Effect of Moisture on Low-Temperature Asphalt Mixture Properties and Thermal-Cracking Performance of Pavements

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Effects of moisture on asphalt mixtures were evaluated by determining the fundamental low-temperature properties of field cores from 22 field test sections at two different levels of moisture, to get an indication of how much these properties may have changed during the pavements' service. The idea was to introduce moisture into the mixtures without causing significant breakdown of the mixtures from stripping or disintegration. The indirect tensile creep and failure test at low temperature, which was selected by the Strategic Highway Research Program (SHRP) to support the mixture specification for thermal cracking, was performed on field cores at two temperatures and two levels of moisture. Master compliance curves and fracture properties were generated and compared to evaluate changes in fundamental low-temperature properties at two different levels of moisture. The properties were input into a thermal-cracking model that was developed at Penn State and is now part of the SHRP SUPERPAVE software in order to determine whether the differences in properties had an effect on thermal-cracking performance in the field. The key finding was that changes in moisture condition within asphalt mixtures have a significant effect on the low-temperature properties of asphalt mixtures and may have a significant effect on the thermal-cracking performance of asphalt pavements. Changes in properties and performance occur even when moisture does not damage the mixture significantly.

Moisture damage of asphalt mixtures is a combined result of moisture-induced changes in mixture characteristics and induced stress in the mixture (*1*). Moisture damage resulting from these two effects, primarily stripping, has been a subject of much research. Even so, there is limited understanding of moisture-induced changes in asphalt mixtures in the absence of stress effects. Some evidence in the literature indicates that moisture changes in the mixture induce changes in mixture properties even when the moisture does not result in mixture damage or disintegration (*2,3,4*). Such moisture-induced property changes may significantly affect the field performance of pavements.

Accurate characterization of low-temperature properties of asphalt mixtures is important to evaluating the thermal-cracking performance of pavements. However, investigations into changes in fundamental low-temperature properties of asphalt mixtures induced by moisture have not been conducted. Therefore, this study was undertaken to evaluate the effects of moisture on the low-temperature properties of asphalt mixtures; the study is part of research being conducted at the Pennsylvania State University as part of a Strategic Highway Research Program (SHRP) research project titled, "Performance Models and Validation of Test Results." Objectives of the work presented in this paper are as follows:

- To investigate the effects of moisture on the low-temperature creep compliance of asphalt mixtures;
- To investigate the effects of moisture on the low-temperature failure limits of asphalt mixtures; and
- To conduct a preliminary evaluation to determine the effects of these changes on thermal-cracking performance.

RESEARCH APPROACH

The study was based on the evaluation of 22 field-test sections that were selected as part of an SHRP thermal-cracking validation effort to provide data on a wide range of materials and environmental conditions in United States. Effects of moisture were evaluated by determining the fundamental low-temperature properties of the field cores from the test sections at two different levels of moisture to get an indication of how much these properties may have changed while the pavement has been in service. The idea was to introduce moisture into the mixtures without causing significant breakdown of the mixtures from stripping or disintegration. The goal was to determine how the presence (or lack) of moisture affected properties, not to cause damage to the mixtures. Visual observations of the field cores clearly indicated that the mixtures had not stripped or disintegrated in service.

Field cores were tested in two ways, either as dry specimens or wetted specimens.

- Dry specimens are those specimens that were tested in the-as-received condition, except that they were kept in a chamber at constant low, relative humidity (30 percent) for at least 3 days before testing.
- Wetted specimens are those specimens to which moisture was introduced by applying the wetting portion of Lottman moisture conditioning procedure AASHTO T-283, (i.e., they were vacuum saturated at 26 in. of mercury for 30 min, then left submerged for an additional 30 min.). The procedure was the most effective way of introducing moisture into the specimens without inducing damage in them. After wetting, the specimens were also placed in a 30 percent relative humidity chamber for at least three days before testing.

The following response variables were measured:

- Creep compliance;
- Tensile strength and strain at failure; and
- The *m*-value, which is the slope of the linear portion of the master creep compliance curve on a log-log scale and is related to the fracture parameters of viscoelastic materials (*5*).

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The indirect tensile creep and failure test at low temperature (ITLT), developed by R. Roque and his coworkers at Penn State (*6,7*), was conducted at three temperatures (0°C, −10°C, and −20°C) for dry specimens, and at two temperatures (−5°C and −15°C) for wetted specimens. The creep portion of the test involved applying static compressive loads on the diametral specimens for 1,000 sec and measuring horizontal and vertical creep strains near the center of both flat faces. Loads were selected according to preestablished protocols in order to keep strains in the linear viscoelastic range. The strength portion of the test immediately followed the creep portion. Without releasing the creep load, the specimen was failed by applying loads at a constant rate of vertical displacement. Master compliance curves and fracture properties were generated for both of these sets of tests, as described elsewhere (*7*).

