Summary Report
on

WATER SENSITIVITY

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by

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ABSTRACT

Asphalt has been used in paved roads for about 100 years in the U.S., and has often been considered to be a good waterproofing material. Engineers have found, however, that water often displaces the asphalt from the aggregate in mixtures and that other types of pavement failure may be manifested in the presence of water.

Since about the 1930's, engineers have been working on tests to determine the water sensitivity of asphalt concrete. Numerous test procedures have been proposed and evaluated, but none have proved to be a clear means of identifying or predicting water susceptibility.

Although many factors may contribute to the deterioration of asphalt concrete, moisture is a key element. There are two mechanisms by which water can degrade the integrity of an asphalt concrete matrix: (a) loss of cohesive strength and stiffness in the asphalt film, and (b) the failure of the adhesive bond between the aggregate and asphalt cement.

The purpose of this report is to review and summarize the available information and the "State of the Practice" in evaluation of asphalt paving mixtures or water sensitivity. Having done this, the available knowledge is to be focused on two major goals for the SHRP project:

1. Define water sensitivity of asphalt concrete mixtures with respect to performance, including fatigue, permanent deformation, and low temperature cracking as well as the effect of aging.
2. Develop laboratory testing procedures that will predict field performance.

The report includes an evaluation of laboratory procedures currently being used and an assessment of the extent of use for each method. Several areas of needed research and discussion of possible methodology are presented and are tied to an outline of the planned research approach.

In conclusion of the study, it was found that a wide range of procedures are being used by the state DOTs, and there appears to be no procedure that is universally acceptable.

A working hypothesis is proposed, stating that the presence of voids in the "pessimum" range may be a major cause of moisture damage in conventional asphalt concrete mixtures. A scheme for evaluating the hypothesis is outlined.

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DISCLAIMER

The contents of this report reflect the views of the authors, who are solely responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the official view or policies of the Strategic Highway Research Program (SHRP) or SHRP's sponsors. The results reported here are not necessarily in agreement with the results of other SHRP research activities. They are reported to stimulate review and discussion within the research community. This report does not constitute a standard, specification, or regulation.

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1.0 INTRODUCTION

1.1 Problem Definition

The development of tests to determine the moisture sensitivity of asphalt concrete mixtures began in the 1930's. Since that time numerous tests have been developed to help identify moisture susceptible asphalt concrete mixtures. Test procedures have attempted to simulate the strength loss from moisture damage that can occur in the field so asphalt mixtures which suffer premature distress from the presence of moisture can be identified. An asphalt mix is identified as being susceptible to moisture if the sample specimen(s) fail a "moisture sensitivity" test. The implication of the failure is that this particular combination of asphalt, aggregate, and antistripping additive (if included) would fail before reaching its design life (10 to 15 years) due to moisture related mechanisms.

Though many factors contribute to the degradation of asphalt concrete pavements, moisture is a key element in the deterioration of the asphalt mix. There are two mechanisms by which moisture can degrade the integrity of an asphalt concrete matrix: (a) loss of cohesive strength and stiffness in the asphalt film that may be due to several mechanisms, and (b) the failure of the adhesive bond between the aggregate and asphalt. When the aggregate tends to have a preference for absorbing water, the asphalt is "stripped" away. This leads to premature pavement distress and ultimately failure of the pavement.

The difficulty in developing a test procedure has been in simulating the field conditions to which the asphalt concrete is exposed. Environmental conditions, traffic and time are the factors which need to be accounted for in developing test procedures to simulate the field conditions. Environmental considerations include; moisture from precipitation or ground water sources, temperature fluctuations (including freeze-thaw conditions) as well as aging of the asphalt. The effect of traffic or moving wheel loads could also be considered as an external influence or environment. Variability in construction procedures at the time the asphalt mix is placed can also influence the performance of a mix in the field. Since most test procedures currently are used in the mix design stage of a project, this variability adds to the difficulty in simulating field performance. Current test procedures measure the loss of strength and stiffness, both cohesive and adhesive, of an asphalt mixture due to moisture. The conditioning processes associated with current test methods are attempts to simulate field exposure conditions, but accelerating the rate of strength loss. An alternative is to subject the samples to a conditioning process, not necessarily simulating field conditions. Testing of the cohesive and/or adhesive properties which would identify a moisture susceptible mix follows the conditioning process. Table 1.1 summarizes the numerous factors that should be considered.

A moisture susceptibility test will have a "conditioning" and an "evaluation" phase. The conditioning phases vary, but all of them attempt to simulate the deterioration of the asphalt concrete in the field (e.g. moisture, temperature). This is accomplished in an assortment of ways as discussed in Chapter 2. The two general methods of evaluating "conditioned" specimens are a visual evaluation and subjecting the specimen to a physical test. In the visual evaluation, observation of the retained asphalt coating is determined following the conditioning process. Typically in the physical test evaluation, a ratio is computed by dividing the result from the "conditioned" specimen by the result from an "unconditioned" specimen. Parameters such as strength, modulus, etc. have been used in this regard. If the ratio is less than a specified value, the mix is determined to be moisture susceptible.

1.2 Purpose and Scope

The problem, as defined by the Strategic Highway Research Program (SHRP), is to:

1) Define water sensitivity of asphalt concrete mixtures with respect to performance, including fatigue, permanent deformation, and low temperature cracking.
2) Develop laboratory testing procedures that will predict field performance.

The purpose of this report is to review the "State of the Practice" in evaluation of asphalt paving mixtures for moisture sensitivity. An exhaustive review of the literature was

Table 1.1. Factors Influencing Response of Mixtures to Water Sensitivity

Variable	Factor
Existing Condition	• Compaction Method • Voids • Permeability • Environment • Time • Water Content
Materials	• Asphalt • Aggregate • Modifiers and/or Additives
Conditioning	• Curing • Dry vs. Wet • Soaking • Vacuum Saturation • Freeze-thaw • Repeated Loading • Drying
Other	• Traffic • Environmental History • Age

conducted using the usual computer searches and personal review of available sources. However, this summary report is aimed at those studies that relate to recent work that describes what agencies are doing now. In summary, the purpose is to:

1) Review current "State of the Practice" by user agencies and develop a summary of the test procedures currently being used for research and by highway agencies to evaluate asphalt concrete for moisture susceptibility.
2) Review of factors involved in the conditioning process used to simulate moisture sensitivity, and evaluate the procedures being used for their effectiveness.
3) Briefly explore promising avenues for research in this SHRP project.

2.0 BACKGROUND

2.1 Test Procedures for Moisture Sensitivity

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

1) Those tests which coat "standard" aggregate with an asphalt cement (with or without an additive). The loose uncompacted mixture is immersed in water (which is either held at room temperature or brought to a boil). A visual determination is then made of the separation of asphalt from the aggregate.
2) Those tests which use compacted specimens; either laboratory compacted or cores from existing pavement structures. These specimens are then conditioned in some manner to simulate in-service conditions of the pavement structure. The results of these tests are generally evaluated by the ratios of conditioned to unconditioned results using a stiffness or strength test (e.g. diametral resilient modulus test, diametral tensile strength test, etc.).

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

2.1.1 Test Procedures

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

a) NCHRP 246 - Indirect Tensile Test and/or Modulus Test with Lottman Conditioning

b) NCHRP 274 - Indirect Tensile Test with Tunnicliff and Root Conditioning

c) AASHTO T-283 - Combines features of NCHRP 246 and 274

d) Boiling Water Tests

e) Immersion-Compression Tests (AASHTO T-165, ASTM D 1075)

f) Freeze-Thaw Pedestal Test

g) Static Immersion Test (AASHTO T-182, ASTM D 1664)

h) Conditioning with Stability Test (AASHTO T-245)

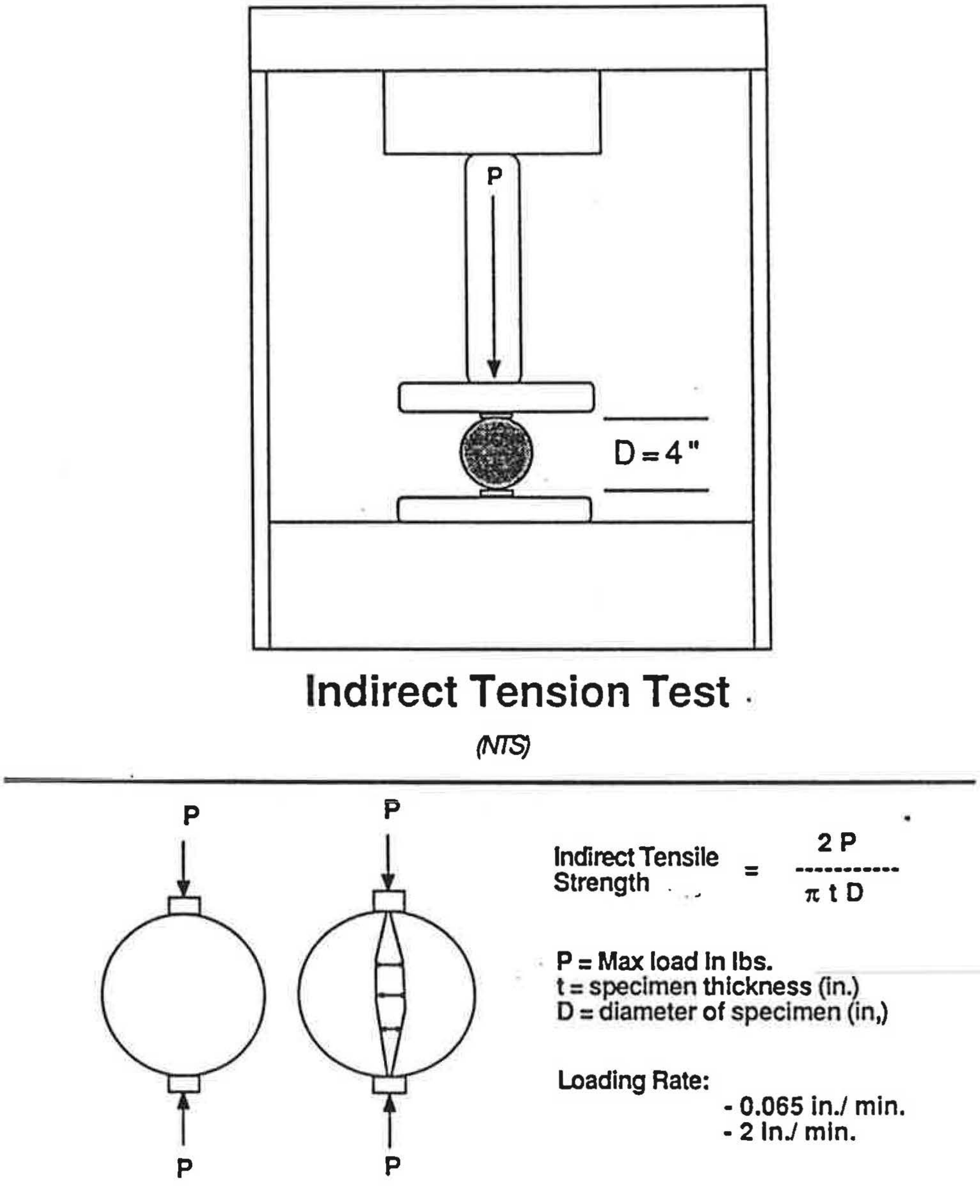
NCHRP 246 - Indirect Tensile and/or Modulus Test with Lottman Conditioning (AASHTO T-283)

In the Lottman procedure, which is summarized in Table 2.1, two analyses are made; one for the short term performance and the other for the long term performance of the mix. The short term analysis is intended to reflect a field performance for up to 4 years and the long term performance estimates the field performance from 4 to 12 years depending on the influence of other factors (Lottman, 1982). The specimens are 4 inches in diameter by 2.5 inches in height and are compacted to the air void content expected in the field. An index of retained strength (IRS) or modulus (IRM) is obtained by dividing the test values from the conditioned samples by the values obtained from the unconditioned samples. Sketches of the indirect tension and resilient modulus test set ups are shown in Figures 2.1 and 2.2, respectively.

To establish a correlation with field data, Lottman (1982) used 5 years of field evaluation on projects in 6 different states. The analysis showed that the tensile strength or resilient modulus ratio may show an increase (a ratio greater than one) during the first four years of the projects life which is termed a "field conditioning or stiffening effect". The stiffening was attributed to the viscosity of some asphalts increasing with the initial presence of moisture in the asphalt mixture and because of aging of the asphalt. It was concluded that failure of a specimen from the short-term conditioning indicates the mix is very sensitive

Table 2.1. NCHRP 246 – Indirect Tensile Test and/or Modulus Test with Lottman Conditioning.

Specimens	9 samples divided into 3 groups Size: 4-in. diameter by 2.5-in. height
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	Depends on method or expected field
Conditioning Procedure	Group I: – Water bath (dry in jars) for 5 hours @ test temperature → Test
	Group II & III: – Vacuum saturation @ 26 in. Hg for 30 min – Atmospheric pressure, submerged, for 30 min
	Group II: – Water bath @ test temperature for 3 hours → Test
	Group III: – Freeze @ 0.0°F for 15 hours – Water bath @ 140°F for 24 hours – Water bath @ test temperature for 3 hours → Test
	Note: Tests can be run at 55°F or 73°F
Damage Analysis	Ratios: Diametral Resilient Modulus Test (ASTM D4123) Diametral Tensile Strength Test $\frac{\text{Group II}}{\text{Group I}}$ Short Term (saturation) $\frac{\text{Group III}}{\text{Group I}}$ Long Term (accelerated)
Advantages	– Conducted on lab mixes, field mixes, or core samples – Severe test – Can differentiate between additive levels – Good correlation with field performance – Does not give biased results toward lime or liquid additive
Disadvantages	– Time consuming (about 3 days for test procedure) – Amount and type of equipment required is not always readily available

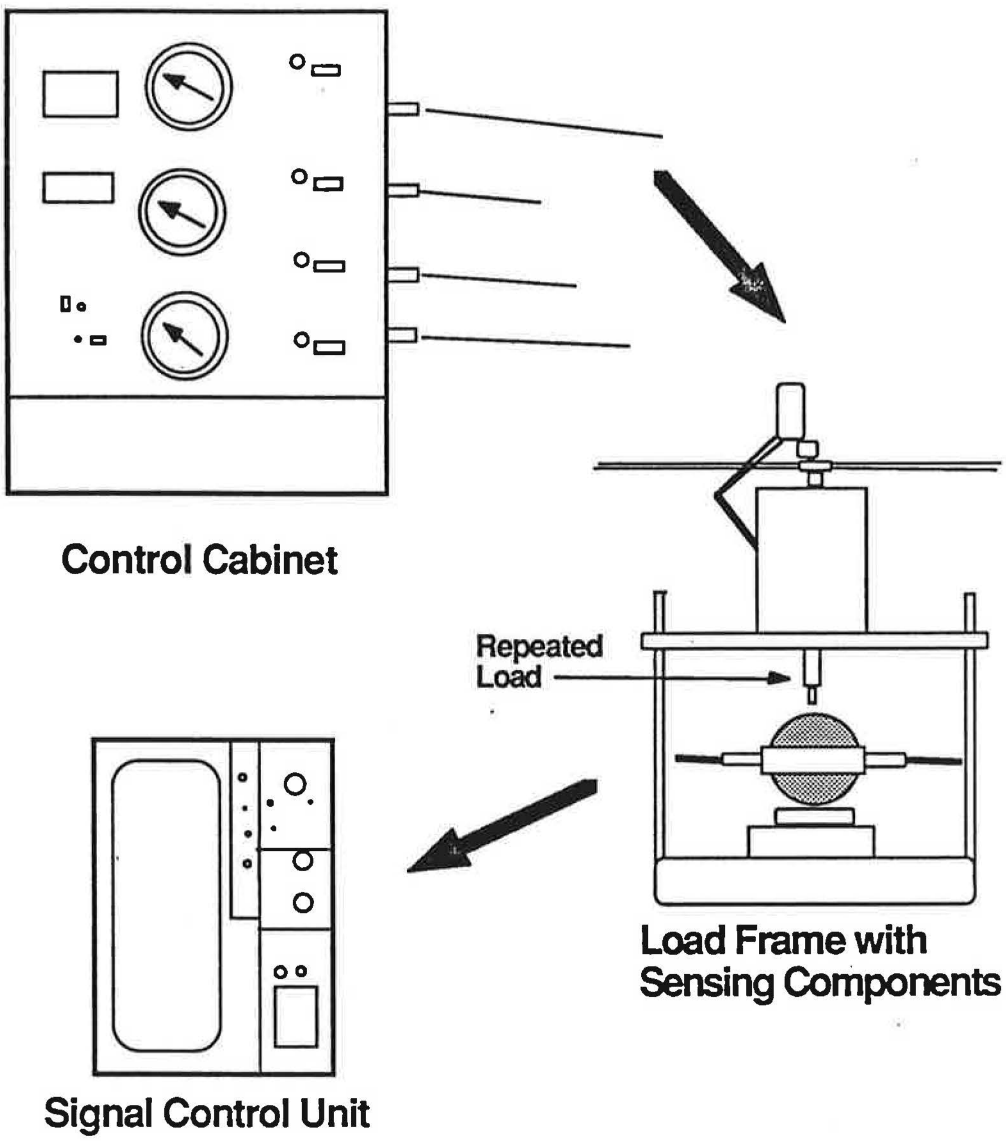


Indirect Tensile Strength $= \dfrac{2P}{\pi t D}$

P = Max load in lbs.
t = specimen thickness (in.)
D = diameter of specimen (in.)

