Development and Evaluation of Test System To Induce and Monitor Moisture Damage to Asphalt Concrete Mixtures

SALEH AL-SWAILMI, TODD V. SCHOLZ, AND RONALD L. TERREL

One of the major research goals of the Strategic Highway Research Program is to develop a relationship between asphalt binder properties and field performance for asphalt concrete mixtures. A part of this effort is concerned with development of a system and procedure to moisture-condition asphalt concrete specimens to determine whether an asphalt-aggregate mixture is susceptible to moisture-induced damage. The development of a computer-controlled loading and data acquisition subsystem used with moisture conditioning and environmental control subsystems is addressed. The three subsystems make up a state-of-the-art test system that is used to determine and measure the factors that most influence the amount of moisture damage. A brief overview of the three subsystems is given, as is a more detailed description of the development and evaluation of pertinent test parameters. Significant findings include (a) many factors affect the reliability of subsystems, and the computer-controlled loading and data acquisition subsystem provides an efficient tool for detecting factors causing variability in test results; (b) specimen instrumentation is simple, reliable, and accurate; (c) specimens 4 in. high and 4 in. in diameter were found to provide results of sufficient accuracy; and (d) specimen orientation was found to be very important.

A major goal of the Strategic Highway Research Program (SHRP) is to relate asphalt binder properties to field performance of asphalt concrete mixtures. Consequently, much of this research program has focused on the factors that influence field performance. Although many factors contribute to the degradation of asphalt concrete pavements, damage attributable to moisture is considered a key element in the deterioration of asphalt mixes.

With the recognition that moisture damage can significantly influence pavement performance, a part of the SHRP research effort has been concerned with the development of a system and procedure having a twofold purpose: (a) to determine whether an asphalt-aggregate mixture is susceptible to moisture-induced damage, and (b) to moisture-condition asphalt concrete specimens to be tested for mixture properties including thermal cracking, fatigue, and permanent deformation (rutting).

Previous work on the development of a moisture-conditioning procedure has been documented elsewhere (*1,2*). This paper addresses the development and evaluation of the test system composed of a computer-controlled closed-loop loading and data acquisition subsystem that is used with fluid conditioning and environmental cabinet subsystems. The three subsystems make up a state-of-the-art test system used to determine and quantify the factors that most influence the amount of moisture damage that occurs in asphalt concrete mixtures.

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A brief overview of the three subsystems, collectively referred to as the environmental conditioning system (ECS), is followed by a more detailed description of the development and evaluation of pertinent test parameters. Provided are details about factors that affect the measurement of resilient modulus (height-to-diameter ratio, deformation measurement, etc.), permeability measurement, and overall water sensitivity evaluation (saturation level, conditioning temperature, etc.). It is shown that considerable effort was required to "debug" the overall test system so that a reliable system producing repeatable results emerged.

TEST SYSTEM

The ECS was designed and fabricated to assist in determining the most important factors in the performance of mixtures in the presence of moisture. The test setup permits evaluation of air voids and behavior of mixtures in several ways, including

- Saturation versus wet (partial saturation),
- Water versus vapor as a conditioning fluid,
- Permeability versus air void content,
- Freezing versus no freezing,
- Volume change effects (i.e., oversaturation),
- Effects of time on rate of saturation or desaturation,
- Continuous monitoring using resilient modulus (M_R),
- Repeated loading versus static loading, and
- Coating and stripping.

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

The ECS was designed and fabricated to provide a means of simulating various conditions within an asphalt pavement. Figure 1 shows the ECS and its subsystems: the fluid-conditioning subsystem, the environmental cabinet subsystem, and the loading subsystem.

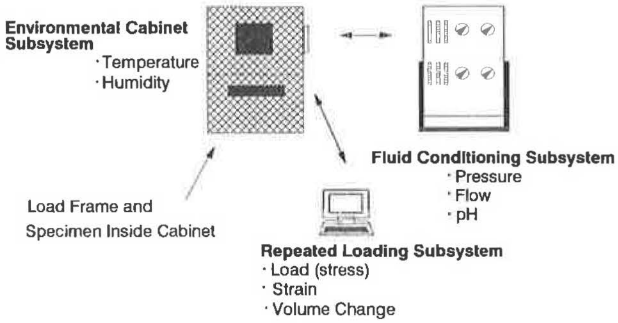

FIGURE 1 Overview of ECS.

