A Test Method for Identifying Moisture Susceptible Asphalt Concrete Mixes

by

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16. Abstract

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Under the Strategic Highway Research Program (SHRP) the Environmental Conditioning System was developed. A comprehensive study of the test setup showed that it is a promising concept that needs further modification and evaluation. In this report, several modifications to the original Environmental Conditioning System are proposed. Results from preliminary evaluation of the system are also included. The new system has been better able to discriminate between poor and marginal mixtures.

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Abstract

Moisture damage is a common problem faced by various highway agencies. Researchers have developed laboratory test methods over the years to identify moisture susceptible asphalt concrete mixtures. However, none of them has been successful in consistently discriminating moisture susceptible asphalt concrete mixtures.

Under the Strategic Highway Research Program (SHRP) the Environmental Conditioning System was developed. A comprehensive study of the test setup showed that it is a promising concept that needs further modification and evaluation. In this report, several modifications to the original Environmental Conditioning System are proposed. Results from preliminary evaluation of the system are also included. The new system has been better able to discriminate between poor and marginal mixtures.

Executive Summary

Moisture damage is a common problem faced by various highway agencies. Researchers have developed laboratory test methods over the years to identify moisture susceptible asphalt concrete mixtures. However, none of them have been able to consistently discriminate moisture susceptible asphalt concrete mixtures.

Under the Strategic Highway Research Program (SHRP) the Environmental Conditioning System was developed. A comprehensive study of the test setup showed that it is a promising concept that needs further modification and evaluation. In this study several modifications are proposed to the original Environmental Conditioning System (ECS). The major aspects of the ECS identified for modifications are the conditioning parameters and the resilient modulus measurement setup. The conditioning parameters were evaluated using the indirect tensile strength ratio rather than the resilient modulus ratio because of the poor precision of the original resilient modulus measurement test setup.

Several parameters that can affect the conditioning of specimens were identified and evaluated in this study. The parameters identified are type and level of saturation, temperature of water flowing through the specimen, water flow rate, level of confinement and conditioning temperature. The results of the study indicated that the static immersion saturation should be used rather than the ECS saturation. The temperature of water flowing through the specimen should be increased from room temperature to the conditioning temperature (i.e., 60 °C). The water flow rate should be increased from 4 ± 1 cc/min to 8 ± 1 cc/min. Confinement levels should be decreased from 255 mm Hg to 64 mm Hg to increase the severity of conditioning.

A new test setup was developed which can measure resilient modulus of asphalt concrete specimens more precisely. The developed setup was further evaluated to increase the precision of the resilient modulus test. The results of evaluation suggested that the static load should be increased from 225 N to 450 N and the gauge length, for resilient modulus measurement, should be increased from 25mm to 38 mm. It is also suggested that the Teflon disks between the end platens and specimen should be removed.

The effects of conditioning parameters were studied to implement a predictive criterion based on resilient modulus. The unconditioned resilient modulus should be measured one hour after flowing water at room temperature, through the specimen at 8 ± 1 cc/min for one hour. One continuous conditioning cycle of 18 hours (instead of three 6 hours of conditioning and 3 hours of cooling cycles) is suggested. The conditioned modulus should be measured 24 hours after the completion of the conditioning period. If the circumferential deformation after 6 hours of conditioning is more than 2 percent of the initial circumference, the mix will be considered as moisture susceptible. If the resilient modulus ratio is less than 0.8, the mix will be considered as marginal material. For resilient modulus ratios greater than 0.8, the mix will be considered as well performing mix. This suggested test procedure and predictive criteria were found effective in identifying two moisture susceptible, two marginal, and one well performing mixtures.

Implementation Statement

The results of the present study suggest that the developed conditioning system may reliably predict moisture susceptibility of the asphalt concrete mixes. The new test setup can potentially be used by various districts to identify moisture susceptible asphalt concrete mixes. Also, the effectiveness of various anti-stripping agents can be evaluated using this test setup.

We believe that the system is ready to be implemented in the Materials and Test Division on a trial basis so that the practical short comings of the system can be identified. More specimens from unknown origins should also be tested to ensure the accuracy of the proposed protocol.

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Chapter 1

Introduction

Problem Statement

Most highway agencies experience a reduction in asphalt pavement life due to moisture damage. According to a survey conducted by Hicks (1991) under a National Cooperative Highway Research Program (NCHRP), thirty-four out of forty-six participating states were experiencing moisture damage of the asphalt pavement. The above-mentioned survey also identified that around 10 to 20 percent of the asphalt pavement roads experience moisture damage in Texas.

Various test procedures have been developed to identify moisture susceptibility of asphalt concrete mixtures in the laboratory. However, these test methods do not always yield accurate results either because they do not simulate field conditions or they are too subjective in nature (Terrel and Swailmi, 1994).

An Environmental Conditioning System (ECS) was developed under the Strategic Highway Research Program (SHRP) to evaluate the moisture susceptibility of asphalt concrete mixes. One advantage of this test is that repeated loading similar to traffic is applied to the specimen (Terrel and Swailmi, 1994). A study conducted by Aschenbrener et al. (1995) suggested that although ECS is a promising concept, further evaluation and modifications are necessary before it can consistently identify moisture susceptibility of AC mixes. A study conducted by Tandon et al. (1997) identified several problems associated with the resilient modulus measurement test setup as well as conditioning procedure of the ECS. The problems were the rigidity of the loading system, linear variable differential transformers (LVDT) assembly system and servo valve capacity. The conditioning procedure was identified to be too mild and needed modifications to increase the severity. A study was undertaken to eliminate the identified weaknesses of the ECS.

Organization

In chapter two, a background information on various test procedures currently used by highway agencies is presented. The development of the ECS and identified weaknesses are also presented in that chapter. Finally, the research approach and selection process for the asphalt concrete mixtures, used in this study, is discussed in that chapter.

In chapter three, the identification and evaluation of the important conditioning parameters are presented. The results of the verification of the modified conditioning parameters are also included.

The development and evaluation of the resilient modulus test setup is discussed in chapter four. Included in this chapter are the effects of several parameters on the resilient modulus test results.

In chapter five, the development of the test procedure and the predictive criteria for identifying moisture susceptible mixtures are discussed. A new test procedure and predictive criteria are proposed in that chapter. The suggested test procedure and predictive criteria are also evaluated in that chapter. Finally, the conclusions and recommendations are included in chapter six.

Chapter 2

Background on Moisture Damage

Moisture damage (or stripping) in AC pavements may be associated with two phenomena (Hicks, 1991). First, water can interact with the asphalt cement to cause a reduction in cohesion with an associated reduction in stiffness and strength of the mixture. Second, water can get between the asphalt film and the aggregates, break the adhesive bond between the aggregate and asphalt, and strip the asphalt from the aggregate. Several distresses in the form of ravelling, ruttting or cracking may occur in the pavement due to stripping. As a result, the life of these pavements can be significantly reduced and the maintenance cost of these pavements can tremendously increase. In this chapter, current tests for identifying moisture damage potential, the development of the ECS, the weaknesses of the ECS and the approach to address the weaknesses of the ECS are discussed.

Current Test Methods for Identifying Moisture Damage Potential

Numerous tests have been developed to identify moisture-susceptible AC mixes since 1930s. However, none of these tests are able to consistently identify moisture susceptible mixes. Some of these tests are based on the visual evaluation of stripping of asphalt cement from the loose asphalt mixes. Whereas, others evaluate the ratio of conditioned to unconditioned strength of the compacted specimen, either laboratory made or from field cores. The following tests are most commonly used to evaluate the moisture-susceptible mix.

1) Boiling Test (a. k. a. Tex-530-C or ASTM 3625)
2) Immersion Compression Test (a. k. a. ASTM D-1075 or AASHTO T-165)
3) Modified Lottman Test (a. k. a. Tex-531-C or AASHTO T-283)
4) Texas Freeze-Thaw Pedestal Test
5) Hamburg Wheel-Tracking Test

Boiling Tests (Tex 530 C or ASTM D-3625)

In this test, a loose AC mix is boiled in distilled water for 10 minutes. After boiling the percentage of stripping is visually evaluated. Aschenbrener et al. (1995) suggest that this test does not represent the actual field condition of the mix because it does not take into account the amount of air voids, permeability and gradation of the mix. Study conducted by Parker and Wilson (1986) indicated that this method failed to identify moisture susceptible aggregates for Alabama AC mixes.

Immersion Compression Test (ASTM D-1075)

In this test, two sets of three specimens each, are prepared. The specimens are 102 ± 2 mm in diameter and 102 ± 2 mm in height. One set of specimens is tested for the compressive strength at 25.0 ± 0.2°C without conditioning. The other set of specimens is conditioned by immersing them in water at 60.0 ± 0.2°C for 24 hours. After conditioning, the set is transferred to another water bath where temperature is maintained at 25.0 ± 0.2°C. After storing the specimens for 2 hours in this bath, the compressive strength of the each conditioned specimen is determined in accordance with ASTM D-1074. If the ratio of conditioned to unconditioned strengths is less than 0.7, the mixture is considered as moisture susceptible. Even though the test is widely used for its simplicity, it cannot always predict the moisture susceptible mixes (Stuart, 1986).

Modified Lottman Test (Tex 531-C)

Two sets of compacted AC specimens, four in each set, are prepared in this test method. The specimens are of 102 ± 2 mm in diameter and 63 ± 1 mm in height. Air voids in the specimens shall be within the range of 7 ± 1 percent. The average indirect tensile strength of one set is measured and considered as the unconditioned tensile strength. The other set is subjected to 60 to 80 percent vacuum saturation, a freeze cycle at -18°C for 15 hours followed by a hot cycle at 60°C for 24 ± 2 hours. This set is then tested for their indirect tensile strength. If the ratio of average conditioned to average unconditioned tensile strengths is less than 0.7, the mix is considered as moisture susceptible. This method is fairly successful in identifying moisture susceptible mixtures and is most commonly used by US highway agencies. However, it is not as reliable for marginally moisture susceptible mixes.

Texas Freeze-Thaw Pedestal Test

In this method, hot mix is prepared at a temperature of 150°C using the fine fraction of aggregate passing #20 and retained on #35 mesh. This mix is then kept in an oven at 150°C for 2 hours and stirred every hour for uniformity of temperature. After two hours it is cooled to room temperature and reheated again to 150°C for compaction to make a briquette of 41 mm in diameter and 19 mm in height. The compaction load is about 27.6 KN (6200 lb) and applied for 15 minutes. The briquette is then cured at room temperature for three days and placed on a pedestal in a covered jar of distilled water. It is then subjected to thermal cycling for 15 hours at -12°C followed by 9 hours at 49°C. The briquette's surface is checked for cracks after each cycle. The measure of water susceptibility depends on the number of cycles required for cracking. According to Parker and Wilson (1986), this method does not correlate well with the field performance. However, this method is useful for gaining a broad understanding of the effects of different parameters that can contribute to the moisture susceptibility of a mix (Graf, 1986).

Hamburg Wheel-Tracking Test

This method is developed in Germany. Steel wheels, 47 mm wide, simultaneously apply a load of about 700 N to a specimen at a rate of fifty passes per minute. The prepared specimen is 260 mm wide, 320 mm long, and 430 mm deep. The initial air void of the specimen is maintained at 7±1 percent. Each specimen is submerged under water at 50 °C and is loaded for 20,000 passes or until 20 mm of deformation occurs. If the rut is less than 4 mm after 20,000 passes, the mix is considered as acceptable. Aschenbrener et al. (1995) found that this method correlates better with the field performance. In their opinion, the acceptance criteria for the Hamburg device needed reevaluation. One shortcoming with the method is that it does not provide any fundamental property of the asphalt concrete mixes.

Development of Environmental Conditioning System

Learning from the short comings of the existing methods, the Strategic Highway Research Program (SHRP) funded a project to develop a system that would better simulate the stripping observed under actual field conditions. The Environmental Conditioning System was developed as part of the SHRP A-003A, "Performance Related Testing and Measuring of Asphalt-Aggregate Interactions and Mixtures" project. The following novel features were incorporated in the ECS:

- Control of temperature over a wide range.
- Traffic condition can be simulated by repeated loading.
- The permeability of the specimen can be measured before and after conditioning of the same specimen.
- Resilient modulus can be measured before and after conditioning.

A schematic diagram of the ECS is shown in Figure 2.1. The system includes a fluid conditioning subsystem, an environmental conditioning chamber and a loading subsystem. The fluid conditioning subsystem maintains a constant flow of water and supply of vacuum to the specimen. It consists of a vacuum pump, a water source, valves, pressure gauges, and flow meters. Constant flow of air or water can be achieved through suction applied by the vacuum pump.

The environmental conditioning chamber can maintain high or low temperatures as well as humidity. The variation of temperature and humidity with time can be programmed according to the test protocol. The loading subsystem can be accommodated within this chamber.

The loading subsystem can simulate traffic condition by applying a repeated haversine wave loading on the specimen. It has a servo-pneumatic system, a personal computer with software and a data acquisition card, a transducer signal conditioning unit, a servo valve amplifier, a load frame, an air compressor, and an air filter. The servo valve, which drives a piston by compressed air, is controlled by a computer. A load can be applied to the specimen by the piston through the load cell. Load and deformation of the specimen can be measured from the signals of the load cell and linear variable differential transducers (LVDT's), respectively.

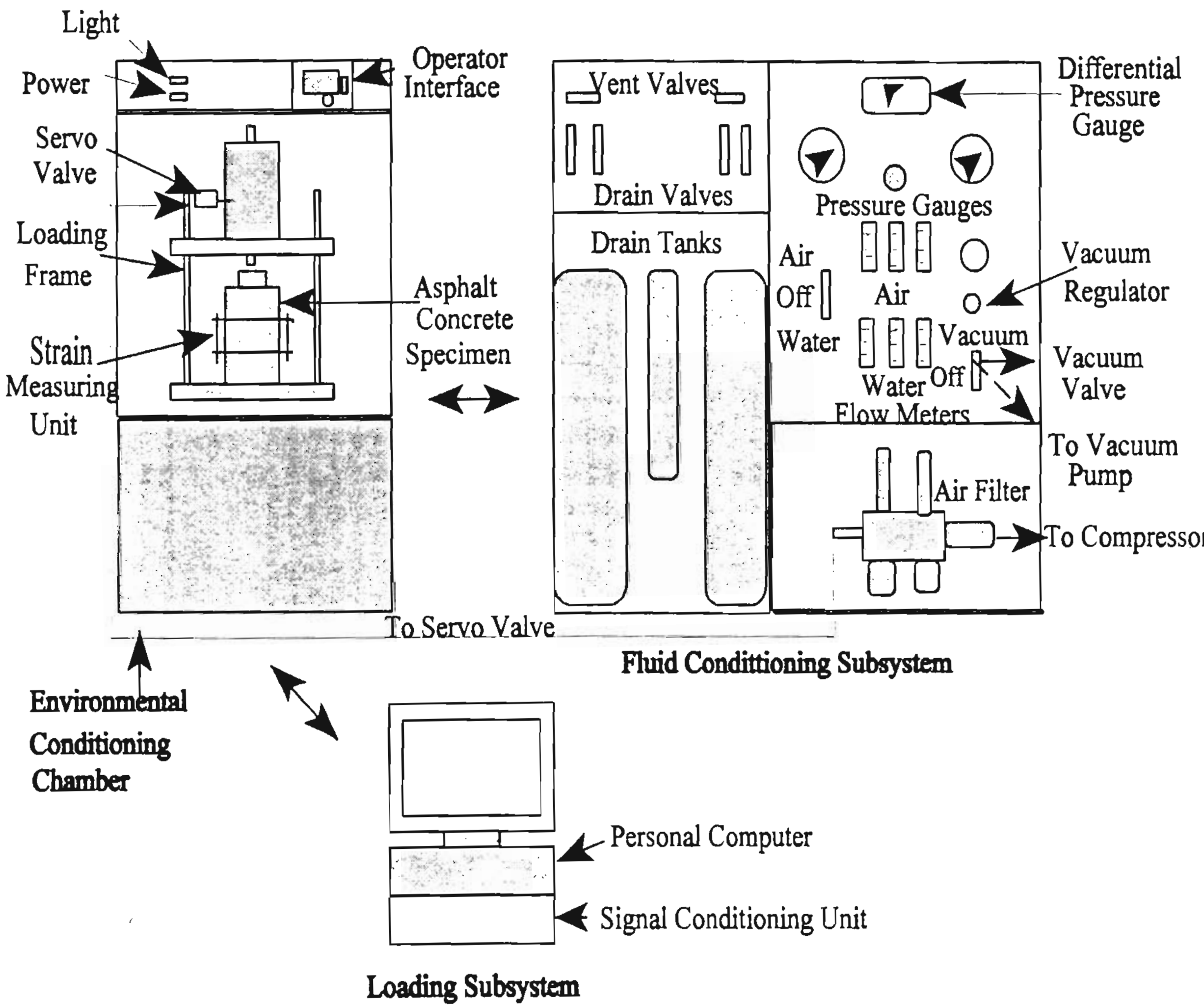


Figure 2.1 - Schematic Diagram of Environmental Conditioning System (ECS)

Original ECS Test Procedure

The specimens used in the original ECS procedure are 102 ± 4 mm high in diameter and 102 ± 4 mm in height. The air void contents of all specimens must be in the range of 7.5 ± 0.5 percent. The loose asphalt concrete mixture is prepared (as per AASHTO TP4-93, Edition 1b) and short-term aged (in accordance with AASHTO PP2-94, First Edition). The short-term aged mixture is compacted using an SHRP gyratory compactor (as per AASHTO TP4-93, Edition 1b). The compacted specimens are left at room temperature overnight to cool, then encapsulated in a latex membrane with silicone, and set aside for a minimum of 15 hours to dry.

The air permeability and dry resilient modulus of the specimen are measured soon after the specimen is placed inside the ECS load frame. The air permeability is determined by flowing air through the specimen at vacuum level of 510 mm Hg (20 in. Hg). The resilient modulus is determined by applying a load in the form of a haversine wave with a loading period of 0.1 second and rest period of 0.9 second. The specimen is saturated by pulling de-aired distilled water through it at a vacuum level of 510 mm Hg (20 in. Hg). The water permeability of the specimen is then determined.

