PAVEMENT CRACKING IN WEST TEXAS DUE TO FREEZE-THAW CYCLING

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Freeze-thaw contraction of the base course material used in west Texas is considered an important element in pavement deterioration. Samples from two compactive efforts were frozen in a biaxial closed system. Suction and temperature within the samples were monitored and volume changes after each freeze-thaw period were recorded. Coefficients of thermal activity were calculated from the dimension measurements. These coefficients showed a relationship with the as-compacted total soil moisture suction, which was similar for all materials. Finite element studies of the thermal strains that develop in a typical pavement showed that the thermally induced tensile stresses in the base course are far in excess of typical tensile strengths for initially intact pavements. The surface course did not develop excessive stress levels. Freeze-thaw cycling produced plastic deformations in all samples, and the permanent expansion or contraction was related to the as-compacted total soil moisture suction. These permanent deformations from freeze-thaw cycling imparted a residual tensile stress to the asphalt concrete. During a freeze, the suction in the sample showed a marked increase, often 10 to 20 times the initial value. The suction then dropped below the initial value during the thaw cycle. This drop was consistent regardless of the thermal activity or plastic deformation. This indicated a reorganization of the moisture in the sample, which may be related to strength losses caused by freeze-thaw cycling. The data in this study give new insight into the mechanism of freeze-thaw in pavement deterioration.

GROWING concern for environmentally controlled cracking of pavements has been stimulated by the relatively large amounts of mileage on roads experiencing cracking that cannot be directly attributed to traffic. Ample evidence of this transverse cracking can be found in the northern United States, Canada, and even in the arid portions of the western United States.

Common forms of environmental influence on pavements are temperature extremes and cycles; moisture movement under a pavement, which is caused by the climate; and radiation. These influences interact to produce massive pavement cracking failures even in the best designed pavements.

This paper examines the freeze-thaw activity of the base course as an important mechanism in pavement cracking.

BACKGROUND

Many studies have investigated the cracking of pavement under extremely low temperatures (4, 7, 19, 22). They have mainly considered the properties of the asphalt concrete surface in predicting cracking during the life of a pavement. This theory cannot explain the large amount of transverse cracking found in the western United States and, in particular, west Texas if, as McLeod claims (13), low-temperature crack-

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ing is commonly found only in areas with a design freeze index above 250. This excludes nearly all of Texas, which currently has extensive transverse cracking problems. Figure 1 shows typical cracking patterns for two widely separated areas in west Texas.

Thermal fatigue or temperature cycling has been studied (19) and used in computer codes to account for the difference between predicted and actual cracking due to low temperatures. The results obtained from these computer codes have still not proved wholly satisfactory, and they give only limited insight into the mechanisms causing this deterioration.

One area missing from the study is an analysis of the foundation material of the pavement system. Much work has been done in the area of frost-heave damage (9, 11). This damage mode requires a near-saturated soil and access to capillary water, neither of which applies to pavement in west Texas.

By using a heat-transfer program developed at the University of Illinois (5), one can obtain reliable temperature distributions in a pavement system that show that the freezing front will seldom penetrate below a typical asphalt concrete surface and base course during a severe winter in west Texas. Thus, if thermal activity were to be studied as a possible area to account for the discrepancies mentioned, the base course would be a logical area to examine.

The base course material is typically an untreated, indurated limestone: caliche. This material, when compacted for use in a roadbed, is an unsaturated soil material with a relatively small percentage of plastic fines. It is usually placed over a subgrade material that is composed of a much higher percentage of plastic fines, often of a more active nature.

The field behavior of the unsaturated soil material depends on its unsaturated, moisture stress state (1). Determination of the separate components of this state requires special equipment, which is not suitable for in situ testing. However, the total moisture energy or suction may be determined conveniently in the field and in the laboratory. The soil moisture suction is a measure of the free energy of the moisture in a soil compared to the free energy of a pool of pure water at the same datum. Thus, as a soil becomes drier and moisture is removed, work must be expended to accomplish this, and energy is in effect taken away. The pure water is commonly given a free energy of zero so that as moisture content decreases the free energy or suction increases in the negative direction. Thus, all suction values are negative quantities.

This energy quantity may be determined by measuring the relative humodity of the soil mass, which is a measure of the relative vapor pressures in the soil (18). The common units are atmospheres, bars (kPa), or psi (kPa). Several methods exist for measuring the soil moisture suction such as tensiometers, gypsum blocks, resistivity blocks, pressure plates, and thermocouple devices. These devices have extremely fine thermocouples to measure dew-point depression temperatures, and they are called psychrometers because they are similar to traditional wet bulb-dry bulb sling-psychrometers. The performance and accuracy of these psychrometers for soils work are discussed in a number of papers (1, 3, 14, 15, 16). Psychrometers are typically suited for laboratory and field work that require a range from 0 to > -142,000 psi (-979 MPa), and they have a nominal accuracy of 5 percent of the reading, including temperature corrections. In the low range of measurements, temperature control during a measurement is extremely important in the psychrometric technique. The newly developed dew-point technique, which has internal temperature compensation and provides a continuous output, overcomes many of the previous complaints about the psychrometric technique.