Fluid-Conditioning Subsystem

This system was designed to test the air and water permeability of asphalt concrete mixtures as well as to provide fluid (water, water vapor, or air) conditioning.

As shown in Figure 2, the test specimen is placed in a load frame. Two differential pressure gauges, connected immediately before and after the specimen, measure the pressure gradient across the specimen, which is controlled by a vacuum regulator.

Environmental Cabinet Subsystem

The heart of the system is a Despatch Industries 16000 Series high- and low-temperature and humidity environmental-conditioning cabinet. The environmental chamber simulates high and low temperatures and humidity levels.

Loading Subsystem

The repeated loading subsystem is an electropneumatic closed-loop system made up of a personal computer with software and an analog-to-digital/digital-to-analog interface card, a transducer signal conditioning unit, a servovalve amplifier and power supply, and a load frame.

Figure 2 shows a schematic of the load frame, which includes a double-acting pneumatic actuator (piston) and servovalve. The servovalve, serviced by compressed air and driven by a computer software program, drives the piston. Loads are delivered by the piston through its load ram to a load cell mounted on the specimen cap, which rests atop the test specimen. The signals from the load cell and linear variable differential transducers (LVDTs) mounted on the specimen are collected by the computer software program and converted to engineering units of stress and strain allowing the calculation of the M_R. Although the software can deliver a variety of loads and waveforms, tests in the ECS have been almost exclusively conducted using a haversine pulse load with a pulse load duration of 0.1 sec, a pulse load frequency of 1 Hz, and a pulse load magnitude of 600 lb.

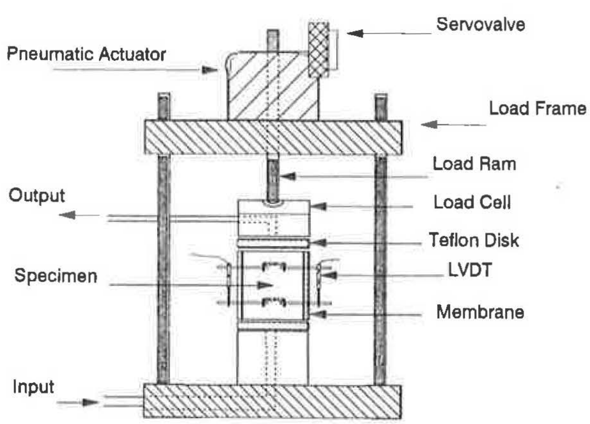

FIGURE 2 Load frame inside environmental cabinet for evaluating water sensitivity.

SYSTEM DEVELOPMENT AND EVALUATION

As stated earlier, the intent of this paper is to describe the development and evaluation of the ECS. Generally, before a full-scale test scheme is started, many questions and details must be evaluated when a testing device is developed. Likewise, before the ECS was used as a testing device for the water sensitivity program at Oregon State University, it was subjected to detailed investigation and refinement to prove its reliability and reproducibility in three aspects: resilient modulus measurement, permeability measurement, and water-conditioning evaluation.

Resilient Modulus Measurement

Many test procedures and types of test equipment have been developed and used in several laboratories and agencies to evaluate the structural properties of the asphalt concrete mixtures. The resilient modulus of compacted asphalt mixtures can be obtained by using either repeated-loading triaxial test or repeated-loading indirect tensile test. These two procedures have been standardized by ASTM as the Standard Test Method for Dynamic Modulus of Asphalt Mixtures (ASTM D3497) and the Standard Test Method of Indirect Tension Test for Resilient Modulus of Bituminous Mixtures (ASTM D4123).

In the ECS, the resilient modulus is defined as the ratio of the applied differential axial stress to the corresponding recoverable (elastic) axial strain. The vertical stress is applied axially by the use of an electropneumatic closed-loop testing system. Applied stress is monitored by a load cell placed on the top of the specimen. Recoverable axial strain is monitored by LVDTs. Stresses and strains are recorded and analyzed by the computer and software package.

