primary concern is the ability of the procedure to strongly differentiate between a stripping aggregate and a non-stripping aggregate. Of equal importance is the ability to show significant improvement of the mixes containing antistripping additives over mixes that do not.

Prior to testing, a number of specific questions that could be obtained from this study were generated to aid in the overall evaluation of the study results:

1. Is there a significant difference in retained moduli (IRM_r) between the partially saturated group and the fully saturated group?
2. What number of conditioning cycles are required to obtain a significant drop in the IRM_r as compared to that obtained after a single cycle? Further, does the IRM_r cease to change significantly after some number of cycles?
3. Do the test results indicate differences in the performance of the 2 aggregate types?
4. Are there significant differences in the IRM_r between the three air void contents within each combination of aggregate, asphalt and additive?
5. For the stripping aggregate (Agg. B), is the IRM_r for the additive mixtures significantly different than that for the untreated mixtures at the same air voids level?
6. One would expect that the IRM_r would be dependent on aggregate type, asphalt, additive treatment, air voids and the number of condition cycles. Therefore, can the following prediction model (or some transposition) for the IRM_r be fit:

$$IRM_r = \beta_0 + X\ [\beta_1(Air) + \beta_2(Agg.) + \beta_3(Add.) + \beta_4(Asph)] \quad ....(5.1)$$

where β_0 = IRM_r intercept @ X = 0 (=100% for original IRM_r)

X = No. of condition cycles

Air = Air voids content (4, 8, 12%)

Agg. = Aggregate type (A=0 or B=1)

Add. = Antistripping additive (none=0, L=1, or P=2)

Asph. = Asphalt type (AR-4000W=0 or AC-20R=1)

β_1, β_2, β_3, β_4 = Slope parameters.

The laboratory work effort is outlined in Figure 5.1. A discussion of the Lottman conditioning used in this study was given in section 2.2.2.

5.2 Experimental Design

Mixes composed of several material variables are evaluated in this study, including 2 aggregate types, 2 asphalts, 2 antistripping additives and 3 air void contents.

Questions 1 and 2 stated above can be answered using a pooled t-test between group means (Devore and Peck, 1986b). The groups as stated here represent the average IRM_r of each cycle of moisture conditioning over the 18 combinations of material groups [representing the partial factorial combinations of treatments - (2 aggregates x 2 asphalts x 3 air voids) + (1 aggregate x 2 additives x 3 air voids) = 12+6 = 18 treatments]. Each cell within the layout will represent the average IRM_r of the 6 replicates. From this analysis, it is anticipated that by answering question number 2, an analysis of variance could be performed on the results at a specific point in time

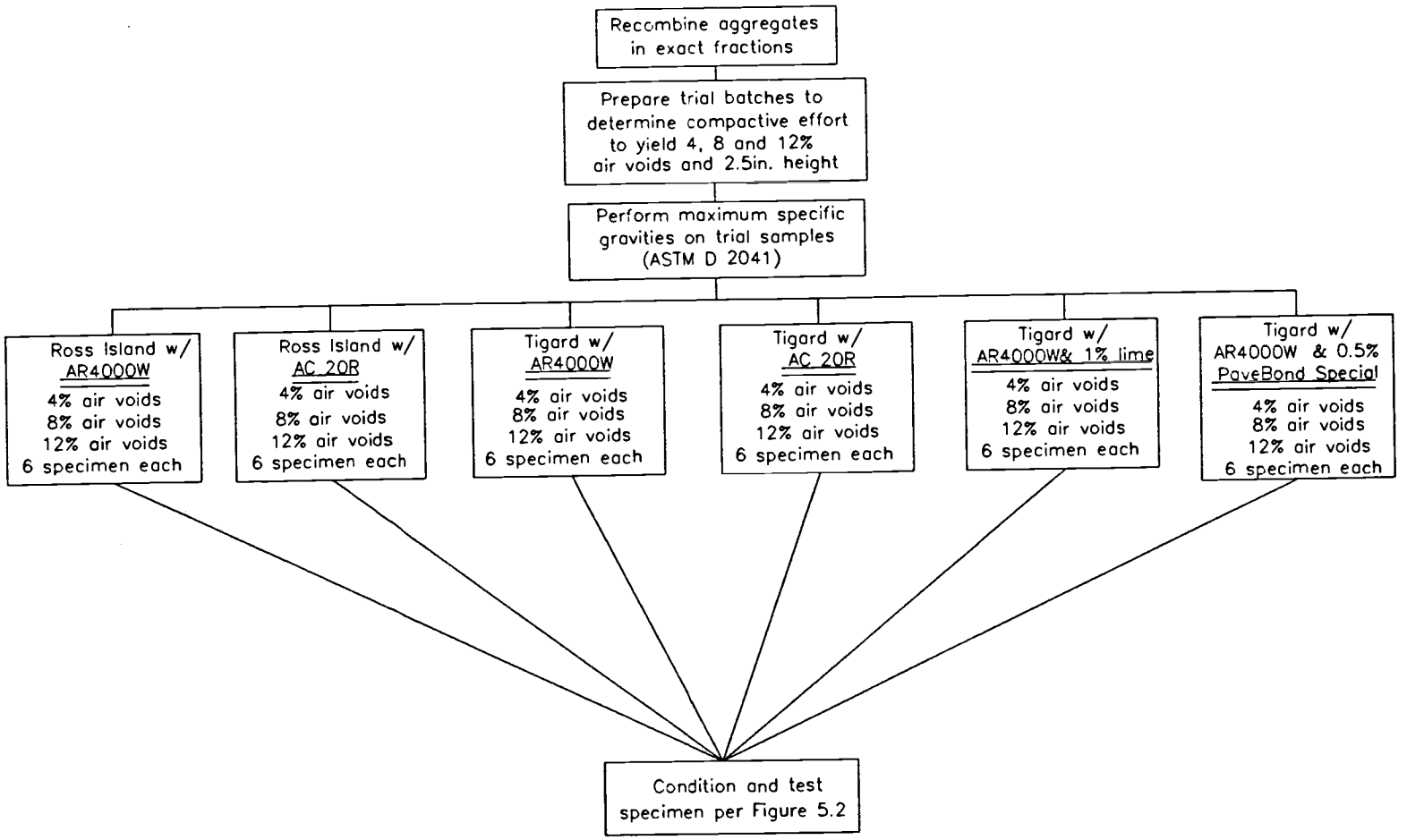


FIGURE 5.1 - Laboratory Program - Factorial Study

(i.e., following some determined number of conditioning cycles). This analysis can be accomplished using a completely randomized design (CRD) with the same 18 combinations of material groups selected as treatments (Peterson, 1985a). By using the computed F_{trt}-ratio from the ANOVA (as shown in Table 5.1), the null hypothesis of equal treatment means can be tested against the alternative hypothesis that treatment means are different. For the test procedure to be sensitive to material changes, it is desired to observe a significant F_{trt}-ratio, that is, be greater than the critical F-ratio for the associated degrees of freedom and significance level.

Specific differences between treatment means can then be tested using the t-test statistic, where the standard error of differences is given by $(2MSE/r)^{1/2}$, and r is the number of replicated specimens (Peterson, 1985a).

The factorial set of samples were tested for total M_r using the Repeated-Load Diametral Test System described in Section 2.1. The following sections describe the methods used to prepare the test specimens.