The use of soil moisture suction is complicated because total soil moisture suction has two forms:

1. Osmotic suction, which is due to salts in the fluid portion of the three-phase soil system, and
2. Matric suction, which is due to the matrix phase, in which the soil particles themselves form various-sized capillaries.

These two components together give the total soil moisture suction (1). To date, most studies have reported suction values in terms of matric suction.

During a freeze, however, the change in suction is due to a decrease in the amount of free water as a result of ice formation (20). This causes both components of suction to increase in magnitude by increasing the ion concentration and decreasing the capillary size. Both of these mechanisms can contribute to a volume change because of changes in the radius of hydration of the ions and forced particle reorientation. Thus, the total suction can be measured without any loss in understanding the mechanisms that will occur in freeze-thaw cycling.

Suction has been used in previous studies to describe the behavior of subgrade material under varied situations. Richards et al. (17) demonstrated the effects of compaction on the initial suction values and the effect of the initial suction on the overall load-carrying ability of the pavement structure. The suction developed in a freezing soil is nearly identical to that obtained for the soil water characteristic (SWC) curve (10). SWC is a plot of suction versus moisture content during wetting and drying of the soil. Figure 2 shows the data for a Na-montmorillonite clay. This relationship shows that the freeze-thaw mechanisms are similar to the wetting-drying cycle and that they may provide a valid analogue to study the freezing phenomenon in soils.

Bergan and Monismith (2) have shown that subgrade material loses load-carrying ability between fall and spring for roads in Canada. Resilient modulus testing clearly showed that freeze-thaw cycles are responsible for the loss. Furthermore, a relationship was shown to exist between suction loss in the soil and the effects of freeze-thaw.

As a soil undergoes freezing, the moisture in the finer voids will not freeze (12). Differing amounts of moisture freeze as the temperature is decreased. The amount of moisture remaining unfrozen at any temperature has been related to original suction levels (20, 21) and to the amount and type of clay fraction, surface area, and original moisture content (6).

Thus, soil suction provides a means for obtaining a description of the energy state in a sample, which would not be shown unless more detailed information such as pore structure, clay mineralogy, and the unsaturated pore pressure parameters were known. Psychrometers provide a means of obtaining in situ information of this energy state of the moisture on a continuous basis regardless of the mechanisms acting. For these reasons, the value of total soil moisture suction was chosen to relate measured material variables to the observed actions of freezing and thawing.

PROCEDURE

Six base course materials from west Texas were collected for this study. The material was chosen to represent typical base courses being used in west Texas where cracking is a major problem. The material was sieved to pass ⅜-in. (0.953-cm) material. The size that is larger than the ¼-in. (0.635-cm) material, which is called for in the compaction specifications, was chosen because the authors felt that by using only the finer portion of the base material they would not adequately represent the behavior of the in situ material.

Mechanical analyses were performed on each material. These are given in Table 1. The distribution curves of the grain size were nearly identical for all the materials, and a nominal 10 percent passed the No. 200 sieve. The data show that all materials are similar, but there is some variation in the plasticity index.

Two moisture density curves were constructed for each material. Modified AASHO compaction produced one curve, and the Harvard miniature compaction with a spring-loaded compactor calibrated to produce 95 percent of modified AASHO compaction produced the other. Psychrometers were placed in preformed cavities in the 4.6-in.-tall (11.6-cm), 4.0-in.-diameter (10.2-cm) modified AASHO samples. The samples were lightly wrapped in tinfoil and heavily coated with wax. Suction determinations were made until an equilibrium value was attained. The psychrometers were sealed with the smaller Harvard samples, 1$\frac{5}{16}$ in. (3.33 cm) wide and 2½ in. (6.35 cm) high, so that suction values could be obtained.

Figure 1. Typical cracking observed in west Texas.