For axial loading the appropriate specimen height, as recommended in ASTM D3497, should be at least 8 in. for a specimen with a 4 in. diameter. However, it was not feasible to water-condition these tall specimens. To compromise between the ASTM D3497 requirement and typical pavement layer thicknesses, a ministudy was conducted to investigate the effect of height-to-diameter (L/D) ratio, on resilient modulus. In addition, other ministudies were conducted to investigate other details, including the effect of glue type for strain gauges (strain gauges were later replaced by LVDTs), and the repeatability of ECS resilient modulus and necessity of using Teflon disks.

Test Specimen Preparation

One mix was used for preparing three specimens 4 in. in diameter and 7 in. high. After density was determined, a vertical alignment jig was used with capping compound to maintain caps perpendicular with the specimen axis according to the requirements of ASTM C617 (Capping Cylindrical Concrete Specimens). After testing the specimens with the full height, 1.0 in. was trimmed from each end with a diamond saw. Capping and testing were repeated for the new 5-in. specimens. Finally, 1.25 in. was trimmed from each end of the 5-in. specimen, which resulted in 2.5-in. specimens that were exposed to the same capping and testing procedure. Trimmed specimen densities and air void calculations were monitored for the three heights.

Test Equipment and Instrumentation

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

1. LVDTs attached to the specimen by a pair of clamps that were cemented to the specimen by plates, maintaining a 2-in. gauge length. Deformations were measured by chart recorder.
2. A pair of strain gauges 1 in. long and a strain indicator for recording strains.

The specimens were loaded using two modes: (a) continuous repeated loading of haversine wave form, and (b) continuous repeated loading of square wave form. A dynamic load of 600 lb was used after the specimens were seated with a 60-lb static load.

Effect of L/D Ratio on Resilient Modulus

Figures 3, 4, and 5 show the relationship between resilient modulus and specimen thickness for the three similar specimens (three test replications). Moduli of the specimens with 2.5-in. thickness are significantly higher than the moduli of the specimens with 5- and 7-in. thicknesses. The wave form (haversine or square) and strain measurement device (LVDTs or strain gauges) have no effect on the trend or general relationship, but they do affect the magnitude: for the same method of strain measurement and load level, the M_R from the square wave mode is higher than the M_R from the haversine wave form.

For the same wave form, strain gauges detect less strain, which resulted with a higher M_R than that from the LVDTs. Strain gauges may not indicate the total strain as the LVDTs do because large stones behind the strain gauges may not transmit the total strain. In contrast, LVDTs with total slippage controlled measure the cumulative strain between two points, which may be more realistic. In addition, during the ECS testing program it has been noticed that the strain gauges mounted on specimens with high air voids (such as 10 percent) experienced major wrinkles under the effect of repeated load-

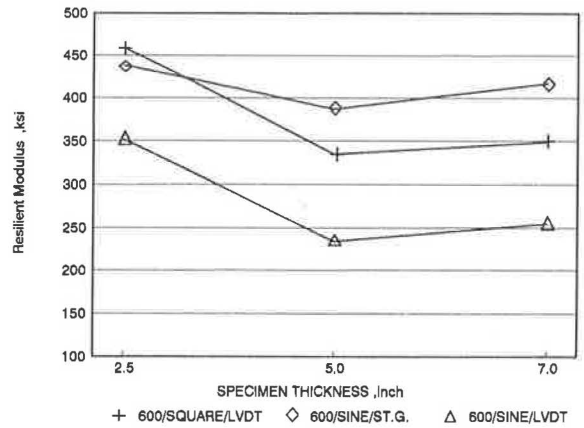

FIGURE 3 Relationship between M_R and specimen thickness for two testing conditions, Specimen 1.

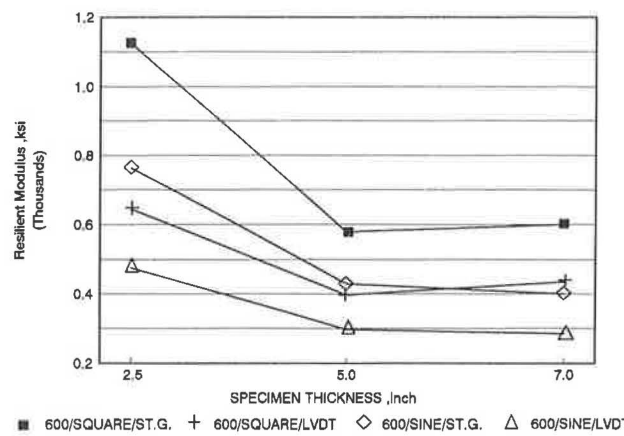

FIGURE 4 Relationship between M_R and specimen thickness for two testing conditions, Specimen 2.