The results were compared to evaluate the changes in fundamental low-temperature properties between dry and wetted mixtures. The properties were input to the thermal-cracking model developed at Penn State as part of a research contract to determine the effect of the differences in properties on predicted thermal-cracking performance (*7*).

MATERIALS AND SAMPLE PREPARATION

Selection of Field Specimens Used in Testing

Thirty-six cores each 6 in. in diameter, from each of the 22 field sections, were included in the thermal-cracking validation study, which was conducted at the Pennsylvania Transportation Institute. Nine cores were randomly selected for testing in the dry condition and six cores for testing in the wetted condition. At each temperature, 69 tests were performed (23 sections times 3 replicates). The order at which each test was performed was selected at random.

Slicing of Field Core Specimens

The specimens, 6 inch diameter were sliced to a thickness of 2 in. with a water-cooled masonry saw equipped with a diamond-tipped blade. The cut provided the smooth surface necessary to mount gage points on a specimen's flat faces.

Specimen Humidity Conditioning

While making field core specimens for mechanical property tests moisture is introduced into the test specimen. A series of procedures is used, including coring, core slicing, and specific gravity measurement. Even though all the cores were stored in sealed plastic bags, the core storage period of the each test section before testing varied by as much as one year. As a result, there was high probability that different moisture effects were induced. A way to standardize the moisture effect throughout the test sections was needed.

A small-scale experiment was conducted to monitor the changes in moisture in specimens stored in the humidity-controlled chamber. Changes in moisture were monitored for laboratory-compacted specimens wetted using Lottman's short-term conditioning procedure (*8*). Changes in moisture were also monitored in field cores after they were submerged for specific gravity determination. Changes in sample weights are plotted in Figure 1. The weight of a saturated specimen changed rapidly for the first 2 days after wetting, after which a slow constant rate of weight change was observed through the 15th day. The weight of most field cores also changed rapidly for the first 2 days.

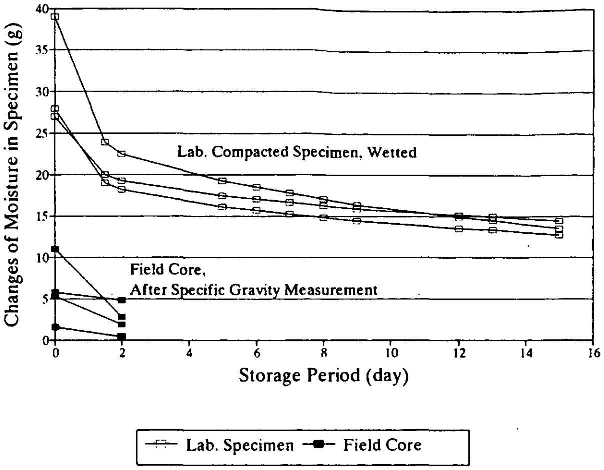

FIGURE 1 Changes of moisture in specimen during humidity conditioning.

On the basis of results presented in Figure 1, it is expected that the moisture level at 3 days after a 5-minute soaking (as required for specific gravity measurement) will be very close to the moisture level before the 5-minute soaking. The fast change in weight during the first few days appears to be caused by evaporation of water entrapped in the surface region of the specimen, whereas the slow change in weight after the first few days appears to be related to permeability or the air-void structure of a specimen.

Therefore, after bulk specific gravity was measured, all specimens were placed in a constant-humidity environment for a minimum of 3 days before testing. Specimens were conditioned at 30 percent relative humidity and at room temperature (20°C).

Specimen Load Conditioning

In order to minimize specimen-seating effects during testing, a preconditioning load sequence was applied to each core during the humidity-conditioning period. The procedure consisted of 100 cycles of loading at 20°C. Each load cycle consisted of a 0.1 sec inverse haversine (compression) followed by a 0.9 sec rest period. The amplitude of the haversine pulse was set to the load corresponding to a horizontal tensile stress of 6.9 kPa (10 psi).

Specimen Temperature Conditioning

Specimens were kept at the constant test temperature for no less than 6 hr before testing. Because little is known about the effects of keeping mixture specimens at very low temperatures for extended periods of time [i.e., low-temperature physical hardening (−*9*)], extended deep-freeze periods were avoided.