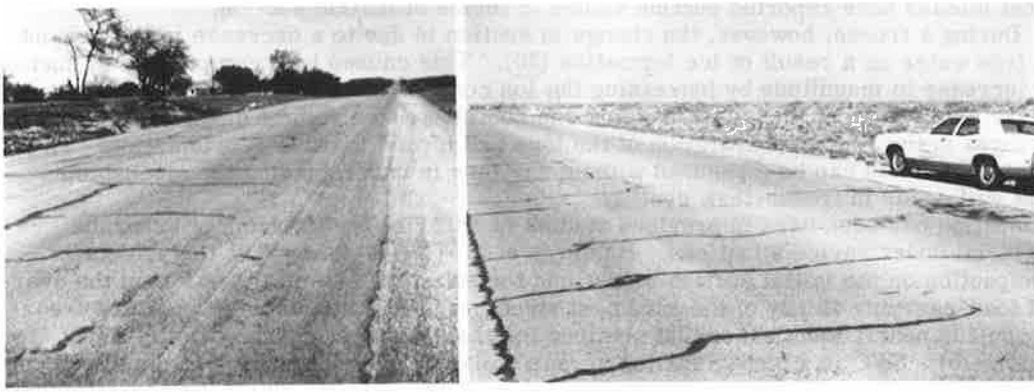


Figure 2. Relationship between water content and suction for freezing and drying, thawing and wetting (10).

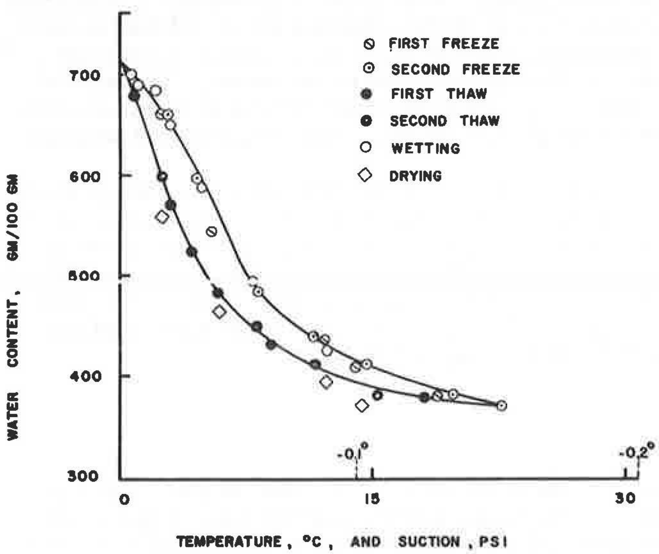


Table 1. Properties of tested base course material.

Material Number	Specific Gravity	Fines Passing No. 200 Sieve (percent)	Liquid Limit (percent)	Plastic Limit (percent)	Clay (percent $< 2\mu$)	Maximum Freeze Coefficient[a]
4	2.65	11	30	21	9.0	-2.7
5	2.68	9	32	21	7.7	-2.5
6B	2.67	10	27	20	6.2	-1.3
6JD	2.69	10	22	18	4.3	-4.0
6FS	2.66	9	16.7	16.5	1.6	-0.5
7SA	2.68	10	22	12	6.5	-1.85

Note: 1 in. = 2.54 cm. 1 C = (1 F - 32)/1.8.

[a] $\frac{\text{in./in.}}{°C} \times 10^{-4}$.

The psychrometers furnished an as-compacted suction value for each sample. These values allowed contours to be plotted on the moisture density curves. Figure 3 shows a typical curve. These data substantiate previous investigations (17), which showed that suction was affected only slightly by compaction effort for a given moisture content. The psychrometers were removed from the Harvard miniature samples but were left within the modified AASHO samples to monitor suction changes during subsequent freeze-thaw testing.

Several methods of freeze-thaw testing are currently used. The open system allows the sample free access to the moisture. The closed system maintains a constant moisture content in the sample. Uniaxial freezing results from the advance of a freezing front along the axis of the sample. Biaxial freezing results from a uniform drop in temperature around the entire sample. The nature of west Texas dictated closed-system testing to control the moisture. Biaxial freezing was chosen because uniaxial freezing has major importance primarily in frost-heave problems and because previous studies have not shown ice segregation or lensing to be a major problem in unsaturated samples of similar materials tested in the closed-system mode of freezing (8).

For freezing, the samples were placed in a constant temperature room at 20 F (-6.7 C). Previous studies show that if volume change is to occur, 10 percent of the total change will occur between ambient and 32 F (0 C). The remaining 90 percent will occur between 32 F (0 C) and 20 F (-6.7 C). Only random minor changes will occur below 20 F (-6.7 C) (8). For this reason, it was felt that to cool the samples to 20 F (-6.7 C) in existing operational environmental rooms would be sufficient. There is not one uniform method for the freeze-thaw testing of soil materials. The freeze parameters will vary in different areas of the country. Studies similar to those done by Dempsey (5) in predicting pavement temperatures during a year should be conducted to define the freeze-thaw parameters in the area in which the material will be used.