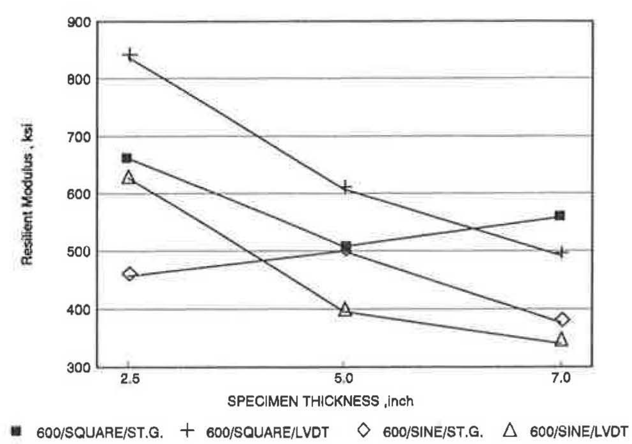

FIGURE 5 Relationship between M_R and specimen thickness for two testing conditions, Specimen 3.

ing with hot-water conditioning. The deformed strain gauges were most likely caused by total deformation due to compaction. Because of such deficiencies associated with the strain gauges and because of their cost, it was decided to switch to LVDTs after a significant part of the ECS testing program, particularly the low-air-void specimens, was completed using strain gauges.

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

Since the resilient modulus value from the ECS is not the true or familiar M_R, the term "ECS-M_R" will be used in this paper for 4-in. specimens. Therefore, there are two important differences between the ECS-M_R and the dynamic modulus defined in ASTM D3497: (a) the height of the specimen is 4 in. instead of 8 in., and (b) the specimen is encapsulated in a rubber membrane throughout the test. In addition to ECS-M_R, a diametral M_R is measured for each specimen before the ECS testing process to be used for reporting the initial specimen strength. All values of M_R in this report stand for ECS-M_R unless otherwise noted.

Effect of Strain Gauge Glue Type

The ECS testing program started with strain gauges that were subjected to a detailed investigation before the full-scale test scheme was begun. The main factor to be evaluated was the effect of glue type on strain gauge performance. To accomplish this investigation, six strain gauges (X_1, X_2, X_3, Y_1, Y_2, and Y_3) were bonded on a plastic specimen 7.5 in. high and 4 in. in diameter. The strain gauges were divided into two groups, and each group was mounted at midheight opposite to the other group. The two groups are (a) X_1, X_2, and X_3 bonded on Side X; and (b) Y_1, Y_2, and Y_3, bonded on Side Y. Three types of glue were used for bonding the strain gauges according to the following identification:

- X_1 and Y_1: 1-in. strain gauge with cyanoacrylate ("superglue");
- X_2 and Y_2: 1-in. strain gauge with Ca-200LS glue; and
- X_3 and Y_3: 1-in. strain gauge with Testor's "airplane" glue.

Specimens were subjected to dynamic repeated loading by using the MTS and strains were monitored by strain indicator. Figure 6 shows resilient modulus results from each strain gauge. The difference between glue types is not significant. The M_R on Side X was higher than M_R on Side Y due to an eccentricity problem that was later corrected. As a result of this experiment, superglue was selected for future strain gauge application because it needs a very short time to cure.

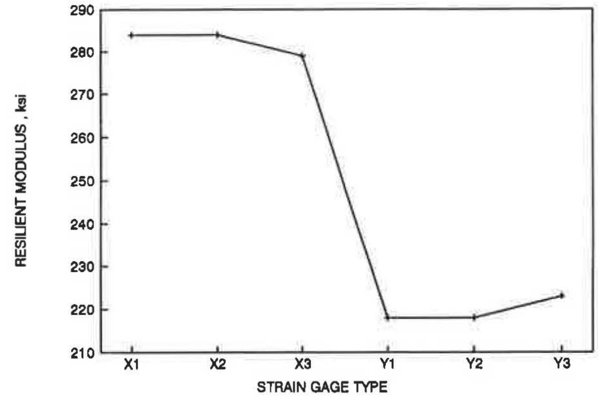

FIGURE 6 Effect of strain gauge mounting glue on M_R.

