# Effects of Temperature and Moisture on the Load Response of Granular Base Course Material in Thin Pavements

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**Theoretical models to account for temperature and moisture effects on granular base course materials are developed. The models, based on a micromechanical approach that treats the granular materials as elastic spheres in contact, can be used to formulate temperature and seasonal adjustment factors for low-volume roads and to estimate when and where seasonal load restrictions are required. The thermal model relates the volumetric expansion caused by temperature increase to the increase of confining pressure, which results in an increase in the pavement modulus. The moisture model is based on thermodynamic laws and considers the granular materials as a two-phase system. One phase represents the soil particles, and the other phase represents an air-water mixture surrounding the soil particles. To verify the models, pavement layer temperatures and Falling Weight Deflectometer deflection readings were taken at hourly intervals throughout the day on two pavement test sections at the Texas Transportation Institute Research Annex. In addition, six farm-to-market roads in different regions of the state of Texas were monitored. Deflection readings, rainfall data, and pavement temperature and suction readings were collected over a 10-month period. A comparison of the predicted moduli at different temperatures and moisture conditions with the backcalculated moduli from deflection basins is made to verify the models. An example problem of the application of the models for the predictive purpose is also presented.**

Nondestructive testing devices have been extensively used to evaluate the structural integrity of pavements by measuring pavement surface deflections. These deflections are known to vary with the temperature and season at the time when testing is conducted. A common method to account for the temperature and seasonal variations is to develop adjustment factors based on observed data. The shortcoming of this approach is that although it can provide reasonable predictions for the location in which the observations were made, it does not explain the phenomenon behind these variations.

The structural integrity of pavements over any period of time (even within the day) can be affected by (a) the variation of moisture content caused by rainfall, temperature gradients, rise and fall of the water table level; (b) daily temperature fluctuations; and (c) freeze-thaw cycles. The fundamental mechanism of temperature and moisture effects on granular materials must be understood to improve the interpretation of surface deflection data. In this study, the models to account for temperature and moisture are theoretical in approach. Rather than formulating empirical relationships, the objective of this paper is to identify the various mechanisms by which the pavement will respond to temperature and moisture changes. The thin pavements considered here are the two-layer surface-treated type. The surface treatment is for waterproofing and also serves as a wearing course. The main load-bearing layer is the granular base course layer.

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## BACKGROUND

The nondestructive testing device and the backcalculation program used in this study are briefly discussed. Published works on methods of modeling temperature and seasonal effects on pavements are also reviewed.

### Nondestructive Methods of Pavement Evaluation

In nondestructive testing of pavement, the deflection basin resulting from a static or dynamic load is recorded and then analytical methods are used to predict or match this basin. The material properties that give this matching basin are assumed to be those of the materials in the field. There are numerous nondestructive testing devices capable of applying dynamic load and recording deflections at various distances from the loading plate. The Falling Weight Deflectometer (FWD) is one of the more popular of these devices that are reported to be able to simulate pavement response under moving load (*1–3*). The FWD imposes an impulse load of between 2,500 lb and 24,000 lb, which is transmitted to the pavement through a 300-mm-diameter circular loading plate; at the same time, surface deflections are recorded by geophones at seven different locations. The loading period roughly corresponds to a wheel speed of 40 to 50 mph. The FWD used in this study was the Dynatest 8000 FWD.

A number of computer programs have been developed to backcalculate layer elastic moduli from deflection basins obtained by nondestructive testing. Most of these programs were developed on the basis of layered elastic theory or the finite element method. A detailed comparison of these programs for backcalculating layer moduli of low-volume roads has been presented by Chua (*4*). In this study, the LOADRATE (*5*) program was used. LOADRATE considers only surface-treated types of pavement. It uses regression equations based on results generated from a finite element program, ILLIPAVE. The equations were developed to relate the nonlinear elastic parameters of the bulk stress model (for the base material) and the deviator stress model (for the subgrade material) with the deflections at the load point and at some distance away from the load. Layer moduli were then calculated from these parameters. This program was developed to analyze vast amounts of deflection bowls very quickly and was written for evaluating farm-to-market roads.