5.2.1 Materials

Aggregates. Two aggregates were used in this study. Aggregate A is from Ross Island Sand and Gravel. This aggregate is a crushed river-run aggregate dredged in the Willamette River in Portland, Oregon. This aggregate has been observed to resist stripping in local area projects. Aggregate B is from Tigard Sand and Gravel. This aggregate is a hillside quarried crushed rock, and has been known to

TABLE 5.1 - Experimental Design ANOVA - Primary Factorial Study

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Treatments	n-1 = 17	SST	MST	F_{trt}
Error	n(r-1)=90	SSE	MSE	
Total	rn-1 = 107	SSTot		

strip excessively in Portland area projects. Portland has a wet, moderate climate which experiences occasional winter freeze. Properties of these aggregates were presented in Section 2.3 of this report.

Asphalts. Two asphalts were evaluated in this study. The AR-4000W and AC-20R(R) were discussed in Section 2.3.3.

Antistripping Additives. Hydrated lime(L) and PaveBond Special(P) were evaluated for the effects in stripping for the B-aggregate. Properties of these additives were given in Section 2.3.3.

It should be noted that this design is not a full factorial because the full range of combinations were not used, specifically, the anti-stripping additives were not used for aggregate A, the known non-stripper.

Air Voids. It was desirable to prepare the laboratory compacted samples over a broad range of typical field air void values. Therefore, 4, 8, and 12% air voids were selected for each factorial combination discussed above. Air voids were determined by the standard test procedure given in ASTM D3203 (1987c), "Percent Air Voids in Compacted Dense and Open Bitumnous Paving Mixtures". Bulk specific gravities of the compacted specimen were determined in accordance with ASTM D2726 (1987d), "Bulk Specific Gravity and Density of Compacted Dense and Open Bituminous Paving Mixtures". The actual air voids achieved are presented later in this chapter.

5.2.2 Specimen Preparation

Six replicate specimens were prepared for each of the 18 factorial combinations; therefore, a total of 108 specimens were prepared for testing in this study. The following sections discuss the batching and mixing process, followed by a summary of the compactive effort required for each mixture at each air void level.

Batching and Mixing. Each aggregate was recombined from 7 separated stockpile sizes to meet the mix design gradation as supplied by the Oregon Department of Transportation. These dense-graded mix gradations were discussed in Section 2.3.3 of this report. The total weight of aggregate was adjusted to obtain a specified 2.5-inch specimen height recommended for modulus testing. The recombined aggregate was placed in a 310°F oven to drive off surface water and bring the aggregate above the mixing temperature of 305°F.

Asphalt was added to the aggregate at a rate supplied by ODOT and presented in Chapter 2. ODOT mix designs are based on the Hveem Method of Mix Design and the asphalt content is presented as a percentage of the total weight of mix. The asphalt content of aggregate A is 5.9% and for B is 6.6%.

A discussion of the antistripping additives and how they were added to the aggregate B mixtures were presented in Section 2.3.3.

Mixing was done by means of a Cox mechanical mixer. Mixing time was two minutes at 305°F.

Kneading Compaction. Compaction of the mixtures was done in general accordance with ASTM D1561 (1987f), "Preparation of Bituminous Mixture Test Specimen by means of the California Kneading Compactor", which was selected for this study on the basis of conclusions and recommendations made in the previous chapter.

Deviations from the standard method presented in ASTM D1561 were necessary to achieve the level of air void contents desired. The standard recommends a compaction temperature of 230°F, a pre-compaction effort of 20 tamping blows at 250 psi and a full compaction effort of 150 tamping blows at 500 psi. Table 5.2 is a summary of the average air voids of 6 replicates per group achieved along with the associated standard deviations. Also included is a summary of the deviations to the recommended compaction effort required to achieve those air void contents.

By observation of Table 5.2, the level of air voids achieved do not necessarily match the target air voids desired. However, the range of air voids (5.12 to 10.99%) should be great enough to show the effects of air voids with respect to moisture sensitivity.

5.3 Test Results

Moisture conditioning of specimens continued until the cycling led to a 50% loss in original M_r (i.e., $IRM_r < 50\%$) of the control specimen (i.e., aggregates w/AR-4000W and no antistripping aggregates). By observation of test results, this criteria occurred

TABLE 5.2 – Summary of Kneading Compaction Effort and Air Voids Achieved – Factorial Study

Sample Group*	Number of tamping blows: Pre-Compaction @ 250 psi	Number of tamping blows: Full Compaction @ 500 psi	Compaction Temp.°F.	Air Voids, % (6 replications/group): ave.	s.dev.	cv
A4	20	150	250	5.12	0.20	3.9
A8	20	85	230	8.12	0.45	5.5
A12	30	0	220	10.00	0.32	3.2
AR4	20	150	250	5.46	0.84	15.4
AR8	20	35	230	7.14	0.41	5.7
AR12	30	0	220	8.87	0.37	4.2
B4	20	150	260	6.44	0.59	9.2
B8	20	95	230	7.65	0.61	8.0
B12	25	0	215	10.07	0.77	7.7
BR4	20	150	260	6.09	0.37	6.1
BR8	20	95	230	6.91	0.45	6.5
BR12	25	0	215	9.50	0.33	3.5
BP4	20	150	260	5.63	0.34	6.0
BP8	20	95	230	6.78	0.48	7.1
BP12	25	0	215	10.99	0.56	5.1
BL4	20	150	260	5.49	0.31	5.7
BL8	20	95	230	6.17	0.54	8.8
BL12	25	0	215	9.21	0.31	3.4

*Sample Group Key:

A = Aggregate A
B = Aggregate B
R = AC-20R (all others without R are mixed with AR-4000W)
P = PaveBond Special
L = Lime
4, 8 and 12 = target air voids,%

following the 5th freeze-thaw cycle. Therefore, the number of conditioning cycles used for all specimen groups was 7, shown below:

Cycle #1 = partial saturation

Cycle #2 = full saturation

Cycle #3 = freeze-thaw cycle #1

Cycle #4 = freeze-thaw cycle #2

Cycle #5 = freeze-thaw cycle #3

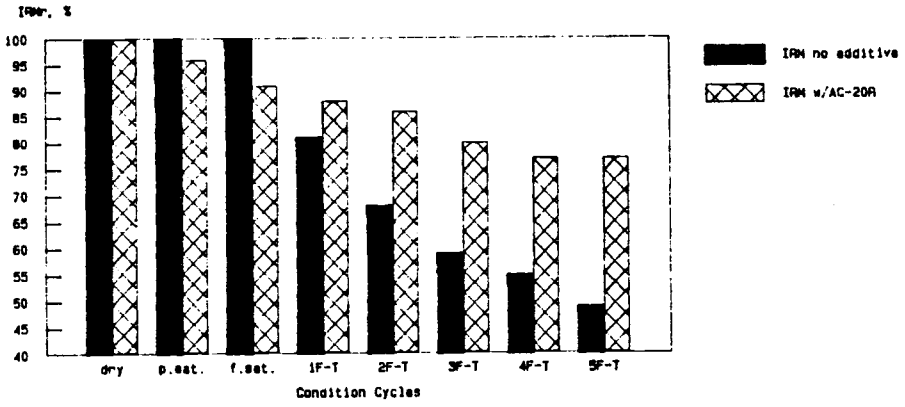
Cycle #6 = freeze-thaw cycle #4

Cycle #7 = freeze-thaw cycle #5

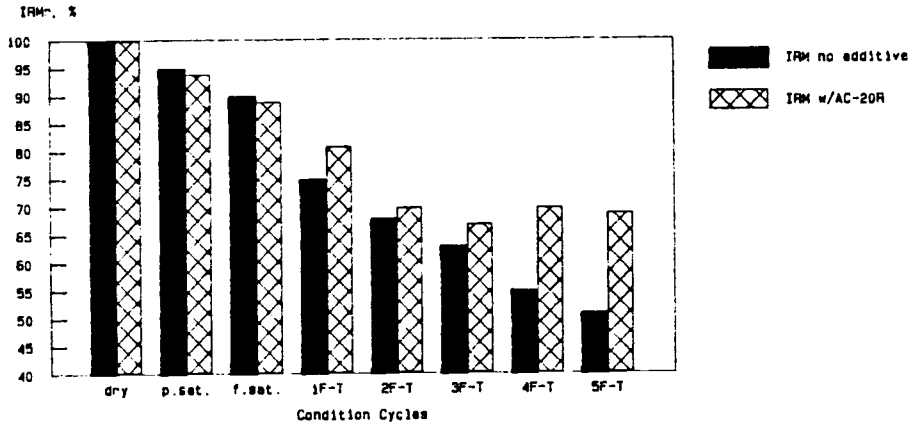
The IRM_r results for aggregate A (the non-stripper) is shown in Figure 5.2. Likewise, the results for aggregate B (the stripper) is shown in Figure 5.3. These graphs show the IRM_r plotted against the successive stages of moisture conditioning, and each bar represents an average of the 6 replicated specimen results. These graphs are intended to visually show the significance of the IRM_r resulting from the analysis described below.

The results of the testing are summarized in Table 5.3, with 7 columns of condition cycles and 18 rows of material groups (i.e., a combination of materials and air voids). A number of relationships can be derived from this table, with the comparison of successive column means by use of the pooled t-test shown at the bottom. These include:

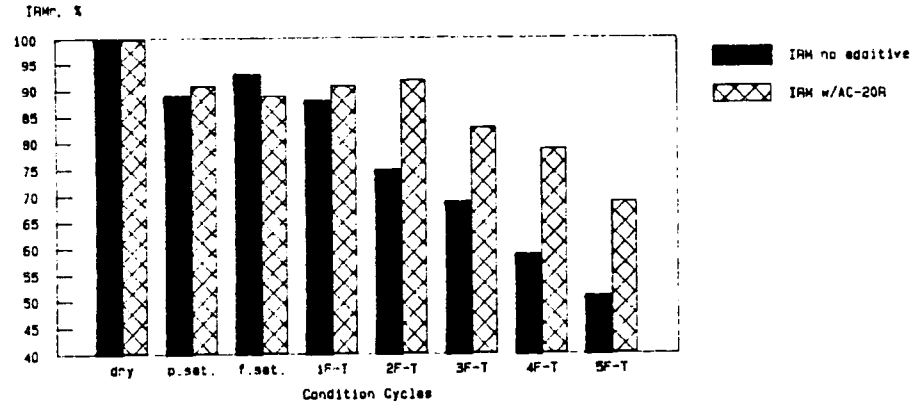
1. The difference between partially saturated specimen and fully saturated specimen is insignificant (the probability



a) Aggregate Type A – 4% air voids

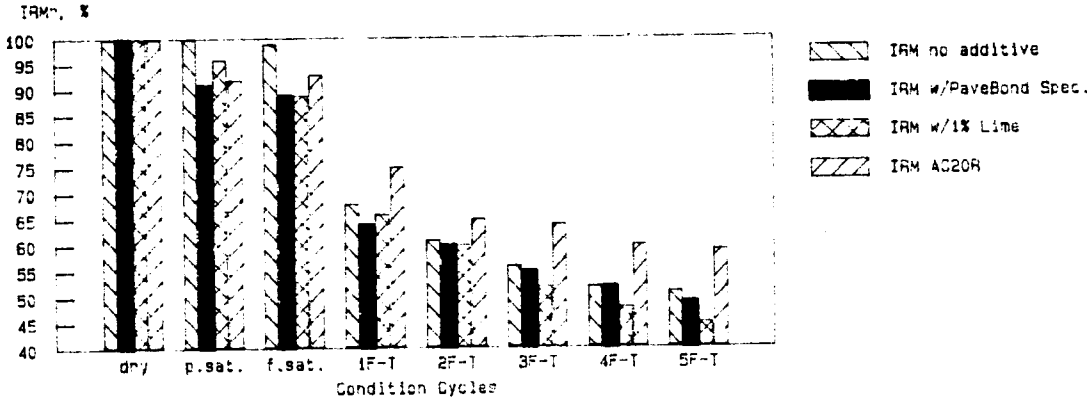


b) Aggregate Type A – 8% air voids

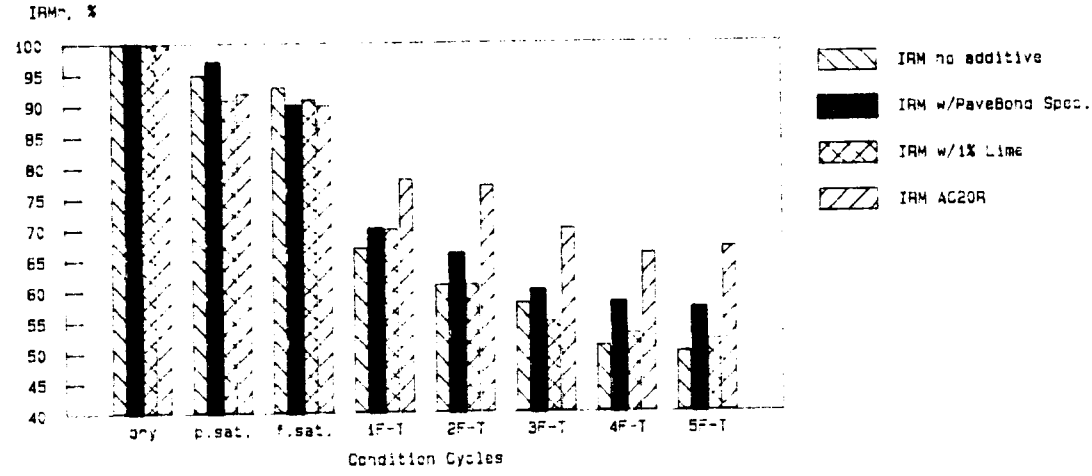


c) Aggregate Type A – 12% air voids

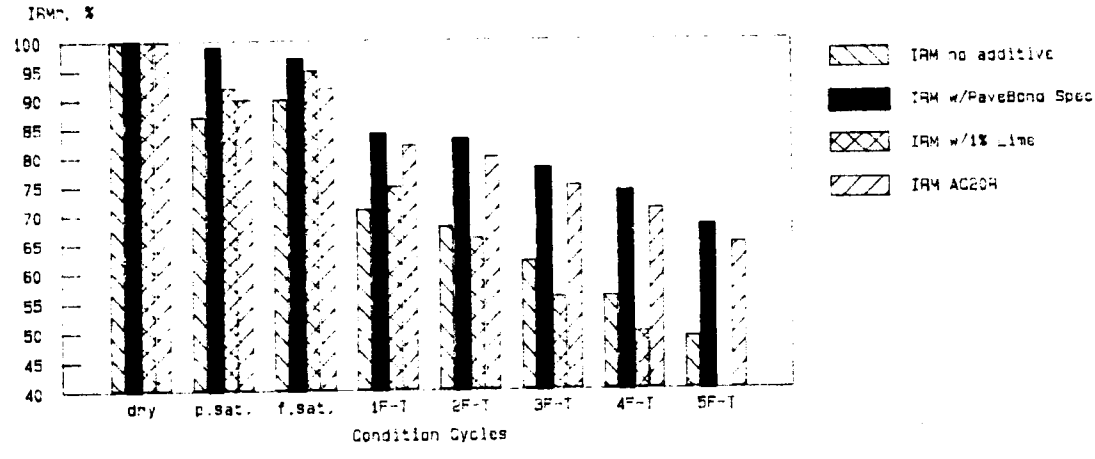
FIGURE 5.2 – IRM_r vs. Condition Cycles – Aggregate A



a) Aggregate Type B – 4% air voids



b) Aggregate Type B – 8% air voids



c) Aggregate Type B – 12% air voids

FIGURE 5.3 – IRM_r vs. Condition Cycles – Aggregate B

TABLE 5.3 – Summary of IRM_r (%) Test Results and Analysis (n=6)