Repeatability of ECS-M_R and Effect of Teflon Disks

Six specimens were used to investigate the repeatability of ECS-M_R and the effect of friction between the specimen and the top cap and bottom base. Teflon disks were used because of the concern that the shorter (4-in.) specimens are affected by the load platens to a greater extent than for taller specimens. The following specimens were used in the study:

- 1 PLAS and 2 PLAS: plastic, 4 in. in diameter and 2.5 in. high;
- 54TB and 62TB: asphalt concrete, 4 in. in diameter and 2.5 in. high; and
- TG61 and WG77: asphalt concrete, 4 in. in diameter and 4 in. high.

Strain gauges 1 in. long were used on specimens 2.5 in. high, and strain gauges 2 in. long were used on the 4-in. specimens. The ECS was used to conduct resilient modulus tests. Two types of ⅛-in.-thick Teflon disk were used: solid and perforated. Tests were performed on each specimen according to the following combinations:

- No disks: No disks were used;
- One disk: One solid Teflon disk, top and bottom;
- Perf. disk: One perforated Teflon disk, top and bottom;
- Two disks: Two solid Teflon disks, top and bottom;
- One disk: One solid Teflon disk, top and bottom; and
- Diff. Or: One solid disk top and bottom with different orientation by rotating the specimens 180 degrees around its vertical axis.

The one-disk setup was conducted twice to show the repeatability of ECS-M_R for the test setting that represents the ECS testing program standard. Figure 7 shows the ECS-M_R for all test setups from each specimen. For all six specimens, the repeatability of one disk setting is very high. Teflon disk and test orientation does not affect the results for the plastic specimen because of Teflon's near frictionless surfaces and high uniformity. Teflon disks and test orientation have a significant effect on ECS-M_R of 2.5-in. asphalt concrete specimens, 54TB and 62TB. The effect of Teflon disks and test orientation on ECS-M_R from 4-in. asphalt concrete specimens is not significant.

It was found necessary to use perforated spacers between the specimen and top cap and base plate to collect any stripped

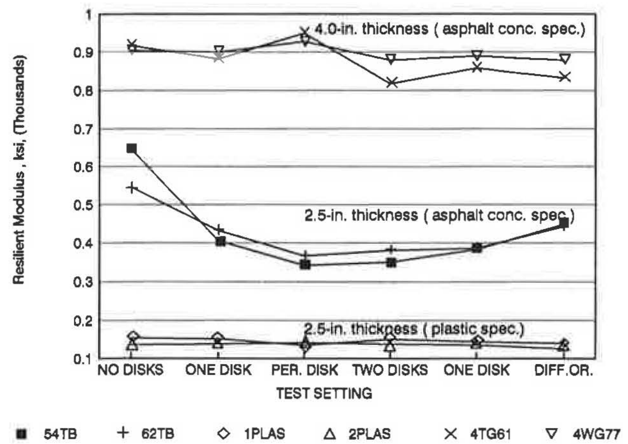

FIGURE 7 Variability of ECS-M_R for different test conditions.

asphalt that might stick on the bottom of the top cap during the water conditioning process and change its serviceability condition. Perforated Teflon disks, top and bottom, are recommended to be used with the ECS testing program.

Permeability Measurement

Permeability K, as defined by Kumar and Goetz (*3*), is the volume of fluid Q of unit viscosity μ passing in unit time Δt through a unit cross section A of a porous medium of length L under the influence of a unit pressure gradient ΔP.

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

There is a general belief that permeability is a better measure of durability than percentage air voids because permeability measures fluid accessibility through the asphalt pavement. Some air voids may not be accessible by water. In the ECS testing program, a relationship is hypothesized between permeability and water damage.

For the air or water flow to pass only through the specimen during the permeability test, the outer surface of the specimen wall must be sealed to close off surface voids. Goode and Lufsey (*4*) used paraffin for sealing to prevent leakage between the specimen wall and the membrane. However, this method destroys the specimen for further use by contaminating the asphalt.