TEST RESULTS AND ANALYSIS

Test results were compared in order to evaluate changes in fundamental low-temperature properties between dry and wetted mixtures. The effect of moisture on mixture properties is summarized in Table 1.

TABLE 1 Effect of Wetting on Mixture Properties

Sec No	Environment	Location	Effect of Wetting on Mixture Properties					
			Stiffness*		Shift Factor ($1/a_T$)	m*	Strength @ -10 C (kPa)	
			@10sec	@longer time			Dry	Wet
1	Dry Freeze Thaw	Chickasha,OK	Same	Dec	Dec	Inc	3878	4341
2		Hackberry,AZ	Same	Same	Mild Dec	Same	3660	4341
6		Oasis,NV	Same	Dec	Mild Dec	Inc	2369	2228
7		Ottawa,KS	Mild Inc	Dec	Same	Inc	2941	2958
11	Dry Hard Freeze	Idaho Falls,ID	Inc	Dec	Dec	Inc	3622	3176
12		Coeur d'Alene,ID	Same	Dec	Mild Dec	Inc	4462	4009
13		Edison,NE	Same	Same	Mild Dec	Same	3114	2892
16		Marysvale,UT	Mild Dec	Dec	Dec	Inc	2678	2315
17		Cody,WY	Mild Inc	Mild Dec	Mild Inc	Same	3427	2410
18		Rangely,CO	Dec	Dec	Mild Inc	Same	2632	1934
21	Wet Freeze Thaw	Glasgow,KY	Inc	Same	Inc	Same	3399	3455
22		Ponca City,OK	Same	Dec	Mild Dec	Inc	2708	2799
23		Berlin,MD	Inc	Inc	Inc	Same	2856	2898
26		Salem,SC	Same	Dec	Same	Inc	1789	1366
27		Trenton,NJ	Inc	Mild Inc	Same	Inc	3742	3221
28		Waynesville,MO	Same	Dec	Dec	Same	2126	1819
31	Wet Hard Freeze	Lawrenceville,PA	Same	Dec	Dec	Inc	2874	2671
32		Huntington,IN	Mild Inc	Dec	Dec	Inc	2153	2332
33		Farmington,ME	Inc	Same	Same	Same	3442	2933
36		Bonnville,IN	Inc	Inc	Inc	Same	2894	2599
37		Farmington,MN	Inc	Mild Dec	Mild Dec	Inc	2921	3405
38		Frazee, MN	Inc	Mild Dec	Mild Dec	Inc	2306	2211

*Same = no change; Dec = decrease; Inc = increase in property induced by moisture

Compliance

Comparisons of master stiffness (inverse of compliance) curves for dry and wetted specimens clearly indicated that the introduction of moisture had a significant effect on the low-temperature stiffness of the mixtures. Figures 2 through 7 show comparisons of master stiffness curves and shift-factor temperature relationships at a reference temperature of −15°C for three mixtures that characterize the types of changes observed to be induced by moisture. Actual measured data were plotted within the measured reduced time range. Outside the measured reduced time range, wetted stiffness was extrapolated using a hyperbolic model to cover the entire reduced time range corresponding to specimens tested in the dry condition.

Compared with dry stiffness curves, the stiffness of wetted mixtures changed very significantly for most mixtures (see Table 1). However, the effect of moisture appeared to be different for different mixtures; it was difficult to find trends among these data. In general, but not always, wetted-mixture stiffness at shorter reduced time (around 10 sec) was the same or greater than dry-mixture stiffness. On the other hand, wetted-mixture stiffness at longer reduced times (10^3 sec or greater) either was generally less than dry-mixtures stiffness or was decreasing more rapidly than dry mixture stiffness.

As indicated in Figures 3, 5, and 7, shift factor/temperature relationships also changed as a result of changes in moisture content in the mixture. Among more than half of the test sections, wetting reduced the shift factors, indicating that wetted rheological property was less temperature-dependent than dry.