The saturated specimen is subjected to a "hot cycle,"i.e., the specimen's temperature is elevated to 60 °C for six hours while subjected to a haversine loading of 900 N (200 lb). The specimen is then cooled down to a temperature of 25 °C for two to three hours. At the end of the eight hours, the conditioned resilient modulus and the water permeability are determined. The process is repeated for two more cycles, i.e., six hours of loading and heating at 60 °C followed by two to three hours of cooling. In colder regions, a six hours of freezing cycle (-18 °C) must be included. If the ratio of the conditioned resilient modulus to the unconditioned resilient modulus falls below 0.7, the mixture is considered as moisture susceptible and vice versa. After resilient modulus testing, the specimen is split into two halves, so that, the amount of stripping can be visually estimated.

Initial studies conducted by Swailmi and Terrel (1994) showed that the ECS can reliably predict moisture susceptibility of asphalt concrete mixes. However, a study conducted by Aschenbrener et al. (1995) suggested that the ECS test setup and procedure needs further evaluation. Tandon et al. (1997) evaluated the ECS and found several problems associated with the resilient modulus measuring system and testing protocol. The weaknesses of the ECS resilient modulus measuring system and testing protocol are discussed in the next section.

Weaknesses of Environmental Conditioning System

One of the problems associated with the original resilient modulus test setup is the rigidity of the loading frame. The loading frame should be rigid enough so that it would not move under the loads applied to the specimen. The study conducted by Tandon et al. (1997) showed that the loading frame should be more rigid.

The capacity of the servo valve was insufficient to apply the desired loads to the specimens. The original ECS test procedure suggested applying loads to the specimen such that the strain of the specimen was within 50 μm/m to 100 μm/m. However, for some stiff mixtures, such level could not be achieved without exceeding the capacity of the servo valve.

The LVDT yoke assembly of the resilient modulus test setup consisted of different materials. Because of variation in the coefficient of thermal expansion between different materials, frequent readjustment of the LVDT was necessary when the temperature of the specimen was increased from 25°C to 60°C. A better yoke assembly or non-contacting transducers are needed to accurately measure the deformations.

According to the original ECS test procedure, the conditioning consisted of subjecting the specimen to cyclic loads at 60°C for six hours while water was continuously passed at 25°C through the specimen at a rate of 4 ± 1 cc/min. Although the temperature of the conditioning chamber was maintained at 60°C, the specimen might not reach 60°C temperature because water was flowing at 25°C through the specimen. A better control of water temperature seemed prudent.

Research Approach

This study was divided into three phases. In the first phase, the parameters affecting the conditioning severity were identified and evaluated. The evaluation criterion was based on the indirect tensile strength (ITS) ratio rather than the resilient modulus (M_R) ratio. The selection of the ITS ratio was necessary due to poor accuracy and precision of the original resilient modulus test setup. The ITS ratio is the ratio of the conditioned ITS to unconditioned ITS. Since the ITS is a destructive test, five specimens of each mixture were prepared and ITS test was performed without conditioning to obtain the average unconditioned ITS. After conditioning specimens for each parameter, the ITS test was performed to obtain the conditioned ITS. The ratio of the conditioned ITS and the average unconditioned ITS was used to evaluate each parameter.

In the second phase of the study, a new resilient modulus test setup was developed and evaluated. The evaluation of resilient modulus test setup was performed using a synthetic specimen. In the third phase, a new predictive criterion was proposed using newly developed resilient modulus test setup. The proposed predictive criterion was also verified in the third phase.

Selection of Materials

Five different asphalt concrete mixtures were used for this research. These materials were recommended by the TxDOT personnel based on their historical performance. The mixes were the Austin, El Paso II, El Paso III, Atlanta, and Corpus Christi. Historically, the Austin mix is not considered as moisture susceptible, the El Paso II and El Paso III mixes are moderately susceptible to moisture damage and the Atlanta and Corpus Christi mixes are severely susceptible to moisture damage. The mix designs as well as the aggregate and binder properties for all the mixes, except for the El Paso II and III mix, were provided by the TxDOT. The Jobe Concrete Company in El Paso provided the mix design and aggregate properties for the El Paso II and III mix. Properties of the mixes are shown in Table 2.1 and aggregate gradations are shown in Figure 2.2.

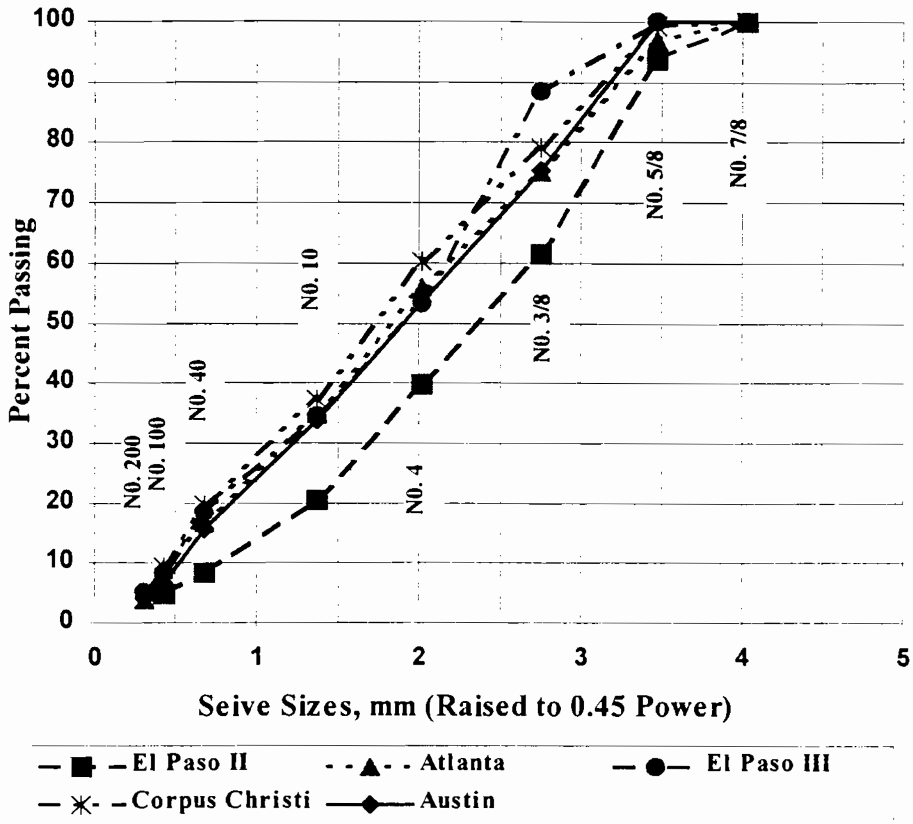


Figure 2.2 - Gradation Chart for the Aggregate of the Mixes

Table 2.1 - Mix Properties of Materials Used in this Study

Specification	Austin	El Paso II	Atlanta	Corpus Christi	El Paso III
Mix Type	Type-D	Type-D	Type-C	Type-C	Type-D
Asp. Type	AC-20	AC-20	AC-20	AC-20	AC-20
Asp. Content	4.8 %	4.9 %	4.9 %	5.2 %	4.7 %
Aggregate Type	Limestone	Crushed Gravel	Siliceous Gravel	Crushed Gravel	Granite (34 %)
Aggregate Content	Type C (20%)	Coarse Aggregate (56 %)	Type C (23%)	3/4 in. Crushed Gravel (17%)	3/8 in. Granite (34%)
	Grade 4 (20%)	Rock Screening (30%)	Type D (42%)	7/16 in. Crushed Gravel (38%)	3/8 in. Crushed Gravel (25%)
	Type F (25%)	Sand (14 %)	Screening (25%)	Limestone Screening (35%)	Screening (32%)
	Manufactured Sand (23%)	N/A	Washed Sand (3 %)	Sand (10 %)	Sand (9 %)
	Field Sand (12%)	N/A	River Sand (7%)	N/A	N/A
Sand Equivalent	79	77	59	80	55
Bulk Specific Gravity	2.607	2.713	2.625	2.570	2.673
Rice Specific Gravity	2.430	2.415	2.425	2.427	2.491

Chapter 3

Identification and Evaluation of Conditioning Parameters

As indicated in Chapter 2, the original conditioning process seems to be too mild to discriminate between well-performing and damage-susceptible mixes. The flow and temperature of the water circulated through the specimen during conditioning were identified as the possible parameters that can be modified. The temperature of the environmental chamber can also be changed to improve the conditioning process. The vacuum level used to flow water through the specimen is a source of concern, since it also exerts a confining pressure to the specimen. Finally, the level of saturation of the specimen should also be considered. Other parameters, such as loading level, the number of cycles, the length of the cycles, the air voids of the specimens, and the dimensions of the specimens were all kept constant.

In this chapter, various parameters related to the conditioning process that were examined are discussed. The modifications suggested to those parameters that can improve the conditioning process are discussed. Finally, the validation of the modified parameters is presented.

Identification of Conditioning Parameters

The basic protocol suggested in chapter 2 was followed to condition the asphalt concrete mixes. However, some aspects of the testing procedure were modified. In the following sections, the justifications for changes made in each aspect of the test are discussed.

Type and Level of Saturation

In the original ECS conditioning procedure, the compacted specimens are encapsulated in a rubber membrane with silicone cement, and set aside for a minimum of 15 hours to dry. For practical purposes, it would be desirable to eliminate this process. The silicone cement eliminates the passage of water around the specimen, and ensures that it seeps through the specimen. The saturation or wetting of the specimen is achieved by circulating high volume (about 10 to 20 liters) of water through the specimen for a period of 30 minutes using a vacuum pump regulated to 500 mm Hg (20 in. Hg). Therefore, a significant amount of distilled de-aired water is required for this task. After the specimen is saturated, the level of saturation cannot be measured because it is impossible to remove the silicone cement from the perimeter of the specimen without damaging it. Hence, the method of saturation needed improvement.

The modified Lottman (Tex-531-C) test procedure uses static immersion to achieve a degree of saturation in the range of 60 to 80% by applying a 500 mm Hg (20 in. Hg) of vacuum. This method of saturation reduces the consumption of distilled de-aired water, and at the same time, the level of saturation can be identified. Since the amount of water flowing through the specimen in static immersion process is significantly less (as compared to the ECS protocol), the silicone cement can be replaced by a commercially available item called the Caulktrim Tape. The advantage of Caulktrim Tape is that the test can be immediately performed after the tape is placed around the specimen. The Caulktrim Tape restricts the flow of water around the specimen at flow rates less than 10 cc/min.

Aschenbrener et al. (1996) suggested that the level of saturation in the modified Lottman (Tex-531-C) procedure could be increased to maximum level, so that mixtures that are marginally moisture-susceptible can be better identified. The CDOT in their procedure (CP L5109) suggested that, the AC specimen should be immersed in distilled water at 25°C in a closed container and subjected to vacuum pressure of 660 mm Hg (26 in. Hg) or higher for a period of 5 minutes. It was also suggested that this procedure would provide maximum degree of saturation without degrading the specimen before conditioning.

One modification suggested to the ECS conditioning procedure is performing static immersion saturation following CDOT's recommendations, and then encapsulating the specimen in Caulktrim tape. This method of saturation saves time, significantly reduces the amount of distilled de-aired water, with an added advantage that the degree of saturation can be identified. In this research, the method suggested by CDOT and the original method used in the ECS were compared to identify the feasibility of substituting the new method in the ECS.

Water Flow

After the initial saturation achieved and during the conditioning process, the water is continuously pulled through the specimen by applying a vacuum of 255 mm Hg (10 in. Hg) to one end of the specimen, and by continuously supplying water at the other end. The suggested rate of water flow is 4 ± 1 cc/min. However, under actual field condition, the continuous flow of water is not necessarily encountered. Therefore, the current conditioning procedure can be modified by eliminating the flow of water through the specimen during conditioning process. This can be achieved by stopping the source of water from the bottom of the specimen. This modified procedure was also compared with the current conditioning process.

Vacuum Level

The original ECS procedure suggested applying a vacuum of about 255 mm Hg (10 in. Hg) to facilitate the flow of water through the specimen and to maintain its saturation throughout the conditioning period. The vacuum also exerts a confining pressure of about 255 mm Hg (10 in. Hg) to the specimen. The specimens tested in the ECS typically contain air voids of about 7 percent. For such specimens, the strength and resistance to deformation are related to the level of confinement. Based on the layered elastic theory, a realistic confining pressure encountered in the asphalt concrete pavement in the field should be less than 255 mm Hg (10 in. Hg).

In this research, specimens were subjected to vacuum levels of 255 mm Hg (10 in. Hg), 128 mm Hg (5 in. Hg), 64 mm Hg (2.5 in. Hg), and 0 mm Hg. At a vacuum level of zero, no excess water would flow through the specimen. A vacuum level of 64 mm Hg (2.5 in. Hg) was selected as a minimum pressure level that could be consistently maintained with the existing system. The vacuum level of 128 mm Hg (5 in. Hg) was selected as an intermediate pressure level. The results are discussed later.

Water Temperature

As indicated in Chapter 2, the temperature within the specimen is unknown during the original ECS tests because water flows at a temperature of 25°C while the chamber temperature is set at 60°C. Therefore, the water was heated to a temperature similar to that of chamber temperature. The water was directed through a temperature bath unit before being introduced to the specimen. The temperature bath unit designed for this purpose is described in Appendix A. Basically, the temperature water bath unit consists of a stainless steel container enclosed in Styrofoam, a heating element, copper tube, and a thermostat. The container is filled with water and then heated using the heating element. The temperature inside the container is maintained using a thermostat. The water for the specimen then flows through a copper tube submerged in the heated water. The distilled de-aired water flowing in the copper tube increases in temperature. The outlet of the copper tube in the bath is connected to the inlet of the specimen via a bypass valve. By calibrating the thermostat, desired level of water temperature can be achieved.

Chamber Temperature

Chamber temperature of 40°C and 60°C were considered in this research. The chamber temperature of 60°C is recommended in the ECS procedure. Since the water flowing through the specimen is at 25°C and the chamber temperature is at 60°C, 40°C may be a good average temperature for the specimen.

Experimental Plan

Three mixtures were selected: 1) a well-performing mix from Colorado, 2) a moisture-susceptible mix from Atlanta, and 3) a marginal mix from El Paso II. As mentioned in the previous section, the original ECS conditioning was not severe enough to damage the moisture susceptible mix. Therefore, the objective of this experimental plan was to increase the severity of the conditioning process so as to damage the Atlanta material and not severe enough to damage the Colorado material. It was also decided to validate the newly developed conditioning procedure by testing the marginal material.

As indicated in the previous section, two methods of saturation (i.e., static immersion and ECS saturation), two levels of water flow (i.e., no water flow and water flow at a rate of 4 ±1 cc/min), four vacuum levels (i.e., 255, 128, 64, and 0 mm Hg), and two chamber temperatures (i.e., 40 and 60 °C) were used to develop a modified conditioning process.

Analyses of Results

In all, 35 specimens from Atlanta mix, 28 specimens from Colorado mix, 5 specimens from El Paso II mix, and 6 specimens from El Paso III mix were tested for various conditioning procedures comprising of various combinations of the variables.

The evaluation of the conditioning parameters was performed using the ITS ratio, since the resilient modulus test setup was in the development stage. The average ITS of five unconditioned specimens was considered to determine the ITS ratio of each conditioned specimen of each mix.

Type and Level of Saturation

Two specimens each of the Atlanta and Colorado mixtures were tested to identify the effects of saturation method. Both specimens were tested at 40°C and 60°C chamber temperatures, and a confining pressure of 255 mm Hg with water flowing at a rate of about 4 ± 1 cc/min. For the static immersion saturation, the vacuum level was maintained at about 660 mm Hg for 5 minutes.

The results of the tests performed are shown in Table 3.1. For the 60°C chamber temperature, the ITS ratio varied from 0.86 to 0.91 for the Atlanta mix, and from 1.02 and 1.01 for the Colorado mix. For the Atlanta mix, the ITS ratio varied from 0.84 for the ECS saturation to 0.78 for the static saturation; while for the Colorado mix, the ITS ratio varied from 1.17 for the ECS saturation to 1.23 for the static saturation. Given the typical variability in the ITS test results, it was judged that the two methods of saturation provide similar results. Therefore, the static immersion was adopted for the modified conditioning process since it has several distinct benefits as compared to the ECS saturation protocol.

Water Flow

As indicated before, under field conditions, water may not continuously flow through the AC pavements. To study this matter, the specimens were saturated and then the flow of water was prevented during conditioning cycles. Since there was no flow of water, the vacuum was also eliminated during the conditioning cycles. The other parameters of the original procedure were kept constant.

Table 3.1 - ITS Ratio Obtained for Two Types of Saturation at 255 mm Hg of Vacuum

Chamber Temperature	Mix	Method of Saturation	
		Static Immersion	ECS
60°C	Atlanta	0.91	0.86
	Colorado	1.02	1.01
40°C	Atlanta	0.78	0.84
	Colorado	1.23	1.17

Specimens from the Atlanta and Colorado mixtures were tested under no flow and zero vacuum conditions (no confining pressure). Both specimens failed (crumbled) within 30 minutes of first conditioning cycles. This phenomenon clearly exhibits the effects of the applied vacuum on the apparent strength of the specimen. Another encouraging conclusion from this exercise was that by controlling the flow of water and the level of vacuum one could fail any mixture. Therefore, an optimum condition between those suggested by the ECS and the one used in this exercise should exist that would discriminate between well-performing mixtures and moisture susceptible ones.

In the next step, the water valve was closed while the vacuum was applied to the specimen. In that manner, a confining pressure was applied to the specimen, but the flow of water was eliminated. The ITS ratios from tests on the specimens from the Atlanta and Colorado mixtures are shown in Table 3.2. Also, shown in the table is the degree of saturation after each conditioning cycle. The obvious problem with that method was that the degree of saturation changed significantly during each conditioning cycle. In each case shown in Table 3.2, the degree of saturation after three cycles was less than 40 percent. As such, this practice was considered not practical, and was not pursued any further.

From the results obtained for the Atlanta mix, the ITS ratio increased from 0.78 for the first cycle to 1.12 for the third cycle at a confining pressure of 255 mm Hg. Similarly, at a confining pressure of 128 mm Hg the ITS ratio increased from 0.81 to 0.88. This may be attributed to the decrease in the level of saturation of the specimens from the first cycle to the third cycle, and hence, a gain in the strength of the specimen. One possible explanation might be that simply 4 ± 1 cc/min water flow might not be enough to maintain the level of saturation within the specimen. Based on that premise, a study was carried out to optimize the flow rate.