Index of Retained Modulus, %

MATERIALS	CONDITION CYCLES 1 Partially Saturated	2 Fully Saturated	3 Freeze Thaw #1	4 Freeze Thaw #2	5 Freeze Thaw #3	6 Freeze Thaw #4	7 Freeze Thaw #5
A4	102.35	101.78	80.60	68.47	59.07	54.89	49.21
A8	94.99	90.45	74.77	67.81	63.49	54.81	50.70
A12	89.70	92.64	87.96	74.78	69.37	58.74	51.04
AR4	95.76	91.29	88.23	86.14	80.20	77.07	76.63
AR8	93.76	89.06	81.48	69.89	67.09	70.09	68.07
AR12	91.10	89.46	91.50	91.90	83.02	78.59	68.83
BR4	91.91	92.79	74.90	65.38	63.63	60.01	59.01
BR8	92.23	90.47	78.17	76.54	70.44	66.28	66.53
BR12	90.26	92.34	81.95	80.09	74.90	71.13	65.03
B4	103.62	98.81	68.20	61.48	55.64	51.79	51.02
B8	94.95	92.84	66.67	61.27	58.13	50.81	49.91
B12	87.15	89.85	71.00	67.50	62.17	56.20	48.81
BP4	90.62	88.79	64.21	59.52	54.54	51.71	49.22
BP8	96.65	90.25	70.33	65.85	60.26	58.49	57.17
BP12	98.80	97.39	83.86	82.97	77.52	73.66	68.20
BL4	95.53	88.71	66.04	60.16	51.70	48.26	45.35
BL8	90.95	90.57	69.98	60.81	54.49	53.09	51.98
BL12	92.54	95.29	74.76	66.28	55.88	50.15	48.30
block mean	94.05	92.38	76.37	70.38	64.53	60.32	56.95
variance	18.70	13.67	68.66	92.88	90.83	97.73	89.34
size	18	18	18	18	18	18	18
t statistic		1.247	7.486	1.999	1.831	1.301	1.047
degrees of freedom		33	24	33	34	34	34
t crit: 0.05 level		2.04	2.07	2.04	2.04	2.04	2.04
0.01 level		2.75	2.81 **	2.75	2.75	2.75	2.75

links of equal means @ 0.05 level

links of equal means @ 0.01 level

** highly significant difference at the 0.01 level

that they are equal is greater than 2 in 10). This accepted hypothesis that the mean IRM_r of the two groups are equal is shown as an insignificant t-statistic in the comparison of column means. This opposes the findings of Tunnicliff and Root (1984).

2. There is a highly significant difference in IRM_r between saturated specimen and specimen subjected to one freeze-thaw cycle (the probability that they are equal is less than 1 in 1000), shown as a highly significant t-statistic in the comparison of successive column means.
3. There are insignificant differences in IRM_r following the first freeze-thaw cycle (the probability that they are equal is greater than 5 in 100), shown as insignificant t-statistics in the comparison of successive column means.

Two tables similar to Table 5.3 were prepared prepared for the results of each aggregate. Table 5.4 presents results and analysis for only aggregate B. Similarly, Table 5.5 represents aggregate A. By comparison of column means for these tables, the above relationships hold true, with exception to number 2. For aggregate B (the stripper), there remains a highly significant drop in IRM_r between saturated specimen and specimen subjected to one freeze-thaw cycle (the probability that they are equal is less than 1 in 1000). However, for aggregate A (the non-stripper), that same difference is not highly significant (the probability that they are equal is greater than 1 in 100 and less than 5 in 100). This is a significant finding.

TABLE 5.4 – Summary of IRM_r (%) Test Results and Analysis for Aggregate B (n=6)

Index of Retained Resilient Modulus, % (n=6)

	CONDITION CYCLES						
MATERIALS	1 Partially Saturated	2 Fully Saturated	3 Freeze Thaw #1	4 Freeze Thaw #2	5 Freeze Thaw #3	6 Freeze Thaw #4	7 Freeze Thaw #5
BR4	91.91	92.79	74.90	65.38	63.63	60.01	59.01
BR8	92.23	90.47	78.17	76.54	70.44	66.28	66.53
BR12	90.26	92.34	81.95	80.09	74.90	71.13	65.03
B4	103.62	98.81	68.20	61.48	55.64	51.79	51.02
B8	94.95	92.84	66.67	61.27	58.13	50.81	49.91
B12	87.15	89.85	71.00	67.50	62.17	56.20	48.81
BP4	90.62	88.79	64.21	59.52	54.54	51.71	49.22
BP8	96.65	90.25	70.33	65.85	60.26	58.49	57.17
BP12	98.80	97.39	83.86	82.97	77.52	73.66	68.20
BL4	95.53	88.71	66.04	60.16	51.70	48.26	45.35
BL8	90.95	90.57	69.98	60.81	54.49	53.09	51.98
BL12	92.54	95.29	74.76	66.28	55.88	50.15	48.30
block mean	93.77	92.34	72.51	67.32	61.61	57.63	55.04
variance	19.68	10.86	39.78	65.93	72.13	72.96	62.65
size	12	12	12	12	12	12	12
t statistic		0.894	9.655	1.747	1.684	1.144	0.770
degees of freedom		20	17	21	22	22	22
t critical: 0.05 level		2.09	2.11	2.08	2.07	2.07	2.07
0.01 level		2.85	2.90	2.83	2.82	2.82	2.82
			**				

links of equal means @ 0.05 level

links of equal means @ 0.01 level

** highly significant difference at the 0.01 level

TABLE 5.5 – Summary of IRM_r (%) Test Results and Analysis for Aggregate A (n=6)

Index of Retained Resilient Modulus, % (n=6)

	CONDITIONING CYCLES						
MATERIALS	1 Partially Saturated	2 Fully Saturated	3 Freeze Thaw #1	4 Freeze Thaw #2	5 Freeze Thaw #3	6 Freeze Thaw #4	7 Freeze Thaw #5
A4	102.35	101.78	80.60	68.47	59.07	54.89	49.21
A8	94.99	90.45	74.77	67.81	63.49	54.81	50.70
A12	89.70	92.64	87.96	74.78	69.37	58.74	51.04
AR4	95.76	91.29	88.23	86.14	80.20	77.07	76.63
AR8	93.76	89.06	81.48	69.89	67.09	70.09	68.07
AR12	91.10	89.46	91.50	91.90	83.02	78.59	68.83
block mean	94.61	92.45	84.09	76.50	70.37	65.70	60.75
variance	19.71	22.57	38.58	103.35	88.69	119.72	139.90
size	6	6	6	6	6	6	6
t statistic		0.815	2.618	1.561	1.083	0.793	0.753
degrees of freedom		10	9	8	10	10	10
t critical: 0.05 level		2.23	2.26	2.31	2.23	2.23	2.23
0.01 level		3.17	3.25	3.36	3.17	3.17	3.17
			*				

links of equal means @ 0.05 level

@ 0.01 level

* significant differences at the 0.05 level

** highly significant differences at the 0.01 level

The suggestion is to observe IRM_r values obtained after one freeze-thaw cycle to analyze the differences in treatments.