It is nearly impossible to determine the effect of changes in the master compliance curve on thermal-stress development without actually performing thermal-stress computations. Thermal-stress development not only depends on the magnitude and shape of the compliance curve at a reference temperature but also on the characteristics of the shift factor/temperature relationship. For example,

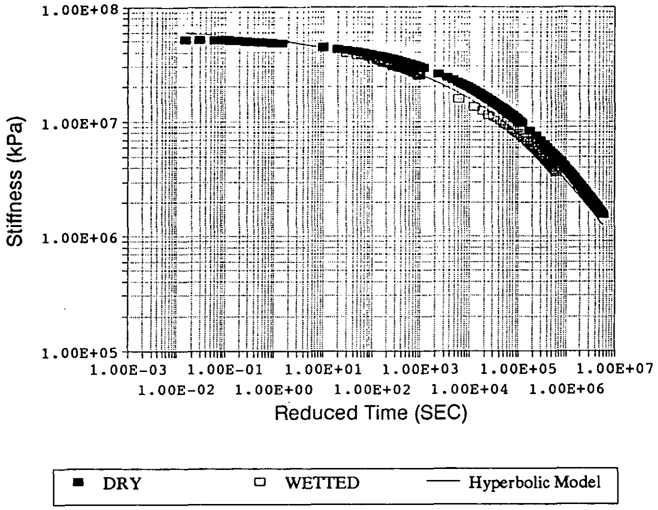

FIGURE 2 **Comparison of dry and wetted master stiffness curves (Section 2).**

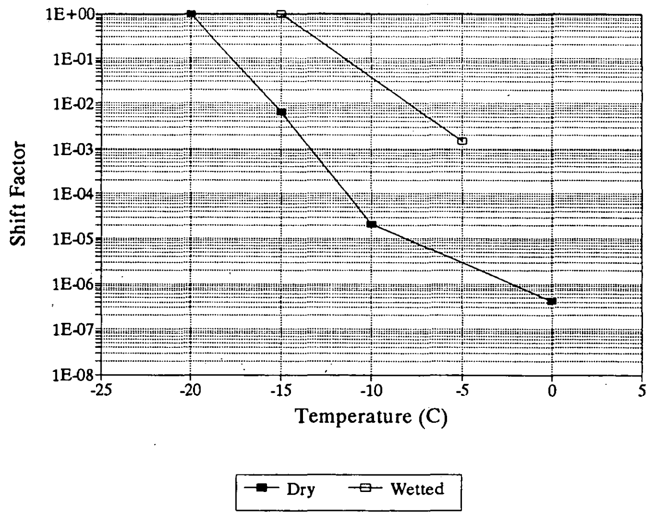

FIGURE 3 **Comparison of dry and wetted shift factors (Section 2).**

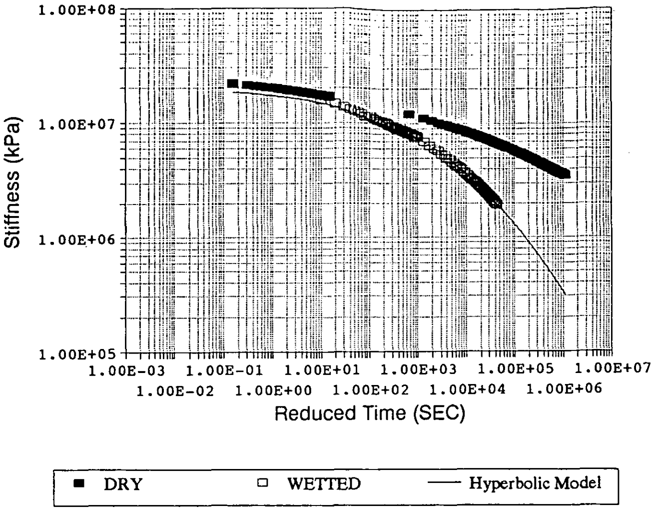

FIGURE 4 **Comparison of dry and wetted master stiffness curves (Section 6).**

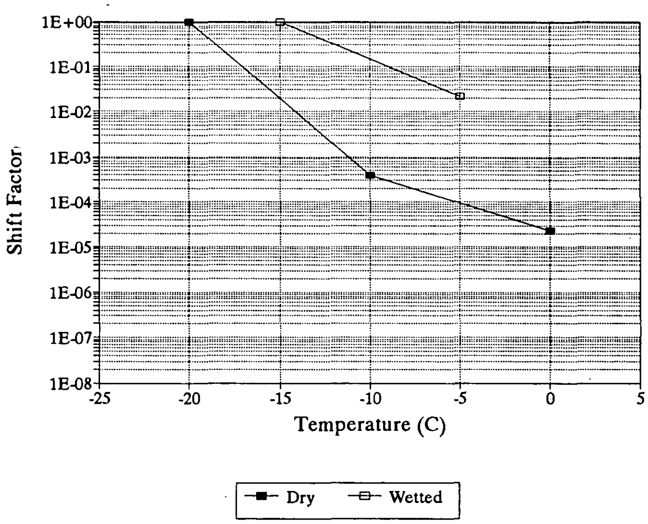

FIGURE 5 **Comparison of dry and wetted shift factors (Section 6).**

two materials may have identical compliance curves at a specified reference temperature, but their compliance at another temperature may be significantly different if their shift factor/temperature relationships are different. These complexities make it extremely difficult to assess the effect of moisture changes simply by looking at how the master compliance curve changed. Therefore, the effect of these changes was evaluated by predicting pavement performance using dry and wetted rheological properties. The results of this evaluation are presented later in this paper. More detailed research is under way that should provide explanations to the observed changes in rheological properties induced by moisture.

Failure Limits