Another method is to place the specimen in a cylindrical rubber membrane fastened to a hollow metal cylinder with hose clamps. This method does not totally prevent leakage between the specimen wall and the membrane, especially with mixtures having coarse surface texture. Another disadvantage of this method is that air pressure in the membrane may cause deformation of the specimen.

Kumar and Goetz (*3*) developed a different technique to prevent leakage. The specimen is placed between lower and upper collars and coated with silicone rubber sealer all around the specimen and part of both collars in order to bind the collars to the specimen. This method prevents the leakage through the specimen wall, but it is rather involved and time-consuming.

In the modified procedure developed at Oregon State University, the middle third of the specimen's surface is coated with silicone and then enveloped with a cylindrical rubber membrane 1.5 in. high (a wide rubber band, cut from a membrane) to provide a smooth surface as shown in Figure 8. After curing for a few hours, the specimen is fitted with a cylindrical rubber membrane, long enough to envelop the sample base and sample top cap. This procedure has been adopted after investigating three levels of silicone seals on the surface of the specimen and under the rubber membrane. Test results from six specimens showed that the "standard" procedure of a single seal at the midpoint was adequate, as shown in Figure 9.

Water Sensitivity Evaluation

An intensive testing program was conducted by using the ECS at Oregon State University. The controlled variables and their treatment levels in a factorial design experiment include

1. Temperature with three treatment levels: hot (60°C), ambient (25°C), and freeze (−18°C).
2. Permeability with three treatment levels depending on the air voids (AV): low (% AV ≤ 6), pessimum (6 < % AV < 14), and high (% AV ≥ 14).
3. Wet conditioning with three treatment levels: dry (No water conditioning) moist [running water through the speci-

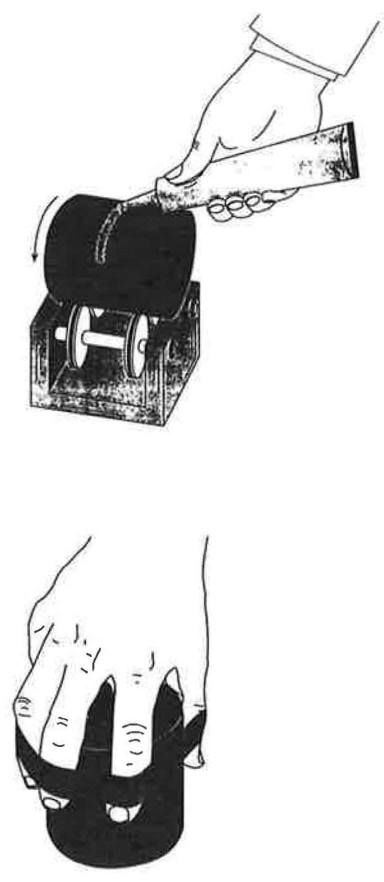

FIGURE 8 Permeability sealing of compacted asphalt mixtures using silicon sealer and rubber membrane.

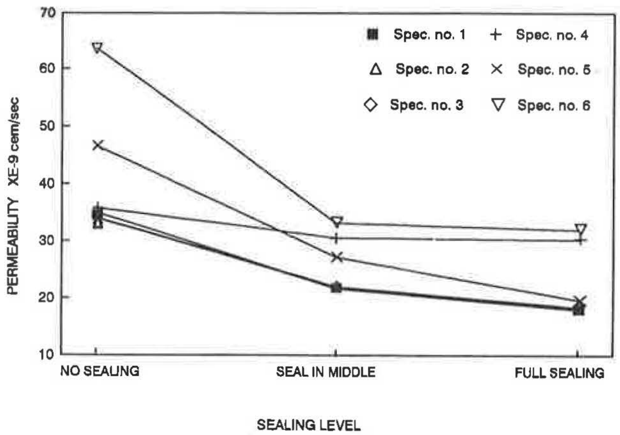

FIGURE 9 Effect of sealing level on permeability.

mens at 25°C under 10 in. of mercury (Hg) vacuum for 30 min], and saturated (running water through the specimen at 25°C under 20 in. of Hg vacuum for 30 min).

The complete study has been documented by Al-Swailmi and Terrel (*1*). Because of space limitations, only two water-conditioning tests will be discussed to show the capability of the ECS in detecting asphalt concrete response under the effect of water conditioning.