Loading Rate:
- 0.065 in./ min.
- 2 in./ min.

Figure 2.1. Test Arrangement for Indirect Tension



$$\text{Diametral Resilient Modulus} = \frac{P\,(v + 0.2734)}{t\ \Delta}$$

P = Max load in lbs.
v = Poisson ratio (.35)
Δ = Horizontal deformation (in.)
t = Thickness of specimen (in.)

Diametral Resilient Modulus Test

Figure 2.2. Test Equipment Arrangement for Diametral Resilient Modulus

to moisture. A ratio of 0.70 or greater is recommended by Lottman. Maupin (1982) reported differentiation between stripping and non-stripping when values were between 0.70 and 0.75. Stuart (1986) and Parker and Gharaybeh (1988) found the test procedure to provide an acceptable correlation between the laboratory and field results. Lottman (1988) has developed a computer program, Asphalt Concrete Moisture Damage Analysis System (ACMODAS 2 and ACMODAS 3) that can be used to predict resistance to field moisture damage from laboratory data. It is anticipated that the OSU team will evaluate this program.

NCHRP 274 - Indirect Tensile Test with Tunnicliff and Root Conditioning

This procedure controls the degree of saturation to ensure enough moisture is present to initiate moisture damage and to avoid unrelated damage, such as stresses induced from oversaturation (see Table 2.2). If saturation has not reached 55% in a conditioned specimen after the initial vacuum soaking, then the specimen is returned for additional soaking until a saturation level between 55% and 80% is reached. The saturation level is determined by dividing the volume of air by the volume of water in the specimen after vacuum saturation. If, after the vacuum soaking the specimen is above the 80% criterion, the specimen is discarded as being too severely saturated, and the process repeated with a new specimen.

The tensile strength ratio (TSR) is used to evaluate the test results. As with the IRS, the TSR is obtained by dividing the value or the tensile strength from the conditioned specimen by the result for the unconditioned specimen. Instead of a minimum ratio, the student's 't' test is performed and the desired confidence level is used to determine the effectiveness. Initial evaluation of the procedure indicates the test appears to be a "good" method for identifying moisture sensitive mixes (Stuart, 1986). See Figure 2.1 for the test setup.

The Tunnicliff and Root procedure (NCHRP 274) is a recent development and does not incorporate a freeze-thaw cycle into the test procedure. It has been suggested that a possible reason that Tunnicliff and Root did not see freezing and thawing as being

Table 2.2. NCHRP 274 – Indirect Tensile Test with Tunnicliff and Root Conditioning.

Specimens	6 samples – 2 groups of 3 Size: 4-in. diameter x 2.5 in. height (for aggregate ≤ 1 in.)
Compaction	ASTM Methods: D1559 or D1561 or D3387
Air Voids (%)	6 to 8 or expected field level
Conditioning Procedure	Sort into groups so average air voids are approximately equal
	Group I: – Store dry at room temperature – Prior to testing, soak 20 min. @ 77°F → Test Group II: – Obtain a 55% to 80% saturation level (20 in. Hg for about 5 min in distilled water) – Reject if saturation is > 80% – Soak 24 hours @ 140°F – Soak 1 hour @ 77°F → Test
Damage Analysis	– Diametral Tensile Strength (ASTM D 4123) – Visual
Advantages	– Can use lab, plant, or field mixes; also cores from existing pavements – Mixtures with or without additives – Time required is moderate – Initial indications show good correlation (based on 80% retained strength)
Disadvantages	– May require trial specimens to obtain air void level – May not be severe enough

significant is that the effect decreases with decreasing levels of water content (i.e., saturation). However, ASTM D4867-88, which was developed from NCHRP 274 permits an optional freeze-thaw cycle. Emphasis is on saturation level of the test specimen, which for a short duration (approximately one day), has been questioned as being insufficient to induce moisture damage (Coplantz and Newcomb, 1988). This test procedure is currently being tested by several agencies in a cooperative effort to determine the success of the procedure in predicting moisture susceptible mixes (Stuart, 1989).

Boiling Water Tests

This test is a result of the assimilation of different boiling tests used by several state agencies (Kennedy, 1983) (see Table 2.3). Kennedy (1983) recommends the test be used as an initial screening procedure because it provides reasonable results for differentiation between stripping and non-stripping mixtures, and it may have use in quality control of field construction.

In Stuart's (1986) evaluation of the procedure, following ASTM 3625, boiling times of one minute and ten minutes were tested. It was concluded that both the one minute and 10 minute boiling periods provided poor results in identifying mixes known to be moisture susceptible. However, others have found the 10 minute test useful for the determination of the presence of additives in the field. Lee and Al-Jarallah (1986) and Parker and Wilson (1986) found the test to provide good correlations between the lab results and field performances and the effectiveness of antistripping additives could be determined. Parker and Gharaybeh (1988) report the boiling test did not evaluate the effects of lime correctly. The lime left a white powdery coating which reduces the shine of the asphalt coating and therefore, the sample can be observed as having a coating deficiency that does not exist.

Several factors can bias the results achieved with the boiling test. The asphalt content and grade has some effect on the results (Parker and Wilson, 1986). It was found that the asphalt content had a minimal effect if all the aggregate were coated prior to boiling the mix. In testing two AC-20 grade asphalts, each from a different manufacturer, "some difference" was noted in the results using aggregate from the same source. It has

Table 2.3 Boiling Water Tests.

Specimens	Field mixture representation @ design AC or Individual aggregate size (coat aggregate with AC) Note: - Use of 200 or 300 gram sample is common - Use of agitation is agency dependent - Specific evaluation techniques vary among agencies
Compaction	None
Air Voids (%)	None
Procedure	- Place 500 ml of distilled water in 1000 ml beaker - Heat to boil, then add mixture - Boil 10 min, stirring 3 times with glass rod - Skim asphalt off surface - Cool to room temperature, dry on paper towel
Damage Analysis	- Visual assessment - Texas Boiling Test < 70% retained indiates moisture susceptibility
Advantages	- Can be used for initial screening - Minimum amount of equipment required - Can be used to test additive effectiveness - May be used for quality control - Can use lab mix or field mix
Disadvantages	- Subjective analysis - Uncompacted mix may not show possible strength, etc., loss - Water purity can affect coating retention - Assessment of stripping in fines is difficult

been found that agitation and extended boiling (3 minutes) have a minor influence in the final coating. Parker and Wilson (1986) estimated an additional 6% loss from the original coating when either agitation or extended boiling was used. Since the use of 95% retained coating is common, including either of these steps can alter the decision to reject a mix or require the addition of additives to a mix. In addition, it was found that the aggregate gradation played a significant role in the boiling test; the more uniform the gradation the lower the rating given to the sample mix. Well graded aggregate samples provided higher correlations to field performance.

A further limitation of boiling test is that it reflects only the loss of adhesion or stripping loss, and does not address cohesion loss.

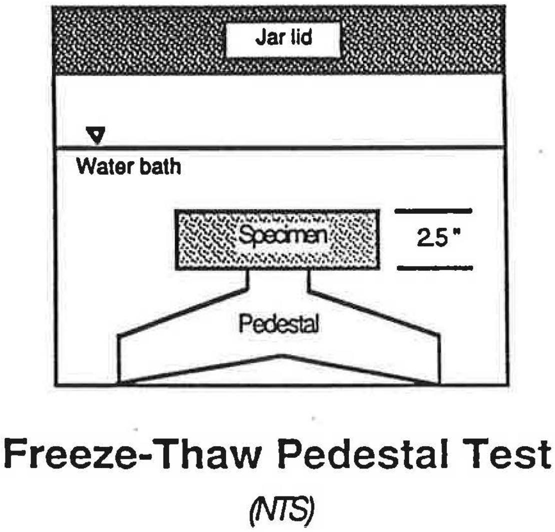
Texas Freeze-Thaw Pedestal Test (FTPT)

This test attempts to simulate viscosity changes of the binder at five years of pavement life. Special briquets are fabricated using one-size fine aggregate then subjected to repeated freezing and thawing in water while resting on a pedestal. The number of cycles until cracking occurs is then correlated to expected pavement life. The procedure is summarized in Table 2.4 and Figure 2.3. The variation or effect of physical properties such as aggregate gradation, density, aggregate interlock, are minimized through the use of a one-size aggregate so that the test primarily evaluates the strength of bonding and binder cohesion.

Parker and Wilson (1986) found the test to provide a poor correlation between the laboratory and field results. Based on the materials available in Alabama, the test showed little potential for identifying moisture susceptible mixes or for isolating components that contribute to stripping. In contrast, Kennedy (1983) asserts that the pedestal test has excellent potential and can be used to determine individual stripping components. Also, good results can be achieved in determining the stripping potential of a mix. Bolzan (1989) found the FTPT useful in evaluating aggregate for moisture sensitivity and in determining

Table 2.4. Texas Freeze-Thaw Pedestal Test.

Specimens	3 to 5 briquets 1-5/8 in. diameter x 3/4 in. height AC @ 5% > optimum Aggregate: Passes 0.850 mm, Retained on 0.500 mm sieve
Compaction	In mold under 6200 lb for 20 min
Air Voids (%)	None
Procedure	- Cure briquets @ 75°F for 3 days - Place specimens on stress pedestal in water bottle - Freeze @ 10°F for 15 hours - Place in warm water 75°F (room temperature) for 45 min - Place in 120°F oven for 9 hours - Repeat, beginning at freeze, if cracking is not present
Damage Analysis	- Visual observation If crack develops in < 10 cycles, moisture susceptible > 20-25 cycles, resists moisture damage
Advantages	- Used to test additive effectiveness
Disadvantages	- Uses only a small portion of the mix - Only fair correlation between field and lab results - Measures only cohesion - Requires special equipment - Takes time, 1 day for each cycle



Criteria:

- Number of cycles until specimen cracks;

< 10 cycles indicates moisture susceptible
10-20 cycles borderline
> 20-25 cycles moisture resistant

Figure 2.3. Test Arrangement for Freeze-Thaw Pedestal Test

the effectiveness of antistripping additives. However, he states the FTPT should be used in conjunction with another test that evaluates the mechanical effects of traffic loading.

Immersion Compression Tests (AASHTO T-165, ASTM D 1075)

This type of test, summarized in Table 2.5 and Figure 2.4, is currently used by many agencies. The loss of adhesion or cohesion is evaluated by subjecting the specimens to a static soak in water at an elevated temperature and then measuring the retained compressive strength. The Asphalt Institute recommends that mixtures with an IRS less than or equal to 75% be rejected.

Static Immersion Tests (AASHTO T-182, ASTM D 1664)

Static immersion tests are intended to evaluate the potential for asphalt concrete mixes to readily strip when exposed to moisture for an extended period. However, it is doubtful that the long term potential for stripping is addressed by this procedure, but it may show some degree of water sensitivity. The primary steps in the test (see Table 2.6), involve immersing a sample of asphalt concrete in distilled water for approximately 17 hours at 77°F and then visually rating the retained asphalt coating.

Conditioning Evaluated by Marshall Stability Testing

A standard conditioning procedure has not been established for the Marshall stability test, shown in Figure 2.5. The conditioning procedure varies with the user agency and is generally an adaptation from one of the existing procedures previously mentioned. An index of retained stability is used to measure the moisture susceptibility of the mix being tested. The same methodology of establishing a ratio of a "conditioned" specimen to an "unconditioned" specimens stability is the criterion used to identify a moisture susceptible mix.

2.1.2 Summary

It is apparent from the literature review and survey of current practice that a variety of test methods have been employed to assess;

Table 2.5. Immersion Compression Test (AASTHO T-165, ASTM D-1075).

Specimens	6 samples - 2 groups of 3 4 in. x 4 in.
Compaction	Double plunger - pressure 3000 psi for 2 min (ASTM)
Air Voids (%)	6
Procedure	Group I: Air cured for ≥ 4 hours @ 77°F → Test
	Group II: - Placed in water bath @ 120°F for 4 days - Placed in water bath @ 77°F for 2 hours → Test (Alternate) - Water bath @ 140°F for 24 hours - Water bath @ 77°F for 2 hours → Test
Damage Analysis	- Visual assessment - Unconfined compression @ 77°F and 0.2 in./min
Advantages	- Uses actual mix
Disadvantages	- Time required can be extensive - Poor reproducibility - Degree of saturation may vary without vacuum - Water quality (ions and salts) can affect moisture sensitivity - Equipment may not be readily available

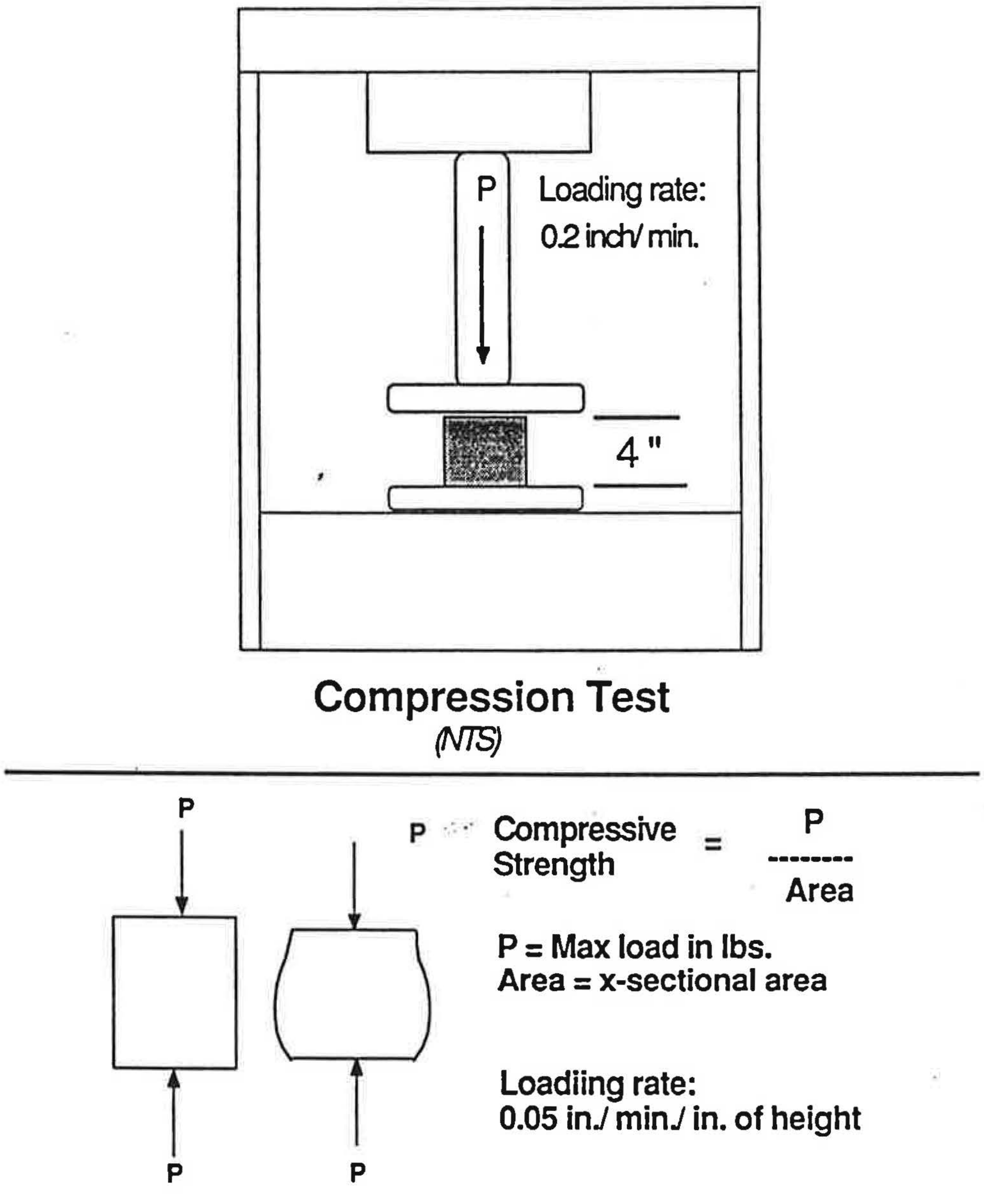
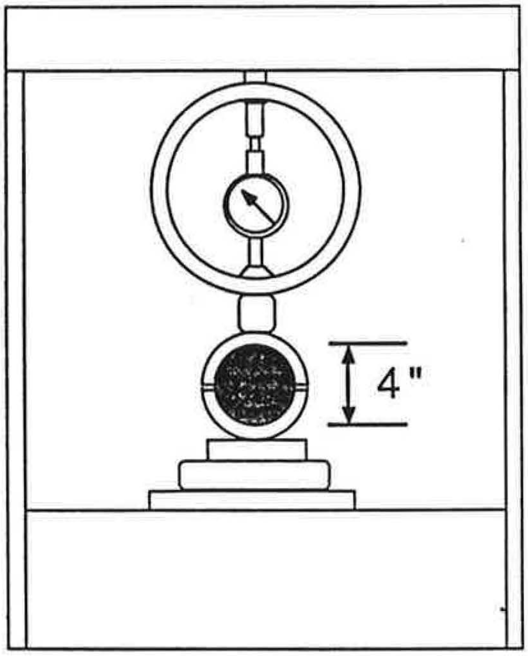


Figure 2.4. Test Setup for Compression Test Following Immersion in Water

Table 2.6. Static Immersion Tests (AASHTO T-182, ASTM D-1664).