Typical variation in the degree of saturation as functions of rate of flow and conditioning period is shown in Table 3.3. The first obvious trend is that the degree of saturation, irrespective to the rate of flow, substantially decreased during the first conditioning cycle, after which it became constant. However, based on the results shown in the table and our experience, the rate of loss of saturation is more gradual when the rate of flow is at or above 8 ± 1 cc/min. Therefore, a rate of flow of 8 ± 1 cc/min has been tentatively proposed in this study.

Table 3.2 - Results from Tests on Specimens of Atlanta and Colorado Mixture when Water Flow was eliminated

Confining Pressure mm Hg	Parameter	Mixture					
		Atlanta			Colorado		
		Conditioning Cycle			Conditioning Cycle		
		1	2	3	1	2	3
255	ITS Ratio	0.78	0.80	1.12	1.23	1.34	1.09
	Degree of Saturation	62%	58%	57%	61%	59%	27%
128	ITS Ratio	0.81	0.80	0.88	1.16	1.03	1.11
	Degree of Saturation	64%	57%	37%	56%	44%	37%

Table 3.3 - Variation in Degree of Saturation with Rate of Flow at Different Stages of Conditioning

Flow (cc/min)	Degree of Saturation (percent)			
	Initial	After 1st Cycle	After 2nd Cycle	After 3rd Cycle
4 ± 1	75.9	59.3	57.3	56.8
6 ± 1	73.2	58.0	56.2	55.6
8 ± 1	72.6	60.5	59.5	58.0
10 ± 1	68.2	58.0	56.3	55.4
12 ± 1	75.2	55.0	46.7	53.2
14 ± 1	74.5	55.2	54.3	54.0

Material: El Paso III

Effect of Confining Pressure (Vacuum Level)

In the previous two sections, it was established that the severity of the conditioning process can be controlled by changing the confining pressure or the chamber temperature. To establish the effects of the confining pressure, specimens from the Atlanta and Colorado mixtures were tested at four confining pressures.

A problem was faced while testing the Atlanta specimens. At lower confining pressures, the specimens experienced excessive deformation. Typical variation in the height and the circumference of a specimen is included in Table 3.4. This test was performed at a chamber temperature of 60°C and a confining pressure of 64 mm Hg. The height of the specimen decreased from 102 to 97 mm and the circumference increased from 319 to 342 mm. Since it is not possible to measure the ITS deformed specimen, it was decided to use another criterion for failure. A specimen was considered as failed if its circumference increased by more than 2% during conditioning. This failure criterion is very similar to those used in the Hamburg wheel tests.

Table 3.4 - Hourly Data for the Representative Sample of Atlanta Mix

Conditioning Period (hr)	Specimen Dimensions	
	Height (mm)	Circumference (mm)
Initial	102	319
1	102	319
2	101	330
3	99	335
4	98	340
5	98	340
6	97	343

The average of typically three ITS ratios obtained from tests performed on different specimens are given in Table 3.5. In all these tests, the water temperature circulated through the specimen as well as the chamber temperature was set at 60°C.

For the Atlanta mixture, the specimens experienced excessive deformation when the vacuum level was at or below 128 mm Hg. Being a highly moisture-susceptible material, this behavior was desirable. For a vacuum level of 255 mm Hg, similar to the level used in the standard ECS conditioning, the ITS ratio was about 0.9 even after three conditioning cycle.

On the other hand, for the Colorado mix, for confining pressures in excess of 64 mm Hg, the ITS ratios were never less than 0.95 indicating that the material is not susceptible to moisture damage. As indicated before, when the specimens from Colorado mix were tested without confining pressure, the specimens failed due to extreme deformation.

Table 3.5 - Comparison of ITS ratio at Different Confining Pressures

Confining Pressure mm Hg	**Mixture**					
	Colorado			**Atlanta**		
	Conditioning Cycle			**Conditioning Cycle**		
	1	**2**	**3**	**1**	**2**	**3**
255	1.17	0.98	1.02	0.86	0.88	0.91
128	1.09	0.80	0.95	D	D	D
64	1.19	1.05	1.00	D	D	D
0	D	D	D	D	D	D

D denotes failure due to excess deformation criteria

Effect of Temperature

To determine the effects of temperature, the tests performed on the Atlanta and Colorado mixes at a temperature of 60°C (see Table 3.5) were repeated for a temperature of 40°C. The ITS ratios measured at the two temperatures are compared in Table 3.6.

For the Atlanta mix, for a confining pressure of 255 mm Hg, the two temperatures yielded similar results. The reason for this matter is not known, since one expects that the specimens conditioned at higher temperatures should exhibit lower ITS ratios. However, at confining pressures of 128 mm Hg and 64 mm Hg, the specimens conditioned at 40°C did not indicate the potential for moisture susceptibility. At these confining pressures, the specimens conditioned at 60°C failed due to excessive deformation.

For the Colorado mix, considering the results from the third cycle of conditioning, the specimens conditioned at 40°C exhibited higher ITS ratios, which can be translated to gentler conditioning. In almost all cases the ITS ratios were larger than unity indicating that the specimens were actually stronger after conditioning.

Table 3.6 - Indirect Tensile Strength Ratios for Specimens Tested

a) Atlanta Mix

Confining Pressure mm Hg	Chamber Temperature					
	40°C			60°C		
	Conditioning Cycle			Conditioning Cycle		
	1	2	3	1	2	3
255	0.78	0.84	0.93	0.86	0.88	0.91
128	1.22	1.13	1.13	D	D	D
64	1.13	1.12	1.41	D	D	D

b) Colorado Mix

Confining Pressure mm Hg	Chamber Temperature					
	40°C			60°C		
	Conditioning Cycle			Conditioning Cycle		
	1	2	3	1	2	3
255	1.11	1.11	1.09	1.17	0.98	1.02
128	1.05	0.92	1.05	1.09	0.80	0.95
64	1.47	1.14	1.14	1.19	1.05	1.00

D denotes failure due to excess deformation criteria

Based on the results of this study, it is recommended that the ECS saturation be replaced by static immersion saturation. The water flow rate of 4 ± 1 cc/min may be increased to 8 ± 1 cc/min flow rate. The confining pressure of 255 mm of Hg may be reduced to 64 mm of Hg, and the water temperature may be increased to 60 °C from 25 °C for increasing the severity of conditioning. For verification purposes, new specimens were subjected to the new protocol. The results are reported in the next section.

Verification of Suggested Conditioning Parameters

For the validation of this conditioning procedure three mixtures were tested; Atlanta (moisture-susceptible), Colorado (well-performing)and El Paso II (marginal). Four specimens of each mixture were tested to validate the process as well as to determine the repeatability.

The specimens prepared from the Atlanta mixture experienced deformations in the circumference in excess of 5% within the first conditioning cycle. The increase in the circumference for each specimen was measured at 30 minute intervals. The time at which a 5 percent increase in the circumference was measured is reported in Table 3.7. On the average, the specimen deformed by 5 percent after 3.5 hours. The time to failure varied from 2 to 5.5 hours.

The specimens prepared from the Colorado mixture did not experience any measurable increase in the circumference after three conditioning cycles. The ITS ratios from the four specimens were always greater than 1, indicating that the mixture was well-performing. The coefficient of variation for the four specimens was about 3 percent, indicating good repeatability.

The El Paso mixture, which is considered as a marginal mixture, also did not experience any significant change in the circumference during the three conditioning cycles. The ITS ratios for the four specimens tested varied from a minimum of 0.61 to a maximum of 0.80 with an average of about 0.69. The coefficient of variation for this material was about 12 percent, which is in line with the coefficients of variations measured during the evaluation phase. The test results suggest that the failure criterion of 0.7 may be replaced by 0.8 for identification of marginal mixtures.

The test results indicate that the modified conditioning parameters seem to be more reasonable than the original conditioning parameters of the ECS test protocol in terms of identifying moisture susceptible as well as marginal materials. The proposed changes seem to be a good compromise between the original ECS conditioning procedure (that is too mild to consistently identify poor-performing materials), and the Hamburg wheel tester (that is too harsh to consistently identify well-performing materials). However, a predictive criterion based on resilient modulus is desirable because it is a nondestructive test and the M_R ratio can be obtained from the same specimen.

Table 3.7 - Test Results Obtained with the Proposed Conditioning Procedure on Three Mixtures

Specimen	Mixture		
	Atlanta	Colorado	El Paso II
	Time to 5% Change in Circumference (hr)	ITS Ratio	ITS Ratio
1	2.0	1.06	0.61
2	4.5	1.05	0.68
3	3.0	1.11	0.80
4	5.5	1.08	0.68
Average	3.7	1.08	0.69
Std Dev	1.5	0.03	0.08
C.V.	41 %	2.8 %	11.6 %

Chapter 4

Development and Evaluation of Resilient Modulus Test Setup

The development and evaluation of the resilient modulus test setup was divided into three steps. In the first step, the original test setup was modified. In the second step, the newly developed test setup was evaluated. Different parameters that would impact the precision of the resilient modulus were studied in the third step.

Resilient Modulus Measurement and Testing Equipment

The results of the study conducted by Tandon et al. (1997) suggested that the original ECS test setup needs further improvements for increasing the reliability of the system. Since the modification of the original test setup was not practical, it was decided to develop a new test setup. The original test setup consisted of a loading system, an environmental chamber, strain measurement system, and a fluid conditioning system. Each system of the new test setup is discussed in the following sections.

Loading System

The measurement setup for M_R tests must be rigid enough to withstand the applied cyclic loads. The test setup should also withstand a 60°C temperature during the conditioning cycle. A hydraulic dynamic servo-valve closed-loop system is quite suitable for this purpose. The one used in this study was manufactured by the MTS corporation. The system is controlled by a computer software called ATS (1995). The diagram of MTS is shown in Figures 4.1 and 4.2. Various components of the test setup are described in the next sections.

A loading capacity of about 9 KN (2000 lb) is desirable to develop strains as high as 200 μm/m for most of the AC mixtures. The capacity of the servo-valve should be at least 50 percent higher than the capacity of the load cell to ensure uniformity in loading. Such capacities are necessary to address

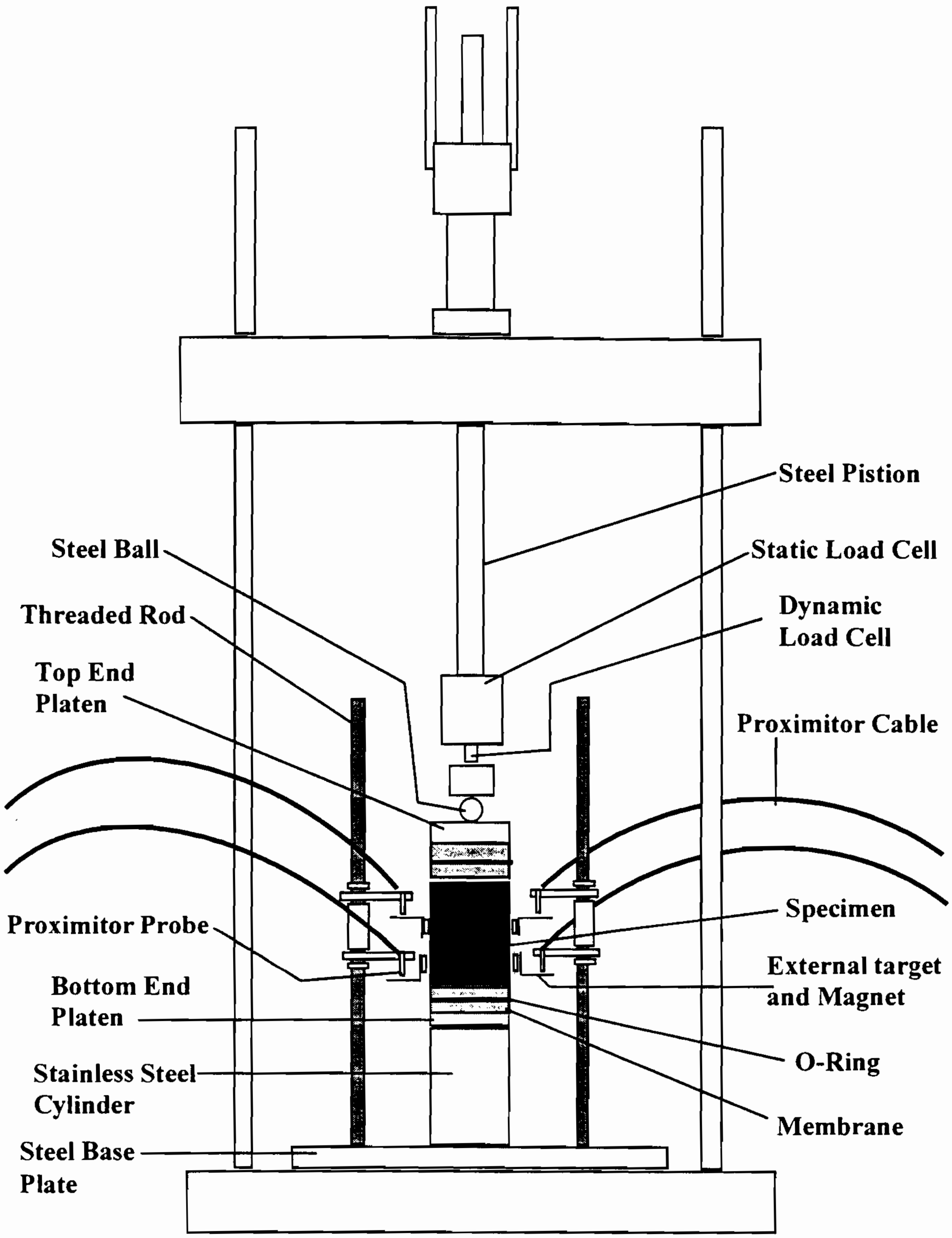


Figure 4.1 - Sketch of Resilient Modulus Test Setup (Not to the Scale)

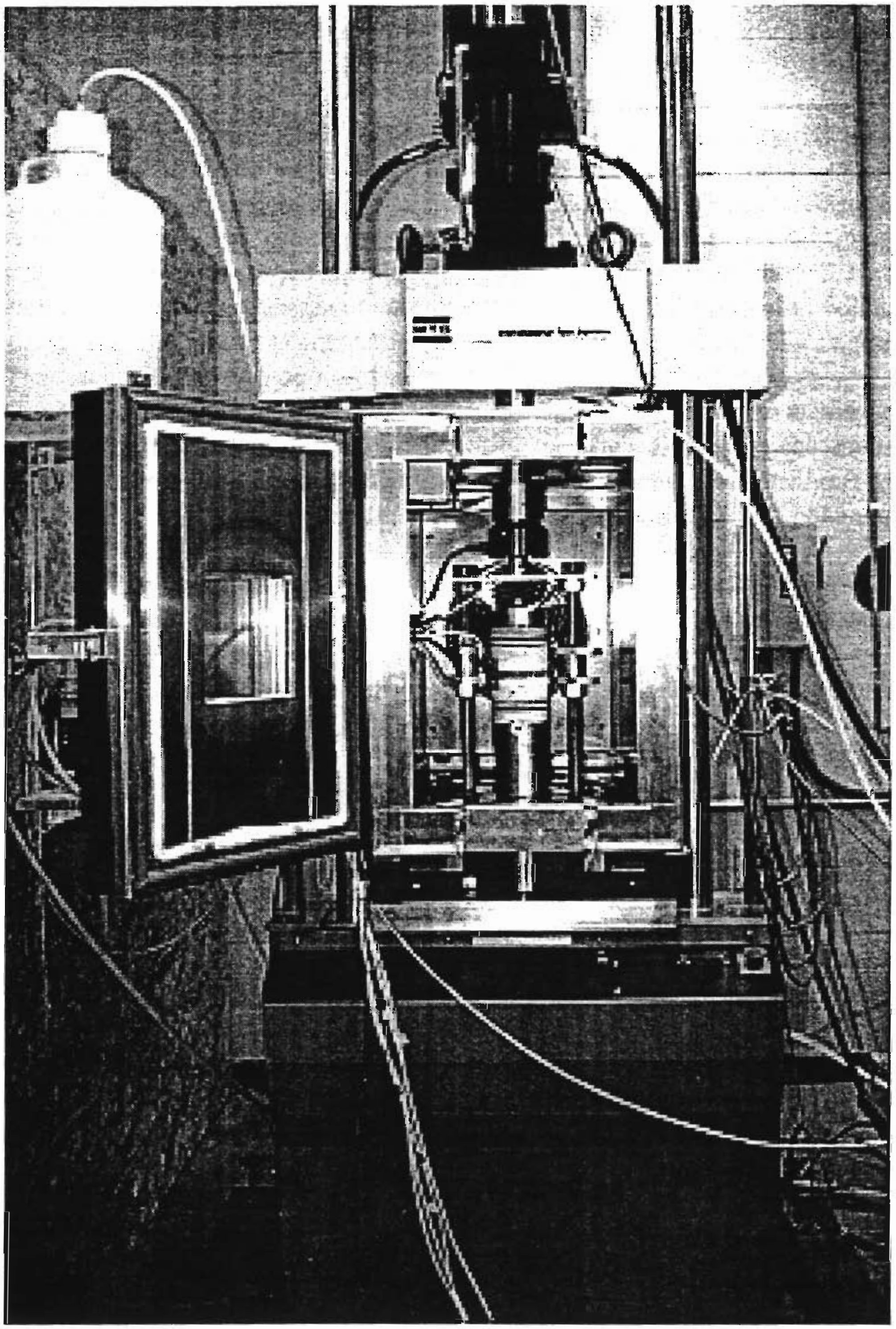


Figure 4.2 - Picture of Modified ECS Resilient Modulus Test Setup

some of the concerns of Tandon et al. (1997) with regards to not being able to consistently load specimens to the strain levels originally recommended for the ECS.

Two load cells are used in this test setup. A static load cell is used for the normal operation of the system, and for the feedback control. A second dynamic load cell is used to accurately measure the applied cyclic loads. Typical outputs of the two load cells are presented in Figure 4.3. Outputs from the dynamic load cells are typically less contaminated with background noise when compared with the output from the static load cells. Since dynamic load cells are not sensitive to static loads, the quite period of loading is fairly close to zero. Static load cells provide the amplitude of the static load applied. The offset of about 500 N load corresponds to the load applied to the specimen. Practically speaking, with the existing data acquisition boards it is much easier to collect more accurate results when the signals during the rest period are centered around zero, as is the case for the dynamic load cell. However, one has to know the amplitude of seating load. Therefore, tests cannot be performed without a static load cell. Typically, the coefficient of variation associated with the dynamic load cells is noticeably better than the static one.