This suggested comparison was accomplished using a CRD with the same 18 treatments (see Table 5.1). Table 5.6 shows these results, and the highly significant F_{trt} indicates that differences between treatment means exist.

Table 5.7 represents results of specific treatment group comparisons following one freeze-thaw cycle. The following comparisons are true:

1. There exists a highly significant difference in IRM_r between the two aggregates (the probability that they are equal is less than 1 in 100). Aggregate A has a higher IRM_r than Aggregate B, suggesting that A does not strip to the same extent as B.
2. The effectiveness of additives on aggregate B (the known stripper) is highly significant at 12% air voids for the PaveBond additive. No other comparison between additive vs. control are significant.
3. The effectiveness of the AC-20R to reduce stripping of aggregate B is highly significant at 8 and 12% air voids (the probability that they are equal to the comparitive control group is less than 1 in 100) and significant at 4% air voids (the probability that that they are equal to the comparitive control group is greater than 1 in 100 and less than 5 in 100).

TABLE 5.6 – Summary of IRM_r Results Following One Freeze–thaw Cycle

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F-ratio
Treatments	17	7010	412	16.1**
Error	90	2300	26	
Total	107	9310		

** Significant at the 0.01 level

TABLE 5.7 - Significant Differences of Treatment Means Following One Freeze-thaw Conditioning Cycle

	Group Comparison		Significance
Effect of Additives at similar aggregate type and air voids content	A4-AR4		**
	A8-AR8		*
	A12-AR12		
	B4-BR4		*
	B8-BR8		**
	B12-BR12		**
	B4-BP4		
	B8-BP8		
	B12-BP12		**
	B4-BL4		
	B8-BL8		
	B12-BL12		
Effect of Air Voids at similar aggregate types and additive types	A4-A8	+	*
	A4-A12	-	**
	A8-A12	-	**
	AR4-AR8	+	*
	AR4-AR12	-	
	AR8-AR12	-	**
	B4-B8	+	
	B4-B12	-	
	B8-B12	-	
	BR4-BR8	-	
	BR4-BR12	-	*
	BR8-BR12	-	
	BP4-BP8	-	*
	BP4-PB12	-	**
	BP8-BP12	-	**
	BL4-BL8	-	
	BL4-BL12	-	**
	BL8-BL12	-	
	Minus (-) sign shows higher air voids with higher IRM_r		
Effect of aggregate type at similar air voids and asphalt type	A4-B4		**
	A8-B8		**
	A12-B12		**
	AR4-BR4		**
	AR8-BR8		
	AR12-BR12		**

KEY: *Significant difference
**Highly significant difference

4. With exception to group comparisons A4–A8, AR4–AR8 and B4–B8, all comparisons show that the higher air voids content have higher IRM_r. Table 5.7 shows which differences are significant.

A prediction model similar to the one given in equation 5.1 can be fit with the data presented in Figures 5.2 and 5.3. Because the test results indicate a significant drop in the IRM_r from full saturation to the first freeze–thaw cycle, and insignificant drops in successsive freeze–thaw cycles, a model could be developed to predict the IRM_r of successive freeze–thaw cycles based on the IRM_r after the first freeze–thaw cycle. Therefore, a fit to the following model was sought:

$$IRM_r = \beta_o + X[\beta_1 agg + \beta_2 air + \beta_3 add + \beta_4 asph] \quad .....(5.1)$$

where: β_0 = IRM_r intercept at X = 0
X = No. of freeze–thaw cycles
1 = freeze–thaw#1
2 = freeze–thaw#2
3 = freeze–thaw#3
4 = freeze–thaw#4
5 = freeze–thaw#5
all other variables defined as before

The computer program STATGRAPHICS (1987) was used to help in the analysis of the least squares fit. By trial, error, and observation of residuals (non–uniform) resulting from the model given as equation 5.1, it was determined that a logrithmic (most likely an exponential decay) model would provide a better fit of the data. Therefore, the

IRM_r results obtained in the laboratory were transformed by the natural logarithm, and the following model was fit:

$$\ln(IRM_r) = \beta_0 + X[\beta_1 agg + \beta_2 air + \beta_3 add + \beta_4 asph] \quad .....(5.2a)$$

or, rewritten

$$IRM_r = \exp(\beta_0)\exp[X(\beta_1 agg + \beta_2 air + \beta_3 add + \beta_4 asph)] \quad .....(5.2b)$$

The least squares fit of this model resulted in the conclusion that "add" (additive type) variable did not add a great deal to the fit of the model (the probability that the "add" slope parameter β_3 is zero is greater than 2 in 10). Therefore the additive type predictor variable was dropped from the model, and the following model was fit:

$$IRM_r = \exp(4.3115)\exp[x/100(-3.7agg - 0.49air + 4.3asph)] \quad ...(5.3)$$

The coefficient of determination (R^2) resulting from this model fit was 0.48, indicating about 48% of the observed variability in the IRM_r is modeled by the predictor variables (air voids, aggregate type, and asphalt type). There is no basis to determine if R^2 is small or large without a lot of experience in problems like this.

5.4 Discussion of Results

As one would have hoped, the M_r test employed for this study was sensitive to material changes. Of primary concern was the ability to discriminate between IRM_r of two types of aggregates, namely a proven stripper and a proven non-stripper. The comparison can be made following the first freeze-thaw cycle.

Because the test is non-destructive, a minimum number of replicates need to be prepared for any group that a user wishes to compare. Kim et al. (1989) suggests using 6-8 replicate specimens for moisture susceptibilty tests. The comparison has the potential to be much more precise than destructive test procedures because the same sample that is tested dry and recorded as the base M_r in the IRM_r ratio is also tested following successive moisture condition cycles, thus reducing the error associated with testing replicate sample groups. The advantage of the IRM_r test over destructive retained strength tests (i.e., split-tension) is increased precision with fewer samples required to perform the tests.

One result of this experiment was the effectiveness (or non-effectiveness) of additives. In all but two cases (B4-BP4 and B4-BL4), the effect of additive treatment was positive (i.e., resulted in a higher IRM_r than the control group). However, the testing was not sensitive enough to detect these effects as being significant, with the exception of the PaveBond Special treatment at high air voids.

The AC-20R polymer modified asphalt appears to be effective for reducing stripping potential in the dense-graded mixes. Through separate studies, rubber asphalts may perform better at lower extreme temperatures than conventional grade asphalts, and their resistance to fatigue appears higher than comparable conventional grade asphalt mixes (Scholz et al., 1987).

Another result of this study was the effect that air void contents have on the IRM_r. In most cases, the IRM_r was higher for high air voids. One explanation for this could be the procedure used in the freeze-thaw cycles (Lottman, 1978). The recommended procedure for

freezing a specimen following a full saturation treatment is to tightly wrap the specimen in a double layer of thin plastic. This is suggested to hold the pore water in the specimen air voids and to prevent drying during the freezing process. The wrapped specimen is then placed in a sealed plastic bag with 10 milliliters of distilled water. This second application is intended to further reduce drying of the specimen. The bagged specimen is transferred to a freezer (0°F ± 3.6°F) for 15 hours. After freezing, the specimen is unwrapped and placed in a distilled hot water bath.