Specimens	Aggregate: 100% • passes 3/8" (9.5mm) sieve • retained on 1/4" (6.3 mm) sieve • 100 grams Water: Distilled, pH 6.0 to 7.0 Asphalt: Type to be used in field
Compaction	None
Air Void (%)	None
Procedure	Mix asphalt and aggregate 2 minutes, cure 2 hours • Place mixture in 600 ml beaker • Cover with 400 ml distilled water at room temperature (77°F) for 16-18 hrs. Evaluate.
Damage Analysis	• Illuminate sample and visual estimate percentage of visible area still coated. • <95% is a 'no go'.
Advantages	• Simple • Low cost • Quick
Disadvantages	• May not be severe enough • Subjective analysis • Uncompacted mix • No assessment of stripping in fines



Marshall Stability Test

(NTS)

- **Stability and flow measured directly from test**
- **Before and after conditioning**
- **Loading rate:**
  - **2 in./min.**

Figure 2.5. Test Arrangement for Marshall Stability

1) the potential for moisture sensitivity in asphalt concrete mixes
2) the benefits offered by antistripping agents to prevent moisture induced damage to asphalt concrete mixes.

So far, one test has not proven to be "superior" as is evident by the number and variety of tests currently being used. From the data and experience to date, it appears that a test has yet to be established that is highly accurate in predicting moisture susceptible mixes and estimating the life of the pavement.

2.2 Evaluation of Procedures

Conditioning a sample or specimen and then evaluating the results of the conditioning can be accomplished by several methods. This section evaluates some of the factors associated with these methods and their influence on the test specimens. Research to date has focused on conditioning procedures and subsequent evaluation techniques. Table 2.7 is a list of factors or criteria that should be considered when evaluating procedures and Table 2.8 is a summary of the test methods evaluated and a brief listing of the various factors that affect their viability. When evaluating various procedures for possible adoption in SHRP, several key questions need to be addressed as indicated in Table 2.9 and these are further discussed in this section. Table 2.9 includes a rating scale of the key factors in terms of their relative importance to the overall potential for success. Table 2.10 is an assessment or ranking of the test procedures based on the weighted criteria shown in Table 2.9. The results indicate that both the Lottman and Root-Tunnicliff procedures have strong features and should be seriously considered.

2.2.1 Conditioning Factors

In order to evaluate the various procedures, the components which make up the conditioning process should be examined. The factors listed below are a part of conditioning procedures for the tests mentioned in section 2.1. In addition, other factors are included which are indirectly related to the conditioning process.

Table 2.7. Criteria for Evaluation of Test Procedures - Water Sensitivity

CRITERIA	FACTORS
Materials	• Asphalt binders should be well documented in terms of physical an chemical properties. • Asphalt binders could be tested separately for adhesiveness. • Aggregates need to be evaluated for petrographic type, durability, shape and texture, zeta potential.
Simulation of Field Conditions	• Compaction in the laboratory should produce a fabric and void structure similar to that constructed in the field. • Curing or aging time should be represented to assure that long term effects are not overlooked in an accelerated test. • Water content (partial vs. full saturation) needs to be evaluated and matched to realistic field conditions and expectations. • Quality of water used during the test needs to be monitored and/or controlled. • The effect of freezing and thawing needs to be incorporated, if appropriate for the local environment.
Ease of Use	• Consideration must be given to the user agency personnel and their facilities so that any adopted procedure can be readily learned and used. • Equipment cost and complexity must be a consideration.
Advantages and Disadvantages	• The relative importance of each factor needs to be evaluated and weighed. • Tests must be compatible with fatigue, rutting, and thermal test systems.
Application of Test Results	• The results of tests should provide insight as to the suitability of various materials, including asphalt, aggregate, and additives. • Quantitative results that can be used in the mixture and pavement performance model(s) are desirable and necessary.

Table 2.8. Evaluation of Water Sensitivity Test Methodologies

METHOD	REFERENCE	APPLICATION OF TEST RESULTS	ADVANTAGES	LIMITATIONS	SIMULATION OF FIELD CONDITIONS	EASE OF USE
1. Lottman	NCHRP 246	• M_R ratio • St ratio (diametral)	• Severe test • Wide range of mixes and cores • Good for lime or liquid additives	• Time consuming (3 days/cycle) • Equipment is expensive and may not be readily available	• Good correlation w/ field performance • Simulates freeze-thaw conditions	• Moderately complex
2. Tunnicliff-Root	NCHRP 274	• Diametral St • Visual rating	• Wide range of mixes, cores • Good for additives • Moderately time consuming	• Requires trial mixes to obtain air void level • May not be severe enough	• Initial use shows good correlation w/ field performance	• Moderately complex
3. Boiling	ASTM 3625	• Stripping potential • Visual rating	• Initial screening • Simple equipment • Lab or field mix • OK for additives	• Subjective analysis • Loose mix only • Water purity has effect	• May indicate potential for stripping	• Simple
4. Texas Freeze-Thaw Pedestal	Kennedy (1983)	• Cracking after number of freeze-thaw cycles indicates degree of moisture susceptibility	• Measures additive effectiveness • Simple	• Only fines used • Time consuming (1 day/cycle) • Measures only cohesion	• Only fair correlation w/ field performance	• Simple, but special equipment required
5. Immersion-Compression	ASTM D1075, AASHTO T-165	• Visual assessment • Minimum compressive strength	• Uses actual mix • Simple	• Time consuming • Air voids play large role • Poor reproducibility	• Correlation not known (if any)	• Simple • Equipment should be readily available
6. Static Immersion	ASTM D1664, AASHTO T-182	• Potential for stripping: <95% coating; no go • Visual assessment	• Simple, quick • Low cost	• Subjective evaluation • Loose mix only • Not sufficiently severe	• Short term stripping potential only	• Simple to do
7. Retained Stability	No standard method	• Ratio of wet (soaked) to dry Marshall stability	• Uses conventional specimens and equipment	• No standard conditioning or criteria	• Not known	• Simple to do

Table 2.9 Weighting Functions Used to Evaluate Various Procedures Used for Water Sensitivity

Feature	Factors	Relative Importance (total = 100)
Materials	• Does the procedure include testing of binders?	15
Simulation of Field Conditions	• Is compaction method or results representative? • Is water conditioning appropriate for intended environment? • Is specimen soaked, saturated, partially saturated? • Is procedure capable of predicting mixture performance? • Is conditioning appropriately severe?	30
Ease of Use	• Is test procedure easy to follow? • Is the equipment cost reasonable? • Are results repeatable, accurate?	20
Useful Results	• Does the procedure permit screening of binders and aggregates prior to mixture tests? • Does the procedure discern potential mixture damage in the presence of water? • Do the test results lend themselves to adjustments in mix design or fatigue and rutting design?	35

Table 2.10. Rating of the Conditioning and Testing Procedures

	Method	Reference	Materials	Simulation of Field Conditions	Ease of Use	Useful Results	Total
1.	Lottman	NCHRP 246	0	25	5	30	60
2.	Tunnicliff	NCHRP 274	0	20	10	30	60
3.	Boiling	ASTM 3625	10	5	10	10	35
4.	Texas F-T Pedestal	Kennedy (1983)	5	5	5	10	25
5.	Immersion - Compression	ASTM D1075 AASHTO T-165	0	10	15	15	40
6.	Static Immersion	ASTM D1664 AASHTO T-182	5	5	10	10	30
7.	Retained Stability	No standard	0	10	15	15	40

Laboratory Compaction Method

There are several methods by which asphalt concrete test specimens are compacted, including the Gyratory shear, Marshall hammer, Hveem Kneading compactor, Double Plunger as well as others. It is not clear how significant a role the compaction method plays in moisture conditioning procedures, but the size and structure of the voids probably are most affected.

In the Lottman (1982) study, each agency used their own compaction method. A significant difference could not be attributed to the compaction method where the Marshall hammer and kneading compactor were used. Lottman permits any one of four compaction methods for the testing procedure. Tunnicliff and Root (1984) results were inconclusive when kneading compaction and the Marshall hammer method were compared, both procedures provided specimens with the required void level, although the gyratory shear method was found to be suitable as well. Boudreau (1989) found kneading compaction to be the preferred method, because variations in precompaction curing could be detected with resilient modulus testing of these specimens. In the AAMAS study (Von Quintus et al., 1988) reports the gyratory shear compaction method most closely models engineering properties that were measured in field cores, but the results indicate that kneading and rolling wheel compaction may also be similar.

The type of compaction method may affect the strength values obtained during testing. Fields and Phang (1967) noted that kneading compaction yielded samples with higher strengths in comparison to the double plunger method. However, the data showed the double plunger method provided a strength loss which was acceptable.

In addition, some of the compaction procedures may result in reduced voids around the surface of the specimens (exuded asphalt) which are not reflective of the internal void structure. This can alter the results by reducing the amount of water allowed into the specimen, especially in "soak saturation" procedures under atmospheric pressure rather than in vacuum saturation. This potential error can be essentially eliminated by the use of partial vacuum saturation. The double plunger method does not create this sealing of the exterior pores and modification of the standard kneading and gyratory compaction methods can also prevent sealing of some of the exterior voids from occurring (Tunnicliff and Root, 1984). For permeability testing, the ends of the laboratory compacted specimens may need to be sawed off.

It would appear that static or Marshall compaction would result in a structure too dissimilar to that found in the field. In another document on this study (Monismith and Hicks, 1989) the gyratory and kneading were found to be about equally representative of the field. This factor is important to the void structure (as opposed to only the total void content). Aggregate orientation and the size and distribution of voids will have an influence on the way that water enters (or flows through) the specimen as well as how water is retained in pores upon drying. In summary, specimens prepared by static or Marshall compaction are not suitable for water sensitivity evaluation.

Sample Cure Time (Aging)

The length of time a specimen is cured or aged after compaction and before testing can affect the test values obtained. This curing creates a test specimen which exhibits higher strength from aging the asphalt. However, it has not been established how this curing/aging affects moisture susceptibility. This might come into consideration if a minimum strength value following conditioning is used in addition to a ratio obtained from a test procedure.

It has been established that allowing a specimen to cure or "age" will give the specimen a higher degree of moisture resistance. Lottman (1982) noted the increased resistance to moisture improved the matching of prediction ratios (laboratory fabricated specimens) to the ratios obtained from companion field cores. Tunnicliff and Root (1984) amended their procedure to allow quick cooling of specimens with a fan instead of curing overnight (16 to 24 hours) before saturation was initiated. Though differences did occur in the tensile strengths and tensile strength ratios, a statistical analysis showed the conditioned and unconditioned specimens to be different even with the quick cure time. Lottman (1982) also noted higher prediction ratios and, therefore, a reduction in the number of specimens identified as moisture sensitive. However, the change was considered to be insignificant and changing the procedure was not warranted.

A standardized approach to laboratory curing has been adopted by some agencies and is expected to be incorporated in SHRP mixture preparations. Following mixing, oven storage at elevated temperature levels to permit better coating and bonding between aggregates and binder and may better represent in-service mixtures that have had time to "set".

Saturation

Saturation is a common link to all of the conditioning procedures and is the key to the laboratory simulation of moisture damage in the test specimens. Saturation is obtained either by immersion of the specimen in static or boiling water and/or by applying a partial vacuum. The vacuum method is used on briquet specimens and draws the water into the specimen to shorten the time required for the specimen to reach the desired saturation level. The saturation level achieved by partial vacuum is primarily responsive to the magnitude of the vacuum utilized and relatively independent of the length of time the vacuum is applied (Tunnicliff and Root, 1984). The temperature at which the specimens are saturated can also affect the time required to achieve the desired saturation level. As the temperature increases, the time required to saturate a specimen decreases with the voids and vacuum pressure constant (Tunnicliff and Root, 1984). One should note, however, that saturation levels based on the amount of voids can be misleading if the void levels vary.

The saturation level sought varies among the conditioning procedures. Lottman (1982) saturated specimens based on time and vacuum pressures to assure that a level of 100% saturation was achieved. Specimens were placed in distilled water under a vacuum of 26 inches Hg for thirty minutes and then left in the water for another 30 minutes at atmospheric pressure. Tunnicliff and Root (1984) attempt to control the level of saturation in the test procedure. The process is trial and error in seeking the desired 55 to 80% saturation in the specimen and can be reached by varying the vacuum pressure, time the vacuum is applied, and the temperature of the water. A variation of the Lottman procedure, sometimes called a "modified" Lottman, calls for a saturation level of 60 to 80% and the vacuum pressure is varied to achieve this saturation level (Scherocman, 1986).

The saturation level can be calculated using two different methods. Either the weight of the original dry specimen in air or the weight of the original saturated surface-dry (SSD) specimen in air can be used as a beginning point. The saturation level is then established as the difference between the weight of the vacuum saturated specimen and either of the beginning weights mentioned, expressed as a volume, divided by the volume of air voids. Tunnicliff and Root (1984) found that using the dry weight of the specimen lead to values which slightly overestimated the saturation level. This result is due to the presence of water on the surface during the SSD condition when determining the air void level being counted as saturation water. However, this error was considered insignificant when it was found that some specimens will hold several grams of water in the SSD condition.

Concern that oversaturation induces damage not associated with moisture damage has resulted in limits placed on the saturation level of specimens after a partial vacuum has been applied (Tunnicliff and Root, 1984). Typically, 80% is considered the critical value used and any test specimens that are inadvertently saturated beyond this level after the vacuum saturation are discarded. Coplantz (1987) reports that higher saturation levels are associated with greater damage and the effect of saturation on tensile strength is illustrated in Figure 2.6. However, conclusive evidence that oversaturation affects the test results have not been established (Stuart, 1986). It has been noted that oversaturation can contribute to low strengths, but whether this is due to moisture damage or oversaturation of the specimen itself is unclear (Tunnicliff and Root, 1984). Oversaturation of a high void mixture would likely be more detrimental than for one with low voids. As a point of clarification in the degree of saturation achieved with different levels of vacuum, Tunnicliff and Root (1984) claimed that Lottman (NCHRP 246) used 28-30 inches Hg which oversaturates the specimen. Thus, Tunnicliff and Root selected 18-22 inches Hg as a suitable range to achieve 55-80% saturation. In fact, however, Lottman's procedure

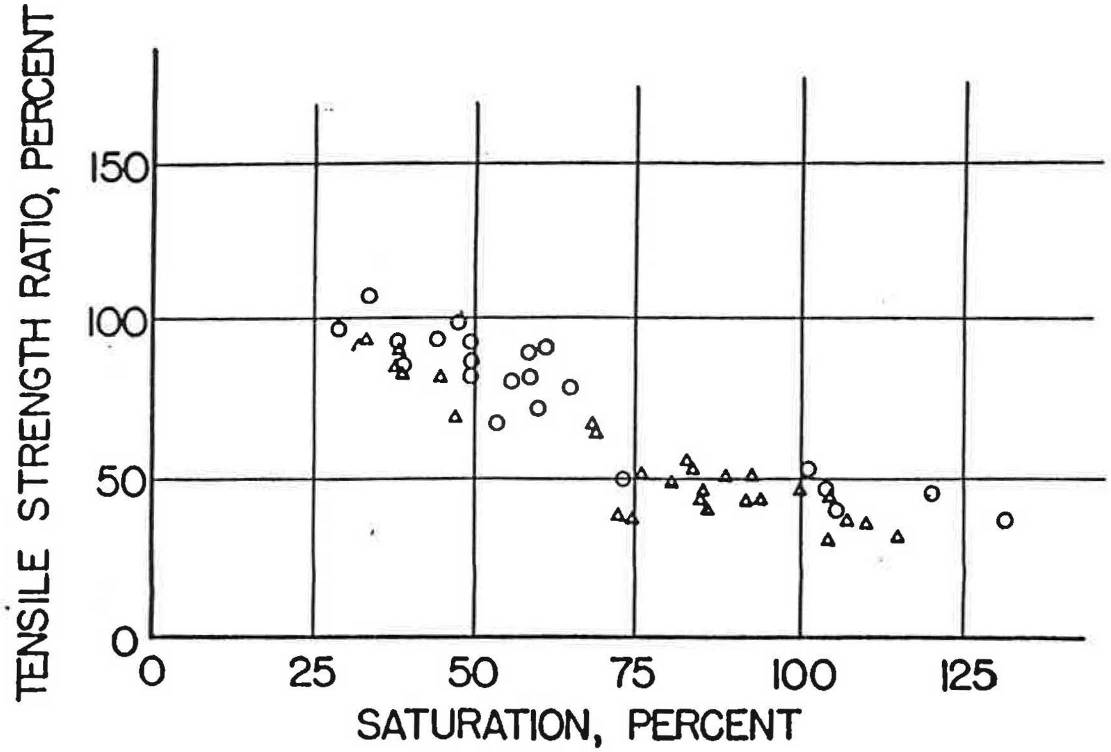


Figure 2.6. Tensile Strength versus Saturation Level for Two Different Chert Aggregates (Tunnicliff and Root, 1984)

(NCHRP 246) uses 26 inches Hg and results in 90-95% saturation, but varies among mixtures and might not oversaturate.