### Monitoring Moisture Presence in Soils

Soils just beneath the base course layer are usually unsaturated. Kersten (*6*) monitored moisture conditions of the upper 6 in. of the subgrade beneath flexible pavements in six states and reported that the degree of saturation of the subgrades averaged 73 percent. In the same study, Kersten also found that only 15 percent of the tests showed a saturation value of 90 percent or greater. Unsaturated soil is different from saturated soil in that it is a three-phase system consisting of solid, water, and air.

Soil suction has been used to characterize the effect of moisture on the volume and strength properties of unsaturated soils. Soil suction is defined as the free energy present in soil water with respect to a pool of pure water located outside the soil at the same elevation (*7*). It is made up of two components, the osmotic, which is due to dissolved salts, and the matrix suction, which is a negative pressure that exists in the soil water as a result of the capillary tension in the water. The soil suction can be measured by several methods, including a psychrometer, which measures the total suction, and a thermal moisture sensor, which measures the matrix suction. The use of the psychrometer is limited to soils with suctions lower (more negative) than $-1$ bar ($-14.51$ psi), while the moisture sensor is used for suctions higher than $-1$ bar.

### Methods of Modeling the Effects of Temperature and Seasonal Variations

Pavement surface deflections have been found to vary with temperature, especially for flexible pavements. For the thick asphaltic concrete type of flexible pavement, higher temperatures are generally associated with larger deflections. Various temperature models have been formulated to simulate temperature in a pavement system. Most of the models have been developed to estimate temperature distribution with depth. One widely used empirical method to predict temperature at depth in an asphaltic concrete pavement has been developed by Southgate and Deen (*8*). This method estimates the temperature at any depth in a flexible pavement up to 12 in. thick provided that the surface temperature, the 5-day mean air temperature, and the time of the day are known. The analytical type of solution uses the Fourier diffusion equation for determining conductive heat transfer in a pavement system (*9, 10*).

There are two approaches to account for the effects of temperature on a pavement system. The first approach involves assigning incremental deflections for each degree of temperature difference between the pavement temperature and the reference temperature (*11–13*). The second method involves the use of a dimensionless multiplicative factor that is applied to a measured deflection at some known mean temperature of the pavement. This type of adjustment factor has been developed for the Benkelman beam (*8, 14*), Road Rater (*15*), and Dynaflect (*16*).

Other empirical formulas have been developed to estimate seasonal variations of pavement strength. From laboratory test results, Thompson and Robnett (*17*) developed a correlation between resilient modulus and degree of saturation for different soil types. Bibbens et al. (*1*) developed laboratory-determined resilient modulus versus moisture content curves. Cumberledge et al. (*15*) monitored five field test sites in Pennsylvania to collect temperature, engineering properties of subgrade soils, and Road Rater deflections. Multilinear regression analysis was performed to relate variations in surface deflections to changes in moisture content, percent of material passing a no. 200 sieve, thickness of pavement, liquid limit, and dry unit weight. Among the variables, changes in moisture content were found to be most influential on pavement surface deflections.

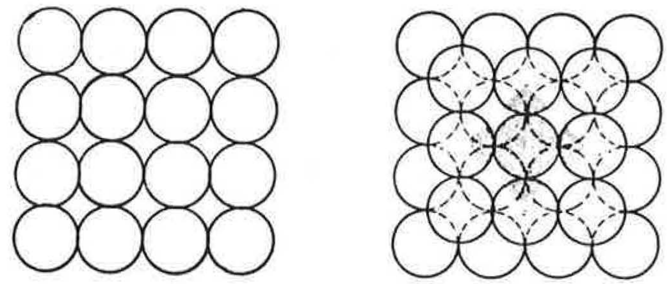
## SIMPLIFIED MODEL FOR THERMAL EFFECTS ON GRANULAR SOILS

There are two main approaches for modeling soil behavior: the phenomenological approach and the micromechanical approach. The phenomenological approach treats the soil as a continuum that may include thousands to millions of soil grains and pores, and it analyzes the mechanism of the continuum as a whole. The micromechanical approach observes the behavior of soil at the grain level and considers the forces and deformations at contact points between individual particles.