The placement of the specimen within the loading subsystem is shown in Figures 4.1 and 4.2. Special care was taken to improve the rigidity of the loading system. The specimen is placed on the bottom end platen, which is tightly attached to steel base plate through a stainless steel cylinder. To minimize the vibration of the specimen, all components should be precisely machined and custom matched.

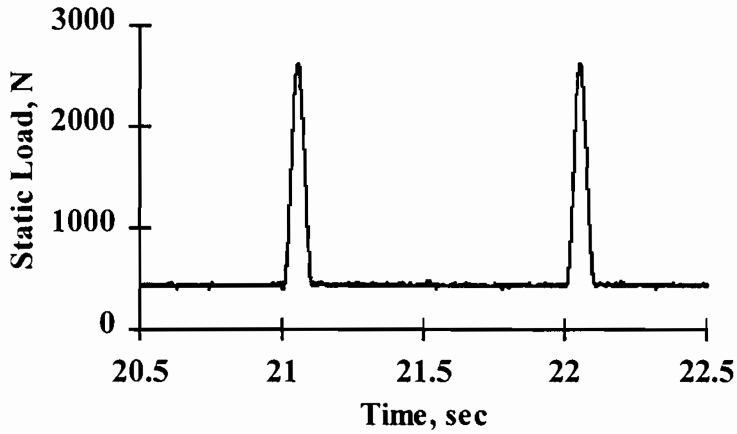
Environmental Conditioning Chamber

The main purpose of this chamber is to maintain a specific temperature within the testing specimen. The fan located at the back of the chamber circulates hot air within the chamber and maintains a constant temperature. During moisture conditioning of the specimen, the chamber temperature is increased to 60°C. The chamber temperature is controlled by a controller that provides feedback from the chamber by a thermocouple. The chamber set point accuracy is 1°C.

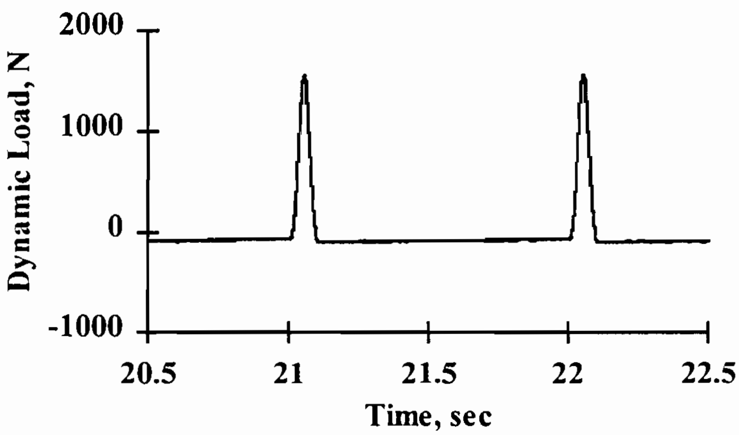
The environmental chamber used with this setup has openings both at the top and at the bottom. The top opening allows the movement of the loading actuator. The bottom opening allows the transfer of the applied loads to a rigid frame, thus, eliminating the possibility of undesirable vibration of the strain measurement setup.

Strain Measurement System

Four proximitors (noncontact eddy-current transducers) are used to measure the deformation of the specimen. The proximitors used here have a nominal sensitivity of about 2 volts/mm. The adjustment of the proximitors and targets is easier than the LVDT yoke assembly. The positions of the proximitors on the specimen are shown in Figure 4.1. Two targets are fixed to the specimen with "Super Glue" on the opposite sides of the specimen. Two other targets are fixed just vertically above the previous targets. A magnet is then used to fix the external target to the specimen over the membrane. The deformation between the two proximitors on one side of the specimen is the difference in the deformations measured by the top and bottom proximitors.



(a) Static Load Cell



(b) Dynamic Load Cell

Figure 4.3 - Typical Outputs of Load Cells

Similarly, the deformation on the other side of the specimen is also measured. The strain experienced by the specimen is the average of deformations on the two opposite sides of the specimen divided by the gauge length.

The eccentricity of the specimen can be checked by inspecting the differences in deformations between the two opposite sides. A typical output from the proximitors for one test is shown in Figure 4.4. The variations in displacement with time measured by the proximitors due to a haversine wave dynamic load are shown in this figure. The displacements due to load are higher for the top proximitors than those of the bottom proximitors. The displacements for the rest periods are different for different proximitors. This happens because the original gaps between the targets and proximitors were set slightly differently. For each proximitor, the displacement is the difference between the peak and the rest period. The measured displacements at a given level (top or bottom) are slightly different. By inspecting these differences, one can judge if the specimen is being loaded uniformly.

Fluid Conditioning System

The original fluid conditioning system of the test setup was used in the modified test setup with one modification. A temperature bath unit (See Appendix A) was added to maintain the temperature of water circulating through the specimen similar to the temperature in the environmental chamber.

Evaluation of Resilient Modulus Measurement Test Setup

The resilient modulus test setup is evaluated by identifying the precision of the strain measurement system, the rigidity of the overall system, and the level of vibration within the system. The results of the evaluation are explained in the following sections.

Precision of the Strain Measurement System

Tandon et al. (1997) reported a coefficient of variation of about 30 percent when the resilient modulus of a synthetic specimen was measured ten times with the original ECS (the LVDT yoke was disassembled each time). When the yoke assembly was not dismantled after each test, the coefficient of variation was 4.8 percent. Therefore, the LVDT yoke assembly of the original ECS was considered as one of the potential items contributing to large variability in the measured resilient modulus of a specimen. In the modified test setup, the LVDT yoke assembly is replaced by proximitors and only external targets (Figure 4.1) are removed while the specimen is conditioned. A study was conducted to identify the effects of disassembly and reassembly of external targets on the resilient modulus measurements. Tests were performed ten times on a synthetic specimen. As shown in Table 5.1, the M_R varied from 1.52 to 1.63 GPa indicating a coefficient of variation of less than 3 percent. The results indicate that the removal of the targets only slightly affect the M_R measurement.

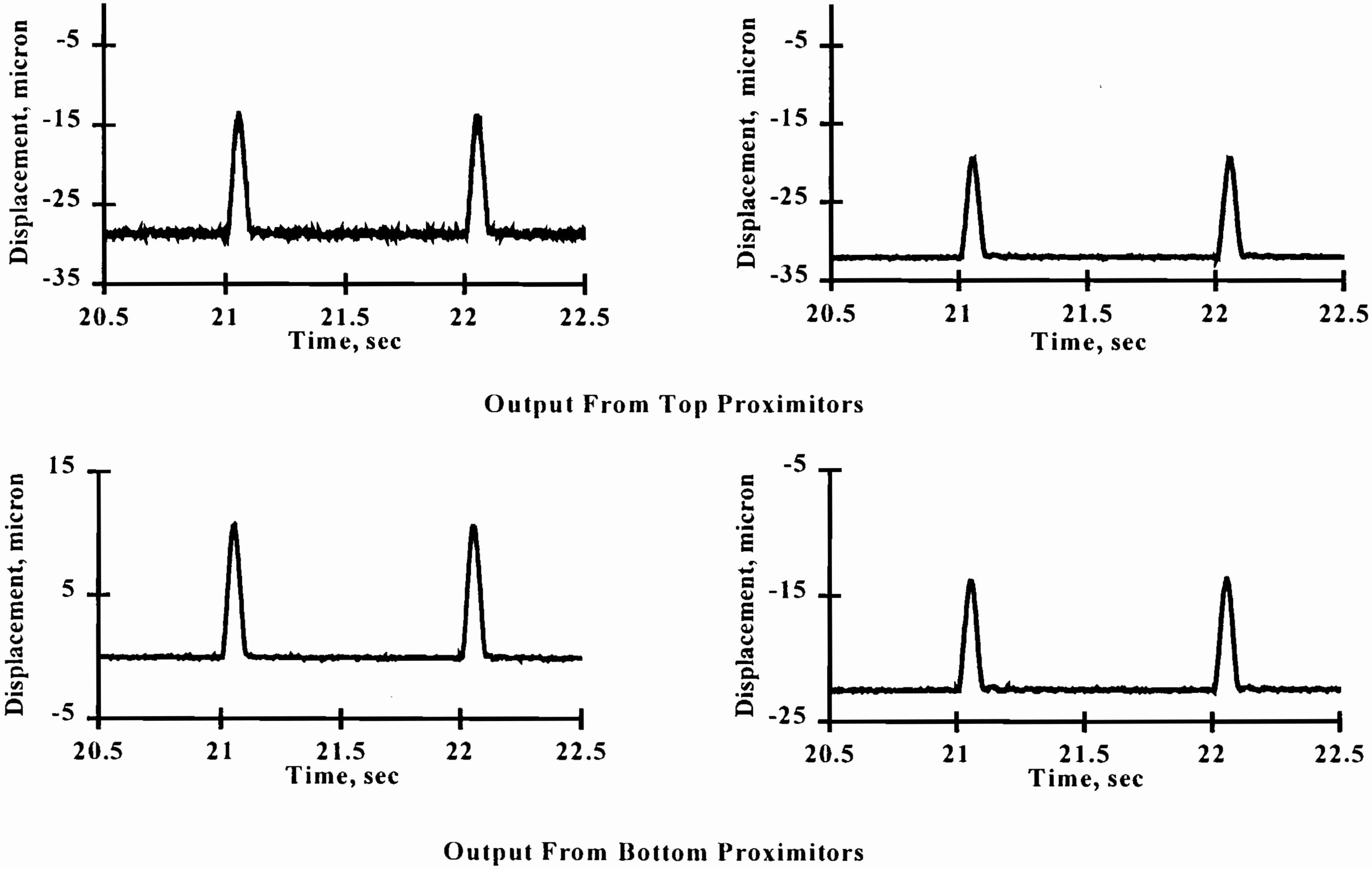


Figure 4.4 - Typical Output of Proximitors

Rigidity of System

The rigidity of the system was evaluated following the procedure proposed by Barksdale et al. (1994). The deformation and stiffness at the bottom platen were measured while applying a static load of 2250 N (500 lb). Deformation at the bottom platen was 1.27 μm (50 μin.) and stiffness of the system was 1.77 GN/m (10^7 lb/in.). The deformation and stiffness of the loading system are considered acceptable.

Table 4.1 - Repeatability of Resilient Modulus Test when Targets are Reassembled after Each Test

Test No.	Resilient Modulus, GPa
1	1.55
2	1.57
3	1.52
4	1.58
5	1.63
6	1.62
7	1.56
8	1.56
9	1.62
10	1.55
Average	1.57
Std. Dev.*	5.5
COV⁺(%)	**2.4**

Specimen : Synthetic, Gauge Length = 25 mm, Static Load = 225 N, Dynamic Load = 2250 N.
* Std. Dev. = Standard Deviation, ⁺COV(%) = Coefficient of Variation in percent

Vibration of System

Tandon et al. (1997) found significant amount of vibration within the loading system of the original ECS. Displacements measured at different locations of the ECS loading system due to dynamic loads varied from 0.5 μm to 2.7 μm when the system was inside the environmental chamber. When the system was placed on a relatively rigid support, the displacements varied from 0.8 μm to 1.8 μm. The magnitude and direction of vibrations also provided the evidence of rocking.

The levels of vibration due to a dynamic loading within the developed system were measured by placing an accelerometer at the bottom end platen and at the base plate. The dynamic loading was 2,250 N (500 lb) haversine pulse of duration of 0.1sec and a rest period of 0.9 sec with a static load of 450 N (100 lb) (similar to Tandon et al.'s experiment). The vibration levels of the system due to the dynamic loading were negligible.

Evaluation of Resilient Modulus Test Parameters

After developing the test setup, resilient modulus tests were performed on a synthetic specimen. Typical results from the ten consecutive tests are presented in Table 4.2. The specimen was dismantled after each test. Teflon disks were used between the end platens and the specimen. As reflected in Table 4.2, the coefficient of variation for resilient modulus was 51.2 percent and the variation between the displacements on the opposite sides of the specimen was 30.6 percent. This result suggests that further modifications were necessary. To implement such improvements, a sensitivity study was carried out to understand the impact of different parameters on the precision of the resilient modulus test. The effects of parameters such as static load, Teflon disks, and gauge length are discussed below.

Table 4.2 - Repeatability of Resilient Modulus Tests after Initial Modifications under a Static Load of 225 N

Test No.	M_R (GPa)	Deformation (µm)			Strain (µm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	1.59	3.96	4.57	4.27	168	14.2
2	2.18	3.45	2.40	2.93	115	36.0
3	2.59	2.45	2.47	2.46	96.7	1.40
4	2.22	2.97	2.47	2.72	107	18.4
5	2.40	2.47	3.51	2.99	118	34.6
6	4.43	1.78	0.798	1.29	50.8	76.2
7	5.88	0.686	1.22	0.955	37.6	56.2
8	1.72	4.04	3.51	3.77	149	14.2
9	1.99	2.90	3.76	3.33	131	26.0
10	1.98	2.87	3.84	3.35	132	28.8
Average	2.71	2.77	2.85	2.81	112	**30.6**
Std. Dev.	1.39	1.01	1.20	1.03	4.06	
COV(%)	**51.2**	36.4	42.1	36.7	36.7	

Specimen: Synthetic, Gauge Length = 25 mm, Dynamic Load = 2250 N, Teflon disks were used, Specimens dismantled after each test.

Static Load

Tests were performed ten times at different static loads by assembling and dismantling the synthetic specimen and strain measurement system for each test. The test results are shown in Table 4.2 for a static loading of 225 N (originally proposed for the ECS), and in Table 4.3 for a static loading of 450 N. The average variation between the deformations measured on the opposite sides of the specimen reduced from 30.6% to 20.6% by increasing the static load from 225 N to 450 N. Similarly, the coefficient of variation of measured M_R reduced from 51.1 percent to 33.5 percent. These improvements are because of better seating of the specimen between the platens. Since further increase of static load may cause permanent deformation of asphalt specimen, 450 N static load was selected for resilient modulus test method.

Table 4.3 - Repeatability of Resilient Modulus Tests under a Static Load of 450 N

Test No.	M_R (GPa)	Deformation (μm)			Strain (μm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	2.20	3.12	2.92	3.02	119	6.80
2	2.85	2.31	2.07	2.19	86.3	10.8
3	2.48	2.64	2.29	2.47	97.1	14.2
4	1.90	3.45	3.68	3.61	142	3.80
5	2.48	2.84	1.92	2.39	93.9	38.6
6	2.16	3.52	2.33	2.93	115	40.6
7	4.81	1.17	1.49	1.33	52.4	24.0
8	3.07	1.81	2.61	2.21	87.1	38.2
9	2.06	2.82	2.89	2.85	112	2.2
10	1.93	3.76	2.80	3.28	129	29.2
Average	2.59	2.75	2.50	2.63	103	**20.6**
Std. Dev.	0.87	0.82	0.62	0.65	2.57	
COV(%)	**33.5**	29.6	24.7	24.8	24.8	

Specimen: Synthetic, Gauge Length = 25 mm, Dynamic Load = 2250 N, Specimens dismantled after each test, Teflon disks were used

Teflon Disk

The effects of Teflon disks were also studied by performing tests similar to static loads. Typical results when the Teflon disks were removed are shown in Table 4.4. When the test was repeated ten times, the coefficient of variation for M_R was 4.2 percent, while the variation in deformations between the opposite sides of the specimen was about 9.6 percent. Table 4.3 contains the results from similar tests but with Teflon disks. As indicated before, in that case the coefficient of variation was typically greater than 30 percent, and variation between opposite sides about 20 percent. These improvements are the result of the better positioning or seating of the specimen between the end platens without the Teflon disks.

One should also be aware of the disadvantage of removing the Teflon disks. Complex stress regimes will develop along the top and the bottom of the specimen during tests, which may affect the accuracy of the actual M_R value of the specimen. Since in the ECS tests the ratio of the before and after moduli is of interest, it was felt that the consistency of the results, obtained by removing the Teflon disks, outweighs the disadvantages of some loss of accuracy in the modulus values.

Table 4.4 - Repeatability of Resilient Modulus Tests When Teflon Disks were Removed

Test No.	**M_R (GPa)**	**Deformation (μm)**			**Strain (μm/m)**	**Variation in Deformation (%)**
		Side 1	**Side 2**	**Average**		
1	1.89	2.63	2.70	2.66	105	2.60
2	1.95	2.94	2.39	2.66	105	20.6
3	1.89	2.74	3.07	2.90	114	11.4
4	1.84	2.99	2.73	2.86	112	9.00
5	1.99	2.80	2.56	2.68	106	4.80
6	2.04	2.61	2.45	2.53	99.6	6.60
7	1.80	2.87	3.12	2.99	118	8.40
8	1.86	3.03	2.70	2.87	113	11.4
9	2.01	2.84	2.60	2.72	107	9.00
10	1.99	2.78	2.58	2.68	106	7.80
Average	1.92	2.82	2.69	2.76	109	**9.6**
Std. Dev.	0.08	0.14	0.24	0.14	5.56	
COV(%)	**4.2**	4.9	8.9	5.1	5.1	

Specimen: Synthetic, Gauge Length = 25 mm, Static Load = 450 N, Dynamic Load = 2250 N, Specimens dismantled after each test.

Gauge Length

Theoretically speaking, the 25 mm gauge length proposed in the ECS original protocol is desirable. However, practically speaking, when one considers the limitations of the LVDT's or proximitors and the data acquisition systems, one would realize that larger gauge lengths would result in more accurate readings. The increase in gauge length may also reduce the localized effects of larger aggregates on the measurements of strains. However, larger gauge lengths may accentuate any rocking motion associated with the flatness of the two ends of a specimen. We theoretically and experimentally considered gauge lengths of 25 mm, 38 mm and 51 mm. Tests similar to previous section were performed on a synthetic specimen and results are presented in Table 4.4, 4.5, and 4.6 for gauge length 25 mm, 38 mm, and 51 mm respectively. The coefficient of variation for the M_R increased from 4.2 percent to 5 percent when the gauge length was increased from 25 mm to 38 mm. This value further increased to 5.6 percent when the gauge length was increased to 51 mm. The variation between the deformations in two sides was 9.6, 6.4, and 15.2 percent for the gauge length of 25 mm, 38 mm, and 51 mm respectively. Based on these test results on a synthetic specimen, the best compromise in terms of accuracy in determining strains and measurement errors is a gauge length of 38 mm.