Comparisons of strengths and m-values between dry and wetted specimens indicated that the introduction of moisture also had a significant effect on the fracture properties of the mixtures. Figure 8 through 10 indicates comparisons of strengths at different temperatures, whereas Figure 11 provides comparisons of m-values for the three sections presented earlier. Again, the m-value is defined as the slope of the linear portion of the master creep compliance curve on a log-log plot. It has been found to be an important fracture parameter in distinguishing between the thermal-cracking performance of different materials. Once again, the effect was different for different mixtures, and it was difficult to draw conclusions or trends from the data. In general, the strengths of wetted specimens were either lower or about the same as the dry specimens, while the m-values of wetted specimens were either higher or about the same as the m-values of dry specimens. Lower strengths result in less resistance to thermal cracking, whereas higher m-values result in better resistance to thermal cracking. As for compliance, it is nearly impossible to tell what the combined effect of these differences in properties might be on thermal-cracking performance simply by

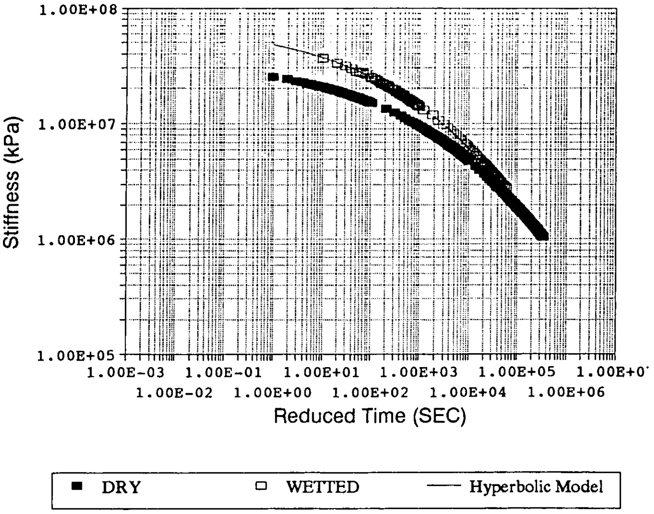

FIGURE 6 **Comparison of dry and wetted master stiffness curves (Section 27).**

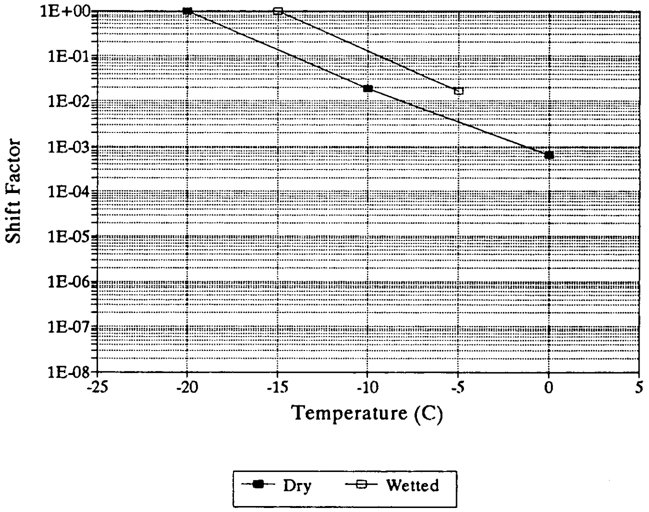

FIGURE 7 **Comparison of dry and wetted shift factors (Section 27).**

comparing the values. Again, performance predictions were made to evaluate the effects induced by moisture.