Most micromechanical models seeking to describe analytically the mechanical behavior of granular soils are based on the Hertzian contact theory that deals with a pair of homogeneous, isotropic, elastic spheres in contact, compressed statically by a normal force (*18*). Other models include an extension of the theory by Mindlin (*19*) and Mindlin and Deresiewicz (*20*) that considers tangential force at contacts. The micromechanical approach has been successful, at least, in the qualitative predictions of the behavior of granular aggregates (*21, 22*).

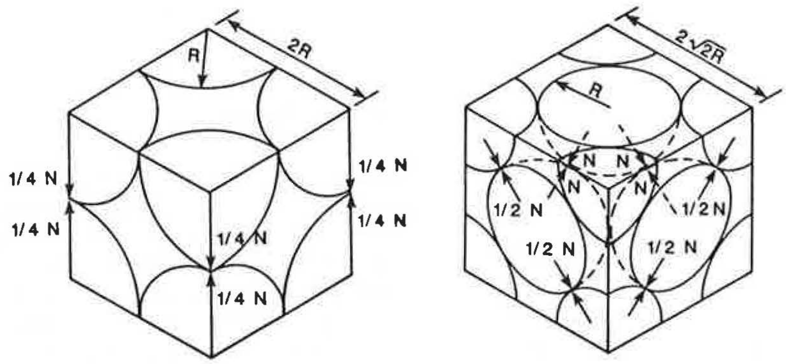
### Modeling Approach

The model developed here views the granular soil as an assemblage of soil particles that are in contact and subjected to temperature changes. Two different packing configurations that represent the densest and loosest arrangement of equal spheres are considered. The packings and the corresponding unit elements are shown in Figure 1. When unit elements are put together, they will form a regular array without addition or subtraction of spheres. The unit element of the simple cubic packing (SC) has a porosity of 47.64 percent, whereas that of the face-centered cubic (FCC) has a porosity of 25.95 percent. For typical granular soils, Ottawa sand, for example, the simple cubic array and the face-centered cubic array will have dry unit weights of 87.23 pcf and 123.4 pcf, respectively. Because



(a) Plan View of Simple Cubic Packing.

(b) Plan View of Face-centered Cubic Packing.




(c) Unit Element of Simple Cubic.

(d) Unit Element of Face-centered Cubic.

**FIGURE 1 Modes of packing of equal spheres.**

the model is developed for two packing configurations, the states between the loosest and densest condition are obtained by statistical estimates.

Granular base course soil particles in the field are subjected to overburden pressure and residual stresses. In this model, the soil particles are assumed to be confined in all directions. As such, owing to the inability of the particles to expand because of the confinement, a rise in temperature will cause an increase in the contact forces between particles. The contact pressures that are related to the confining pressure will then affect the stiffness of the soil. The resilient modulus is assumed to be related to the confining pressure in the following manner:

$$E = K_1\, \theta^{K_2} \tag{1}$$

where

$E$ = resilient modulus,
$\theta$ = bulk stress (sum of the three principal stresses), and
$K_1$, $K_2$ = constants.

It should be noted that other nonlinear models for resilient modulus where changes of confining pressure can be implemented can be used instead of Equation 1. The change of modulus with respect to the change of bulk stress is obtained by taking the derivative of Equation 1, which yields

$$\Delta E = K_1 K_2\, \theta^{K_2 - 1}\, \Delta\theta \tag{2}$$

It can be seen that a rise in temperature will result in an increase of the stiffness, which will of course depend on the initial level of confining pressure and on the material properties.