Table 4.5 - Repeatability of Resilient Modulus Tests for a Gauge Length of 38 mm

Test No.	M_R (GPa)	Deformation (µm)			Strain (µm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	1.91	3.90	4.60	4.25	112	16.4
2	2.04	3.87	3.86	3.87	101	0.4
3	2.00	3.85	4.09	3.97	104	5.8
4	1.86	4.25	4.40	4.33	114	3.4
5	1.92	4.18	3.86	4.02	106	8.0
6	1.92	4.20	4.00	4.10	108	5.0
7	1.88	4.27	3.93	4.11	108	8.2
8	2.18	3.96	3.90	3.93	103	1.4
9	2.04	3.98	3.95	3.96	104	0.8
10	1.95	3.77	4.33	4.05	106	13.8
Average	1.97	4.03	4.09	4.06	107	**6.4**
Std. Dev.	0.10	0.19	0.26	0.14	3.76	
COV(%)	**5.0**	4.6	6.4	3.5	3.5	

Specimen: Synthetic, Static Load = 450 N, Dynamic Load = 2250 N, Specimens dismantled after each test, Teflon disks were not used

Teflon Disks and Asphalt Specimens

The evaluation of test setup, in previous section, was performed using a synthetic specimen. The results of the evaluation suggested that the Teflon disks, used between the end platens and specimen, should be removed to improve the precision of the measurement test setup. However, the main purpose of using Teflon disks was to reduce the end friction and entrap asphalt escaping from the specimens. Tandon et al. (1997) also suggested that the resilient modulus measurement test setup is more precise when the LVDT yoke assembly is not disassembled. Since both conditioned and unconditioned resilient modulus will be measured without dismantling the specimen, it was decided to identify the precision without dismantling the specimen while using Teflon disks.

A specimen of the Atlanta mix (poor performing mix) was prepared and tested. The results are shown in Tables 4.7 and 4.8. The coefficient of variation for ten resilient modulus tests decreased from 4.8 percent to 2.5 percent when the Teflon disks were not used. When Teflon disks were not used, the variation in deformations between the opposite sides also decreased from 11.6 percent to 2.8 percent. The test results indicate that the use of Teflon disks between the specimen and the end platens will reduce the precision of the resilient modulus test setup and should be eliminated.

Table 4.6 - Repeatability of Resilient Modulus Tests for a Gauge Length of 51 mm

Test No.	M_R (GPa)	Deformation (μm)			Strain (μm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	2.21	5.31	5.78	5.54	109	8.40
2	2.30	5.56	5.82	5.64	112	4.60
3	2.45	6.00	4.99	5.49	108	18.2
4	2.28	6.66	5.02	5.84	115	28.0
5	2.08	6.51	5.11	5.81	114	24.2
6	2.23	5.80	5.40	5.60	110	7.00
7	2.10	6.16	5.27	5.72	113	15.6
8	2.06	6.04	5.81	5.92	117	3.80
9	2.13	6.50	5.08	5.79	114	24.6
10	2.29	5.89	4.99	5.44	107	16.4
Average	2.21	6.04	5.33	5.69	112	**15.2**
Std. Dev.	0.12	0.43	0.35	0.16	3.16	
COV(%)	**5.6**	7.1	6.6	2.8	2.8	

Specimen: Synthetic, Static Load = 450 N, Dynamic Load = 2250 N, Specimens dismantled after each test, Teflon disks were not used.

Table 4.7 - Repeatability of Resilient Modulus Tests on Asphalt Concrete Specimen with Teflon Disks when Specimen was not Dismantled

Test No.	M_R (GPa)	Deformation (µm)			Strain (µm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	4.67	3.40	3.36	3.38	88.6	2.40
2	4.51	3.55	3.47	3.51	92.1	4.40
3	4.39	3.47	3.62	3.55	93.1	8.40
4	4.33	3.44	3.71	3.57	93.8	14.8
5	4.37	3.34	3.73	3.53	92.7	22.0
6	4.17	3.56	3.82	3.69	96.8	14.4
7	4.08	3.63	3.89	3.76	98.7	13.6
8	4.20	3.45	3.83	3.64	95.5	20.8
9	4.03	3.72	3.85	3.78	99.3	6.80
10	4.04	3.64	3.80	3.72	97.6	8.80
Average	4.28	3.52	3.71	3.61	94.8	**11.6**
Std. Dev.	0.21	0.12	0.18	0.13	3.35	
COV(%)	**4.8**	3.4	4.7	3.5	3.5	

Specimen: Atlanta Mix, Gauge Length = 38 mm, Static Load = 450 N, Dynamic Load = 3340 N.

Table 4.8 - Repeatability of Resilient Modulus Tests on Asphalt Concrete Specimen without Teflon Disks when Specimen was not Dismantled

Test No.	M_R (GPa)	Deformation (μm)			Strain (μm/m)	Variation in Deformation (%)
		Side 1	Side 2	Average		
1	3.86	3.33	3.48	3.41	88.9	4.40
2	3.82	3.40	3.49	3.45	90.5	2.60
3	3.68	3.57	3.57	3.57	93.7	0.20
4	3.73	3.47	3.58	3.52	92.4	3.20
5	3.74	3.50	3.52	3.51	92.2	0.60
6	3.64	3.65	3.58	3.62	94.9	2.00
7	3.60	3.70	3.59	3.65	95.6	3.00
8	3.65	3.50	3.69	3.59	94.3	5.00
9	3.59	3.56	3.73	3.65	95.6	4.60
10	3.61	3.58	3.67	3.63	95.2	2.40
Average	3.69	3.53	3.59	3.56	93.4	**2.8**
Std. Dev.	0.094	0.11	0.083	0.084	2.19	
COV(%)	**2.5**	3.1	2.3	2.3	2.3	

Specimen: Atlanta Mix, Gauge Length = 38 mm, Static Load = 450 N, Dynamic Load = 3340 N.

Chapter 5

Development of Predictive Criteria Based on Resilient Modulus

The test protocol suggested in chapter three to evaluate moisture susceptibility of mixtures was based on the indirect tensile strength (ITS) ratio criterion. However, the test protocol had to be modified based on resilient modulus test because it is a nondestructive test. To properly replace the ITS ratio with resilient modulus ratio, several issues had to be resolved. These issues are discussed in this chapter. A new test procedure and predictive criteria are suggested. Finally, an evaluation of the suggested test procedure and predictive criteria is presented.

Unconditioned Resilient Modulus

As indicated before, in the ECS test procedure, the unconditioned M_R of the specimen is measured without any conditioning or saturation. However, to implement this with the modified setup, the specimen needed to be dismantled for static saturation. This step will contribute to the variability in the test results. Also, a study conducted by Fwa (1995) suggested that the resilient modulus as well as the ITS of the specimen vary with changes in the levels of saturation. In view of these findings, it was decided to first identify the levels of saturation in the specimens during conditioning cycles and then to identify the appropriate situation to measure the unconditioned resilient modulus. A preliminary study was conducted on three different specimens of the Austin mix. As shown in Table 5.1, the specimens lose approximately 15 percent of the saturation during the first hour of flow, after which the degree of saturation remains more or less constant.

Since the conditioned and unconditioned M_R should be measured at the same levels of saturation, it is prudent to measure the unconditioned modulus after circulating water for one hour at room temperature (after static saturation). Also, waiting for one hour after static saturation may yield more consistent results as the excess water trapped between the specimens and the end platens can drain out. Thus, the unconditioned resilient modulus may be measured after one hour of water flowing at the rate of 8 ± 1 cc/min at room temperature and then waiting for an hour.

Table 5.1 - Variation in Degree of Saturation with Time from Static Immersion

Test No.	Level of Saturation (percent)		
	After Static Saturation	After 1 hr of Water Flow	After Conditioning for 18 hr
1	96.6	79.6	79.1
2	99.2	81.0	78.5
3	98.1	80.7	78.2

Conditioned Resilient Modulus

The resilient modulus of a mix is sensitive to temperature, therefore, both unconditioned and conditioned modulus should be measured at the same temperature. Since in the original ECS test procedure, water was circulated at 25°C, the specimen cooled down to room temperature in two to three hours. However, the modified procedure uses higher water temperature. It is quite possible that the specimen needs more than three hours to cool to 25°C.

The accurate measurement of specimen temperature is a difficult task because the temperature is quite different at the surface compared to the center of the specimen. One indirect alternative is to measure the M_R of the specimen after certain intervals. When the M_R becomes independent of time, the specimen must have reached an equilibrium condition.

Two mixes were studied to evaluate the effect of cooling period on resilient modulus. The test results are shown in Table 5.2. Both specimens were conditioned for 6 hours at 60°C and cooled for 3 hrs. After cooling the resilient modulus of the El Paso III specimen was found to be 2.2 GPa but the modulus continuously increased during the next 9 hours of cooling period and became stable after that period. The modulus was 2.8 GPa after 12 hours cooling period. The resilient modulus of the specimen increased only by 0.1 GPa after further cooling of 12 hours. Similarly, for the El Paso II mix the modulus increased from 1.6 GPa, which was measured after 3 hours cooling period to 2.2 GPa which was measured after 12 hrs of cooling period. During the next 12 hours of cooling, there was no appreciable change in the resilient modulus of the specimen.

Such long cooling periods for three cycles of conditioning will increase the test time by 3 days. Therefore, a decision was made to continuously condition the specimen for 18 hours rather than three conditioning cycles of 6 hours each. This may be justifiable since typically small significance is placed on the intermediate M_R ratios. Hence, the specimen should be conditioned continuously for 18 hours and the conditioned resilient modulus should be measured when the specimen cools down to the room temperature, i.e., 24 hours after conditioning of the specimen.

Table 5.2 - Variation in Resilient Modulus with Time after Conditioning

Time After Conditioning (hr)	MR (GPa)	
	El Paso II	El Paso III
3	1.6	2.2
4	1.8	2.3
5	1.9	2.4
6	2.0	2.5
8	2.1	2.6
12	2.2	2.8
24	2.2	2.9

Suggested Test Procedure

The specimen preparation for the proposed method is identical to the original ECS protocol. One major change is the use of noncontact sensors for measuring deformation. As such, internal targets are fixed to the specimen with "Super Glue." As it will be described later, the specimen is then subjected to a static immersion saturation with a vacuum level of 660 mm Hg (26 in. Hg) for 5 minutes.

The specimen is enclosed within a membrane and placed between the top and bottom end platens of the M_R test setup. Water at room temperature is circulated through the specimen at a rate of 8 ± 1 cc/min for one hour with a vacuum level of 64 mm Hg (2.5 in. Hg). The vacuum is released for one hour, after which the unconditioned resilient modulus is measured. One hour of waiting period is necessary to drain any excess water that may have been trapped between the specimen and end platens. For resilient modulus tests, a haversine wave dynamic loading with a duration of 0.1 sec and a rest period of 0.9 sec is used. A static load of 450 ± 15 N (100 ± 3 lb) is applied. The dynamic load is adjusted by trial and error so that the specimen is subjected to a strain level of 100 ± 10 μm/m.

The specimen is then conditioned for 18 hours. During the conditioning, the flow of water is maintained at 9 cc/min and the vacuum level at 64 mm Hg (2.5 in. Hg). The temperature of the environmental chamber and water circulating through it is maintained at 60°C. A 0.1 second haversine load of 900 ± 15 N (200 ± 3 lbf) is applied during the conditioning period with a rest period of 0.9 second. An axial compressive static load of 225 ± 15 N (50 ± 3 lbf) is maintained throughout the conditioning.

If the circumference of the specimen increases by more than 2 percent after 6 hours of conditioning, the material is considered as moisture-susceptible. At that point, the conditioning process is stopped and the specimen is removed from the setup. All other specimens are conditioned for 18 hours and allowed to cool at room temperature for 24 hours. After the cooling period, the resilient modulus of the specimen is measured again. This modulus is considered as the conditioned resilient modulus. If the M_R ratio falls below 0.8, the mixture will be considered as marginal material. If M_R ratio is above 0.8, the mixture will be a well performing mix.

Evaluation of Suggested Test Procedure

To verify the conditioning and resilient modulus parameters identified in this study, five specimens each of four mixtures were tested. The tested mixtures were: Austin (well performing), El Paso II (marginal), Atlanta (poor performing), and Corpus Christi (poor performing). Three specimens of the El Paso III mix were also tested.

The test results of the Austin mix are shown in Table 5.3. The unconditioned M_R for five specimens varied from 4.1 to 5.0 GPa with a coefficient of variation of 7.7 percent. The M_R measured after conditioning varied from 3.7 to 4.9 with a coefficient of variation of 1.1 percent. These results indicate that the test setup is reasonably precise. The variation of M_R ratios are shown in Figure 5.1. The M_R ratios of all five specimens were above 0.8 indicating that the modified ECS can accurately identify the well performance of this mixture.

The test results of the El Paso II mix are shown in Table 5.4. The unconditioned M_R for five specimens varied from 2.9 to 3.4 GPa with a coefficient of variation of 7.8 percent. The conditioned M_R varied from 2.1 to 2.5 GPa with a coefficient of variation around 6.0 percent. Figure 5.2 shows the variation of M_R ratios. The M_R ratios of all specimens were between 0.6 and 0.8 indicates that the mixture is a marginal material, as it should have.

The ITS ratios of the Austin mix and El Paso II mix are shown in Table 5.5. The variation in the ITS ratio for the Austin mix is shown in Figure 5.3. The ITS ratio of the mix varied from 0.9 to 1.1 with a coefficient of variation of 7.6 percent. The average ITS ratio of the mix was about 1.0. The variation in the ITS ratio for the El Paso II mix is shown in Figure 5.4. The ITS ratio for the mix varied from 0.57 to 0.76 with a coefficient of variation of 10.8 percent. The average ITS ratio of the mix was 0.66. The ITS ratio of the Austin and El Paso II mix also satisfied the predictive criteria suggested by Tandon et al. (1997) for well performing and marginal material, respectively.

The test results of the Atlanta mix and Corpus Christi mix are shown in Table 5.6 and Table 5.7, respectively. As mentioned before both of these mixes are historically known as being moisture susceptible. Specimens of both mixes deformed during the conditioning period. As the deformation was excessive after 6 hrs of conditioning for each specimen, the experiment was aborted, and the changes in the dimensions of the specimens were measured. The changes in circumference after 6 hrs of conditioning are shown in Figure 5.5 for the Atlanta mix. The circumferential deformations for the mix varied from 3.1 percent to 5.0 percent with a coefficient of variation of about 20 percent. Average circumference deformation for the mix was about 4.3 percent. The circumferential deformations for the Corpus Christi mix after 6 hrs of conditioning, as shown in Figure 5.6, varied from 3.8 percent to 6.6 percent with a coefficient of variation of about 20 percent. The average change in the circumference of specimens of the Corpus Christi mix was 5.2 percent. Thus, the modified ECS also accurately identified poor performing mixes.

The resilient moduli measured on the El Paso III specimens are shown in Table 5.8. The unconditioned M_R for five specimens varied from 3.7 to 4.5 GPa with a coefficient of variation of 7.3 percent. The conditioned M_R varied from 2.6 to 3.1 GPa with a coefficient of variation around 6.7 percent. The variation of M_R ratios are shown in Figure 5.7. The M_R ratios of all specimens were between 0.66 to 0.73 indicating that the mixture is a marginal material. The ITS ratios of the mix are shown in Table 5.9. As shown in Figure 5.8, the variation in the ITS ratio for the mix varied from 0.69 to 0.79 with a coefficient of variation of about 5.4 percent. The average ITS ratio of the mix was about 0.75, which also satisfied the criteria suggested by Tandon et al. (1997) for marginal material.

Table 5.3 - Variation in M_R Ratio for the Austin Mix

Test No.	Voids in Total Mix (%)	M_R (GPa)		M_R Ratio
		Unconditioned	Conditioned	
1	7.7	4.8	4.5	0.94
2	7.4	4.1	3.9	0.95
3	7.9	5.0	4.9	0.98
4	7.8	4.7	4.3	0.93
5	7.7	4.3	3.7	0.85
Average	7.7	4.6	4.3	0.93
Std. Dev.	0.2	0.4	0.5	0.05
COV (%)	2.43	7.7	11.1	5.1

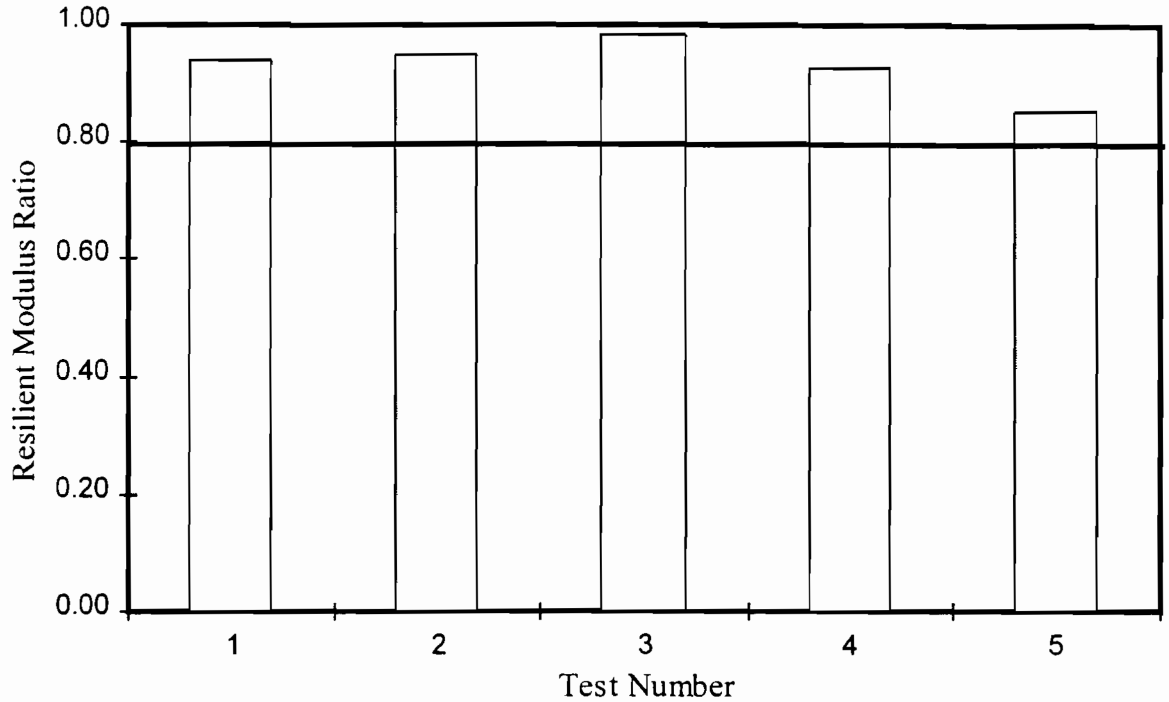


Figure 5.1 - Resilient Modulus Ratio of the Austin Mix

Table 5.4 - Variation in M_R Ratio for the El Paso II Mix

Test No.	Voids in Total Mix (%)	M_R (GPa)		M_R Ratio
		Unconditioned	Conditioned	
1	7.4	3.4	2.2	0.63
2	7.7	2.9	2.1	0.73
3	7.2	3.0	2.2	0.75
4	7.6	3.3	2.5	0.74
5	7.7	3.0	2.3	0.74
Average	7.5	3.1	2.2	0.72
Std. Dev.	0.2	0.2	0.1	0.05
COV (%)	2.9	7.8	6.0	6.8