Stripping Observations

After the ITLT test at −5°C was conducted pictures were taken to monitor the stripping on split faces of test cores—for both dry and wetted cores—to monitor and compare the changes in stripping induced by moisture. In most cases, no changes in stripping or disintegration by wetting were observed which may imply that the wetting procedure used in this research was not severe enough to induce any moisture damage, as that was the intent of the study. As mentioned earlier, the basic idea was to introduce moisture into mixtures without causing significant breakdown of the mixtures.

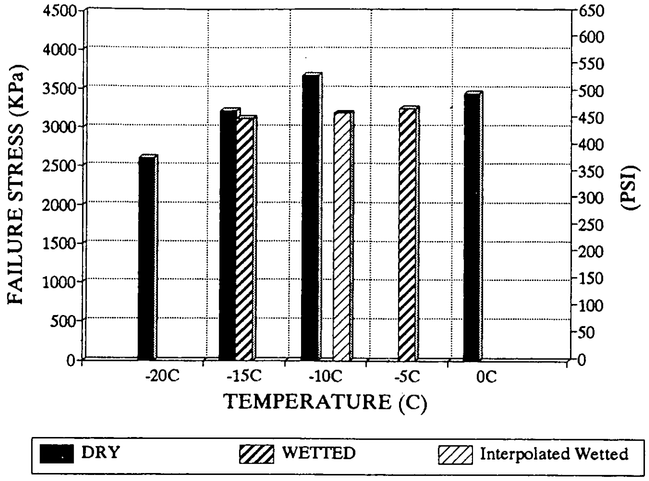

FIGURE 8 **Comparison of dry and wetted strengths (Section 2).**

Effect of Wetting on Thermal-Cracking Performance

Generally, but not always, moisture makes asphalt mixture less stiff and weaker in strength. As far as the thermal-cracking performance of pavement is concerned, an increase in mixture compliance (reduction in stiffness) reduces thermal stress, thereby reducing its thermal-cracking potential. On the other hand, a comparable decrease in strength increases thermal-cracking potential. A decrease in $1/a_T$ (shift factor/temperature relationship) results in higher stiffness at temperatures above the reference temperature, which consequently increases thermal-cracking potential for mixtures with identical compliance curves at a specific reference temperature. Moisture in a mixture generally increases the m-value, which results in better resistance to thermal cracking. Thus, as mentioned earlier, it is nearly impossible to tell what effect these changes will have on thermal-cracking performance without actually performing thermal-stress computations and performance predictions.

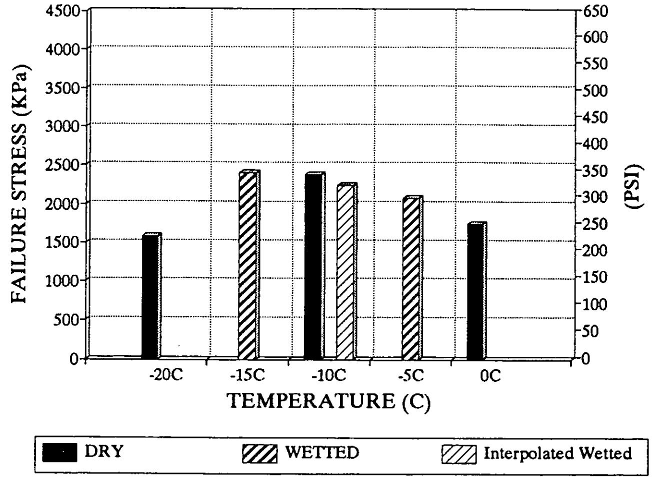

FIGURE 9 **Comparison of dry and wetted strengths (Section 6).**

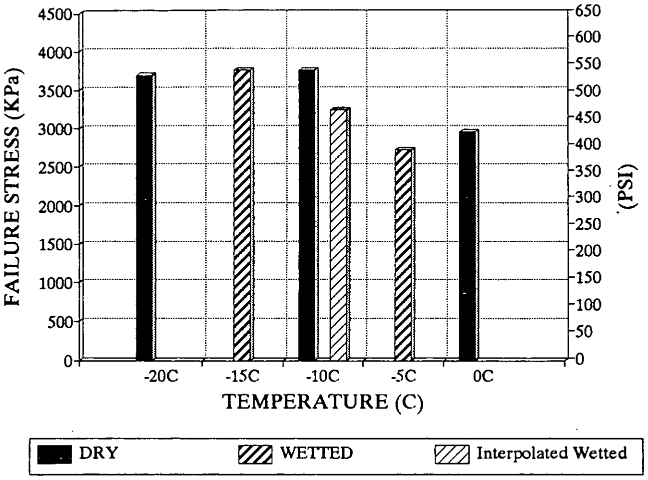

FIGURE 10 Comparison of dry and wetted strengths (Section 27).