### Development of the Simplified Model

According to Hertzian contact theory, the centers of two spheres in contact under a normal force $N$ will approach one another by an amount $z$ given by

$$z = 2\left[\frac{\omega N}{R^{1/2}}\right]^{2/3} \tag{3}$$

in which

$R$ = radius of the spheres,
$\omega$ = $\frac{3}{4}[(1 - \nu^2)/E]$ is a property of the material,
$E$ = elastic modulus, and
$\nu$ = Poisson's ratio.

The volumetric strain of the sphere is given by

$$\frac{\Delta V}{V} = \frac{3\Delta L}{L} = 3\frac{Z}{2R} = \frac{3}{R}\left[\frac{\omega N}{R^{1/2}}\right]^{2/3} \quad (4)$$

Referring to Figure 1c, when a uniform pressure $p_{sc}$ acts on the unit element of the simple cubic (SC) array, the normal force $N$ is related to $p_{sc}$ by

$$N = 4R^2 p_{sc} \quad (5)$$

and substituting $N$ into Equation 4 gives

$$\frac{\Delta V}{V} = 3\,(4\omega\, p_{sc})^{2/3} \quad (6)$$

Similarly, for the face-centered cubic (FCC) array,

$$N = \sqrt{2}R^2 p_{FCC} \quad (7)$$

and substituting $N$ into Equation 4 gives

$$\frac{\Delta V}{V} = 3(\sqrt{2}\omega\, p_{FCC})^{2/3} \quad (8)$$

When the unit elements are subjected to temperature increase, $\Delta T$, the volumetric strain in Equations 6 and 8 can be expressed as

$$\frac{\Delta V}{V} = \alpha_\nu\, \Delta T \quad (9)$$

where $\alpha_\nu$ = cubical thermal coefficient, which is approximately three times the linear thermal coefficient, $\alpha$.

According to Smith et al. (*23*), an assembly of randomly packed like spheres may be regarded as an arrangement of separate clusters of simple cubic array and face-centered cubic array, each present in a proportion to yield the observed porosity, $n_{obs}$, of the assembly. Thus, if $x$ represents the fraction of close-packed spheres, then

$$n_{obs} = x\, n_{FCC} + (1 - x)\, n_{sc} \quad (10)$$

Similarly, the hydrostatic pressure, $p$, acting on a granular medium with a porosity $n$ can be approximated by

$$p = x\, p_{FCC} + (1 - x)\, p_{sc} \quad (11)$$

The pressures for the two different cubic arrays can be obtained from Equations 6 and 8, and Equation 11 becomes

$$p = \left(\frac{x}{\sqrt{2}\omega} + \frac{(1-x)}{4\omega}\right)\left(\frac{1}{3}\alpha_\nu \Delta T\right)^{3/2} \quad (12)$$

The hydrostatic pressure in Equation 12 is caused by a change of temperature. If the initial bulk stress is $\theta$, the pressure from the preceding equation is the change of the bulk stress, $\Delta\theta$, due to temperature variations. The new modulus can then be calculated by adding the change of modulus from Equation 2 to the original modulus.

### Material Properties

The elastic modulus and thermal coefficient that appear in the equations shown earlier are for the individual soil particles and not for the soil mass. For their micromechanical model, Ko and Scott (*22*) assumed that the sand grains are the same material as silicon glass, and used the elastic modulus of $10 \times 10^6$ psi and Poisson's ratio of 0.17. Yong and Wong (*24*) reported that the elastic modulus and the Poisson's ratio of Ottawa sand grains is $12.5 \times 10^6$ psi and 0.17, respectively. Willis and De Reus (*25*) designed and constructed an apparatus that mainly consisted of a temperature control box with optical lever to measure the linear thermal coefficient of different types of rocks. These results are shown in Table 1, which lists the properties, namely, elastic modulus and linear thermal coefficient, of different types of materials.