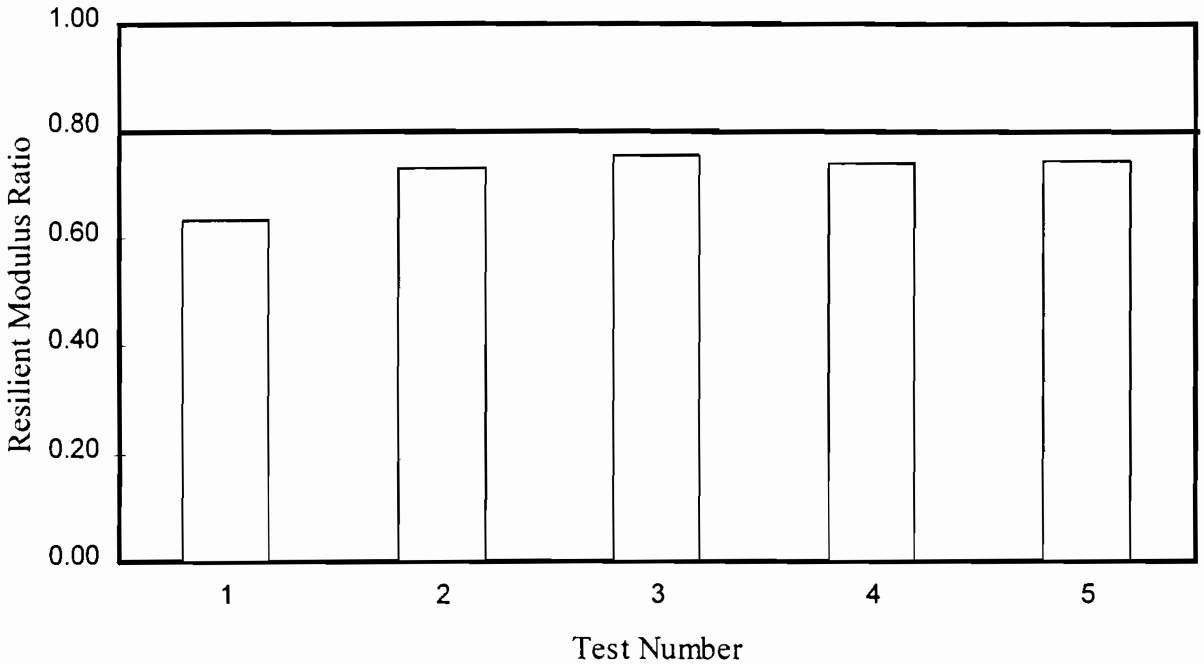


Figure 5.2 - Resilient Modulus Ratio of the El Paso II Mix

Table 5.5 - Variability in the Indirect Tensile Strength Ratio for the Austin and El Paso II Mixtures

Test No.	Austin Mix		El Paso II Mix	
	Conditioned ITS*, MPa	ITS ratio	Conditioned ITS+, MPa	ITS ratio
1	0.69	1.10	0.33	0.57
2	0.59	0.94	0.37	0.64
3	0.68	1.08	0.37	0.64
4	0.66	1.05	0.41	0.70
5	0.58	0.92	0.44	0.76
Average	0.64	1.02	0.38	0.66
Std. Dev.	0.05	0.08	0.04	0.07
COV (%)	8.0	7.6	11.0	10.8

*Average Unconditioned ITS of the Austin mix = 0.63 MPa

+Average Unconditioned ITS of the El Paso II mix = 0.58 MPa

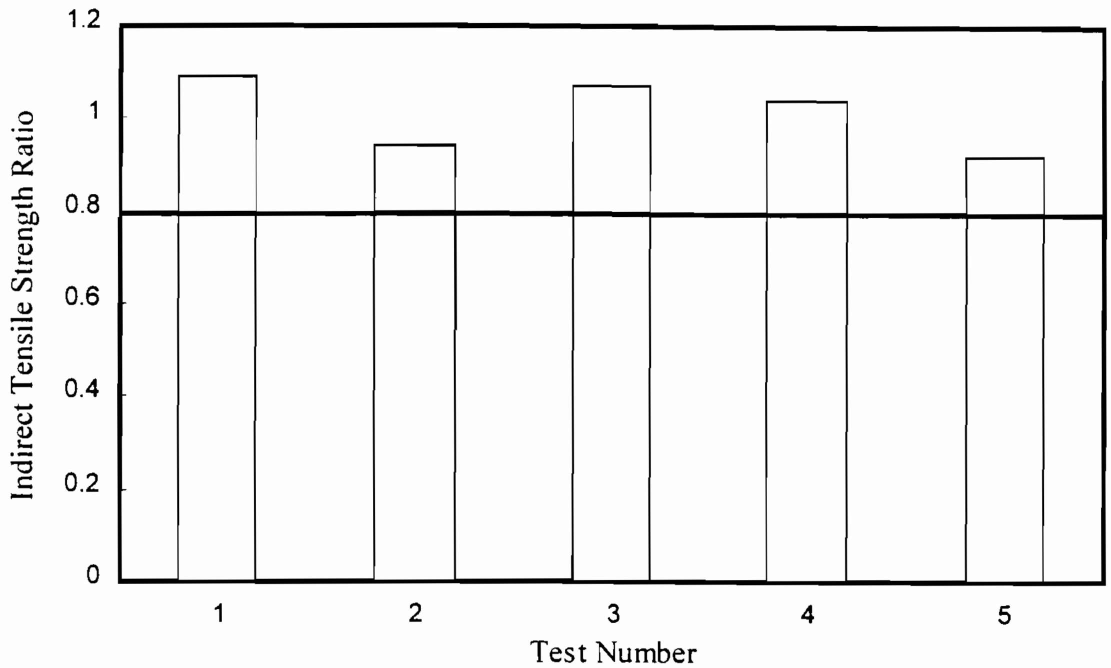


Figure 5.3 - Indirect Tensile Strength Ratio of the Austin Mix

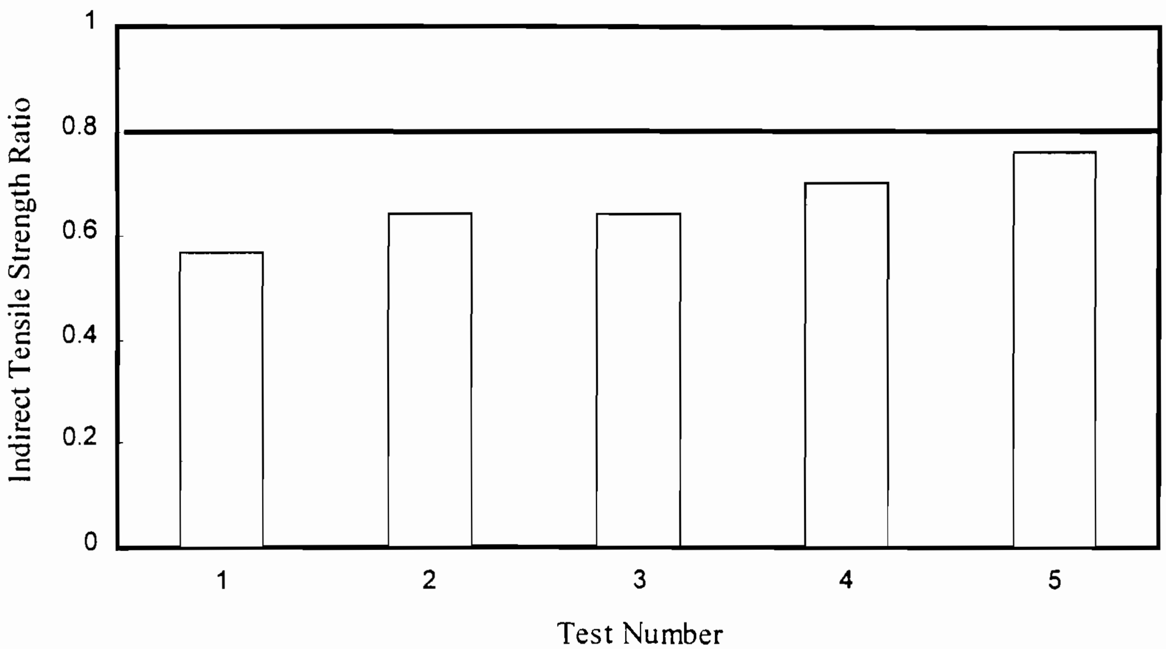


Figure 5.4 - Indirect Tensile Strength Ratio of the El Paso II Mix

Table 5.6 - Variation in the Circumferential Deformation for the Atlanta Mix

Test No.	Voids in Total Mix (%)	Unconditioned M_R (GPa)	Circumference (mm)		Change in Circumference (%)
			Initial	Final	
1	7.6	2.4	318	334	5.03
2	7.4	2.7	318	328	3.14
3	7.6	3.0	318	333	4.72
4	7.4	2.9	318	334	5.03
5	7.6	2.7	318	330	3.77
Average	7.52	2.8	318	331.8	4.34
Std. Dev.	0.11	31.2	0	2.68	0.84
COV (%)	1.46	7.8	0	0.81	19.5

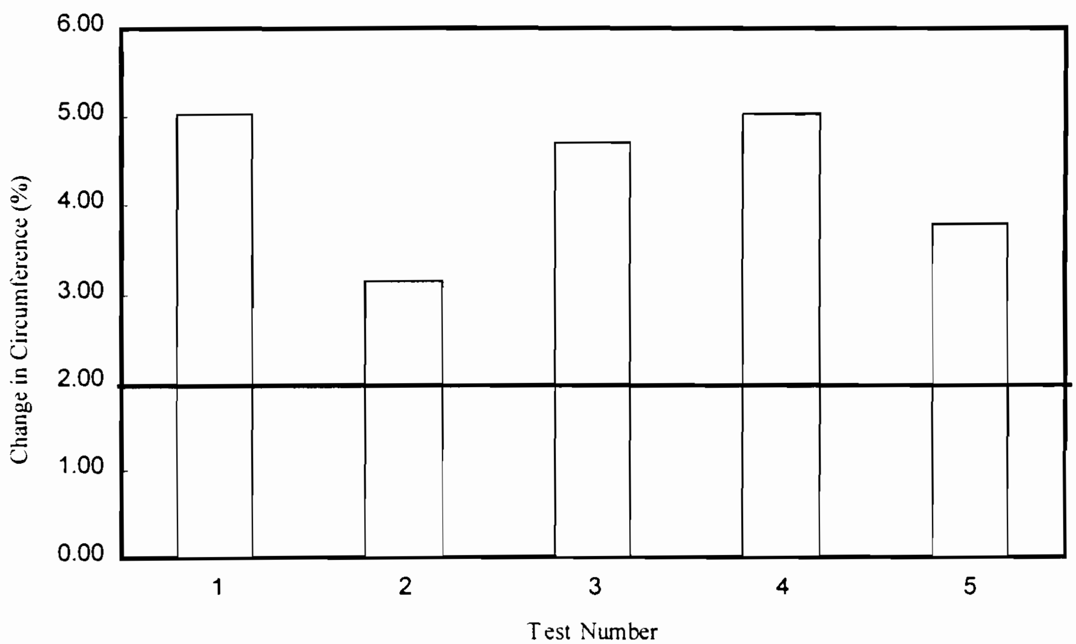


Figure 5.5 - Change in Circumference of the Atlanta Mix

Table 5.7 - Variation in the Circumferential Deformation for the Corpus Christi Mix

Test No.	Voids in Total Mix (%)	Unconditioned M_R (GPa)	Circumference (mm)		Change in Circumference (%)
			Initial	Final	
1	7.5	2.8	318	335	5.35
2	7.6	3.0	318	339	6.60
3	7.4	3.4	318	335	5.35
4	7.0	3.0	318	330	3.77
5	7.6	3.2	318	333	4.72
Average	7.5	3.1	318	334.4	5.16
Std. Dev.	0.10	45.4	0	3.29	1.03
COV (%)	1.33	10.3	0	0.98	20.1

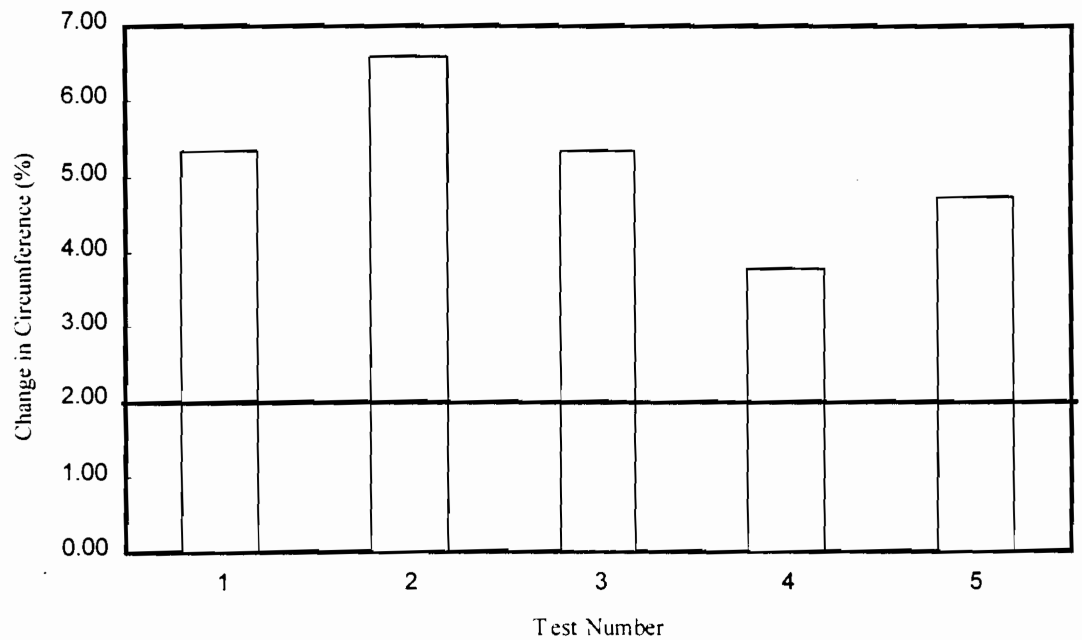


Figure 5.6 - Change in Circumference of the Corpus Christi Mix

Table 5.8 - Variation in M_R Ratio for the El Paso III Mix

Test No.	Voids in Total Mix (%)	M_R (GPa)		M_R Ratio
		Unconditioned	Conditioned	
1	7.6	4.5	3.1	0.69
2	7.7	4.2	2.8	0.66
3	8.0	3.7	2.6	0.70
4	8.0	4.2	2.9	0.69
5	8.0	4.0	2.9	0.73
Average	7.86	4.1	2.8	0.69
Std. Dev.	0.19	0.30	0.19	0.02
COV (%)	2.48	7.3	6.7	3.5

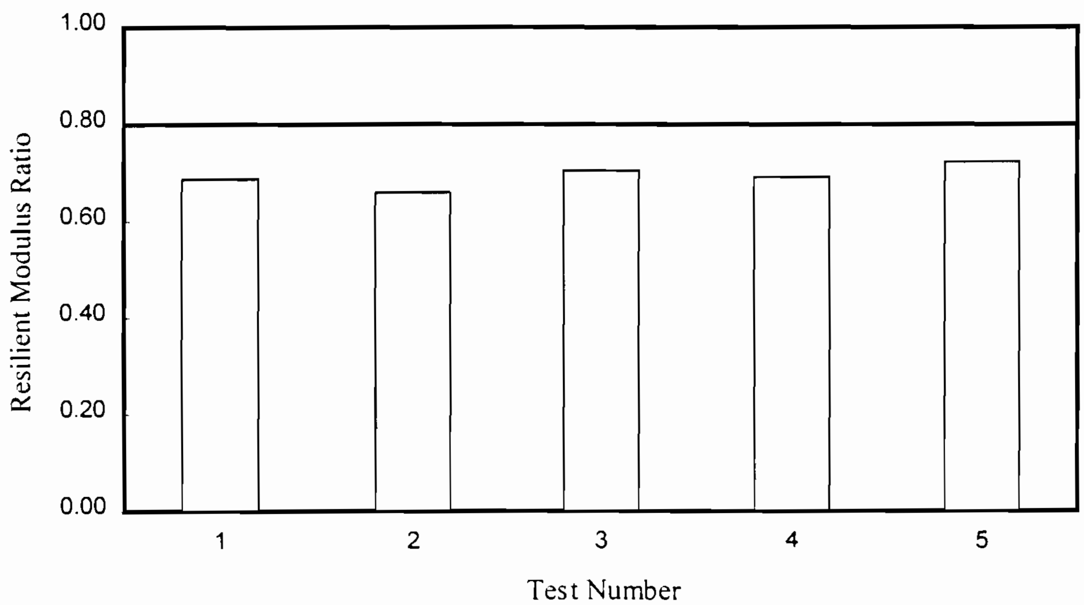


Figure 5.7 - Resilient Modulus Ratio of the El Paso III mix

Table 5.9 - Variability in Indirect Tensile Strength for the El Paso III mix

Test No.	Conditioned ITS* (MPa)	ITS ratio
1	0.55	0.78
2	0.51	0.73
3	0.48	0.69
4	0.55	0.79
5	0.52	0.74
Average	0.52	0.75
Std. Dev.	0.03	0.04
COV (%)	5.7	5.4