The height and diameter of each sample were recorded with a dial gauge and micrometer to 0.0001 in. (0.0003 cm). The temperature was monitored by using thermocouples embedded with the psychrometers in the modified AASHO samples. The samples were frozen for a different period of time depending on their size. The modified AASHO samples were frozen completely in 24 hours, and the Harvard miniature samples were frozen after 12 hours. The thaw periods were of a similar length.

EXPERIMENTAL DATA

Results of the freeze-thaw cycling tests produced three major sets of data:

1. Thermal strain due to a freeze,
2. The permanent deformation remaining after a freeze-thaw cycle, and
3. Suction values during and after a freeze-thaw cycle.

The thermal strains were converted to a coefficient of thermal activity, which was calculated in two parts. The total thermal deformation was divided into two parts: (a) Ten percent of it was assumed to occur from ambient temperature down to 32 F (0 C), and (b) the remaining 90 percent was assumed to occur from freezing to 20 F (-6.7 C). The coefficient of thermal activity was calculated by dividing the thermal strain, change in height divided by original height, by the corresponding change in temperature. This gave two coefficients: The first applies to situations in which the temperature remained above freezing (the thermal coefficient), and the second applies to situations when the temperature fell below freezing (the freezing coefficient). When plotted directly on the moisture density curves, the freezing coefficient produces contours similar to those obtained by Hamilton (8). Typical curves are shown in Figure 4. These data showed that contraction prevailed in all materials tested. When these freezing coefficients are plotted against $\log_{10}$ of the as-compacted suction, a unique relationship is observed, which is shown in Figure 5. Generally, as suction increases, the freeze coefficient becomes more contractive.

The plastic, or residual, strains produced in a sample are similar to data obtained

Figure 3. Compaction curve and soil moisture suction values for base material.

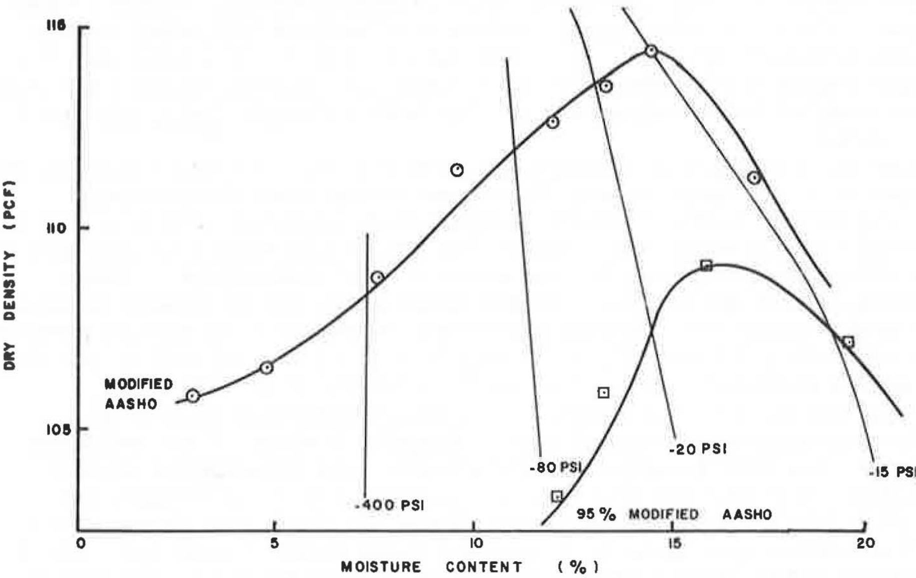
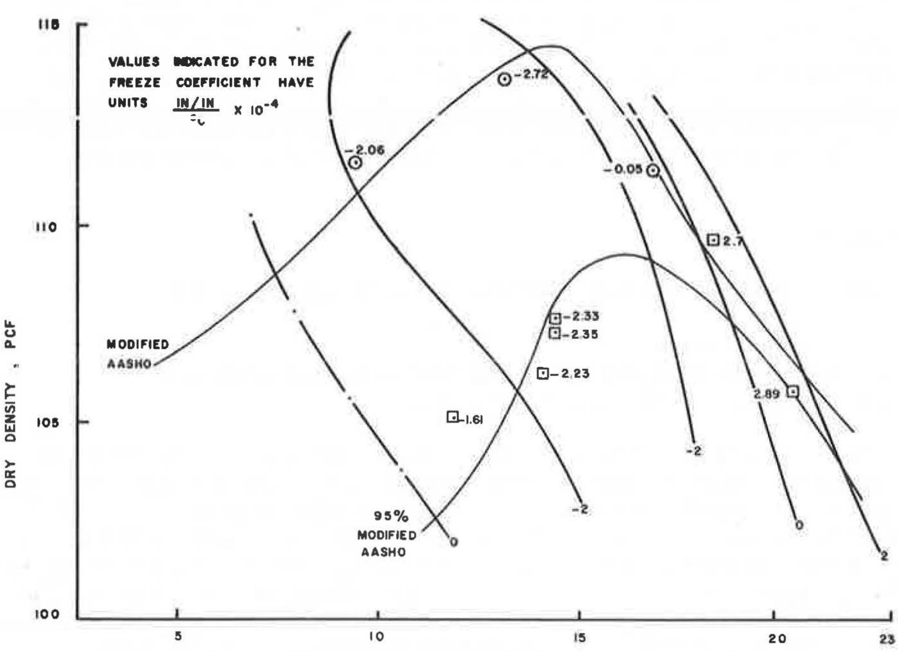