Several aspects of moisture sensitivity testing may not be appropriate for saturated specimens. Although saturation in the laboratory is probably more severe and tends to accelerate moisture damage, it may not be very representative of the field. Also, maintaining some high degree of saturation while conducting other tests such as fatigue or creep may not be practical. Asphalt mixtures in the pavement tend to retain moisture at some level that is in equilibrium or in balance with the void structure and the mixtures environment (temperature, humidity, etc.). It would appear that testing a specimen in this condition would be realistic and could be achieved by wetting (by partial vacuum) to some water content above the equilibrium. Thus, each compacted mixture would be tested under conditions appropriate for that mixture rather than being forced into an unnatural state.

Swell

The relevance of information provided by measuring the swell after conditioning the test specimens is not clearly defined. Some believe that swell data provides little information because the values tend to be small (Stuart, 1986). However, the data should be collected and recorded with excessive values indicating that further examination is required (Tunnicliff and Root, 1984). The definition of "excessive swell" and its significance was not noted. Lottman measured swell in the NCHRP 9-6(1) project (AAMAS study, Phase II, Vol. II draft final report) on 4-5 mixtures from different states. Swelling ranged from 0.02 to 0.48% and the higher swelling values seemed to be associated with higher levels of stripping. A synthesis on information gathered by agencies who routinely use a swell test in identifying moisture susceptible asphalt mixtures would be helpful in answering this question.

The propensity for swelling may be worthwhile to examine and the source of swelling may be helpful in evaluating moisture damage. Swelling is most likely related to water entering one or more types of voids; voids in the mixture, between the asphalt film and aggregate surface, or within the asphalt film itself. The first two could also be related to water affecting clay fractions within the aggregate or mineral filler. If swelling could be linked to degree of damage or loss of modulus or strength, it should become part of a standard test.

Air Voids

The influence of voids on the moisture susceptibility of an asphalt concrete mixture is currently understood in only a general sense. The general rule is; "the lower the void content, the less likely water is to enter the asphalt mix". Scherocman (1986) states that mixes with less than 2% to 3% voids have a low probability while mixes with an air void content above 6% have high probability, of sustaining moisture damage. Stroup-Gardiner and Epps (1987) found that changes in air voids can significantly affect the strength of a mix but have little influence on the percentage of retained strength after conditioning. Research specifically directed at the influence of air voids on moisture sensitivity was not found, but some researchers have noted these trends with air voids in the analysis of other factors associated with moisture sensitivity testing. Tunnicliff and Root (1984) conducted limited testing on air voids in conjunction with saturation levels which led to a modification in the procedure, and they noted that further study of the affect of air voids is needed. A more detailed look at the nature of air voids will be included in SHRP contract A-003A.

Freeze-Thaw

The incorporation of the freeze-thaw cycle is an adaptation from Lottman's (1978) work presented in NCHRP Report 192 (1978). Initially, vacuum saturation conditioning was applied to laboratory specimens and the results of the strength tests compared with the companion core samples. The strength loss from this conditioning was not severe enough so further moisture conditioning processes were evaluated. The end result was the incorporation of a freeze-thaw cycle in the moisture conditioning process to induce a loss of strength in the laboratory specimens that would closely match the strength loss observed in companion field cores. The use of a freeze-thaw cycle in the moisture conditioning process has been criticized by Tunnicliff and Root (1984); they suggest that the freeze portion of the cycle does not simulate preferential wetting and can induce film rupture damage which is not stripping related. Some have argued the Lottman procedure is too severe because of internal water pressures that develop when transitioning from the vacuum freeze-thaw to warm water soak. In addition, degradation of the aggregate may occur during the freeze-thaw sequence if the aggregate is weak or porous (Lottman, 1982). It has been reported that the use of a freeze-thaw cycle can create a negative bias toward low air void specimens (Boudreau, 1989). This is attributed to the drainage that occurs within the specimen prior to the water actually freezing during the freeze portion of the procedure; the higher the air void content, the greater the drainage.

Others have found the use of a freeze-thaw cycle in the procedure enables a good correlation between the laboratory test results and field performance (Scherocman et al.,1986) and in identifying known moisture sensitive aggregate (Boudreau, 1989). The long term effectiveness of an asphalt concrete mix may be determined by conducting multiple freeze-thaw cycles. As the number of cycles increase the damage per cycle decreases. Also, the order of retained ratios for a given group of additives would likely change (Coplantz and Newcomb, 1988; Scherocman et al.,1986). Mixes with and without additives which have the higher retained values after several freeze-thaw cycles (five to seven) would indicate better long-term performance (Scherocman et al., 1986; Coplantz, 1987).

The use of freeze-thaw conditioning may not be a universally useful procedure because pavements in warmer climates do not experience freezing, yet do exhibit moisture damage. For example, a mixture that fails a process that incorporates freezing and thawing may perform very well in a warm climate. Thus applying universal criteria to the test results would result in eliminating mixtures that would otherwise be suitable. Use of freezing and thawing of mixtures needs to be examined in terms of fundamental behavior rather than a simple phenomenological correlation with field performance. Freezing of mixtures in the presence of water may cause behavior similar to that in portland cement concrete with local fracture or rupture of asphalt films which in turn may lead to accelerated moisture intrusion.

Test Water

The composition of the test water is important to the testing process. Most procedures require the use of distilled or deionized water. It has been found that the composition of the water, in particular the pH level, can change during testing. Lime may contaminate the water raising the pH level higher when testing asphalt mixes with lime treated aggregate (Coplantz, 1987). Graf (1986) noted when replacing the deionized water with lime soak water that the number of freeze-thaw cycles a specimen withstood, using the Freeze-Thaw Pedestal Test, increased tremendously. The criterion for the test (FTPT) is that a mix completing 25 or more cycles is determined not to be moisture susceptible, however, specimens placed in the lime soak water withstood more than 100 cycles. Even when the water was replaced with deionized water, after several cycles in lime soak water, the specimens lasted another 70 to 80 cycles (Graf, 1986).

In recent years, there is evidence that acid rain is more severe than originally expected in some locations. The authors are not aware of research on this effect on asphalt pavements but it could be a consideration in the development of test procedures.

Asphalt

Asphalt characteristics have been related to the moisture susceptibility of asphalt concrete mixtures. Viscosity has been identified as the prominent physical characteristic that affects the stripping process (Majidzadeh and Brovold, 1968; Schmidt and Graf, 1972). However, other studies indicate that chemical composition, source, and other factors play a role (Kennedy et al., 1983). Low viscosity asphalts are probably better able to wet or coat an aggregate, however, they may be more readily displaced by water as seen in the boiling water test, but there does not seem to be any similar evidence for compacted mixtures. While the higher viscosity asphalts are less likely to be displaced from the preferential wetting of the aggregate surface by water, it is more difficult to coat all of the aggregate surface. Additionally, the chemical composition of the asphalt can affect the rate of emulsification of the asphalt and moisture (Fromm, 1974). Other factors such as surface changes, chemical bonding, polarity, role of additives, source of asphalt crude, and others need to be assessed and are the subject of other SHRP contracts that will be closely monitored for input to this project.

Aggregates

The adhesion of asphalt cement to aggregate is related to the physical and chemical properties of the aggregate in addition to those of the asphalt. There have been some differences of opinion on the contribution of the chemical nature of the aggregate to the adhesion process. Siliceous aggregates have been classified as hydrophilic and tend to strip more readily than limestone aggregates which have been classified as hydrophobic (Taylor and Khosla, 1983). Mertson and Wright (1959) proposed another method of classification of aggregates. They indicate that both limestone and siliceous aggregates are readily wetted and indicate that both types are truly hydrophilic in character. The terms proposed by Mertson and Wright are "electropositive" for limestone aggregates and "electronegative" for siliceous aggregates. These two types of aggregates represent extremes found in aggregate classifications. A schematic classification system for aggregate, based on their system, is shown in Figure 2.7. Therefore, selection of an asphalt source and additives to prevent stripping is also dependent on the aggregate type.

Experience to the contrary has been reported by Mathews (1958). He indicates that relatively few aggregates are known to be completely resistent to the action of water under all conditions of practical use. He also asserts that the notion that "acidic" rocks have a higher potential for stripping that basic rocks is inaccurate.

Yoon and Tarrer (1988) report that the chemical and electrochemical interaction between water and the aggregate surface play a greater role in stripping than the physical characteristics of the aggregate. They state the Zeta potential of the aggregate surface in water and/or the pH of the water imparted by the aggregate could be used to measure stripping potential. The higher the Zeta potential and/or pH value, the higher the probability for stripping. Further evaluation of these factors is the subject of a portion of SHRP contract A-003B.

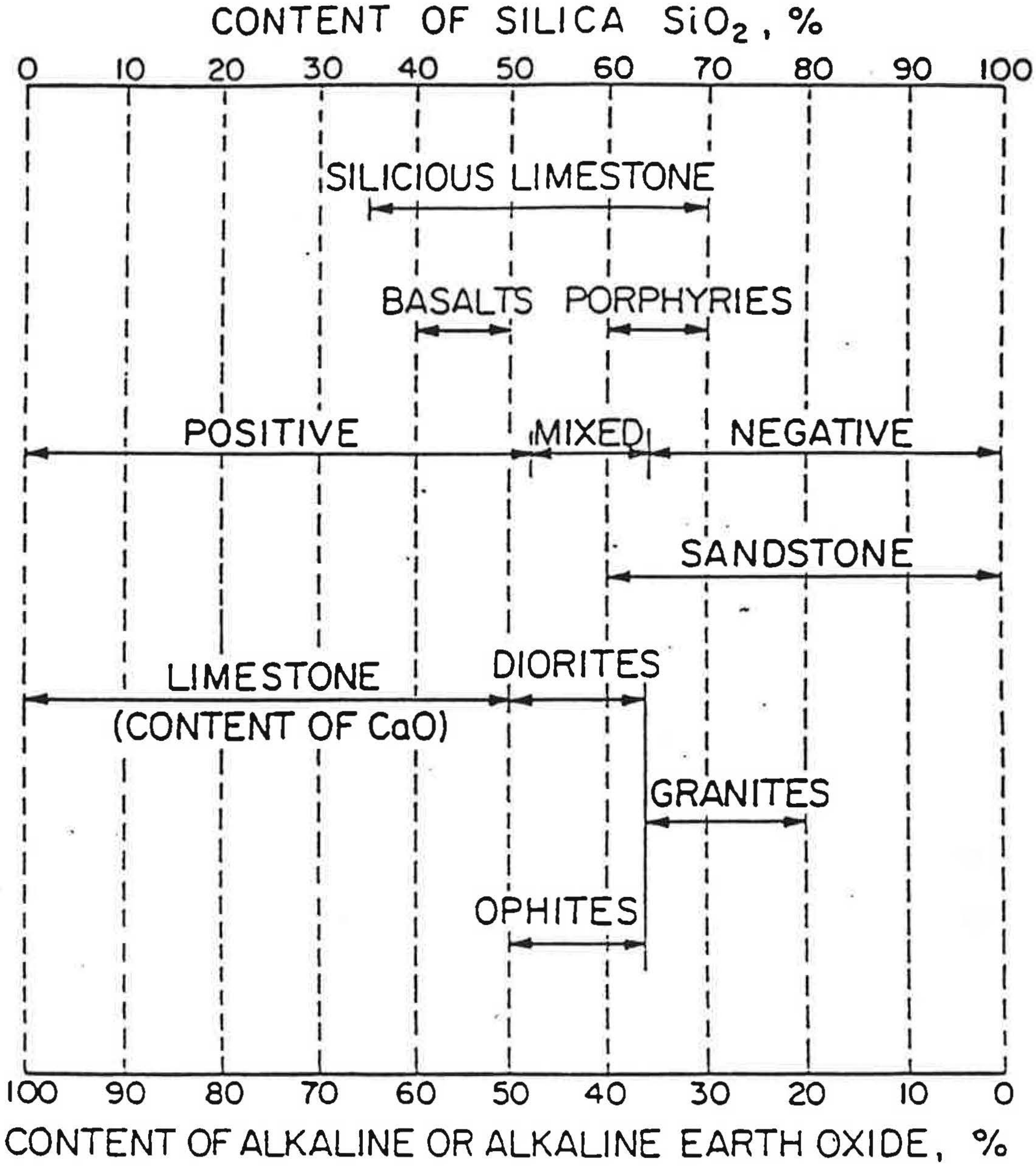


Figure 2.7. Classification System for Aggregates (after Merton and Wright, 1959)

2.2.2 Evaluation Techniques

Testing of asphalt concrete for moisture susceptibility has two primary steps; conditioning and evaluation. As indicated earlier, the conditioning process has taken on several forms which range from static immersion to boiling to freezing of the test specimen. The test methods involve three primary means of evaluating the conditioned samples or specimens; visual observation, destructive testing, and non-destructive testing. The evaluation phase of the procedures assess the damage incurred by the specimen during the conditioning phase. It is at the completion of the evaluation that the determination of whether a mix is moisture susceptible is established.

Visual Evaluation

Visual evaluation of asphalt concrete specimens is the method used to determine the percentage of retained asphalt coating on the aggregate, or in the case of the freeze-thaw pedestal test to evaluate the structural integrity of the specimen, after the sample has been "conditioned". The visual evaluation method is fundamental in boiling tests and static immersion tests. The primary problem with this method is the subjective nature of the evaluation. Sometimes, in an attempt to limit the subjectivity of the visual evaluation, rating boards or patterns, similar to those shown in Figures 2.8 and 2.9, are used to aid the rater and help establish consistency in the results. Another method is the use of more than one rater and then averaging the results.

In addition, differences in how and when specimens are evaluated can further decrease the precision of the results. For boiling tests it is common to place the sample on a paper towel and evaluate the mixture when it has dried. Parker and Wilson (1986) found that the timing of the evaluation can play a significant role in percent coating rating given to an asphalt sample after the boiling test. Samples that were drained immediately after the boiling sequence may change in coating from 50% just prior to drainage, up to 75% to 80% when evaluated. This is due to the hot asphalt recoating the aggregate from the remaining asphalt. Although the asphalt coating on the aggregate is thinner, the visual evaluation

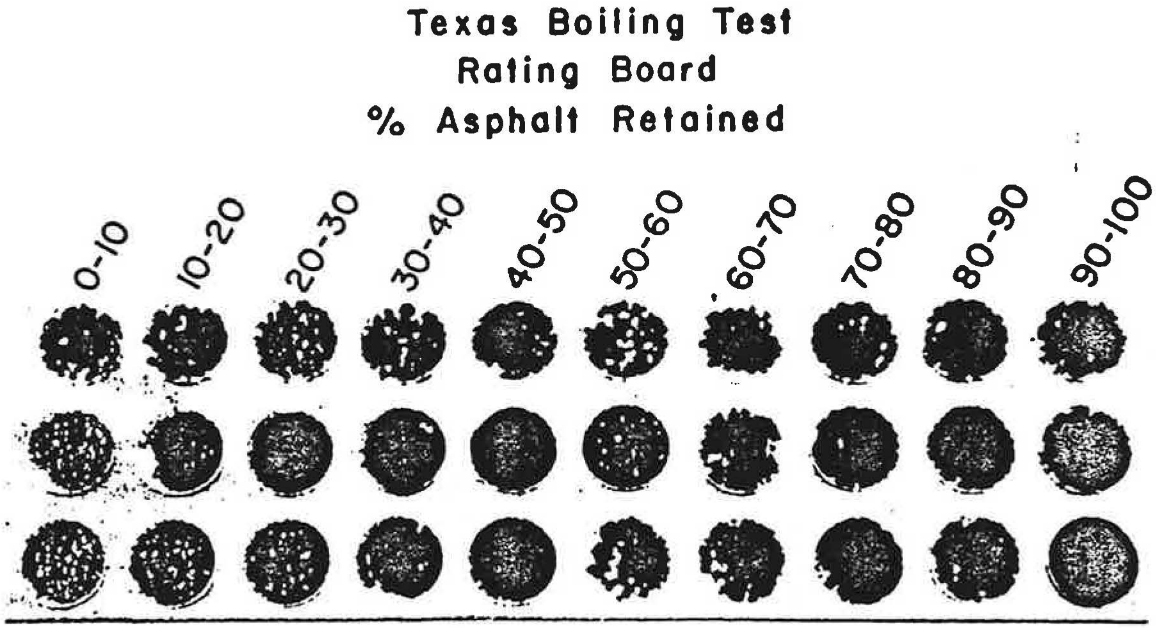


Figure 2.8. Visual Evaluation Rating Board (Kennedy, 1983)