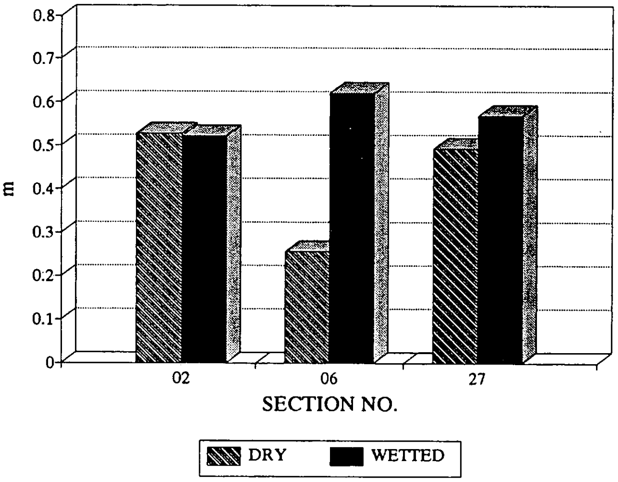

FIGURE 11 Comparison of dry and wetted *m*-values.

A mechanics-based thermal-cracking model developed at Penn State, which has been incorporated into the SHRP SUPERPAVE software, was used for this analysis. The model predicts the amount (or frequency) of thermal cracking as a function of time. Inputs to the model include: fundamental properties (master relaxation modulus curve and fracture parameters A and n) obtained from the ITLT, pavement structure, and site-specific weather data. The model predicts thermal stress as a function of pavement depth on an hourly basis throughout the analysis period. Thermal stresses are used to predict crack propagation and the amount of transverse thermal cracking as a function of time. Pavement temperatures used in these computations are predicted from daily air temperature data using the FHWA Environmental Effects Model (*10*). Thermal stresses are computed using an algorithm based on Boltzmann's superposition principle as it applies to viscoelastic materials. Viscoelastic mixture properties (i.e., the master relaxation modulus curve) as measured by the ITLT test are used for these computations. Thermal stresses are then used to determine stress intensity factors for use in the Paris law of crack propagation [$\Delta C = A\,(\Delta K)^n$]. Thus, the average depth of transverse cracks within the pavement is computed on a daily basis. A probabilistic approach is then used to determine the amount of cracking in the pavement. A detailed description of the model is presented elsewhere (*7*).

A generalized four-element Maxwell model was selected to represent the viscoelastic properties of the asphaltic concrete mixture. Mathematically, the generalized Maxwell model is expressed according to the following Prony series expansion:

$$E(\xi) = \sum_{i=1}^{4} E_i e^{-\xi/\lambda_i} \tag{1}$$

where $E(\xi)$ is the relaxation modulus at reduced time ξ, and E_i, λ_i are Prony series parameters for master relaxation modulus curve.

The Prony series was fit to the ITLT compliance data obtained from both the dry and wetted specimens for input into the thermal-cracking model. Details concerning the Prony series parameter fitting are presented elsewhere (*7*). Thermal-cracking predictions then were made for each test section, using both dry and wetted properties, to determine the difference in predicted performance. All other input data were the same for both sets of predictions.

The effect of moisture on mixture properties was reflected in the predicted thermal-cracking performance of the pavement sections. The results of thermal-cracking predictions for the three test sections for which properties were presented earlier in the paper, are presented in Figures 12 through 14. As expected, the effects of moisture on predicted performance varied significantly from mixture to mixture: very little difference in thermal-cracking performance was observed for some sections (e.g., PTI Section 2; Figure 12), whereas significant differences were observed in other sections (e.g., PTI Section 6; Figure 13). As mentioned earlier, moisture affects numerous mixture properties (i.e., compliance, strength, shift factor, and m-value each of which may contribute to the thermal-cracking performance of a particular mixture. The combined effect of such moisture-induced property changes determines whether moisture has been beneficial, harmful, or has had no effect on thermal-cracking performance.