If done properly, the fully saturated specimen (full saturation implies all voids in the specimen are completely filled with water) will freeze with all voids completely full of water. This in turn will lead to substantial void volume changes due to the expansion of pore water to ice. However, by observation, the higher air void groups partially drained from top to bottom prior to freezing, and the lower air void groups did not drain as much, implying that the lower air void groups would probably show a relatively larger change in air voids due to the freezing condition. This could explain why the lower air void groups generally showed lower retained modulus ratios (IRM_r) than the higher air void groups.

After testing was completed and the effect of air voids on the IRM_r was detected, the air void content for each sample were redetermined using the following technique. All samples were air dried at room temperature for 5 months following the 5th freeze-thaw cycle. One group of 6 specimen (AR4) was then subjected to a 48-hour vacuum dessication and another group (B4) to a 48-hour 120°F oven. It was determined that neither method of drying proved to drive off any

remaining water, therefore all samples were assumed "dry" after the 5 month storage at room temperature. In all cases, a range of 4 - 11 grams of water were retained by the samples after the 5th freeze-thaw cycle and following the "drying" period (implies less than 1% moisture retention for a 1200 gram specimen). Therefore, the new air voids were determined using the original dry weight of each specimen, and the respective buoyant and saturated surface dry weights of the conditioned specimen for the calculation of air voids presented in ASTM D-2726 (1987d).

Table 5.8 shows the comparison between the average air voids per group at the dry state and the redetermination of the same specimen following the 5th freeze-thaw cycle. The change in air voids shown in this table illustrates a trend of greater changes for the lower air void groups and smaller changes for the higher air void groups. This trend suggests that the conditioning process may negatively bias low air void groups. The process was developed for samples compacted to 7-8 percent air voids (Lottman, 1978).

The change in air voids also suggests damage to the specimen that is not stripping. It has been shown in previous studies that the M_r is sensitive to air void contents (Hicks et al., 1985). Therefore, the final M_r values obtained after the 5th freeze-thaw cycle were corrected for the change in air voids. By correcting for air void changes, one can visualize damage to the specimen that can only be attributed to moisture damage. The correction to the M_r was determined using a sensitivity analysis presented in Transportation Research Record, 1034 (Akhter and Witczak, 1985). The results of this sensitivity analysis are presented in Table 5.9. The final column in this table represents

TABLE 5.8 - Air Void Content Comparison
Before and After Conditioning

Sample Group	Pre-testing Air Voids,% Ave.	S.Dev.	Post Testing Air Voids,% Ave.	S. Dev.	Change*
A4	5.12	0.20	6.53	0.19	1.41
A8	8.12	0.45	9.31	0.28	1.19
A12	10.00	0.32	10.89	0.34	0.89
AR4	5.46	0.84	6.36	0.64	0.90
AR8	7.14	0.41	8.44	0.41	1.30
AR12	8.87	0.37	10.47	0.58	1.60
B4	6.44	0.59	7.89	0.57	1.45
B8	7.65	0.61	8.98	0.55	1.33
B12	10.07	0.77	10.85	0.58	0.78
BR4	6.09	0.37	7.42	0.34	1.33
BR8	6.91	0.45	8.10	0.40	1.19
BR12	9.50	0.33	10.39	0.60	0.89
BP4	5.63	0.34	7.30	0.89	1.67
BP8	6.78	0.48	8.26	0.47	1.48
BP12	10.99	0.56	11.55	0.50	0.56
BL4	5.49	0.31	7.25	0.27	1.76
BL8	6.17	0.54	7.59	0.58	1.42
BL12	9.21	0.31	10.18	0.27	0.97

*Change = Difference in air voids = Post testing air voids - Pre testing air voids.

TABLE 5.9 - Correction to the IRM_r Due to Air Void Changes

Sample Group	Initial Measurements		Final Measurements Following 5th Freeze-Thaw			Final Measurements Expected by RS Factor	
	Air Voids % (Pi)	Dry M_r, ksi (A)	Air Voids% (Pf)	M_r, ksi (B)	IRM_r%	M_r, ksi* (C)	IRM_r**
A4	5.12	636	6.53	313	49.2	583	57.6
A8	8.12	508	9.31	258	50.7	472	57.8
A12	10.00	393	10.89	200	51.0	372	56.2
AR4	5.46	331	6.36	253	76.6	313	81.9
AR8	7.14	309	8.44	210	68.1	285	75.7
AR12	8.87	218	10.47	150	68.8	197	78.4
B4	6.44	842	7.89	429	51.0	770	59.5
B8	7.65	782	8.98	390	49.9	721	57.7
B12	10.07	552	10.85	269	48.8	527	53.3
BR4	6.09	464	7.42	274	59.0	428	66.8
BR8	6.91	465	8.10	309	66.5	432	73.6
BR12	9.50	308	10.39	200	65.0	292	70.1
BP4	5.63	956	7.30	470	49.2	862	59.0
BP8	6.78	884	8.26	506	57.2	807	66.0
BP12	10.99	469	11.55	320	68.2	454	71.4
BL4	5.49	900	7.25	409	45.4	807	55.8
BL8	6.17	885	7.59	460	52.0	811	60.3
BL12	9.21	575	10.18	278	48.3	542	54.1

* Expected Final M_r estimated by the Relative Sensitivity (R.S.) Factor presented in TRR No. 1034 pg 74 Table 5.

** Corrected for a change due to air voids = [(A - C) + B] / A

% change in M_r (due to a change in air voids only!)

$\% \Delta M_r = R.S. \times (Pf - Pi) / Pi$ where Pi = initial air voids
Pf = final air voids
$R.S. = -0.059(Pi) - (7 \times 10^{-4})$

Using % M_r to estimate final M_r:

M_r (est) f = M_r initial x (100% - $\% \Delta M_r$)

This value M_r (est) f = Resilient modulus anticipated due on to a change in air voids.

The difference between M_r (est) f and M_rf (measured) is the change in modulus due mainly to moisture damage.

the expected IRM_r of each group due only to moisture damage, and shows a considerable amount of M_r loss following the 5th freeze-thaw cycle.

Following all testing and redetermination of air voids, the samples were heated at 120°F for 15 minutes and split apart by hand. Visual inspection of the broken specimens revealed no apparent stripping. Figures 5.4 - 5.6 show typical photographs of the sample groups. Uncoated aggregate is due only to fractured aggregate near the faces of the specimen, most likely fractured during compaction.

From Table 5.9, it was shown that the change in IRM_r due to moisture damage exists. Because stripping was not visually evident in the specimens, the test results did not detect stripping with respect to the loss of adhesion. However, because there was a substantial drop in the IRM_r, the test results must imply moisture damage associated with the loss in cohesion. This conclusion is reasonable in that all specimens retained 4 - 11 grams of water after the 5th freeze-thaw cycle. This retained water is believed to have either slightly changed the phase of the asphalt or emulsified with the asphalt, leading to a softening of the binder associated with a reduction in cohesion.

5.5 Conclusions and Recommendations

Based on the evaluation of the study results, the following conclusions appear warranted:

1. The test procedure developed and evaluated shows evidence associated with moisture damage to asphalt concrete mixtures, based on IRM_r measurements and evaluation.