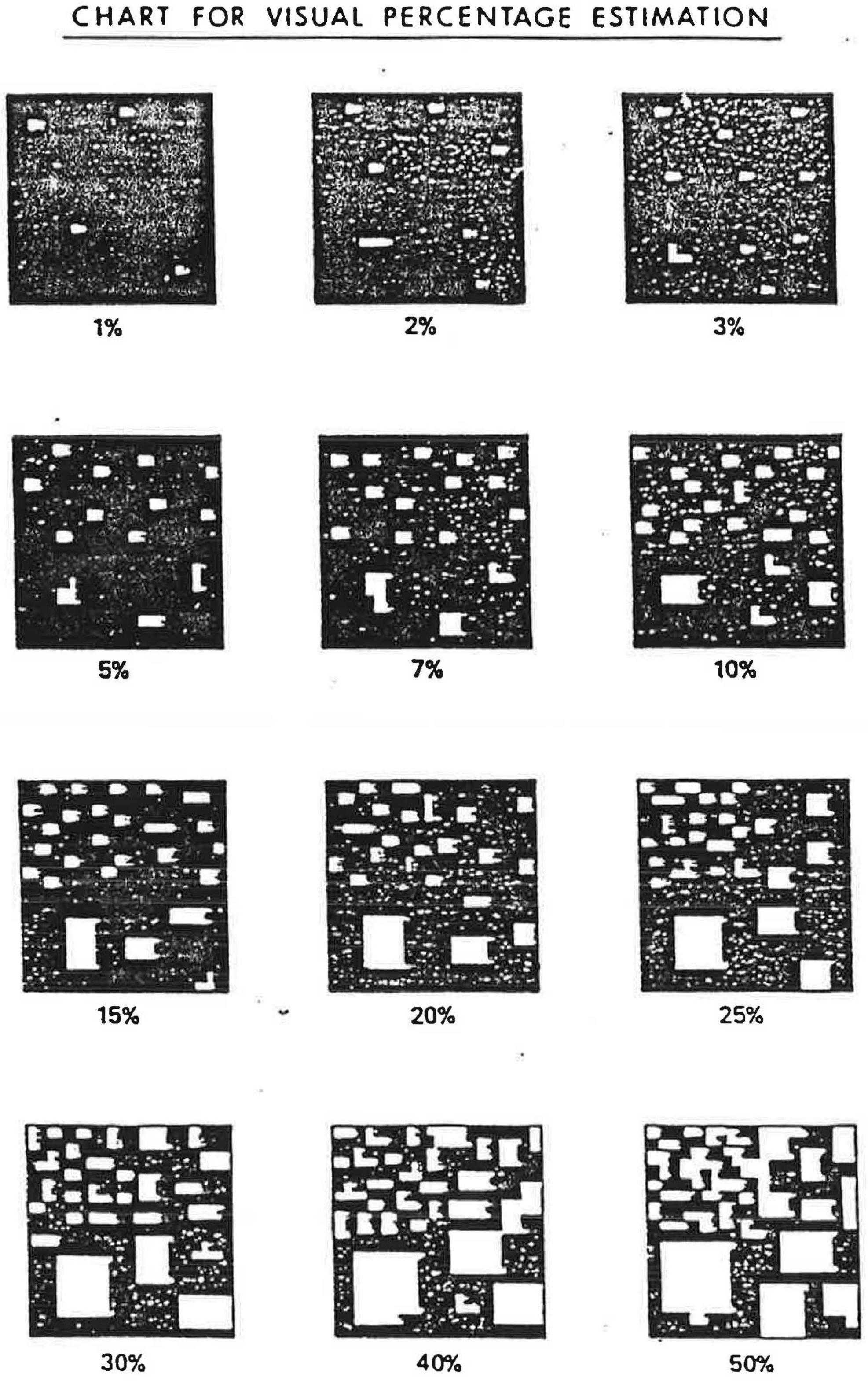


Figure 2.9. Visual Evaluation Rating Pattern (Ontario, 1986)

does not account for the film thickness. This is in contrast to the static immersion tests where the sample is typically rated while still in the container and immersed in water.

The NCHRP 246 method recommends that following the indirect tensile test, the specimen be split open and the percent stripping (and other characteristics) be evaluated on the split-open interior faces. In the NCHRP 9-6(1) AAMAS study, Lottman used a stereo zoom microscope to estimate the percent stripping in the fine aggregate and a magnifying glass for the coarse aggregate, then calculated total percent stripping by pro-rating each fraction on a 60:40 basis.

Visual evaluation of mixtures relate only to stripping potential and should be restricted to a minor role in any evaluation procedure. Observation after boiling in water may be an indicator of potential problems, however, the subjectivity in judgement and the details of methodology make it an unlikely stand-alone procedure. The best possible use of this approach would be for pre-screening of materials prior to mixture testing.

Destructive Evaluation

This method of evaluation includes compression, stability, and indirect tensile testing of specimens. In each of these methods a compressive load is applied until the specimen fails. The strength of the specimen is a measure of:

1) the cohesive characteristics of the asphalt,
2) the mechanical interlocking of the aggregate,
3) strength of the aggregate, and
4) the adhesive properties of the asphalt to the aggregate.

Further, the aggregate should not degrade unless excessively weak or fractured during a freeze-thaw cycle during conditioning.

The loading rates common to the procedures are either 0.065 or 2 inches per minutes. The 2 in./min. loading apparatus is common to many laboratories and appears not to influence the results. Maupin (1979) did not find a significant difference using a 95% confidence interval between the results obtained using the indirect tensile test at a loading rate of 0.065 inches/minute at 54°F or using a Marshall stabilometer with a loading rate of 2 in./min. at 77°F.

A shortcoming of testing to failure is that only one discrete point is known at the time of test and numerous specimens are required to define a trend over a range of conditions. In addition, at least with the diametral tension test, the properties of interest (i.e., modulus, shear, etc.) are not tested and are sacrificed for the sake of a test that is simple to perform. Another possible shortcoming is the comparison of dry vs. moisture conditions specimens by using a ratio of strength results. The strength of a dry specimen may be unrealistic because field conditions are rarely dry. Some minor level of water conditioning (such as the equilibrium water content discussed earlier) might be a better "before" condition.

Non-Destructive Evaluation

Non-destructive testing has the advantage that the dry specimen can be tested, conditioned, and tested again to note any changes in the measured properties. The diametral resilient modulus is the test parameter most used and measures the elastic deformation that occurs under repeated impulse loading. This approach is intended to simulate the elastic response of the pavement in the field under traffic loading.

A better understanding of the effect of water on asphalt mixtures can be determined through carefully controlled tests such as those conducted by Schmidt and Graf (1972), as shown in Figure 2.10. The data in this figure confirms that shown in Figure 2.6, that wetting (saturation) reduces the strength or modulus to about 50 percent of the original dry value. Several other observations of Figure 2.10 indicate factors that need to be evaluated in the development of a test procedure, including at least the following:

- The modulus continues to deteriorate with time while the specimen remains saturated.
- The modulus is completely recoverable upon drying (vacuum desiccation).
- It is very difficult to completely dry a specimen once it has been wetted.

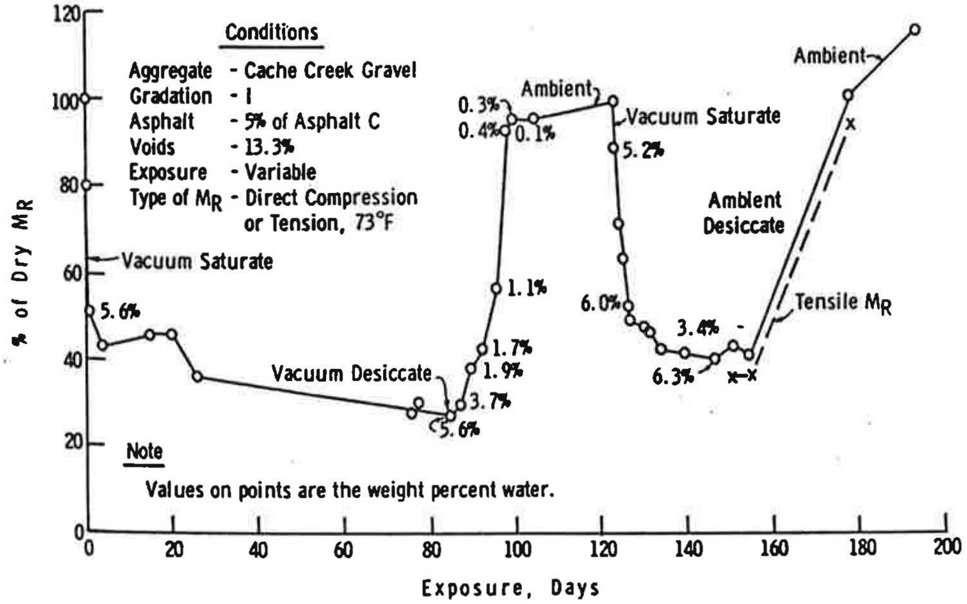


Figure 2.10. The Resilient Modulus of Asphalt Concrete is Sensitive to Changes in Moisture Conditioning (Schmidt and Graf, 1972)

- Upon resaturation, the maximum water content reached is higher than for the first cycle, indicating a change in the structure or voids.
- The modulus increases with time, both in saturated and dried conditions, indicating aging or some combination of factors.

The complex behavior illustrated in Figure 2.10 makes it difficult to select a discrete set of conditions for evaluation. A better understanding of the basic behavior of mixtures is required before an effective procedure can be developed.

Elimination or reduction of variability among test samples, which is inherent in destructive testing procedures, is one reason for interest in resilient modulus testing. There are currently several studies underway to refine this test method and to evaluate variability through round-robin testing. These include work at Oregon State University and Oregon DOT as well as cooperative testing among several Triaxial Institute member organizations on the west coast. With proper calibration of equipment, correlations among laboratories can be quite good, and even better for within laboratory testing. Limited tests at the University of Idaho have shown the variability of water conditioned specimens to be somewhat greater than for the dry specimens and may also illustrate that a universal conditioning procedure applied to all mixtures may not be appropriate.

2.2.3 Discussion

Common to many procedures is the soaking of the specimen in water at an elevated temperature to accelerate the process by which moisture damage occurs. The use of one freeze-thaw cycle is also used in some procedures. Coplantz and Newcomb (1988) report, from their evaluation of four different conditioning procedures, that vacuum saturation alone did not induce moisture related damage to the mixture. This is supported in other work by Coplantz (1987). In a report by Busching et al. (1986), it was determined that high saturation levels that would occur in wet environments would significantly affect retained strengths even in the absence of freeze-thaw cycles. Parker and Gharaybeh (1987) report lower tensile strength ratios from a conditioning procedure that included a freeze-thaw cycle as opposed to a vacuum saturation followed by soaking. The results from one cycle have shown good results in distinguishing moisture sensitive mixtures (Lottman, 1982; Boudreau, 1989). While multiple freeze-thaw cycles may provide a better indication of the asphalt mixes long term performance (Coplantz, 1987; Scherocman, 1986), the length of time required makes this test method prohibitive.

In evaluating the ratios determined from conditioned and unconditioned samples, consideration should be given to the actual strength level of a specimen and not be based solely on the modulus or tensile strength ratios during the decision on whether a mix is moisture sensitive. Scherocman et al. (1986) and Busching (1986) report that the use of chemical additives can significantly increase the unconditioned strengths of test samples. The increase in strength for the conditioned specimen may be less than the strength increase for the unconditioned specimen. Therefore, a lower retained strength ratio may occur even though the values for both the conditioned and unconditioned samples have increased. Lottman, White, and Frith (1988) provide an excellent discussion of evaluation of mixtures using ratios of unconditioned to conditioner properties and relate them to predicted pavement life.

Which conditioning procedure to use and how best to evaluate the results of the conditioning procedure is still open. While the NCHRP 274 (Tunnicliff and Root) and the NCHRP 246 (Lottman) procedures, or some close variation of, appear to be widely used and accepted, there are still questions. Von Quintus et al. (1988) found "poor correlation" when using NCHRP 274 and AASHTO T-283 conditioning when evaluating the results by tensile strength and resilient modulus ratios. The best results from this study were from the NCHRP 274 conditioning using an indirect tensile strength ratio for evaluation. Also, they suggest the measure of tensile strain at failure be measured, which would provide a better evaluation of the adhesive bond between the asphalt and aggregate.

2.3 Testing - Current Practice

As part of an NCHRP (1989) study concerning moisture damage in asphalt concrete pavements, a letter survey was sent to transportation agencies in 1988 asking the participants to identify test procedures they use to detect moisture susceptible asphalt concrete mixtures. Responses identified several test procedures currently employed by the various agencies. An example of one question and the rating scale is shown in Figure 2.11. The effectiveness rating is based on a scale from 0 to 9 with 0 reflecting a procedure that is not effective in identifying moisture susceptible mixes and a rating of 9 for a procedure that is 100% effective in identifying moisture susceptible mixes. There were 44 respondents to the questionnaire, 39 of them were state DOTs replies. Also, responses were received from; Ontario, New Brunswick, Nova Scotia, and Alberta from Canada and from Puerto Rico. Of the 44 respondents, 9 currently do not test for moisture susceptibility in their asphalt concrete mixes. These states and the states which did not respond are listed in Table 2.11 and the geographic location of the responding agencies is shown in Figure 2.12.

2.3.1 Current Agency Practice

A summary of procedures used by several agencies, their effectiveness as interpreted by the agency, and any variations to a standard procedure which is closely followed is shown in Table 2.12. As shown in the table, the most common procedures include:

1) NCHRP 274 Indirect Tension test with Tunnicliff and Root conditioning procedure
2) NCHRP 246 Indirect Tension test with Lottman Conditioning
3) Boiling tests
4) AASHTO T-165 Immersion/Compression tests
5) Agency Conditioning procedure followed by AASHTO T-245 test
6) AASHTO T-182 Static Immersion test

The immersion-compression test (AASHTO T-165), the most common procedure, is currently used by 11 agencies. The Tunnicliff and Root procedure (NCHRP 274) was identified by eight agencies; however, it was unclear how many of these agencies have the test incorporated into their specifications and how many are partaking in a FHWA study to identify the feasibility of the test. Variations of the boiling test receive wide use (eight

Question:

What test procedure do you specify or use to identify and reduce moisture-related problems? (Rate 0 to 9 from Not Effective - Very Effective.)

a) AASHTO T182 ______
b) AASHTO T165 ______
c) Resilient Modulus Ratio ______
d) ____________ ______
e) ____________ ______
f) ____________ ______
g) ____________ ______
h) ____________ ______

Please provide a copy of your procedure not published in ASTM or AASHTO.

Scale:

9 | <u>100% Effective</u>
6 | <u>Moderately Effective</u>
3 | <u>Slightly Effective</u>
0 | <u>Not Effective</u>

Figure 2.11. Survey Question and Rating Scale

Table 2.11. Agencies Without Moisture Sensitivity Test Procedures or Did Not Respond to Survey.

No Procedure	Connecticut Maine (just started) Michigan Minnesota Nebraska New York North Dakota Vermont West Virginia
No Response	Delaware Georgia Hawaii Indiana Kansas Nevada New Hampshire New Mexico Ohio Rhode Island Wyoming

Figure 2.12. Geographic Location of State Agencies Using Various Moisture Sensitivity Test Procedures

Table 2.12. Moisture Sensitivity Tests – Current Agency Practice

Standard Procedure	Agency (Effectiveness)	Variations from the Standard Procedure	Moisture Sensitivity Criteria
NCHRP 274 (Tunnicliff and Root)	Kentucky (7)		
	Tennessee (2)		
	Nova Scotia (6)		
	South Carolina (7)	• No mention of low void note (< 6.5% voids, sat ≥ 70%)	
	Texas (8)	• Unconditioned set remains dry (in plastic bag) soak 3–4 hours • Conditioned – includes freeze cycle	
	Oklahoma (8)	• Conditioned – includes freeze cycle • Diametral compressive load (no strip)	
	Mississippi (8)	• Procedure not sent	75%
	Illinois (8)	• Visual evaluation of specimen	5% max
NCHRP 246 (Lottman)	Colorado (7) Washington (9)		
Modified Lottman	Iowa (6) Pennsylvania (NA) Virginia (7)	• AASHTO T-283	
AASHTO T 165/T 167 Immersion-Compression	Colorado (5)		
	Florida (9)		
	Idaho (8)		85%
	Montana (7)		
	Missouri (6)		
	New Brunswick (2)		
	Oregon (7)		
	Utah (6)		
	Wisconsin (5)		
	Arizona (6)	• Compression 95–97% of 75 blow Marshall	Regional 40, 50, or 60% +10% Interstate

Table 2.12. (continued)

Standard Procedure	Agency (Effectiveness)	Variations from the Standard Procedure	Moisture Sensitivity Criteria
Conditioning with AASHTO T-245 test (Marshall Stability)	Arkansas (5)	Dry: • Test Wet: • Vacuum 1 hr @ 30 mm Hg (dry) • Submerge (open valve) • Water bath, 24 hrs, 140°F Test	75% Min
	Ontario (6)	Dry: • Water bath, 1 hr, 77°F Test Wet: • Vacuum 1 hr, submerged • Water bath, 24 hrs, 140°F • Water bath, 1 hr, 77°F Test	70% Min
	Puerto Rico (9)	Dry: • Water bath, 30-40 min, 140°F Test Wet: • Water bath, 24 hrs, 140°F Test	75% Min
	Alberta (8)	Dry: • Test Wet: • Water bath, 24 hrs, 140°F Test	70% Min
Boiling	Alabama (2)	Determine: • Additive presence	95%
	Arkansas (3)	• Additive acceptance	95%
	District of Columbia (5)	• Stripping	95%
	Louisiana (9)	• Additive acceptance	90%
	Maryland (7)	• Stripping/additive acceptance	95%
	South Carolina (5)	• Additive acceptance	80%
	Tennessee (3)		
	Texas (6)	• Stripping/additive acceptance	
AASHTO T-182	Alaska (5), ATM T-14	24 hrs, 120°F water bath, rate nearest 10%	70%
	Florida (9)		95%
	Iowa (6)		95%
	New Brunswick (1)		95%
	Massachusetts (6)	24 hrs, inspect, 1 week, inspect again	90%
	Ontario (6)	24 hrs	65%

agencies currently), primarily to determine the effectiveness of antistripping additives. Another test is generally used to determine the moisture susceptibility of the asphalt mixture. Only three of the eight respondents, District of Columbia, Maryland, and Texas, are using the boiling test to identify moisture susceptible mixtures. The other five agencies utilize the test for additive effectiveness analysis. Additional test methods which were less common are listed in Table 2.13.