## MODEL FOR MOISTURE EFFECTS ON GRANULAR SOILS

Lamborn (*26*) formulated a micromechanical model to represent the load-deformation behavior of a partly saturated soil using the thermodynamic laws. The model consisted of

TABLE 1 MATERIAL PROPERTIES OF ROCKS (*25*)

| Material | Elastic modulus ($\times10^6$, psi) | Linear thermal coefficient ($\times10^{-6}$) |
|---|---|---|
| Chert | 3.1-18.0 | 6.0-7.2 |
| Quartzite | 3.8-10.2 | 6.2-6.9 |
| Sandstone | 2.9- 4.0 | 6.3-6.6 |
| Basalt | 11.4-13.9 | 3.9-5.9 |
| Granite | 7.6- 9.8 | 2.8-5.3 |
| Limestone | 5.1-12.6 | 1.8-5.4 |
| Dolomite | 2.5-10.0 | 4.0-5.0 |

equal spheres in contact, surrounded by an air-water mixture, each considered as a different phase. Both phases were modeled as homogeneous, isotropic, linear elastic materials. An equation that relates the mean principal stress acting on the system to the Helmholtz free energies per unit initial volume of the two phases, and the strain tensor was developed. The equation is given as

$$\bar{\theta} = C_s \frac{\partial \bar{F}_s}{\partial \varepsilon_{kk}} + C_w \frac{\partial \bar{F}_w}{\partial \varepsilon_{kk}} \quad (13)$$

where

$\theta$ = mean principal stress,
$C_s$, $C_w$ = initial volume fractions for solid and water, respectively,
$F$ = Helmholtz free energy, and
$\varepsilon_{kk}$ = $\Delta V/V$ = volumetric strain.

The overbar denotes the average values of the quantities, and the subscripts $s$ and $w$ represent the solid and water phase, respectively. A change in suction will alter the Helmholtz free energy of the water phase, but not the solid phase. Thus, the first term on the right-hand side of the preceding equation is equal to zero because of suction change. The change in the mean principal stress, $\Delta\theta$, is obtained by taking the derivative of Equation 13 with respect to the volumetric strain, and yields

$$\Delta\theta = C_w (\Delta P_w) \quad (14)$$

where $\Delta P_W$ equals the change in mean principal stress of the water phase, which is equivalent to the change in suction. Thus,

$$\Delta\theta = -\Delta(\text{suction})\ (V_w/V_T) \quad (15)$$

where $V_w$ equals the volume of water and $V_T$ equals the total volume.

Equation 2 can then be rewritten to include the change of the bulk stress caused by the temperature and the suction change,

$$\Delta E = K_1 K_2\ \theta\ K_2 - 1\ (\Delta\theta_T + \Delta\theta_s) \quad (16)$$

where the subscripts $T$ and $s$ denote temperature and suction, respectively.

## FIELD STUDIES

### Test Sites and Instrumentation

Two field studies were made. The first part involved taking FWD deflection readings on two surface-treated pavement sections at the TTI Research Annex at various temperatures. The tests were conducted at hourly intervals throughout the day several times in a year. The tests were conducted at different temperatures in the same day in an attempt to eliminate seasonal effects.

The second field study involved collecting data from six farm-to-market road sections located in different regions of the state of Texas. Monthly FWD readings as well as monthly subgrade soil suctions and temperatures at different depths were collected for 10 months. The locations of the test sites were selected on the basis of different climatic zones and subgrade soil types. The characteristics of the test sites are summarized in Table 2.

Wooden roods with thermocouples attached at different depths were inserted into the pavement sections. Thermal moisture sensors were installed in Districts 11 and 21 and measure matrix suction. As for District 8, psychrometers, which measure the total suction, were used because this area is dry. Base and subgrade materials were also retrieved from all of the test sections for laboratory testing.