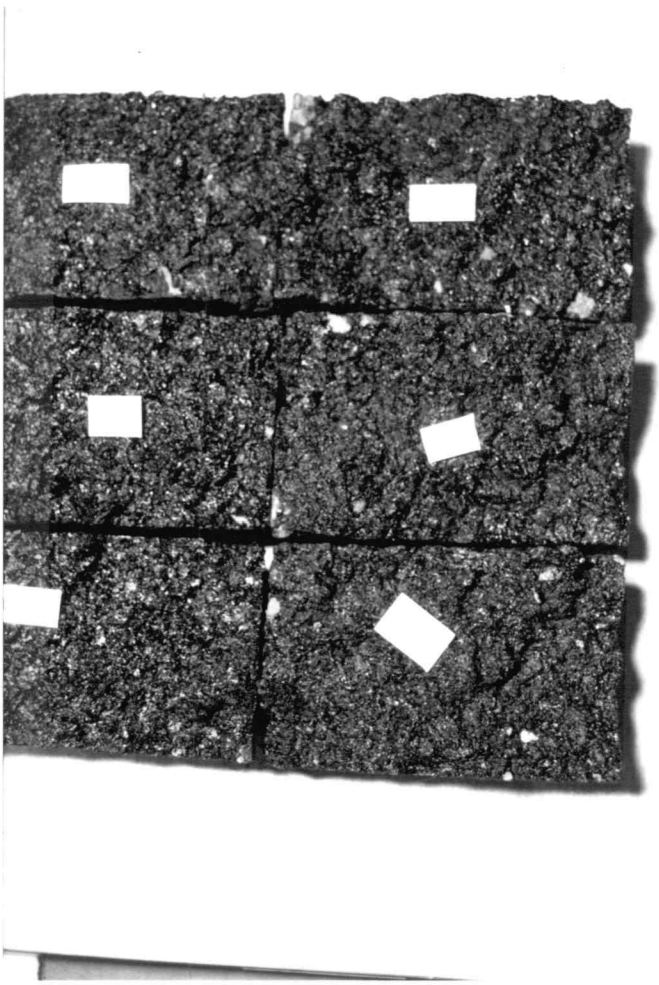


FIGURE 5.4 – Typical Specimens at Low Air Void Contents Following 5 Freeze–Thaw Cycles

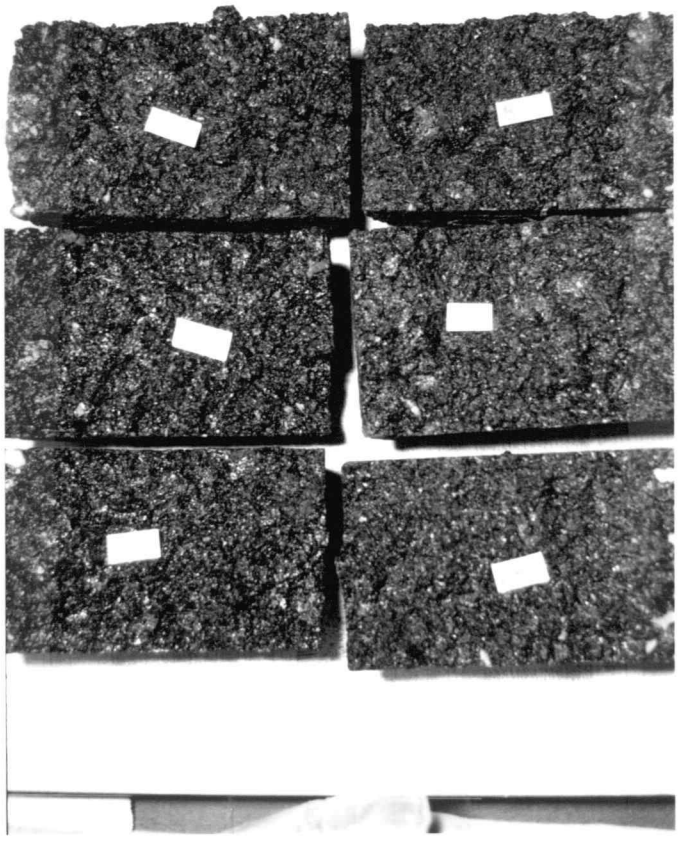


FIGURE 5.5 – Typical Specimens at Intermediate Air Void Contents Following 5 Freeze–Thaw Cycles

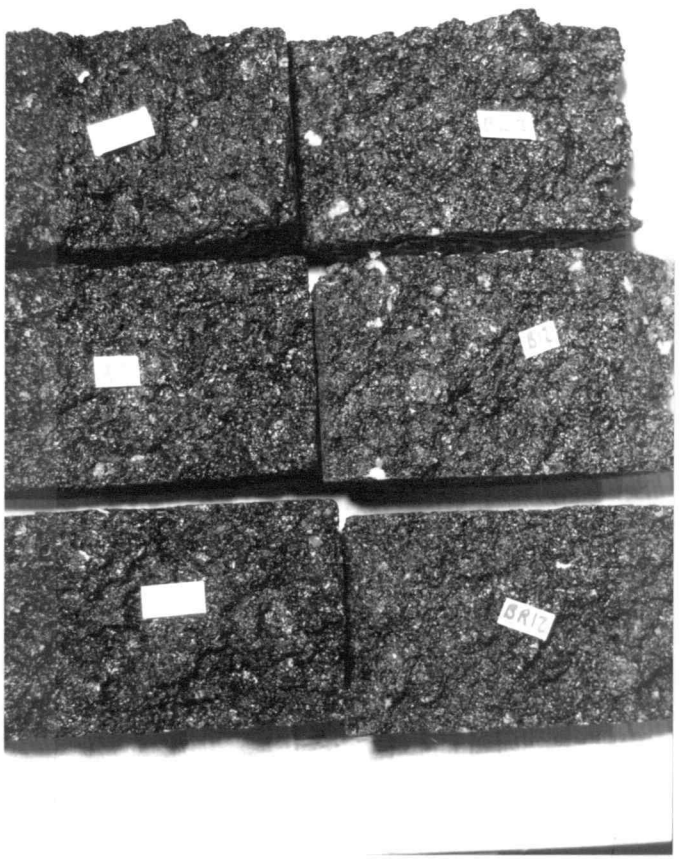


FIGURE 5.6 – Typical Specimens at High Air Void Contents
Following 5 Freeze–Thaw Cycles

2. The loss in M_r associated with moisture damage was significantly greater for the proven stripping aggregate when compared to the proven non-stripping aggregate. The comparison can be made following full saturation plus one freeze-thaw conditioning cycle, and is valid for all levels of air voids tested.
3. The test procedure has a high potential to differentiate between material changes; however this study showed the AC-20R asphalt to be the only additive to show significant effectiveness in preventing stripping.
4. The test procedure detected partial damage to the AC specimen that was not associated with moisture damage. This damage was due to expansion of the specimen during the freezing treatment.
5. The test procedure detected moisture-induced M_r loss (as measured by the IRM_r) to be the greatest for the lower air voids groups and lowest for the higher air void groups, and the differences were significant. This may be explained by partial drainage of high air void groups prior to freezing.
6. The loss in M_r due to moisture damage measured by the IRM_r can be accounted for most realistically by the cohesion mechanism theory rather than the adhesion mechanism theory. This conclusion is based on the visual inspection of all specimen following the 5th freeze-thaw cycle. Evidence of adhesion failure was not apparent.