The variations noted in Table 2.12 are deviations from the standard procedure as described in the NCHRP publication or the appropriate AASHTO standard listed under the "Standard Procedure" column. One exception is the boiling test which is not currently standardized by AASHTO and the ASTM procedure (D3625) specifies only a one minute boiling time where most agencies use 10 minutes. The effectiveness given each procedure is based on the agencies interpretation on how well the procedure predicts the moisture susceptibility of a mix. In Figure 2.13 the effectiveness ratings shown in Table 2.12 have been plotted. The figure illustrates that most agencies find the procedure they use at least moderately effective (a rating of six). The variations within a given procedure as listed in the figure prevents specific comparisons. While it would be expected that agencies view the test they use as at least close to moderately effective, it is surprising the number of agencies which rate the their procedure, either an eight or nine, as very effective. This high rating was unexpected due to the diversity of results, noted earlier in this report, from various studies on the correlation of current test procedures with field performance. In addition, it is puzzling why there is so much stripping reported by agencies when they believe their current testing methodology adequately predicts the potential for stripping.

2.3.2 Test Variability

In evaluating the effectiveness of a particular test reported by an agency, one needs to be aware of the variability within a test procedure. Even though two agencies may classify their methods and procedures for the evaluation of moisture susceptibility by the same title, the actual material preparation and conditioning may be quite different.

Table 2.13. Additional Moisture Sensitivity

Method	Agency (Effectiveness)
Swell	California (NA) Montana (6)
Moisture Vapor Susceptibility	California (NA)
Abrasion	California (NA)
Adhesion "Agitation Tests"	California (NA) Utah (5) Montana (6)
Experience	South Dakota (9)
Other	North Carolina - AASHTO T-11

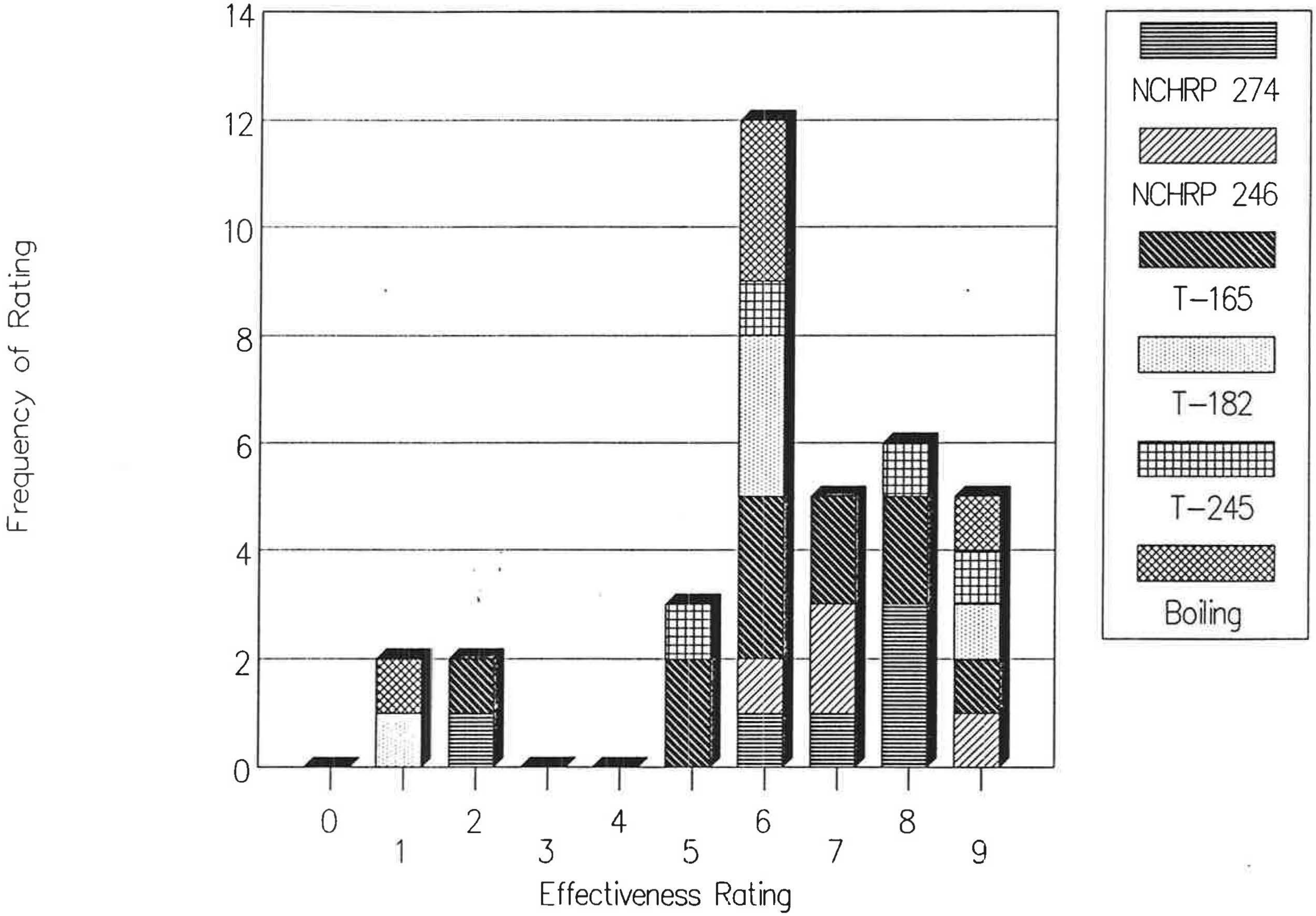


Figure 2.13. Effectiveness of Each Test Procedure as Determined by Each State Agency

The boiling test is a simple test procedure which involves boiling a loose asphalt mixture in a container for 10 minutes and then visually evaluating the retained coating. In reviewing the questionnaire returned by some of the agencies, even these procedures are inconsistent. Cooling times before adding the asphalt mixture to the boiling water range from no specified time (in fact it appears the mixture is added while still hot) to a 24 hour cooling period prior to addition of the mixture. The type of water was specified as either distilled or deionized, potable, or no specification was mentioned. Agitation of the mixture during the boiling is required by some agencies. Most require the use of a "representative sample" of the asphalt mixture, the amount generally being either 200 or 300 grams. A criteria of 95% retained coating is common; however, 80% is used by one agency. Evaluation of the asphalt mixture for retained coating can vary from 30 minutes after completing the boiling and drainage to 24 hours when the mixture is completely dry. Though each of these differences may not dramatically influence the results, they do reflect the non-standardization that exists even in a simple procedure.

The index of retained stability, the tensile strength ratio and index of retained strength are physical test methods currently used by highway agencies to evaluate specimens after conditioning. The effectiveness of these methods of evaluation cannot be attributed solely to the results attained from the testing. Conditioning procedures can vary considerably. The index of retained strength, from the immersion-compression (AASHTO T-165 and T-167) may be the exception because agencies which adopt this procedure tend to follow the standard procedure as published by AASHTO. The index of retained stability is not based on a defined conditioning procedure and the variations associated with the conditioning process have been noted in Table 2.12. The tensile strength ratio is used by several agencies. Therefore, when evaluating results from different sources using this procedure, an evaluation of the conditioning procedure is also required. As shown in Table 2.14, there are variations in the conditioning procedures that will affect the determination of the moisture susceptibility. The tables illustrate the variation within each step of the procedures that occurs in methods that base the results on this test method.

Table 2.14. Conditioning Procedures for Tensile Strength Evaluation

Tensile Strength Ratio (TSR)	
Unconditioned Samples:	
STEP 1:	- Air Bath @ 77°F for 24 hours - Water Bath @ 77°F for 20 minutes - Water Bath @ 77°F for 2 hours - Water Bath in plastic bags @ 77°F for 3-4 hours - Stored at room temperature
STEP 2:	- Test Diametral Tensile Strength
Conditioned Samples:	
STEP 1:	- Vacuum saturate until saturation * * 55% to 80%, discard if > 80% * 60% to 80%, discard if > 80% Note: saturation calculated by; - Air dry weight - SSD weight in air - Vacuum saturate for 30 minutes then leave submerge at atmospheric pressure for 30 min.
STEP 2:	- Wrap in plastic and freeze for 15 hours - None
STEP 3:	- Water Bath @ 140°F for 24 hours
STEP 4:	- Water Bath @ 70°F to 80°F for 1 to 5 hours - Water Bath @ 77°F for 1 hour - Water Bath @ 77°F for 3 to 4 hours
STEP 5:	- Test Diametral Strength Rates; - 2 in./min. - 0.065 in./min.

Also worth noting is the treatment of the "unconditioned" specimens. As indicated in Table 2.14, the treatment of an "unconditioned" specimen can range from testing a dry specimen to soaking the specimen for two hours at 77°F or soaking at an elevated temperature of 140°F for one hour. The significance of these differences and their influence on results was not noted in the literature.

2.3.3 Discussion

There are a variety of tests presently being used to identify moisture susceptible mixtures. Many agencies have identified the tests they have selected as being moderately effective or better. It is surprising the number of states which do not even have test procedures for evaluating potential moisture damage problems and presumably have water damaged pavements while nearby states are experiencing moisture related damage in their pavements.

In evaluating a given test procedure against another, one must be aware of the full procedure as well as the associated criteria. A comparison of the effectiveness of one boiling test versus one from another agency or in comparing the use of tensile strength ratios versus stability ratios is invalid without evaluating the full methodology used in the procedures being evaluated.

3.0 PROMISING METHODOLOGIES AND RESEARCH IDEAS

From the earlier discussion, it is readily apparent that there is no clear cut method of testing or predicting moisture sensitivity in asphalt mixtures. Although some procedures appear to do a reasonable job in some aspects, there is no completely acceptable method at present. The diverse methods currently being used by various state DOTs is evidence of this uncertainty.

The several projects funded through NCHRP were attempts at developing new and better methods. These and the other procedures discussed have appeared to proliferate methods rather than consolidate and standardize. Stuart (1986), in his FHWA study attempted to compare many of the more promising methods and, in particular, evaluate the Tunnicliff-Root method which is the more recent, but the results were largely inconclusive. As a follow-up to that study, the FHWA has funded a multi-state evaluation of the Tunnicliff-Root method along with others. These states, Indiana, Montana, New Mexico, and Oregon will extend the testing conducted by Stuart, but use local aggregates, etc., to make the evaluations more regional. At this writing (October, 1989), the results of these studies are not yet available.

For the purpose of SHRP contract A-003A, it does not appear that again evaluating all the existing methods using MRL materials, etc., would be particularly fruitful. Rather, the opportunity to extend this knowledge and background experience into new areas does seem to be worthwhile.

Several areas of research will be explored in this project as discussed in the following pages. A detailed workplan has been prepared as a separate document, but an outline of this plan is provided herein as Appendix A.

Throughout the SHRP contract work, particularly contracts A-003A and A-003B, there is need to investigate ideas or concepts before a proven new test procedure can be developed and recommended. As an interim procedure, a "modified Lottman" procedure will be used to provide basic information on the SHRP laboratory materials and mixtures. From the evaluation provided in Chapter 2, both Lottman and Root-Tunnicliff were judged approximately equivalent (see Table 2.10). For convenience, the modified Lottman approach was selected and this procedure is outlined in Appendix C. This procedure is not a recommendation for others, but was selected and developed for internal use within the SHRP research program. The principal deviation from AASHTO T-283 is that the evaluation following conditioning is for resilient modulus only and does not include splitting tensile strength on a routine basis.

3.1 Gaps In Current Knowledge

Keeping in mind the overall goal of this project, relating asphalt binder properties to performance of mixtures, it is important to tie in the activities and results of other SHRP studies related to water sensitivity. Basic studies of adhesion of asphalt to aggregate, permeability of asphalt films, behavior of asphalt and aggregate at the interface, and aging all relate to the ultimate behavior of mixtures.

There are many variables that affect the way that moisture influences performance, but their relative importance is not well known. Some of the unknown factors will be addressed in the SHRP program, while others are outside the scope or beyond the time and funding capabilities. Several areas that need better understanding include at least the following:

1) Effect of traffic loading on moisture sensitivity.
2) Effect of permeability of compacted mixtures and the relationship between voids and permeability.
3) Effect of voids, including size, distribution, and how they are interconnected.
4) Effect of the interface between aggregate and asphalt.
5) Effect of moisture on:
    - modulus, fatigue, rutting, strength
    - adhesion
    - aging, and with time in general including the rate that wetting or saturation occurs (i.e., environment)

6) Effect of asphalt source and type.

Comments and ideas expanding on these areas are included in the following pages.

3.2 Effect of Traffic

Rolling wheel loads may not have much effect on water sensitivity unless some of the voids or pores in the mixture are saturated. Excessive pore water pressure may have a disruptive effect on the mixture, perhaps destroying bonds and causing rupture. None of the existing methods incorporate this factor, but it should be investigated. Another reason for considering loading is the known behavior of wet or saturated mixtures during load tests: the modulus may be as much as 50% lower than when dry (see Figure 2.10). This factor alone may reduce the life of a pavement in terms of fatigue or rutting, irrespective of any loss of bonding.

One approach to investigating this phenomenon would be to continuously (repeated loading) load a specimen, monitoring the modulus, while cycling it slowly through ranges of wetting and drying. This could be accomplished by loading in a triaxial cell, but having the specimen connected externally to a "conditioner" that could wet, dry, heat, cool, etc., to simulate varying environmental conditions. Various conditional changes could then be associated with their respective change in resilient modulus. A possible test setup for this approach is shown in Figure 3.1. A standard briquet specimen can be used so that axial loading and resultant deformation is measured using strain gages attached directly to the asphalt concrete specimen. This apparatus is planned for use in the SHRP research, but will not necessarily be a part of a test procedure to be recommended for routine use.

3.3 Permeability

It is generally understood that the air voids in a mixture play a role in the pavement's longevity; higher air voids are associated with reduced service life. One of the apparent uncertainties in moisture susceptibility testing is the role of voids and their degree of saturation with water at the time of conditioning and/or testing. Boudreau (1989) has found that freeze-thaw damage is greater in specimens with lower air voids, for example.

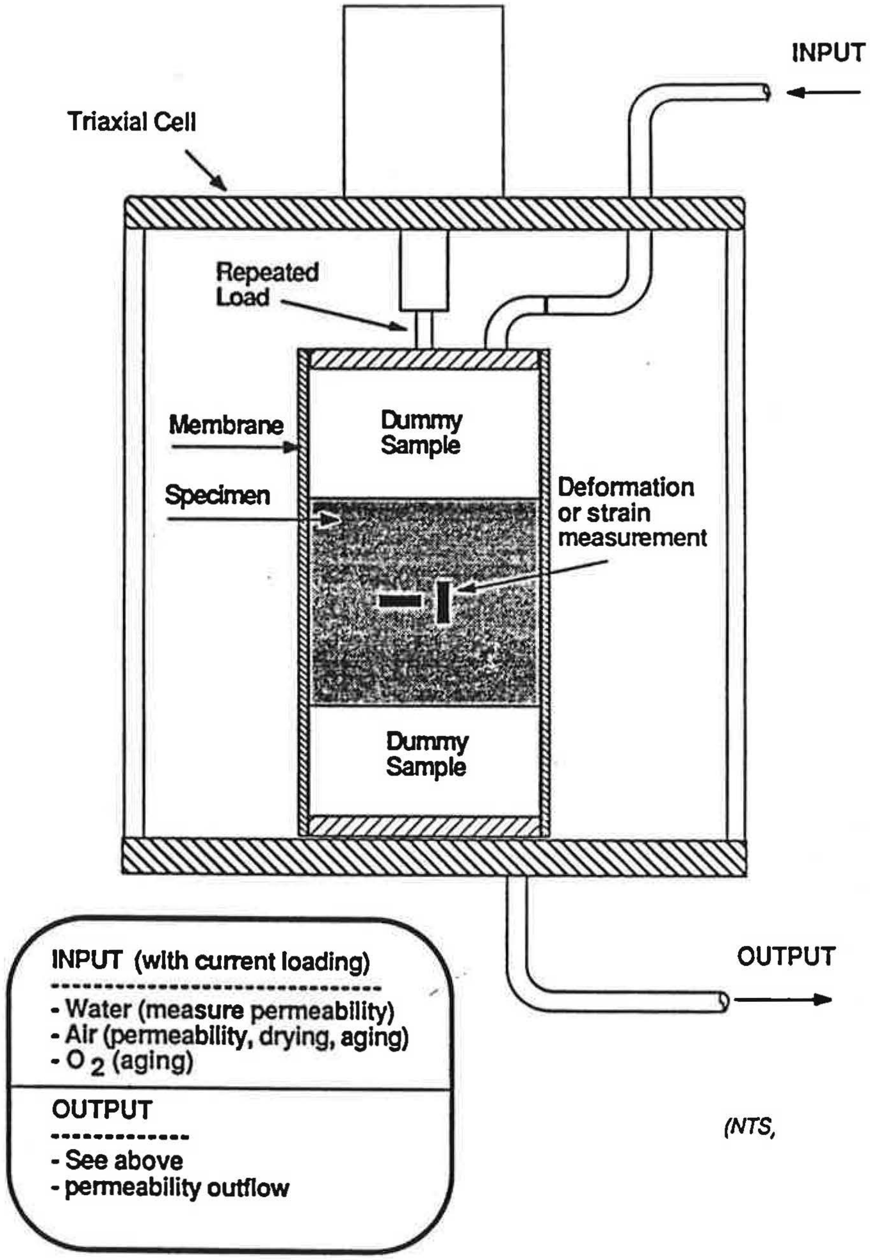


Figure 3.1. Test Setup for Evaluating a Range of Moisture and Temperature Conditions While Continuously Monitoring Resilient Modulus

This is in contrast to the generally understood concept that mixtures with lower air voids have a greater longevity in moisture conditioning. Although not well understood, it appears that the freeze-thaw mechanism plays an important role that may be different from other asphalt failure mechanisms in the presence of water.