*Average Unconditioned ITS of the El Paso III Mix = 0.70 MPa

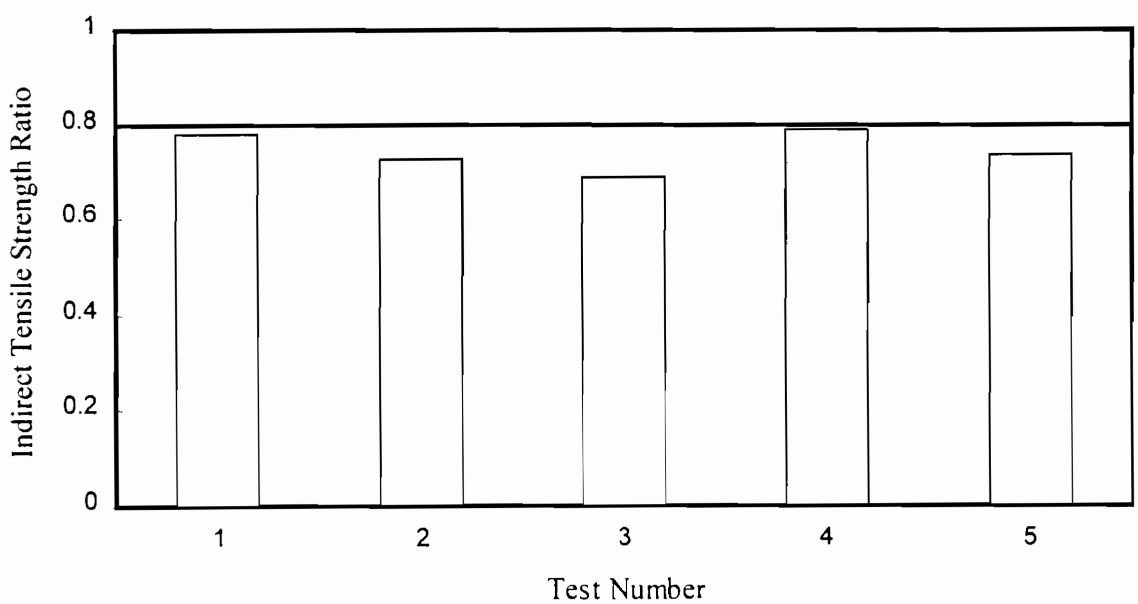


Figure 5.8 - Indirect Tensile Strength of the El Paso III Mix

Chapter 6

Conclusions and Recommendations

Conclusions

In this research, various parameters that can affect the severity of conditioning were evaluated. Also, the conditioning stages at which unconditioned and conditioned resilient moduli should be measured were identified and evaluated. Preliminary test results indicate that the modified conditioning parameters and resilient modulus procedure can consistently identify moisture susceptible mixes. The following items conclude and summarize the results of this research:

1) A resilient modulus measurement test setup with a higher loading capacity, which is more rigid and precise in comparison to the original ECS was designed and tested.

2) Before the unconditioned resilient modulus is measured, the specimen should be saturated using static immersion, water at room temperature should be circulated through the specimen for 1 hour, and the specimen should be allowed to drain for one hour. The conditioned M_R should be measured 24 hours after the 18 hours of conditioning is completed.

3) The strain level of the specimen should be maintained at 100 ± 10 μm/m during resilient modulus measurement of the specimen. The variation between two opposite sides of the specimen should be within 15 percent.

4) A static load should be maintained at 450 N during resilient modulus measurements on the specimen.

5) Teflon disks should not be used during resilient modulus measurements and during the conditioning period.

6) Gauge length of 38 mm should be used for resilient modulus measurement.

7) The original ECS conditioning procedure was modified to increase its severity in the following ways:

- The ECS saturation was replaced by the static immersion saturation to increase saturation levels and reduce test period.
- The temperature of water circulating through the specimen was increased from room temperature to 60°C.
- The rate of water flow was changed from 4 ± 1 cc/min to 8 ± 1 cc/min to maintain an optimum level of saturation.
- The level of vacuum (confining pressure) was changed from 255 mm of Hg to 64 mm of Hg.
- Existing three conditioning cycles of 6 hrs (and 2 to 3 hrs of rest period) were replaced by a continuous conditioning period of 18 hrs.

8) If the specimen deforms more than 2 percent of its initial circumference than the mix is considered as moisture susceptible. If the conditioned to the unconditioned M_R ratio is lower than 0.8, the mix is considered as marginal material. If the M_R ratio is higher than 0.8, the mix is considered as well performing mix.

Recommendations

Based on this study following recommendations are suggested for future research:

1) Further evaluation of the system with other mixtures should be carried out to finalize the protocol criteria.

2) The procedure and setup should be evaluated by AC mixes with antistripping agent.

3) Environmental conditioning that simulates cold climate should be studied.

4) Further study is needed to reduce the testing period.

5) A parametric study based on changing the properties of different elements (i.e. asphalt and aggregate) in the mix should be carried out to understand their effects on the moisture susceptibility of the mix.

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Appendix A

Temperature Water Bath Unit

This Appendix describes the development of a temperature water-bath as an accessory to the Environmental Conditioning System (ECS). To improve the conditioning of the specimen it is required to flow water through a specimen at a temperature which is equal to the chamber temperature. To minimize the loss of heat while flowing water at higher temperatures, it is necessary to install the temperature water-bath after the fluid conditioning subsystem and before the water carrying tube enters the ECS chamber.

The temperature water-bath is basically made of a stainless-steel container equipped with a heating element and a thermostat to control the temperature of the bath. Figure A.1 shows the arrangement of the water bath. The rectangular stainless steel container is 480 mm in length by 125 mm in width by 150 mm in depth and filled with water. A copper tube, 7.5 m long and 10 mm in outer diameter, is coiled into a helical spring and submerged in the container. The two ends of the copper tube come out of the water-bath through a stainless steel cover fitted on top of the container. A 200-watts heating element is screwed to the cover plate such that it dips vertically down into the water-bath. A thermostat is connected to the heating element to maintain a constant temperature. To avoid any contact with the water, the wiring is encased in an aluminum box and glued to the top of the cover plate. The container is enclosed in a case made of 25 mm thick Styrofoam sheet to avoid heat loss from the sides and the bottom.

One of the ends of the copper tube is connected to the source of the distilled de-aired water through the fluid conditioning system, and the other end is connected to the specimen inlet. The distilled de-aired water flowing in the copper tubing is heated as it circulates within the heated water bath, gradually reaching the temperature of the bath as it exits at the outlet. The tube carrying water from the outlet to the specimen is covered with cotton padding to avoid any loss of heat.

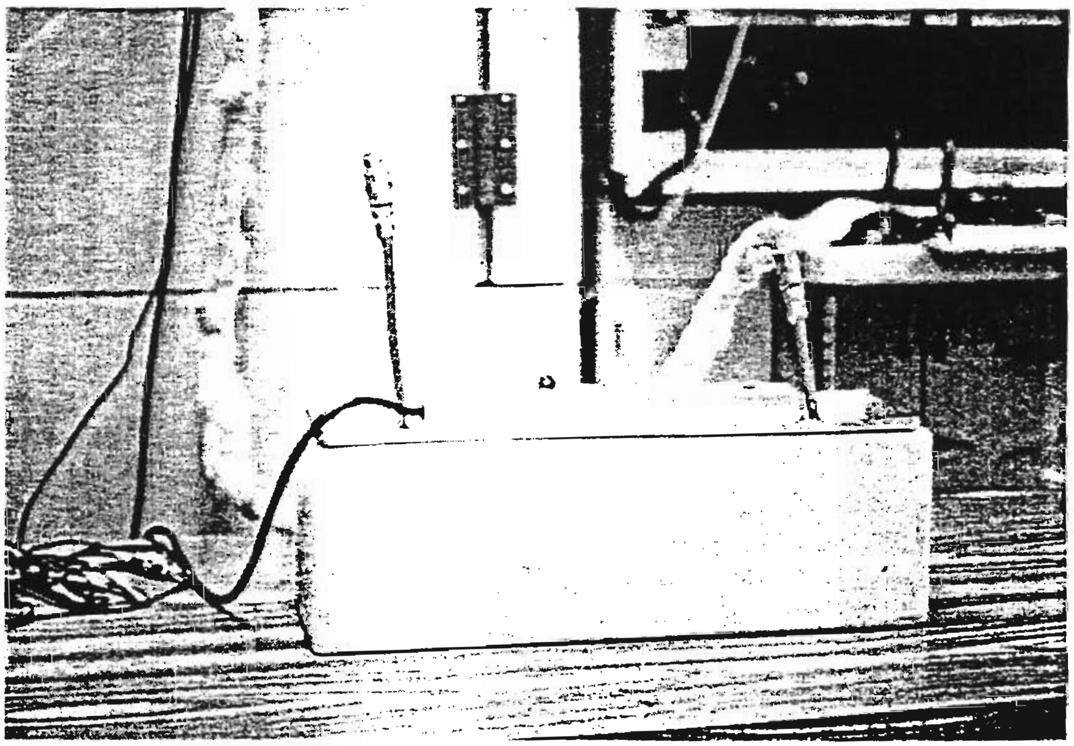

Figure A.1 - Temperature Water-Bath

Appendix B

Proposed Modified Environmental Conditioning System Test Procedure

1. Scope

1.1 This method determines the water sensitivity or stripping characteristics of compacted asphalt concrete mixtures under Texas climatic conditions. This method can be used to evaluate laboratory mixtures.

1.2 The values stated in SI units are to be regarded as the standards.

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 TxDOT Documents

Tex-207-F	Determination of Density of Compacted Bitumen Mixtures
Tex-221-F	Sampling Aggregate for Bituminous Mixtures
Tex-222-F	Method of Sampling Bituminous Mixtures
Tex-500-C	Sampling Bituminous Materials, Pre Molded Joint Fillers, and Joint Sealers

2.2 AASHTO Documents

MP1	Specification for Performance Graded Asphalt Binders
TP4	Practice for Preparation of Asphalt Concrete Specimens by means of the SHRP Gyratory Compactor
PP2	Practice for Short and Long Term Aging of Hot Mix Asphalt (HMA)
T167	Method for Compressive Strength of Bituminous Mixtures

2.3 ASTM Documents

D8 Standard Definitions of Terms Relating to Materials for Roads and Pavements

D3549 Method for Thickness or Height of Compacted Bituminous Paving Mixture Specimens

3. Terminology

3.1 Definitions for many terms pertaining to asphalt may be found in ASTM D8 and MP1.

4. Summary of Test Method

4.1 Compacted asphalt concrete test specimens are subjected to a conditioning process. The moisture sensitivity characteristics of the compacted mixtures are determined based upon measurements of resilient modulus or indirect tensile strength ratios.

5. Significance and Use

5.1 The water sensitivity characteristics of an asphalt concrete mixture can be used to determine, evaluate or characterize its suitability for use as a highway paving material.

6. Apparatus

6.1 *Material Test System (MTS)* - The system must be capable of applying static axial loads of 450 ± 15 N (100 ± 3 lbf) and dynamic axial load pulses of 9000 ± 15 N (2000 ± 3 lbf) in a haversine wave form with a load duration of 0.1 sec and a rest period of 0.9 sec between load pulses. The System is illustrated in Figures B.1 and B.2.

6.2 *Environmental Conditioning Chamber* - This chamber must be capable of maintaining a constant temperature of 60°C (140°F) for 18 hours.

6.3 *Fluid Conditioning Subsystem* - It must be capable of "pulling" distilled and de-aired hot water through a specimen at specified vacuum levels. The system must also be able to maintain a constant flow of water through the specimen and constant confining pressure to the specimen. This subsystem is shown in Figure B.3.

6.4 *Testing Machine* - A hydraulic testing machine that meets the requirements specified in the apparatus in T167.

6.5 *Specimen End Platens* - Two stainless steel end platens as shown in Figure B.1. The end platens shall be 102 ± 4 mm in diameter by 50 ± 2 mm thick. At the center of each end platen shall have a hole of 5.0 ± 0.5 mm in diameter for drainage of water through the specimen. The end of the platens which will face the specimen shall be patterned with grooves as shown in Figure B.4. At the mid-height, each platen shall have a groove around the perimeter. The width and depth of the grooves shall be sufficient to hold the O-rings described in 6.7.

6.6 *Rubber Membrane* - A rubber membrane of approximately 150 mm (6 in.) in length with a 100 mm (4 in.) nominal diameter.

6.7 *O-Rings* - Two O-rings with a 100 mm (4 in.) nominal diameter.

6.8 *Vacuum Picometer* - A vacuum picometer installed with a vacuum gauge and connected to the vacuum pump.

6.9 *Water Heating Bath* - A water bath capable of maintaining a constant temperature of 90°C (200°F). It has an inlet of 10 mm diameter. A coiled brass pipe of 10 mm in diameter shall be submerged in the heated water bath (See Appendix A).

6.10 *Miscellaneous Apparatus* - Calipers, spatula and vacuum source.

7. Materials

7.1 Commercially available Caulktrim tape of 41 mm in width.

7.2 Compressed air

7.3 40 L of distilled de-aired water

8. Sampling

8.1 Sample the asphalt binder in accordance with Tex-500-C.

8.2 Sample the aggregate in accordance with Tex-221-F.

8.3 Sample the asphalt concrete mixtures in accordance with Tex-222-F.

9. Specimen Preparation

Step	Action
1	Prepare the asphalt concrete mixture sample in accordance with TP4. This mixture should be sufficient for two specimens of final compacted dimensions equal to 102 ± 4 mm in diameter by 102 ± 4 mm in length.
2	Subject the prepared concrete mixtures to short-term aging in accordance with PP2 (SHRP 1025).
3	Heat or cool the asphalt concrete mixtures to the specified compaction temperature.
4	Compact the mixtures in accordance with TP4. Compact a sufficient amount of material to ensure that the final compacted test specimen is 102 ± 4 mm in length.
5	Determine the air voids of the two specimens in accordance with Tex-207-F. Air voids of the specimens to be tested shall be within 7 to 8 percent. Otherwise, discard the specimen.
6	Measure the diameter and length (thickness) of the specimens at four locations, at approximately the quarter points as described in ASTM D3549. Record the average diameter and thickness to the nearest 0.1 mm.
7	Place one specimen in a plastic zip lock bag (to prevent any possibility of aging) and store it at room temperature until further tested. Attach internal targets (0.5 cm square metallic iron) at a difference of 38 mm (1.5 in.) in two opposite side of the other specimen using "Super Glue." Wait Overnight for setting of Super Glue.

10. Static Immersion Saturation of the Specimen

Step	Action
1	Place the specimen in the vacuum picometer filled with distilled water. Make sure that the specimen is completely submerged in the water. Connect the vacuum picometer to the vacuum source.
2	After the vacuum gauge reads 660 mm Hg (26 in. Hg), start the stop watch and subject the specimen to this vacuum level for five minutes.
3	Calculate the percent of saturation for the specimen according to the Tex 531-C procedure.

11. Test Set-up

Step	Action
1	Remove the specimen from the water bath and wipe the extra water surrounding the specimen.
2	Stick two Caulktrim tapes of length equal to the circumference of the specimen (320 mm) and width equal to 40 mm, from the top and bottom edge of the specimen. Then enclose the specimen in 150 mm long rubber membrane, centering the specimen within the membrane so that there is an approximately 25 mm overlap at each end.
3	Place the specimen vertically on top of the bottom end platen.
4	Place the top end platen on top of the specimen. The grooved surface of the platen shall face the specimen.
5	Extend the rubber membrane to the top and bottom end platens and seal by placing O-rings over the membrane on each groove of the end platens. Place a spherical stainless steel ball at the center on top of the top end platen. Align this assembly, such that the load cell is in line with the axis of the end platens and the specimen. Connect all the quick disconnect fittings. Make sure that the connections include the heating apparatus between the source of water and the specimen.

12. Maintaining Equilibrium Saturation Condition

12.1 Apply water through the specimen at the rate of 9 cc/min for 1 hour and wait another hour to drain excess water that might have trapped between the specimen and the end platens.

13. Determination of Unconditioned Modulus

Step	Action
1	Apply a static load of 450 ± 15 N (100 ± 3 lbf).
2	Attach the targets to the specimen and adjust the proximitors in such a position that the reading in monitor due to the proximitors is in between -4 to -3 volt.

Step	Action
3	Measure resilient modulus by applying a static load of 450 ± 15 N (100 ± 3 lbs) and dynamic pulse load of 2250 ± 15 N (500 ± 3 lbs). The dynamic load shall be a haversine wave form. The load duration shall be of 0.1 sec and a rest period of 0.9 sec between the pulses. The number of loading cycle shall be 25 and record the data from the last 5 cycles. Analyze the data according to the calculations specified in section 17 to measure resilient modulus. The strain shall be in between 100 ± 10 μm/m and the variation between the displacements in two opposite side of the specimen shall not be more than 15 percent.
4	If the strain is not within the limit adjust the dynamic pulse load to reach within the limit. Increase the pulse load to increase the strain or decrease the pulse load to decrease the strain. If the variation of displacements between two sides is not within the limit discard the specimen and use another specimen for testing.

14. Warm Climate Conditioning

Step	Action
1	Maintain the temperature of the water in the heating apparatus at 90°C (194°F). Open the vacuum valve and set the vacuum pressure to 64 ± 15 mm of Hg (2.5 ± 0.5 in. of Hg) at the outlet gage. Open the water valve and the water flow meter. Adjust the water flow to 8 ± 1 cc/min. Make sure the temperature of the flowing water is at 60°C (140°F) and then close the bypass valve. If not, adjust the thermostat.
2	Maintain the temperature of the environment cabinet at 60 ± 0.5°C (140 ± 1°F). Apply an axial compressive static load of 225 ± 15 N (50 ± 3 lbf) and axial compressive dynamic pulse load of 900 ± 15 N (200 ± 3 lbf) to the test specimen. The dynamic load should be a haversine wave form with a load duration of 0.1 sec and a rest period of 0.9 sec between load pulses. Apply the loads continuously throughout a hot conditioning period of 18 hours ± 5 minutes. Measure and record the circumference at the mid section of the specimen after six hours of conditioning. Stop the loading if the change in circumference exceeds 2 percent of the initial circumference of the specimen after 6 hours of conditioning.
3	Reduce the temperature of the environmental chamber to 25°C (77°F). Close the vacuum valve, water valve, flow meter and open the bypass valve. Therefore, opening the system to the atmospheric pressure.
4	Let the specimen cool for 24 hrs at 25°C (77°F).