On the basis of these conclusions, it appears that the test procedure needs modifications so as not to bias mixes based on air void contents. It was shown that the laboratory specimen compacted to low air void contents "stripped" significantly more than the high air void groups. This was explained by the fact that the high air void specimens partially drained prior to freezing, therefore the pore water had less of a damaging effect compared with "undrained" saturated specimen at lower air voids. The following recommendations for the test procedure are given:

1. All saturated specimen should be frozen in a fully submerged condition so that no drainage can take place. Therefore, a set of saturated specimens can be placed in a pan at least 1/2-inch deeper than the height of the specimens (suggest using a 3-inch deep pan for specimens of 2.5-inch height). By freezing this way, the specimens will be confined by external forces caused by the surrounding frozen water, which may better similate freezing conditions of confined pavements in the field. This may also lead to a reduction in expansion of air voids associated with the freezing condition, which in turn led to damage not associated with moisture damage.
2. Along these lines, it is recommended that air voids be re-determined following each conditioning cycle. This is important to correct for damage that is not stripping. The correction to the M_r due to air void changes in this study was made using a sensitivity analysis presented in Transportation Research Record 1034 (Akhter and Witczak,

1985). It is recommended that a similar sensitivity analysis be performed to estimate modulus loss due to changes in air voids over the conditioning cycles.

6 CONCLUSIONS AND FINAL RECOMMENDATIONS

The main goal of this study was to develop an improved test method to quantify the moisture susceptibility of an asphalt concrete (AC) mixture and allow a quantitative assessment of the effectiveness of antistripping additives.

The procedure to determine stripping potential in laboratory compacted AC specimen by means of a Repeated-Load Diametral Test System was selected over other available alternatives because the test is non-destructive. This reduces the total number of specimen required by destructive tests such as the split tensile test to obtain significant relationships between the different mixtures analyzed in this study. A total of 108 specimen were prepared for the Primary Factorial Study (6 replicate specimens at each of the 18 levels of treatments - ie. aggregate type, asphalt type, additive type, and air void content). These specimens were tested for resilient modulus (M_r) at their dry state and after each of 7 moisture conditioning cycles. To obtain the same level of significance for comparisons made in this study using destructive test methods, a total of 864 specimen (108 specimen x 8 cycles including dry state) would have needed to be prepared.

The moisture-conditioning process used in this study was in accordance with NCHRP 192 (Lottman, 1978). A partial saturation treatment as recommended in NCHRP 274 was also used prior to full

saturation and freeze-thaw conditioning (Tunnicliff and Root, 1984). The measurement used for comparison between treatments was the Index of Retained Modulus (IRM_r).

6.1 Conclusions

The following conclusions are drawn from the findings of the Parametric Study and Compaction Study:

1. The M_r computed from the Repeated-Load Diametral Test System has a high potential to differentiate between material changes (ie., air voids, aggregate type, and asphalt type).
2. The test conditions that yield reliable M_r results with the highest degree of sensitivity to material changes include:
    a. 0.1 second load duration
    b. 0.33 hertz load frequency
    c. 50 to 60 microstrain induced diametral strain level
3. The test temperature that yields M_r results with the highest degree of sensitivity to material changes at the above testing conditions is 40°F. However, temperatures up to 60°F were found to result in values with a high degree of sensitivity as well, and 73°F resulted in values that were not significantly sensitive to material changes. The highest allowable temperature is desired. The 60°F test is practicle inside a controlled temperature box (i.e., refrigerator).

4. The preferred method of measurement using the above developed conditions is the total M_r based on the increased precision this measurement has over the instantaneous measurement.
5. Based on replication of both air voids and resulting M_r values, kneading compaction is the most desirable method of sample preparation, although the findings of this experiment showed that the gyratory-shear method of compaction could be used as well. The static method and Marshall method of compaction were ruled out because these methods produced specimens which resulted in M_r values that were not distinguishable between the two curing procedures studied.

Based on the evaluation of the Primary Factorial Study, in which the test method developed would allow for a quantifiable means to assess moisture damage, the following conclusions appear valid:

1. The test procedure developed and evaluated shows evidence associated with moisture damage to asphalt concrete mixtures.
2. There is no significant difference between partial saturation and full saturation with respect to the effect of the IRM_r.

3. Visual inspection of the moisture-conditioned specimens revealed that the loss in M_r associated with moisture damage was due mainly to a loss in cohesion.
4. The results detected partial damage to the AC specimen that was not stripping, but was due to an increase in air voids as a result of pore water expansion during the freeze cycle. It is very difficult to quantify the amount of damage due to this increase in air voids.
5. The test procedure developed has good potential in differentiating between a proven stripping aggregate and a proven non-stripping aggregate. This differentiation can be made following full saturation plus one freeze-thaw condition cycle.
6. The test procedure has a high potential to differentiate between material changes, and more specifically, the effects on the IRM_r of different antistripping additives for the B-aggregate, only the PaveBond Special at high air voids appeared to be effective. The AC-20R appeared to be a significant additive to reduce moisture damage at all air void contents.
7. The loss in M_r due to moisture damage as measured by the IRM_r was, in general, significantly greater for the lower air void groups as compared to higher air voids with the same specimen constituents. The test procedure appears to negatively bias low air void groups and positively bias high air void groups. The bias in the procedure is

believed to be related to the freeze cycle used in the conditioning process.

8. The moisture conditioning process evaluated in this study needs modifications. The process seems to be most severe with low air void groups, and less severe with high air void groups. It is desirable to develop a procedure to standardize the damage effects (i.e., control the degree of saturation during the freeze cycle). Field performance indicates low air void pavements are usually less effected by moisture than are high air void pavements, therefore, a conditioning process that does not negatively bias low air voids is essential.

6.2 Recommendations

Based on the conclusions made on the study results, the following recommendations for further research are given:

1. Although the test procedure developed herein has a high potential to detect quantitatively the effects of moisture susceptibility, it is recommended that the damage that is not stripping also be quantitatively assessed. This type of analysis would need to be undertaken as a future separate study, similar to the sensitivity study by Akhter and Witczak (1985).
2. To further reduce physical damage to the specimen that is not stripping, it is suggested to freeze the saturated specimen in a fully emerged distilled water bath. This

will guarantee full saturation at the time of freezing, therefore, eliminating the partial drainage problem detected in the higher air void groups. This type of freezing may also minimize void changes associated with the freezing pore water. The internal forces created by freezing pore water may be neutralized by the external forces of frozen water surrounding the specimen, leading to minimal void volume change due to the process of one freeze-thaw cycle. This idea could be checked by preparing a reasonable number of replicate specimen (i.e., ± 1% air voids) and subjecting half to the freeze-thaw used in this study and the other half to this recommended procedure. A comparison of air voids following a complete freeze-thaw cycle should be made at the conclusion of each of five successive cycles. If the change in voids in the proposed method is minimal over the cycles, another study similar to the Primary Factorial Study should be undertaken.

3. It is further recommended that the freeze-thaw cycle used in this study be modified as the moisture conditioning process used to initiate stripping. Although Lottman found a good match in the microstructure of lab cores following full saturation plus one freeze-thaw cycle with field cores subjected only to full saturation (Lottman, 1978), the results of lab cores do not allow for an assessment of damage that is not stripping. The partial saturation plus 24 hour soak at 140°F, as recommended by Tunnicliff and

Root (1984), may lead to considerably less damage that is not stripping, and should be investigated with the Repeated-Load Test System direct M_r techniques for quantification of moisture-susceptible mixes. This method of moisture conditioning, plus tensile strength measurements, resulted in sensitivity to moisture damage, effectiveness of antistripping additives and dosage of additives, and asphalt cements from different sources (Tunnicliff and Root, 1984). The strength loss associated with the conditioning can only be attributed to moisture damage by either loss of cohesion, adhesion or a combination of both.

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