Rather than air voids themselves, the feature more attributable to varied behavior in the presence of water may be permeability, either by water or air, or both. Several studies (James, 1988; Lottman, 1971; Davies and Walker, 1969) have shown there is some relationship between say stripping and permeability. Others (Kumar and Goetz, 1977; Blight, 1977) have used air permeability as a means of controlling the quality of mixtures (i.e., relative compaction) in the field.

Because the intrusion of water or air probably has more bearing on behavior or performance of a mixture, permeability may be a better indicator than voids. For the purposes of this study, the same laboratory set-up as described above (Figure 3.1) could be used to measure permeability. A range of permeability (as controlled by varying compactive effort) could be used to evaluate and optimize the mixture.

In currently used procedures such as Root-Tunnicliff, the emphasis has been on degree of saturation of the specimen. However, achieving a pre-determined level (60-80 percent) of saturation is not easily accomplished, and some other standard moisture condition needs to be developed. As discussed in section 2.2.1 (Conditioning Factors), exposure to excess water (partial vacuum) followed by drying to an equilibrium level may be more realistic.

3.4 Related Environment

While the effect of water is the main issue in this subtask, the effect of air (oxygen) and chemistry of the water is important also. In addition, the effect of time enters into the picture when one is trying to develop an accelerated test or conditioning procedure to represent many years in the field. For example, the pH of water used for conditioning is important in obtaining realistic results, but the expected pH in the field will depend on groundwater as well as water within the mixture as affected by additives, etc. Short term

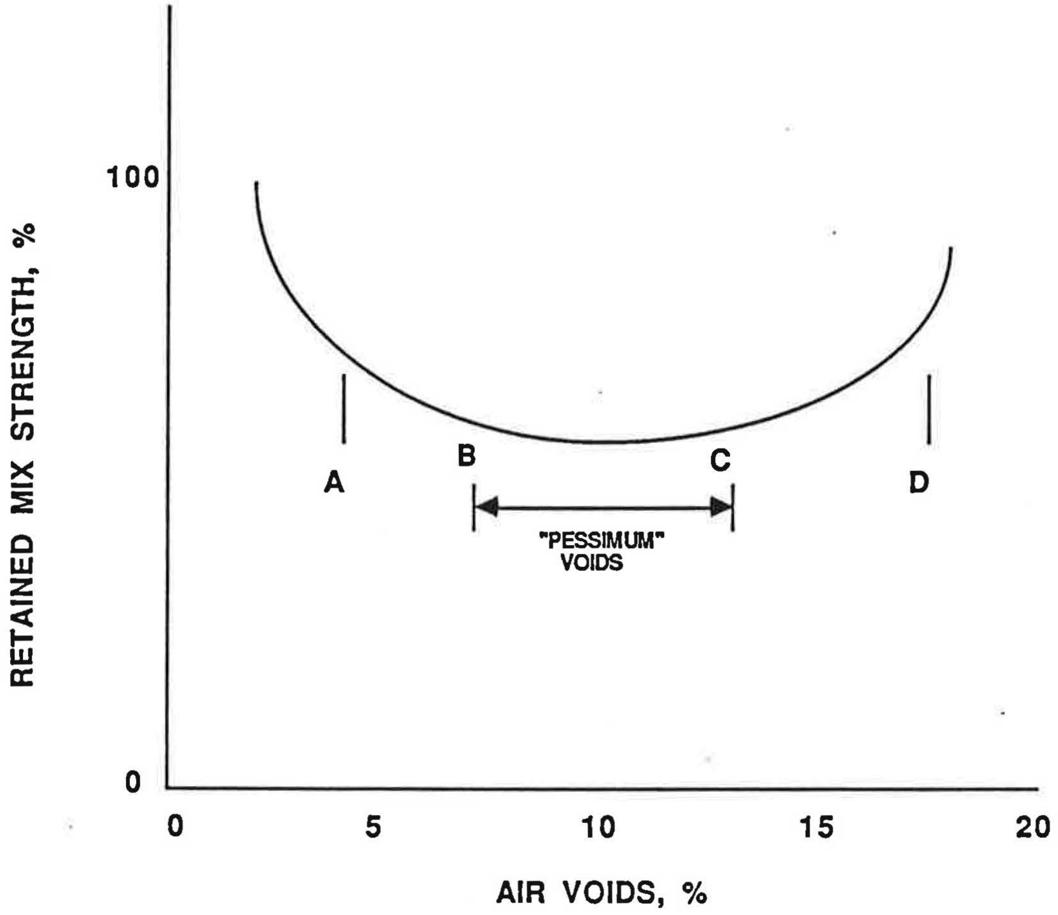


Figure 3.2. Relationship of Air Voids and Relative Strength of Mixtures Following Water Conditioning Showing the Region of Pessimum Voids

effects of these factors may be different from long term, so the understanding of them relative to each other is important. Further, dry conditioning and/or preparation of the mixture/specimens will be an important factor in the relative effectiveness of susceptibility to water.

The modified triaxial cell shown in Figure 3.1 is designed to permit the flow of water, air (dry, moist), oxygen, treated water, etc., through the specimen. The effect of these different fluids in the mixture may more closely simulate field conditions so that their relative importance can be assessed.

3.5 Effect of Moisture on Performance

The methods currently being used typically rely on strength changes to determine water sensitivity. For example, the ratio of wet to dry tensile strength is used to compare mixtures. The procedures have been developed empirically to relate the apparent condition (tensile strength) at some future time (say five or 10 years) with a laboratory conditioning process. However, the tensile strength itself may not be related to any measure of performance.

One of the goals in this study is to sort out the relative importance of moisture (and aging) on the performance in terms of fatigue, rutting, and low temperature cracking. Some testing of specimens to measure these factors will need to be done on mixtures that have been conditioned to represent a longer term situation. For example, what effect does partial saturation have on the fatigue life? On rutting resistance? Most previous testing has been done on relatively new and dry specimens, so some behavioral characteristics may have been masked or overlooked. Early on, a method for conditioning these specimens prior to testing will need to be devised.

Freezing and thawing of asphalt mixtures also has a damaging effect, particularly in the presence of water. The degree of saturation and the size of distribution of air voids may also play a crucial role in much the same way that they do in portland cement concrete. The volume change that takes place upon freezing of water must be accommodated in the mixture and if the voids are filled, there is no relief, so stresses increase. Minor cracks and disbonding may occur during the freeze cycle that probably do not completely heal during warmer cycles, thus a loss in modulus and/or strength results.

3.6 Hypothesis for Moisture Damage Mitigation

The effect of water on asphalt concrete mixtures has been difficult to assess because of the many variables involved. Most existing procedures to test the sensitivity to water are based on phenomenological processes. One of the more widely used methods is "Lottman" conditioning (NCHRP 246) and its variations, which include freeze-thaw and/or wet-dry conditioning to simulate the real pavement condition after several years service. Evaluation is usually based on ratios of resilient modulus or tensile strength, comparing the original dry specimen with the conditioned wet specimen. Among the many variables that affect the results of the above approach is the air voids in the mixture. The very existence of these voids as well as their characteristics can play a major role in performance. Contemporary thinking would have us believe that voids are necessary and/or at least unavoidable. Voids in the mineral aggregate are designed to be filled to a point less than full of asphalt cement to allow for traffic compaction and thus avoid an unstable mix. But if one could design and build the pavement properly, allowing for compaction by traffic would be unnecessary. In the laboratory, we design mixtures at, say 4% total voids, but actual field compaction may result in as much as 8-10 percent voids. Why do we need to put up with trying to construct a pavement that is so difficult to compact?

Hypothesis. Existing mixture design and construction practice tends to create an air void system in asphalt concrete that may be a major cause of moisture related damage.

Figure 2.10 illustrated that the strength or modulus of asphalt mixtures (such as M_R) will be reduced as much as 50 percent when wet or "conditioned" by water. In a more general way, Figure 3.2 shows this same effect of loss in M_R when wetted, but over a range of air voids. The amount of M_R loss depends upon the amount and nature of the voids. As noted in Figure 3.2, at less than 4 percent voids, the mixture is virtually impermeable to water, so is essentially unaffected. Region B to C is where we usually end up constructing pavements, with more voids than we like to admit. As the voids increase to D and beyond, the M_R becomes less affected by water because the mixture is free draining.

The region B to C in Figure 3.2 can be called "Pessimum" void content because it represents the opposite of optimum. Pessimum voids actually represent both a quantitative (amount of voids) and qualitative (size, distribution, interconnection) concept as they affect the behavior and performance of pavements.

Experimental Approach and Support for Hypothesis. The laboratory research being developed to test the above hypothesis will include the development and use of a modified triaxial cell as shown in Figure 3.1. For a given specimen (4-in. diameter by 2.5-in. high), several factors can be varied and monitored by measuring M_R. These factors include:

- temperature (hot, cold, freeze, thaw)
- water condition (dry, moist, saturated)
- permeability (which may be a better measure than void content)
- loading (traffic)

The initial experiments will include the four core mixtures and will evaluate the void structure and effect of water on mixtures.

In the event that all the various factors can be interrelated and understood, a system of evaluation will need to be developed (i.e., a test procedure). Because there are so many variables involved, the usual matrix of variables and test conditions may not be feasible. Rather, it is anticipated that the ultimate procedure may resemble a decision tree. One or two screening tests may precede any actual mixture evaluation. Consequently, the complex experimental work required to evaluate water sensitivity may follow the same procedure, as shown in Figure A.1 of Appendix A. This suggested scheme includes a two-phase approach wherein mixtures are made from materials that pass a screening system. The conditioning of compacted specimens would differ, depending upon the expected service conditions (traffic and climate).

For the experimental phase of this research project, several paths of wetting, drying, freezing, thawing, etc., may need to be evaluated along with the rate at which these occur. Two possible configurations of conditioning are shown in Figure A.2 of Appendix A and illustrate possible differences that could occur when specimens are wetted quickly or more slowly. A continuous monitoring of these conditions by repeated load resilient modulus will help assess the relative importance of each condition. An advantage of the set-up will be minimizing the specimen variability; a single specimen will be used for each series of conditioning. From analysis of the behavior, critical or important conditions can be identified for utilization in a more simplified conditioning procedure for routine use.

Several factors will be evaluated that should lend support to the above hypothesis. These include at least the following:

- Successfully performing mixtures can be designed outside the pessimum range of void content.
- Impermeable mixtures can be designed to resist rutting through the use of modifiers and proper aggregate design, thus avoiding water sensitivity and aging.
- Draining mixtures (open-graded) can be designed to resist loads while being waterproofed with thick asphalt films that are also more resistant to aging through the use of modifiers.
- Both impermeable and open-graded mixtures are easier to construct using conventional equipment and methods.
- The void structure in the pessimum region (Figure 3.2) may be much more conducive to water damage than either lower or higher voids. The trend of Figure 3.2 is illustrated in Figure 3.3 (Santucci et al., 1985) where core samples subjected to Lottman conditioning tend to decrease in strength and then increase as void content increases, above about 10 percent.
- Pessimum voids may be of a size that retains water and thus continuously depresses the strength. And, this water and void combination may induce

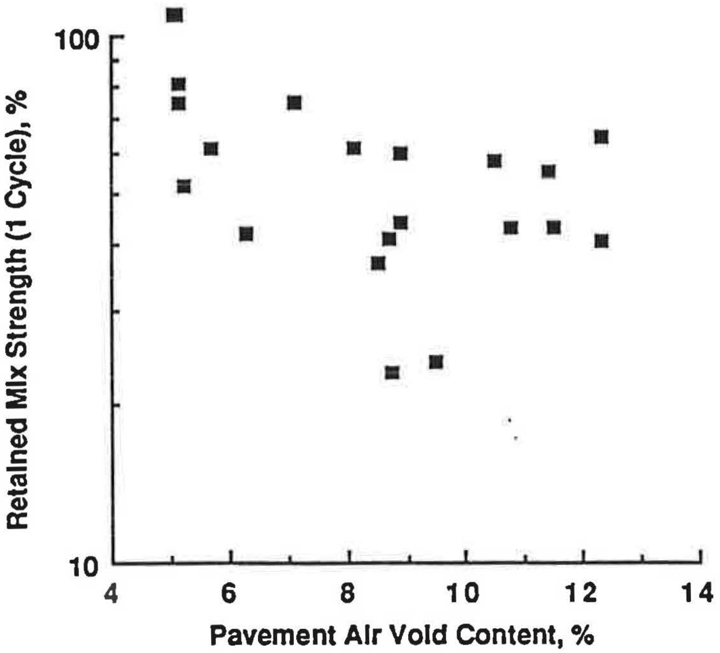


Figure 3.3. Effect of Pavement Air Voids on Retained Mix Strength (from Santucci et al., 1985)

freeze-thaw damage in much the same manner as for portland cement concrete.

- Moisture vapor in the voids may be more conducive to stripping because it more readily penetrates the mixture to reach the aggregate-asphalt interface.
- The tendency of some mixtures to swell in the presence of water may be due to the nature of water uptake in the pessimum void region and whether or not water physically enters the asphalt matrix or film.
- Once a hot mix is placed in the pavement, it tends to take up moisture from its surroundings and establishes an "equilibrium" water content that varies little from year to year. This is true whether it began in a batch plant (dry) or drum mix plant (not as dry). Mixtures with voids outside the pessimum region would have less tendency to take up or retain water.

In summary, it would appear that the proposed testing and research plan (detailed in a separate document) may provide insight to mixture behavior in the presence of water. This, in turn, should lead to the development of a more realistic conditioning and evaluation procedure for water sensitivity.

4.0 RELATIONSHIP BETWEEN TEST METHODS AND FIELD PERFORMANCE

Moisture sensitivity usually manifests itself through other modes of distress such as rutting or ravelling (stripping) rather than as a form of distress in itself. As such, some degree or form of moisture sensitivity must somehow be related to the performance of pavements. However, there has been very little work done to directly link these phenomena.

4.1 Existing Methods

Most attempts at relating laboratory testing of asphalt aggregate mixtures to field performance have been only discrete points. In this approach, a laboratory specimen is subjected to a predetermined conditioning such as vacuum saturation, followed by freezing, then thawing, and then tested, for say tensile strength. The strength of core samples are taken from a pavement constructed using the same materials is compared to those in the laboratory. Doing this for a series of projects over a period of time, then allows one to match up strength and/or condition to develop a measure of performance. With enough experience, one can begin to develop a model from which predictions might be made.

To date, the best approach to relating laboratory tests to performance has been developed by Lottman (1988) in his computer program ACMODAS C. This program is based on the relative life approach (Lottman, 1989) in which the performance life is first estimated based on if the pavement were always dry using other models. Input to the program is laboratory data from indirect tensile strength and resilient modulus tests. Accelerated moisture conditioning can be selected depending upon the appropriate choice for a given agency, location, etc. Output is in the form of expected performance life based on fatigue cracking and rutting in the wheelpath. Also, the tensile strength and modulus cut-off ratios are predicted using ACMODAS C for both fatigue cracking and rutting.

4.2 Verification

Verification of relationships between laboratory test methods and field performance is an on-going process. Several projects are known that were well documented when they were constructed several years ago. It is anticipated that these pavements will be examined, sampled, and tested to provide correlation data. Further, the continuation of the NCHRP project (AAMAS) includes several current field projects that may be included. This project will continue to build on this experience and in light of new information and developments. In addition, programs such as ACMODAS C will be used to aid in this process and may serve as the basis for future versions.

5.0 CONCLUSIONS AND RECOMMENDATIONS

It is evident that the development of standardization in the moisture susceptibility testing area is needed. It is difficult at best to evaluate the various results when these results are based on different tests or a test with the same name but different methodology. Presently, several test procedures receive wide spread use and are perceived as being effective in identifying moisture susceptibility in asphalt concrete mixes. However, the variance in procedures prohibits the development of a large data base from which an in-depth analysis can be made. Some tests, as noted earlier, have demonstrated a "good" correlation with field performance. However, it is not uncommon to find mixed reviews as to the effectiveness of a procedure. There is little evidence of laboratory testing followed by evaluation of field performance to establish a direct correlation. Most "field correlation data" is established from obtaining "approximately the same materials" placed in the field, then testing these materials to establish a correlation (Stuart, 1986; Tunnicliff and Root, 1984) or using testing procedures to evaluate the performance where the moisture sensitivity of the material (primarily aggregate) is "known".