Figure 4. Moisture density curves and freeze coefficients for base material.



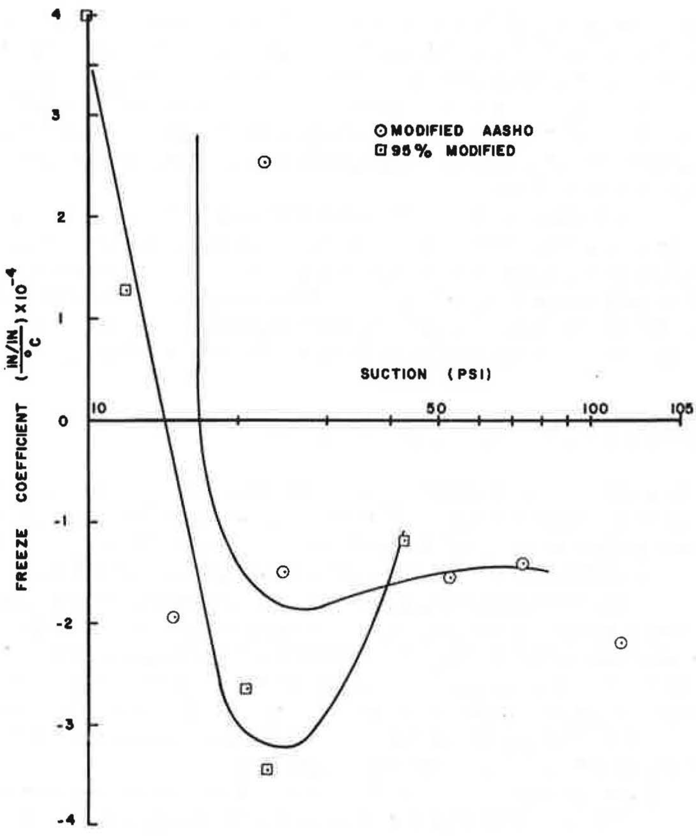


Figure 5. Freeze coefficient plotted against $\log_{10}$ of suction and varied compactive efforts for base material.

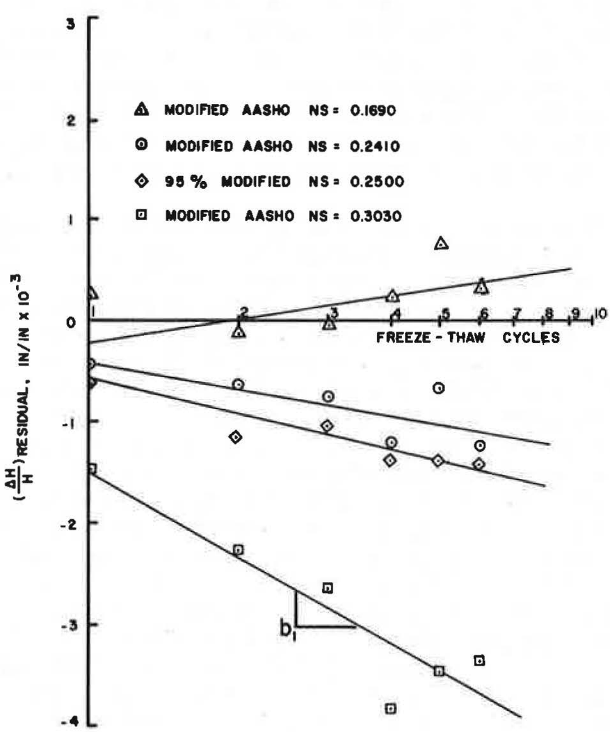


Figure 6. Residual strain plotted against $\log_{10}$ of number of freeze-thaw cycles.

in triaxial repetitive load tests. The residual strain plotted against $\log_{10}$ of the number of freeze-thaw cycles is a linear relationship; this is shown in Figure 6. The slope of each line, obtained by standard linear regression techniques, is plotted against $\log_{10}$ of the suction in Figure 7. This relationship shows the influence of suction on residual strains to be the opposite of that for the freeze coefficient; i.e., as suction increases, the residual contraction decreases and even produces expansion for high values of suction.