15. Determination of Conditioned Modulus

15.1 After a cooling period of 24 hrs at 25°C (77°F), determine the resilient modulus of the specimen according to the procedure explained in section 13.

16. Evaluation Based on Resilient Modulus

16.1 Determine the ratio of the unconditioned to the conditioned resilient modulus. Categorize the mix as moisture susceptible if the circumference deformation is more than 2 percent after 6 hours; as moderately moisture susceptible mix if the ratio is below 0.8; and as well-performing mix if the ratio is more than 0.8.

17. Evaluation Based on Indirect Tensile Strength

Step	Action
1	After determining the conditioned resilient modulus of the specimen, determine its indirect tensile strength at 25°C (77°F) along with the indirect tensile strength of the dry and unconditioned specimen.
2	Determine the ratio of the conditioned to the unconditioned indirect tensile strength and report it as ITS ratio. Categorize the mix as moisture susceptible if the circumference deformation is more than 2 percent after 6 hours of conditioning; as moderately moisture susceptible mix if the ITS ratio is below 0.8; and as well-performing mix if the ITS ratio is greater than 0.8.

18. Calculations

18.1 Calculate Cross Sectional Area (cm^2):

$$A = \frac{\pi d^2}{400} \tag{1}$$

where:

d = average diameter of the test specimen, mm

18.2 From recorded data of last five cycles loading for resilient modulus measurement test determine the following

18.2.1 Stress per load cycle:

$$\sigma_i = \frac{p_i}{A} \tag{2}$$

where:

p_i = difference in peak and base load per cycle, N
A = area of the specimen

18.2.2 Recoverable axial strain per cycle:

$$\epsilon_{i,1} = \frac{\delta_{i,1,u} - \delta_{i,1,l}}{h} \tag{3}$$

$$\epsilon_{i,2} = \frac{\delta_{i,2,u} - \delta_{i,2,l}}{h} \tag{4}$$

$$\epsilon_{i} = \frac{\epsilon_{i,1} - \epsilon_{i,2}}{2} \tag{5}$$

where:

$\delta_{i,1,u}$ = deformation measured by the upper proximitor in side 1
$\delta_{i,1,l}$ = deformation measured by the lower proximitor in side 1
$\delta_{i,2,u}$ = deformation measured by the upper proximitor in side 2
$\delta_{i,2,l}$ = deformation measured by the lower proximitor in side 2
$\epsilon_{i,1}$ = strain in side 1
$\epsilon_{i,2}$ = strain in side 2
ϵ_{i} = average strain of the specimen

18.2.3 Resilient modulus per cycle:

$$M_{R,i} = \frac{\sigma_i}{\epsilon_i} \tag{6}$$

18.3 Determine the average resilient modulus of the last five cycle

$$M_R = \frac{\sum_{i=1}^{5} M_{R\,i}}{5} \tag{7}$$

19. Report

Item	Subject
1	Asphalt binder grade, aggregate type and gradation, and the asphalt binder content to the nearest 0.1 percent.
2	Mixing and compaction conditions - the following information is applicable:
3	Laboratory Mixing Temperature, nearest 1 °C.
4	Laboratory Compaction Temperature, nearest 1 °C.
5	Laboratory Compaction Method.
6	Compacted Specimen Height, nearest 0.1 mm.
7	Compacted Specimen Diameter, nearest 0.1 mm.
8	Compacted Specimen Area, nearest 0.01 sq.cm.
9	Compacted Specimen Density, nearest 0.1 kg/m^3.
10	Compacted Specimen Air Voids, nearest 0.1 percent.
11	Report the water conditioning results in a table listing the unconditioned M_R and conditioned M_R and their ratio.
12	Report the water conditioning results in a table listing the unconditioned indirect tensile strength and conditioned indirect tensile strength and their ratio.

20. Precision and Bias

20.1 Precision - Data to support a precision statement for this test method has not been developed.

20.2 Bias - No justifiable statement can be made on the basis of this test method because there is no reference value available.

21. Keywords

Asphalt concrete, bituminous mixtures, bituminous paving mixtures, moisture sensitivity, stripping potential, resilient modulus, indirect tensile strength.

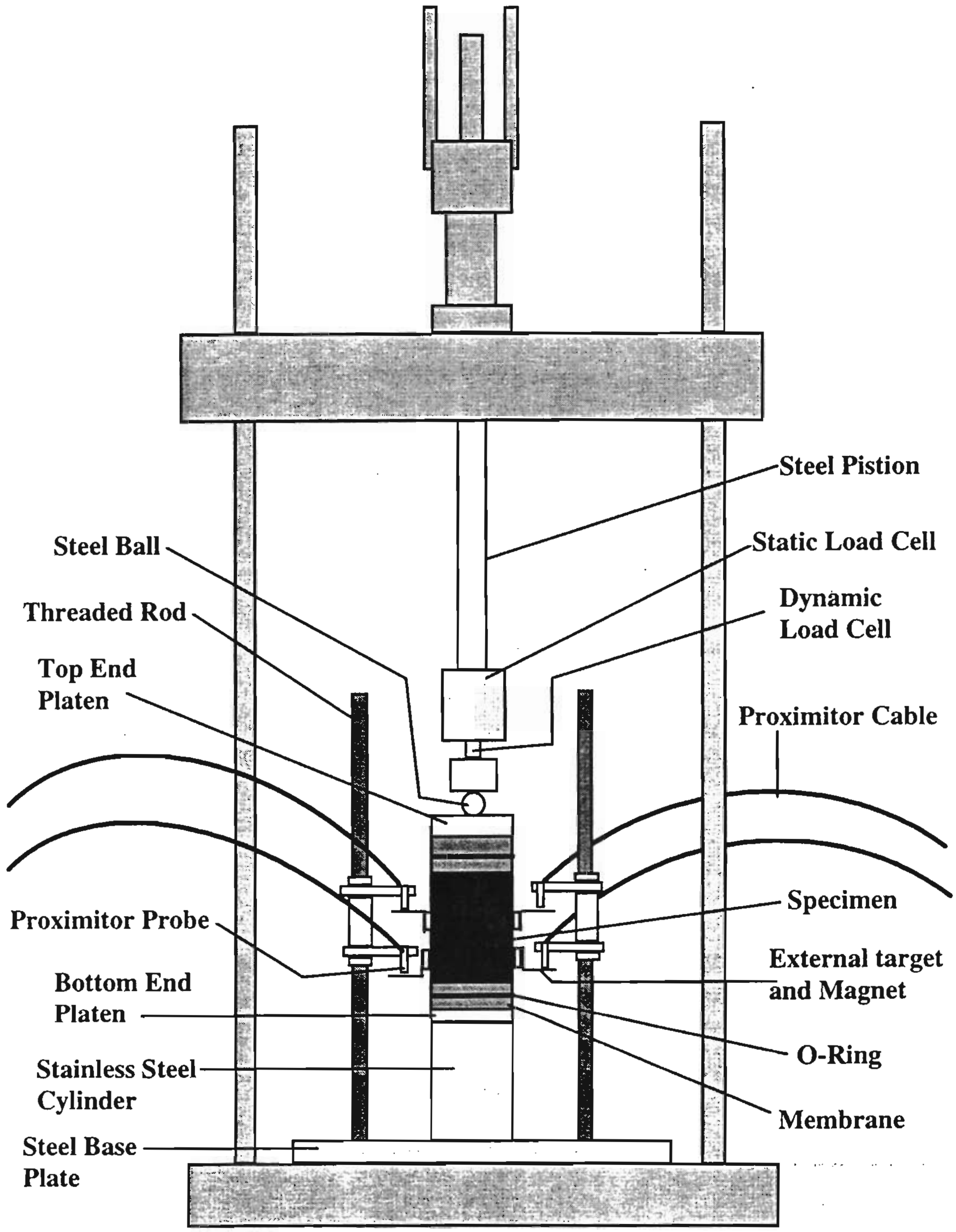

Figure B.1 - Schematic Diagram of MTS (Not to the Scale)

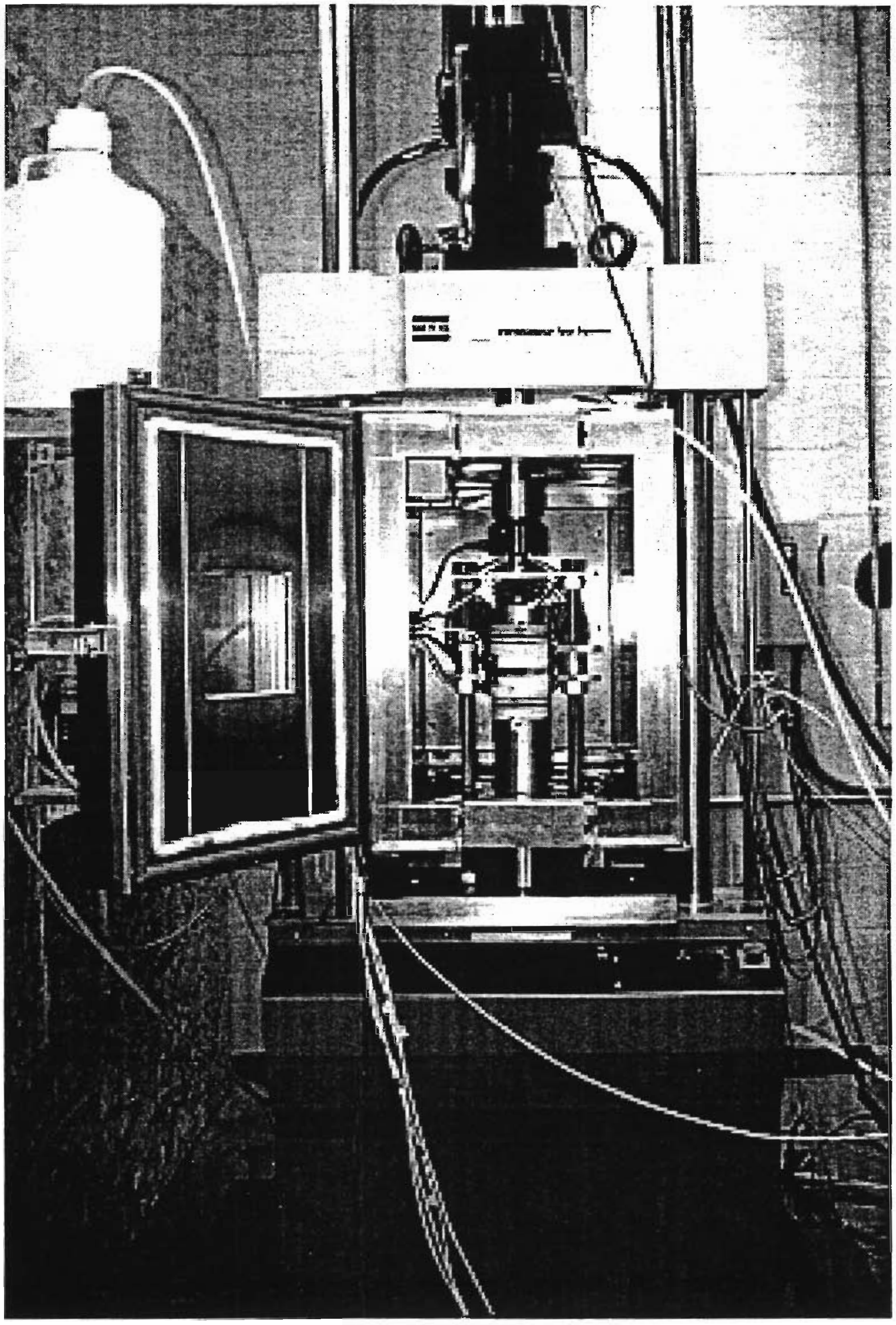

Figure B.2 - Picture of Modified ECS Resilient Modulus Test Setup

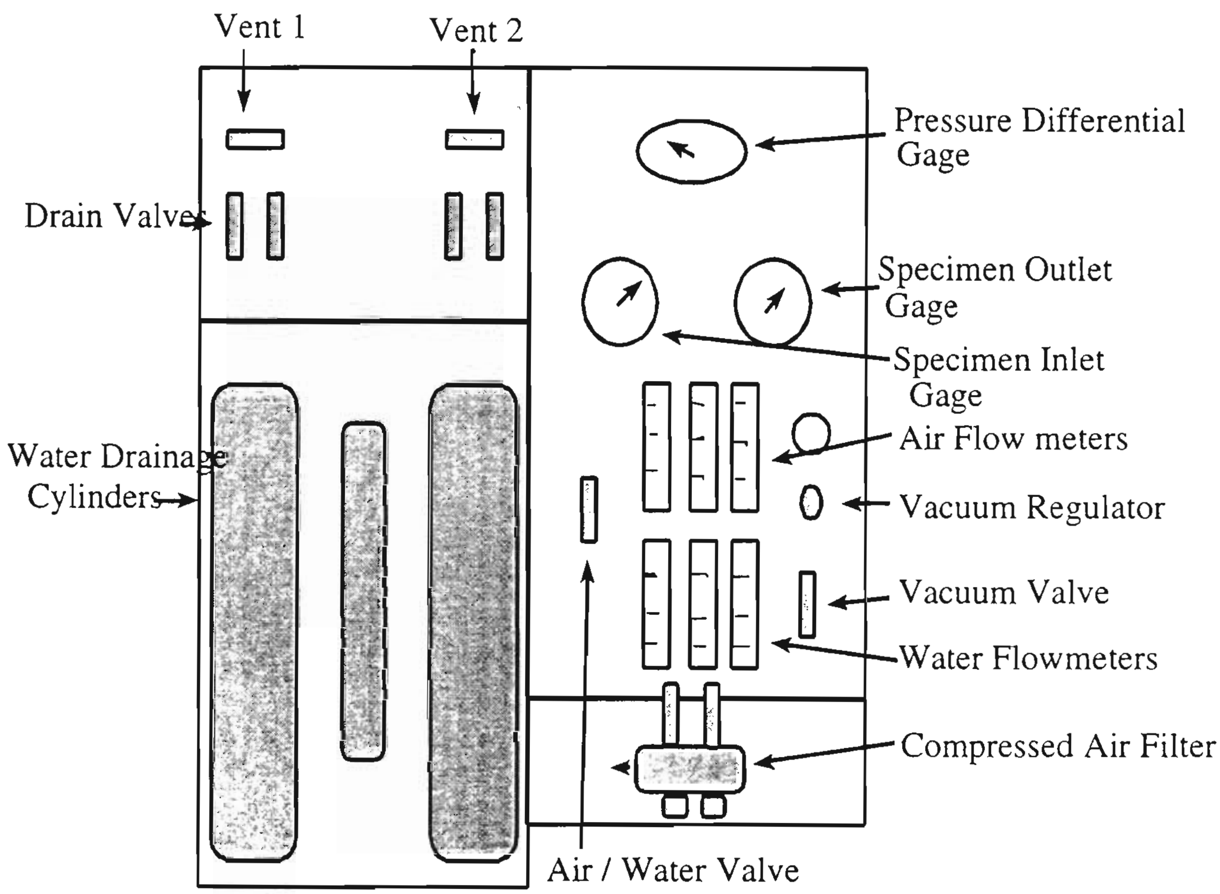

Figure B.3 - Fluid Control Panel (Front View)

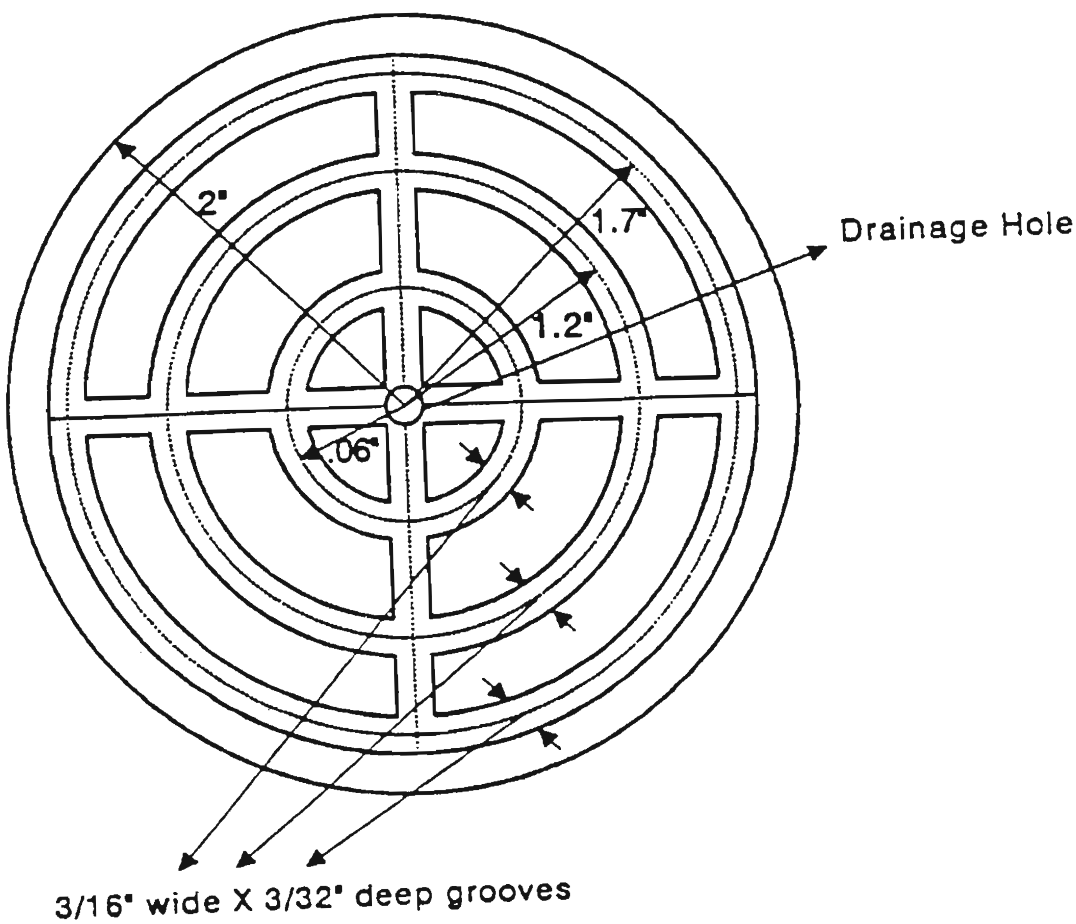

Figure B.4 - Groove Pattern for End Platens