5.1 Conclusions

Based upon the available literature and the on-going evaluation of presently available procedures, the following conclusions appear warranted:

1) There is no procedure that is universally acceptable to all or even most user agencies.
2) A wide range of procedures is currently being used.
3) Each of the published procedures has one or more shortcoming that fails to address an important variable or consideration.
4) None of the published procedures relate asphalt properties to field performance of mixtures, which is one of the objectives of the SHRP program.

5) Even among these agencies using a common method, there is considerable variability in conditioning and testing so that data are not comparable among laboratories.

5.2 Recommendations

At least on a preliminary basis, the following recommendations are suggested:

1) Monitor and evaluate the basic comparison studies on adhesion and water sensitivity in order to address all the factors that are important in the full mixture.
2) The relative importance of each conditioning variable (temperature, water content, loading, etc.) needs to be studied in order to assess which of them used to be incorporated into a mixture evaluation system.
3) Develop a test procedure to permit the evaluation of (2) above. For example, see Figure A.1 in Appendix A.
4) Develop appropriate criteria for the effect of moisture on mixtures.
5) Develop a simplified conditioning, testing, and evaluation system that adequately considers the important variables and can be readily used by agencies. The procedure should include two levels of evaluation and criteria: (a) acceptance or rejection (screening) of one or more materials, and (b) appropriate reduced modulus or other parameters (if any) to be used in design considerations.
6) Develop (or modify (5) above) a procedure for conditioning mixtures to be used for other tests such as fatigue, rutting, and cracking.
7) Test the hypothesis that avoiding the "pessimum" void content in mixture design and construction will result in less water sensitive mixtures that still retain adequate performance in fatigue, rutting, and thermal cracking.

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Appendix A

Test Plan - Moisture Sensitivity

1. Purpose

To evaluate the most promising methods for measuring water sensitivity of mixtures:

a. Screening for materials acceptibility

b. Testing for parameters for use in design and for conditioning prior to testing in fatigue, creep, etc.

2. Possible Methods

a. Testing aggregates (mineralogy, zeta potential, etc.) and asphalt (composition, peel test, etc.) separately.

b. For the interim, use modified Lottman for "base" of comparision. For evaluation and to determine end point field condition, use repeated load triaxial cell modified to provide for permeability, wetting, drying, aging (O_2), and temperature control.

c. Identify parameters most important to simulate and measure water sensitivity (adhesion and cohesion).

3. Materials - First Phase Initial Study

- 2 asphalts, optimum design asphalt content
- 2 aggregates, one gradation
- 2 levels of voids and/or permeability
- 1 or 2 anti-strip additives

4. Tests to Evaluate Moisture Sensitivity

- Resilient modulus (diametral)
- Tensile strength
- Resilient modulus (triaxial) continuously while subjecting specimen to changing conditions, including temperature and different levels of saturation, permeability, etc.
- See Figure A.1 for possible equipment configuration.
- See Figure A.2 for possible conditioning and testing sequence.

5. Evaluation of Results

- Compare results to "base" condition to estimate long-term field condition.
- Establish accelerated conditioning that will be representative of in-service.
- Use existing projects where feasible.

6. Verification of Conditioning Method

a. Literature - several recent studies have compared the various conditioning procedures

b. Existing Projects

  - FHWA (Stuart) and states (OR, UT, MT, NM, IN) are doing various conditioning procedures to compare Tunnicliff-Root with Lottman and others. These results will be used to evaluate current procedures.

  - AAMAS Study (current phase)

  - A-003B will use modified Lottman for interim to tie to A-003A.

c. Re-examine existing older projects used by Lottman for field verification.

7. Recommendations

Too early to tell

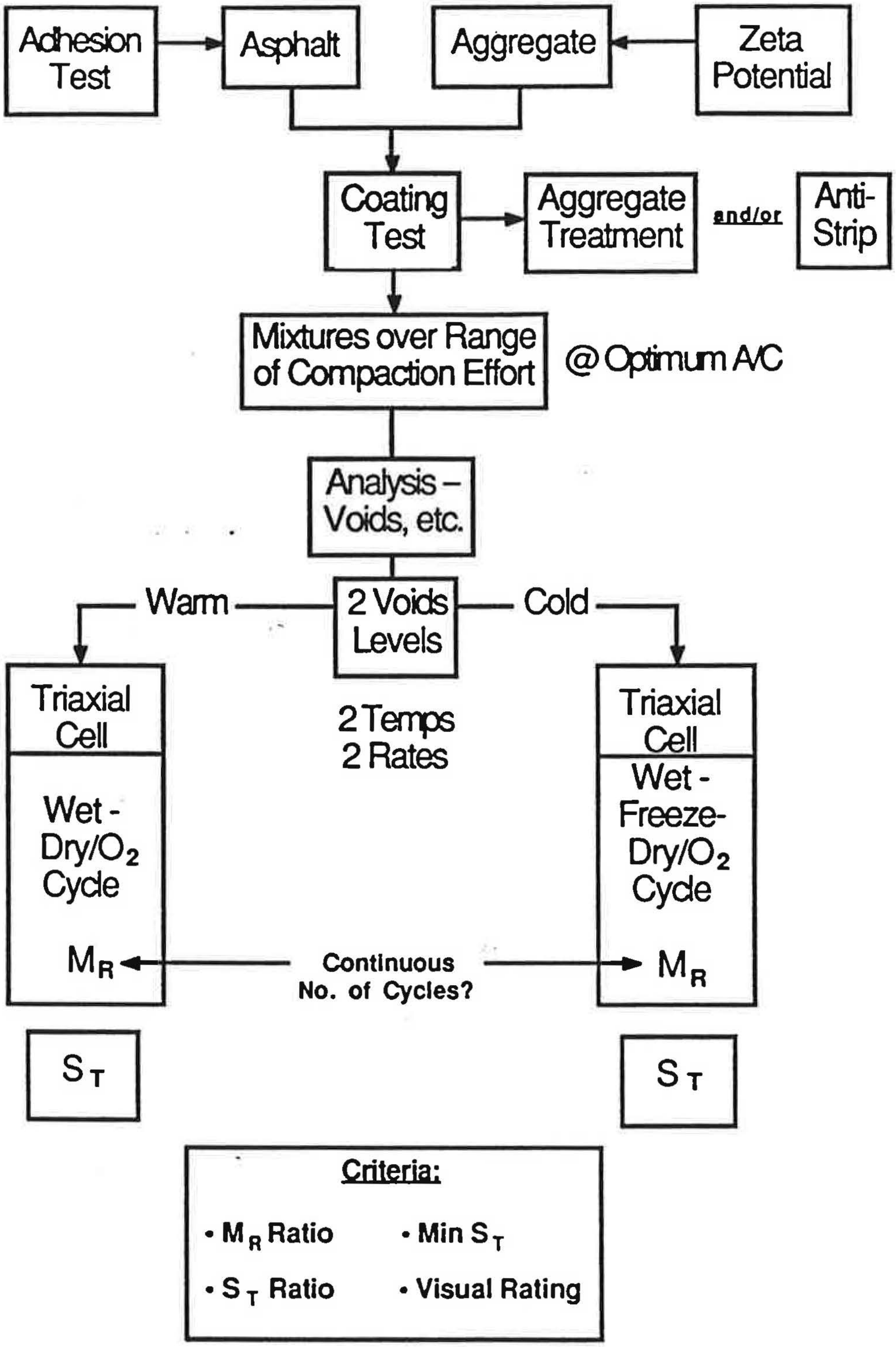
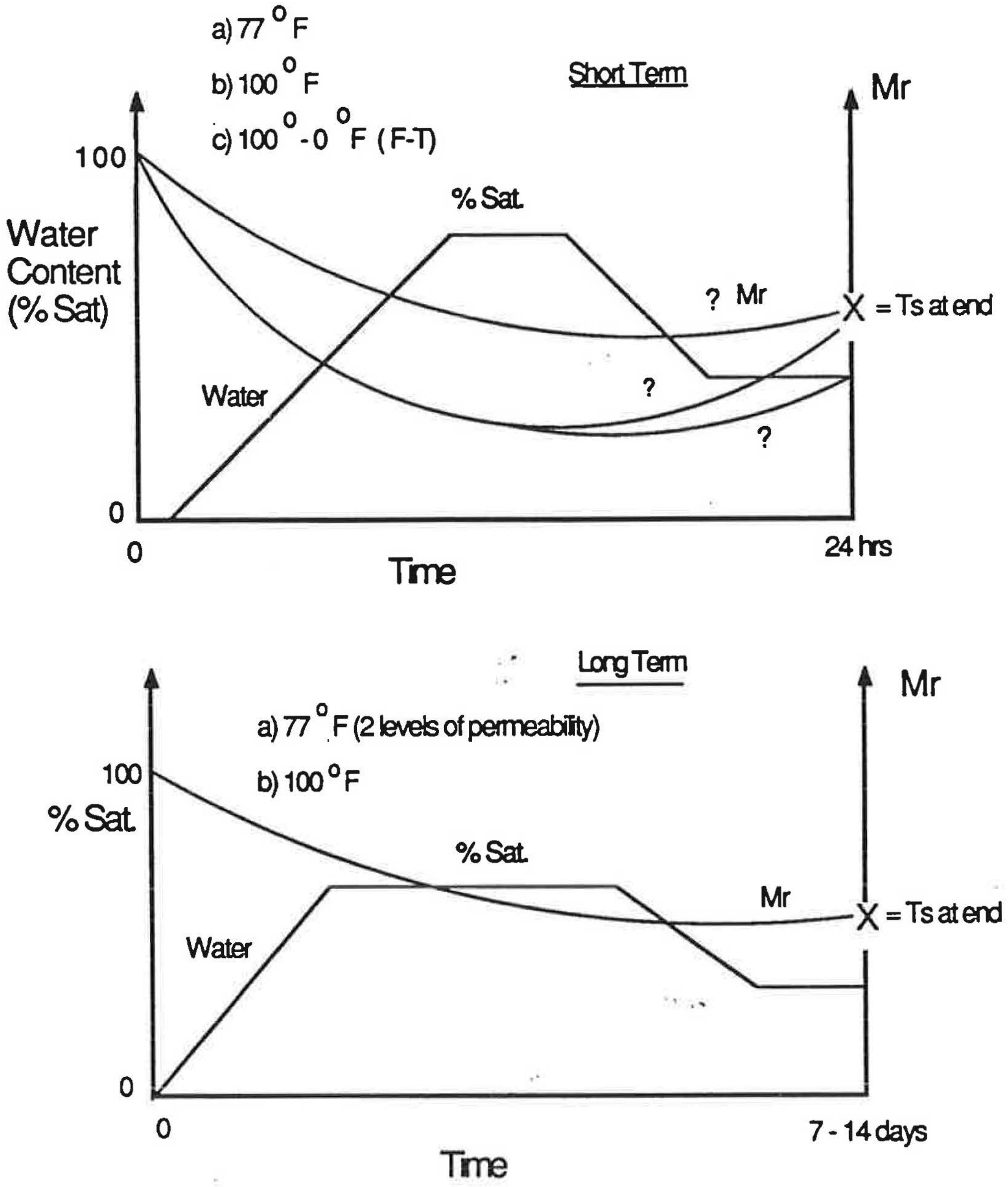


Figure A.1. Improved Test for Water Sensitivity



Control: dry specimens
Additives: one or two; - liquid
- lime

Figure A.2. Possible Testing Sequence in Triaxial Cell for Short and Long Term Conditioning

Appendix B

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Appendix C

Resistance of Compacted Bituminous Mixture to Moisture Induced Damage

Modified for use at OSU under the SHRP contract

AASHTO DESIGNATION: T 283-85

1. SCOPE

1.1 This method covers preparation of specimens and measurement of the change of diametral tensile modulus resulting from the effects of saturation and accelerated water conditioning of compacted bituminous mixtures in the laboratory. The results may be used to predict long term stripping susceptibility of the bituminous mixtures, and evaluating liquid antistripping additives which are added to the asphalt cement or pulverulent solids, such as hydrated lime, which are added to the mineral aggregate.

2. APPLICABLE DOCUMENTS

2.1 AASHTO Standards:

T 166	Bulk Specific Gravity of Compacted Bituminous Mixtures
T 167	Compressive Strength of Bituminous Mixtures
T 168	Sampling Bituminous Paving Mixtures
T 209	Maximum Specific Gravity of Bituminous Paving Mixtures
T 245	Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus
T 246	Resistance to Deformation and Cohesion of Bituminous Mixtures by Means of Hveem Apparatus
T 247	Preparation of Test Specimens of Bituminous Mixtures by Means of California Kneading Compactor
T 269	Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures

M 156 Requirements for Mixing Plants for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures

2.2 ASTM Standards:

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

3. SIGNIFICANCE AND USE

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

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

4. SUMMARY OF METHOD

4.1 Six test specimens for each set of mix conditions, such as, plain asphalt, asphalt with antistripping agent, and aggregate treated with lime, are tested (Note 1). Each set of specimens is divided into and tested in dry condition for resilient modulus. The other set is subjected to vacuum saturation followed by a freeze and warm-water soaking cycled and

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1 - It is recommended to prepare two additional specimens for the set. These specimens can then be used to establish the vacuum saturation technique as given in Section 9.3.

then tested for resilient modulus. Numerical indices of retained resilient modulus properties are computed from the test data obtained on the two subsets: dry and conditioned.

5. APPARATUS

5.1 Equipment for preparing and compacting specimens from one of the following AASHTO Methods: T245 and T247, or ASTM Method D3387.

5.2 Vacuum Container, preferably Type D, from ASTM Method D2041 and vacuum pump or water aspirator from ASTM D2041 including manometer or vacuum gauge.

5.3 Balance and water bath from AASHTO T166.

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

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

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

5.7 10 ml graduated cylinder.

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

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

5.10 Apparatus as listed in ASTM D4123.

6. PREPARATION OF LABORATORY TEST SPECIMENS

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

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

6.3 After curing, place the mixture in an oven at 275°F (135°C) for 2 hours prior to compaction. The mixture shall be compacted to 7 ± 1.0 percent air voids or a void level expected in the field. This level of voids can be obtained by adjusted the number of blows in AASHTO T245; adjusting foot pressure, number of tamps, levelling load, or some combination in AASHTO T247; and adjusting the number of revolutions in ASTM D3387. The exact procedure must be determined experimentally for each mixture before compacting the specimens for each set.

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

7. PREPARATION OF CORE TEST SPECIMENS

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

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

8. EVALUATION OF TEST SPECIMENS AND GROUPING

8.1 Determine theoretical maximum specific gravity by mixture by AASHTO T209.

8.2 Determine specimen thickness by ASTM D3549.

8.3 Determine bulk specific gravity by AASHTO T166. Express volume of specimens in cubic centimeters.

8.4 Calculate air voids by AASHTO T269.

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

9. PRECONDITIONING OF TEST SPECIMENS

9.1 One subset will be tested dry and the other will be preconditioned before testing.

9.2 The dry subset will be stored at room temperature until testing. The specimens shall be wrapped with plastic or placed in a heavy duty leak proof plastic bag. The specimens shall then be placed in a 77°F (25°C) bath for 2 hours and then tested as described in Section 10.

9.3 The other subset shall be conditioned as follows:

9.3.1 Place the specimen in the vacuum container supported above the container bottom by a spacer. Fill the container with distilled water at room temperature so that the specimens have at least 1 inch of water above their surface. Apply partial vacuum, such as 20 inches Hg for a short time, such as five minutes. Remove the vacuum and leave the specimen submerged in water for 30 minutes.

9.3.2 Determine bulk specific gravity by AASHTO T166. Compare saturated surface-dry weight with saturated surface dry weight determined in Section 8.3. Calculate volume of absorbed water.

9.3.3 Determine degree of saturation by comparing volume of absorbed water with volume of air voids from Section 8.4. If the volume of water is between 55% and 80% of the volume of air, proceed to Section 9.3.4. If volume of water is more than 80%, specimen has been damaged and is discarded. Repeat the procedure beginning with Section 9.3.1 using less vacuum and/or time.

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

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

9.3.6 After 16 hours, place the specimens into a 140° ± 1.8°F (60° ± 1°C) water bath for 24 hours. As soon as possible after placement in the water bath, remove the plastic bag and film from the specimens.

9.3.7 After 24 hours in the 140°F (60°C) water bath, remove the specimens and place them in water bath already at 77° ± 1°F (25° ± 0.5°C) for 2 hours. It may be necessary to add ice to the water bath to prevent the water temperature from rising above 77°F (25°C). Not more than 15 minutes should be required for the water bath to reach 77°F (25°C). Test the specimens as described in Section 10.

10. TESTING

10.1 Determine the resilient modulus (M_R) of dry and conditioned specimens at 77°F (25°C) in accordance with ASTM D4123-82 (1987).

11. CALCULATIONS

11.1 Express the numerical index or resistance of asphalt mixtures to the detrimental effect of water as the ratio of the original strength that is retained after the freeze-warm water conditioning. Calculate as follows:

$$\text{Resilient Modulus Ratio} = \frac{M_{R2}}{M_{R1}}$$

where:

M_{R1} = average resilient modulus of dry subset, and

M_{R2} = average resilient modulus of conditioned subset.