The suction behaved as expected during freezing. Measured values jumped well up above -700 to -800 psi (-4830 to -5520 kPa) during a freeze, indicating that there is, effectively, less free water available. During the thaw portion of the cycle, the suction fell below the original value. This drop was consistent for all samples independent of whether the thermal activity was expansion or contraction. Suction values for two samples undergoing freeze-thaw are shown in Figure 8.

INTERPRETATION AND ANALYSIS

Data indicate that thermal activity of a soil can be related to the total soil moisture suction of the sample. This term indicates that suction variations, although very small, are highly influential in the thermal activity (or freeze behavior) and in the plastic or residual behavior of a soil undergoing freeze-thaw cycling, although in opposite directions.

Thermal activity data show a rather narrow range in which soils exhibit a change from expansive to contractive behavior during freezing. This range may vary considerably from material to material depending on the initial suction, which will be unique to each material. This can be seen when the freeze coefficient is compared with moisture content alone (Fig. 4). This demonstrates the need for identifying the clay mineralogy in the base course material because it is highly influential in determining the suction level that develops.

Thermal behavior of a base course is influenced somewhat by the compactive effort. The point at which the thermal activity changes from expansion to contraction is consistently shifted to the wet side of the optimum moisture content as compactive effort increases. This means that increased compaction effort would produce a material more likely to exhibit freeze contraction over a larger range of water contents because most material is compacted near, or dry of, optimum moisture (Figs. 4 and 5).

Suction has an opposite influence on the residual deformation. As suction increases, the sample becomes drier, and the residual deformation will change from contraction to expansion (Fig. 6). Compaction effort changes the residual deformation characteristics; therefore, increased compaction reduces residual shrinkage for the same suction value.

The heat transfer program mentioned earlier was used to calculate several temperature distributions from west Texas weather data. These calculations show that the freezing front nearly always penetrates the base course but never penetrates to the subgrade during any winter. Typical profiles were used in an elastic, finite element computer code to predict induced tensile stresses due to thermal strains.

The finite element code was modified slightly to more closely model the situation as it occurs in the field. The initial and final temperature distributions in Figure 9 were used. The coefficients of thermal activity above and below freezing were stored with typical values of Young's modulus above and below freezing. Figure 10 shows these values and the mesh configuration for an initially uncracked pavement.

Figure 11 shows the maximum induced tensile stresses in the asphalt and base course plotted against the freezing coefficient of the base course. It clearly shows that the range of values determined for the samples in this study will produce excessive tensile stresses, which can easily crack the base course of an initially uncracked pavement. The asphalt concrete surface develops tensile stresses, which are nearly the same as typical asphalt concrete tensile strength values. Therefore, the asphalt concrete will be less likely to crack than the base course material.

As the temperature rises above freezing, the thermal stresses will be relieved; however, the base course undergoes permanent residual deformation as a result of the

Figure 7. Residual strain versus freeze-thaw cycles plotted against suction.

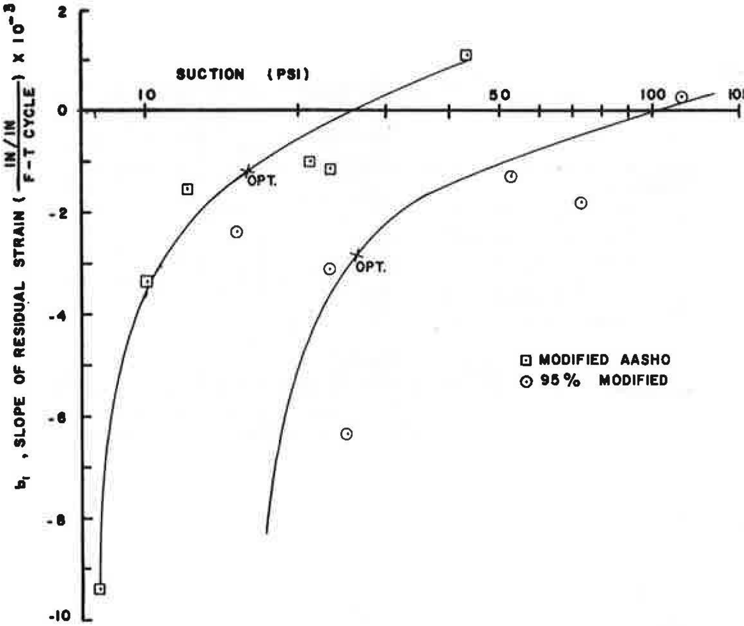


Figure 8. Suction values during thaw cycle and frozen values for two samples.