In summary, the introduction of moisture resulted in little or no change in the thermal-cracking performance of 13 test sections,

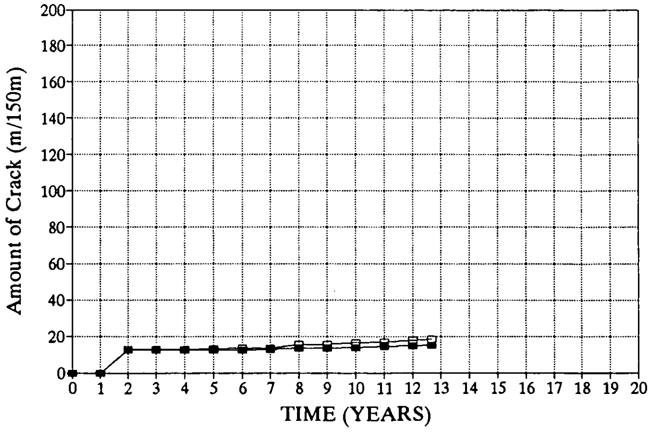

FIGURE 12 Effect of moisture on thermal cracking performance (Section 2).

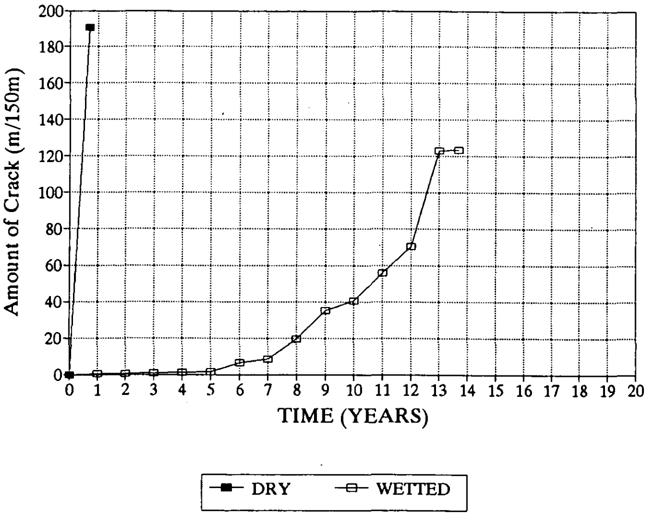

FIGURE 13 Effect of moisture on thermal cracking performance (Section 6).

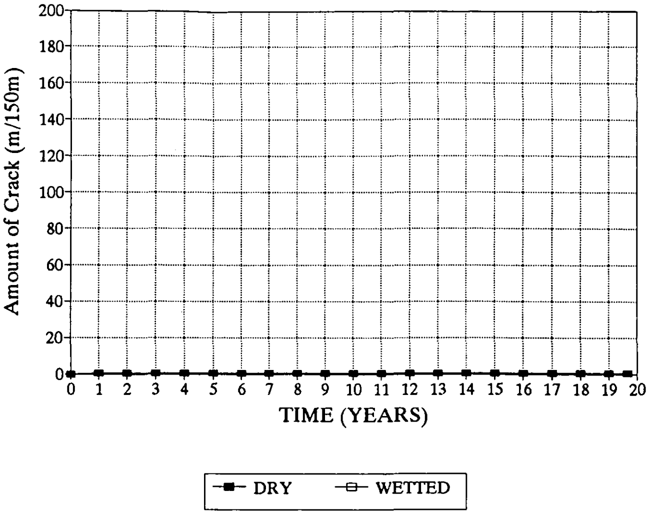

FIGURE 14 Effect of moisture on thermal cracking performance (Section 27).

significantly improved the performance of 6 test sections, and significantly reduced the performance of 2 test sections. It should be noted that the fact that no change in predicted performance was observed for a particular section in a particular environment does not mean that this same change in properties would not produce a significant change in performance in a different environment. It appears that the effects of moisture may be both mixture and environment dependent. At this point, it is not entirely clear why moisture had a different effect on different mixtures. It appears that these changes may be related to the pore structure of the mixture, whether or not the pore water froze, and the effect of freezing on the structure of the mixture. More research is being conducted to evaluate these effects.

CONCLUSIONS

Conclusions from this work may be summarized as follows:

- Changes in moisture condition within asphalt mixtures significantly affect the low-temperature properties of asphalt mixtures. Generally, but not always, the introduction of moisture into the mixture results in lower strength and higher compliance at longer reduced times. The magnitude of the moisture-induced changes in properties is highly mixture dependent.
- Changes in moisture condition within asphalt mixtures may have a significant effect on the thermal-cracking performance of asphalt pavements.
- Changes in properties and performance occur even when moisture does not damage the mixture significantly.

These results clearly indicate that great care must be exercised to bring field cores to standard moisture condition before laboratory testing for determination of fundamental low-temperature properties. Further research is recommended to identify mixture characteristics that lead to mixtures whose properties and performance are significantly affected by moisture changes.

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