Materials

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

1. Aggregates: granite, RB, nonstripper and gravel, RL, a known stripper.
2. Asphalts: AAG-1 and AAK-1. These were selected because of their different compositional and temperature-susceptibility characteristics.

These four asphalt-aggregate combinations were used to fabricate mixtures.

Test Procedure

The water-conditioning procedure is summarized for a typical test and includes several steps, depending on the mixture and variables being evaluated.

1. A specimen 4 in. in diameter and 4 in. high is mixed and compacted.
2. Physical measurements (density, voids, etc.) are determined.
3. Circumferential silicon seal is applied, and specimens are mounted in load frame.
4. LVDTs are mounted.
5. Preconditioned resilient modulus is determined.
6. Permeability (air) is measured.
7. Specimen is wetted according to desired procedure and permeability (water) is measured.
8. Conditioning cycles are begun according to the desired sequence. Table 1 shows a typical conditioning chart that includes the variables for each test.
9. The resilient modulus (M_R) and water permeability (K) are measured at 25°C after each cycle.
10. Upon completion of conditioning, the specimen is split open and the degree of stripping determined.

Effect of Saturation Level

One of the capabilities of the ECS is to isolate and evaluate a single factor among a wide range of factors. In the ECS water-conditioning procedure, the degree of saturation is defined by a standardized vacuum level. The wetting vacuum level, before the water-conditioning cycling, is either 10 in. Hg for moist or 20 in. Hg for saturated. A vacuum level of 10 in. Hg is then maintained during conditioning. Vacuum level appears to be more representative for the ECS procedure because retaining some vacuum (10 in.) during water conditioning maintains a constant level of saturation better than for static immersion conditioning.

For evaluation of the saturation level, 2 two-specimen sets were compacted for one air void level from the same asphalt-aggregate mix, RL–AAK-1. One set was then wetted to achieve the moist condition, and the second set was wetted to achieve the saturated condition. All specimens were then subjected to the same water-conditioning procedure, same temperature level, and repeated loading, as shown in Table 1. Figure 10 shows the retained modulus (average of each set) obtained by dividing the M_R after each conditioning cycle by the original dry M_R. The specimens subjected to the higher wetting level (i.e., saturated) experienced more water damage.

TABLE 1 Conditioning Chart for Figure 10

CONDITIONING FACTOR		CONDITIONING STAGE			
		WET *	CYCLE-1	CYCLE-2	CYCLE-3
Vacuum (in. Hg) :	Saturated	20	10	10	10
	Moist	10	10	10	10
Ambient Temp.(C) **		25	60	60	60
Duration (hr.)		0.5	6	6	6

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

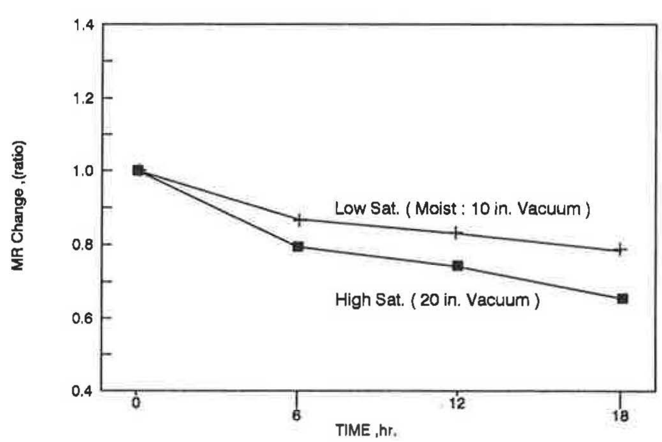

FIGURE 10 Effect of vacuum level on M_R: hot-saturated and hot-moist conditionings with continuous repeated loading.

Effect of Conditioning Temperature

To evaluate conditioning temperature 2 two-specimen sets were compacted to the same air void level using the same asphalt-aggregate combination, RL–AAK-1. Before conditioning, the specimens were tested for M_R at 25°C. Both sets were then subjected to the same wetting procedure to achieve a saturated level (i.e., pulling 25°C water under a vacuum level of 20 in. of Hg for 30 min). After wetting, one set was subjected to three 6-hr "hot cycles" at a temperature of 60°C with continuous repeated loading while a vacuum of 10 in. of Hg was maintained. Between cycles the specimen temperature was reduced to 25°C and the M_R was measured. The second set was tested in the same manner except the specimen temperature remained constant at 25°C throughout. Figure 11 shows that the specimens subjected to the hot cycles (60°C) experienced a significantly higher degree of water damage than did the specimen cycled at ambient temperature (25°C).