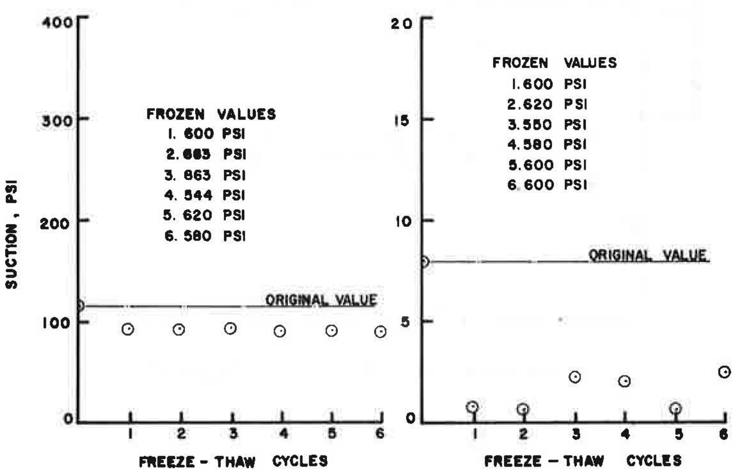


Figure 9. Temperature distributions used in finite element analysis.

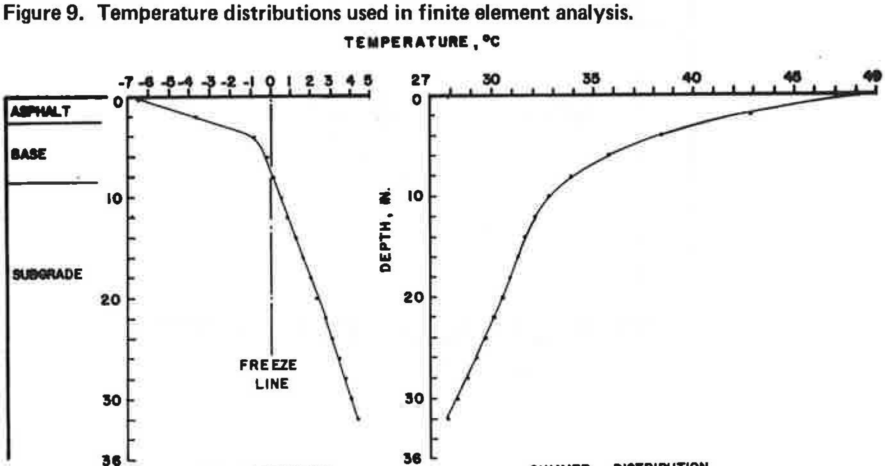


Figure 10. Cross section of pavement and typical values used in finite element analysis.

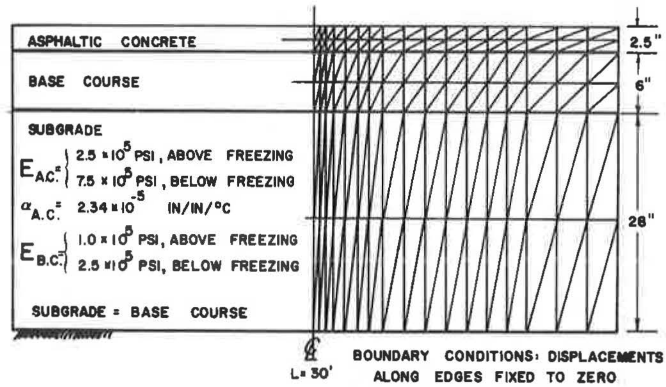


Figure 11. Thermal tensile stresses in asphalt and base course plotted against freeze coefficient of base course.

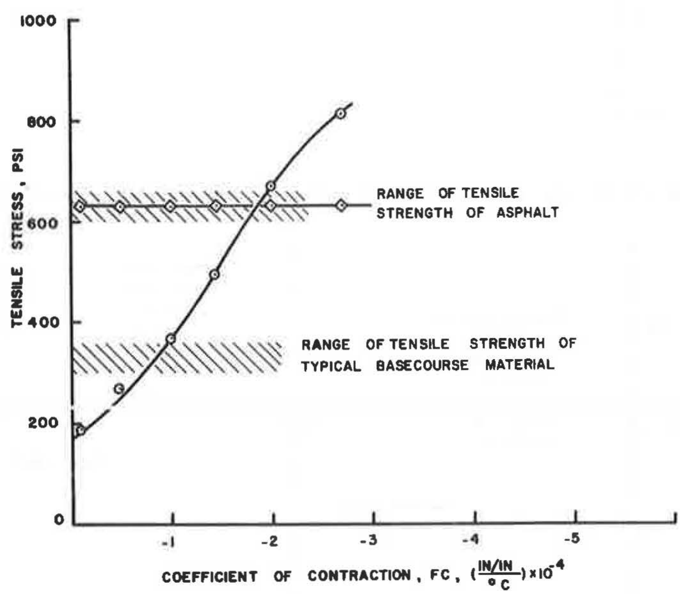
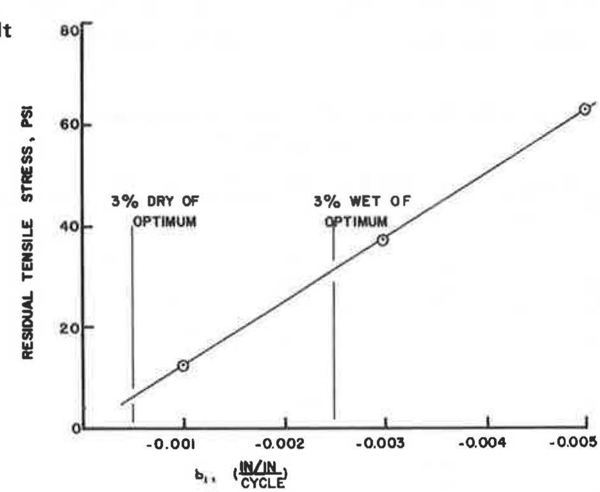


Figure 12. Residual stresses in asphalt concrete due to volume change for four freeze-thaw cycles.



freeze-thaw cycle. As there may be several freeze-thaw cycles, which extend into the base curing during any winter, the total change in volume could be appreciable. This action may induce residual tensile stresses in the asphalt concrete.

Typical values of residual volume change were converted to strains, assuming isotropy. These strains were then used in the previously mentioned finite element code to predict stresses. Figure 12 shows induced tensile stresses in the asphalt concrete plotted against the residual constants for various samples compacted near optimum moisture. These values of b_1 represent samples covering a range of 3 percent dry of optimum to 3 percent wet of optimum. This shows that after a winter there will be some residual stress left in the pavement structure. These stress levels, while not high enough to crack the asphalt concrete, will serve to reduce the life of the pavement. This result assumes the base course and the asphalt concrete remain bonded together.

CONCLUSIONS AND RECOMMENDATIONS

This study deals with the environmental deterioration of pavements in west Texas due to freeze-thaw. Previous models have not considered base course material as an important cause of transverse cracking due to temperature cycles or extremes. The mechanisms involved in pavement cracking in west Texas are better explained by the thermal activity of the base course material than by the properties of asphalt concrete surfaces. Data presented in this study clearly show that the base course is active when undergoing freeze-thaw cycling. Any analysis of pavement cracking due to low temperature or thermal fatigue should include a characterization of the base course.

The base course material is much more thermally active, than the asphaltic concrete. The calculated freezing coefficients possessed a unique relationship with the total soil moisture suction. The freezing coefficients for the base course material produced the tensile stresses produced by the coefficients in the base were greater than tensile strengths, but stresses in the asphalt concrete were of the same order of magnitude as typical tensile strengths. Thus, during a freeze, the base course would be likely to crack before the asphalt.

Soil moisture suction was selected to describe the behavior of the material during freeze-thaw cycling because it required no extensive experiments to determine the quantities that are reflected in the influence of grain size, pore size, particle structure, clay mineralogy of a sample, and the energy state. It was also found that the level of compaction effort produced a difference in thermal behavior: Increased compaction may increase freeze contraction while it reduces the residual contraction. Thus, an increase of compactive effort will reduce the likelihood of damage due to freeze-thaw cycling but will increase the likelihood of tensile cracking due to a single hard freeze.

A more theoretically correct analysis would include the viscoelastic behavior of the asphalt concrete and base course. Inclusion of this behavior would show stress relief in the pavement caused by the time between temperature extremes. This stress relief would be far greater in the asphalt concrete than in the base course and, therefore, would not seriously affect the conclusions regarding the freeze behavior of the pavement during freeze-thaw. However, the residual stress levels in the asphalt would be overpredicted by the analysis used in this study.

Studies concerning additives that reduce the thermal activity of frost-susceptible materials should be applied to the base course to limit thermal activity and thereby to reduce the chance of cracking in the base course, which would readily reflect through the asphalt concrete surface.

This analysis has concerned itself mainly with the effect of freeze-thaw on the formation of transverse cracks. Although the formation of longitudinal cracks is not addressed directly, it is explainable by the data presented. As the base course shrinks during a freeze to cause transverse cracking, it will also contract inward from the shoulders, and tensile stresses will develop in the base course as a result of the restraint offered by the asphalt concrete surface. These tensile stresses will produce longitudinal cracking if they exceed the tensile strength, which could then reflect through the asphalt concrete to the surface. Thus, longitudinal cracking may be related to an environmental factor in much the same way as transverse cracking is.

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The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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