SUMMARY AND CONCLUSIONS

The development of the ECS required considerable effort to mitigate the problems associated with seemingly minor details (e.g., L/D ratio, strain gauges versus LVDTs, amount of silicone sealing required) such that a reliable and practical system producing repeatable results emerged. Although the following conclusions (which are based on data to date) appear warranted, it should be noted that this is an ongoing study and that the conclusions should be regarded as tentative.

As for the loading subsystem, the effect of the height-to-diameter ratio was shown to have significant import in the determination of resilient moduli of asphalt concrete specimens. Resilient modulus tests indicated that specimens having an L/D ratio of less than unity showed greater variability and significantly greater magnitudes than did specimens having L/D ratios greater than unity. Furthermore, it was shown that modulus tests on specimens having an L/D ratio of 5/4 had essentially the same variability and magnitude as those for specimens with L/D ratios of 7/4. With these results and the expectation that most production laboratories can easily produce 4-in.-high specimens (but may need to retool to produce specimens of greater height), a 4-in. height and 4-in. diameter were selected as a standard.

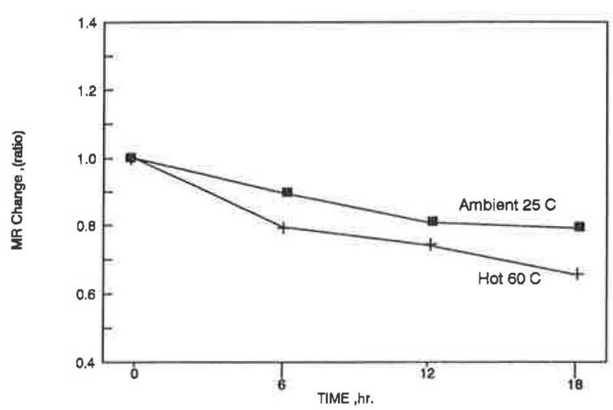

FIGURE 11 Effect of conditioning temperature on M_R.

Comparisons between LVDTs and strain gauges showed little or no significant difference on dry specimens. However, the use of strain gauges presented problems of practicality during actual testing. That is, the strain gauges wrinkled under the effect of repeated loading with hot-water conditioning. Therefore, the use of LVDTs was adopted for strain measurement during the resilient modulus tests. Although the use of strain gauges for the ECS was abandoned, tests on the type of glue used to bond the gauges to the specimens showed no significant difference between glue types, thus cyanoacrylate ester (superglue) was recommended for such application, because of its quick drying time.

Tests evaluating the use of Teflon disks (used to minimize shear stresses at the top and bottom of the specimen during modulus testing) indicated that perforated disks are suitable and that no significant difference exists between the type or number of disks. Duplicate tests using one disk at each interface indicated that the ECS-M_R is indeed repeatable.

As for permeability measurement, it was shown that partially sealing the specimen (sealing the middle third) with silicone cement is adequate; that is, fully sealing the specimen is unnecessary—the two methods indicate no significant difference.

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

ACKNOWLEDGMENTS

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REFERENCES

1. S. Al-Swailmi and R. L. Terrel. Evaluation of Water Damage of Asphalt Concrete Mixtures Using the Environmental Conditioning System (ECS). *Journal of the Association of Asphalt Paving Technologists*, 1992.
2. C. Curtis, R. L. Terrel, L. M. Perry, S. Al-Swailmi, and E. J. Brannon. Asphalt Aggregate Interactions. *Journal of the Association of Asphalt Paving Technologists*, 1991.
3. A. Kumar and W. H. Goetz. Laboratory Measurement of Permeability of Compacted Asphalt Mixtures. In *Transportation Research Record 659*, TRB, National Research Council, Washington, D.C., 1977.
4. J. F. Goode and L. A. Lufsey. Voids, Permeability, Film Thickness versus Asphalt Hardening. *Proc., Association of Asphalt Paving Technologists*, Vol. 34, 1969, pp. 430–462.