TABLE 2 CHARACTERISTICS OF TEST SITES

| Site | Closest weather station | Annual rainfall (in.) | Base course | | | | Subgrade | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Thickness (in.) | %passing #200 | Classification AASHTO | Classification Unified | LL/PL | %passing #200 | Classification AASHTO | Classification Unified |
| Annex 10 | Easterwood | 39.1 | 16 | - | - | - | - | - | - | - |
| Annex 11 | Easterwood | 39.1 | 16 | - | - | - | - | - | - | - |
| D8/FM1235* | Abilene | 23.26 | 8 | 3 | A-1-a | GP | 43/31 | 58 | A-7-6 | CH |
| D8/FM1983 | Roscoe | 23.35 | 8 | 5 | A-1-b | SW | 25/16 | 27 | A-2-6 | SC |
| D11/FM2864 | Nacogdoches | 39.7 | 8.5 | 11 | A-1-b | SW-SM | 43/33 | 58 | A-7-6 | CH |
| D11/SH7 | Nacogdoches | 39.7 | 9.5 | 7 | A-1-b | SP-SM | 18/- | 5 | A-2-4 | SP-SM |
| D21/FM491 | Raymondville | 27.48 | 8 | 4 | A-1-a | GW | 26/17 | 43 | A-6 | SC |
| D21/FM497 | Raymondville | 27.48 | 8.5 | 7 | A-1-a | SP-SM | 31/20 | 32 | A-2-6 | SC |

* D denotes district

### Observed Temperature Variations

The results of the tests obtained from the TTI Research Annex are discussed in this section. Figure 2 shows a plot of air temperature, base course temperature, and subgrade temperature variations within a day as obtained in September for Test Section 11. The base course temperature followed the same pattern as the air temperature except that there exists, as expected, a time lag between the two. In the afternoon, the base temperature reached its highest point approximately 2 hr after the air temperature. At night, the heat trapped in the pavement dissipated slowly, causing the temperature of the base course to be higher than the air temperature. This is illustrated in Figure 3. From Figure 2, it appears that the subgrade temperature did not fluctuate much within a day.

Two deflection basins obtained at the highest and lowest base course temperatures of the day are plotted in Figure 4. Even though the base course modulus is higher at 104°F, it does not necessarily imply that the deflection at every sensor location is lower at 104°F than at 84°F. As such, the deflection change at any individual sensor cannot be used as an indication of the variations of the pavement moduli. It is partly for this reason that in this study the changes of the pavement moduli, rather than the deflection at any one sensor, are used to determine the temperature effects.

### Observed Moisture Variations

Monthly data were collected from the farm-to-market roads, and these include temperature and suction for both base course and subgrade, rainfall from the closest weather stations, and FWD deflection readings. There were problems in obtaining the suction readings at FM1983 and FM2864. The psychrometers in FM1983 gave only base course suction readings for several months, while the moisture sensors in FM2864 did not produce any readings at all. For the rest of the test sections, however, both the psychrometers and moisture sensors gave reasonable readings. For suction readings, a larger negative value corresponds to a drier soil and usually indicates a drier month.

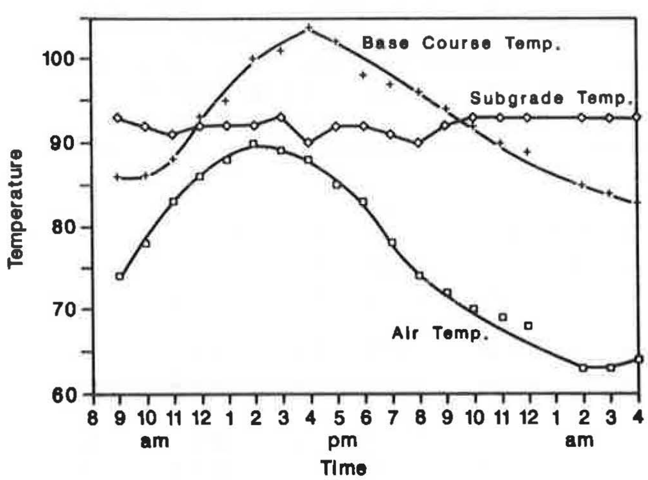



**FIGURE 2 Typical variation of temperature within a day (Section 11 TTI Annex).**

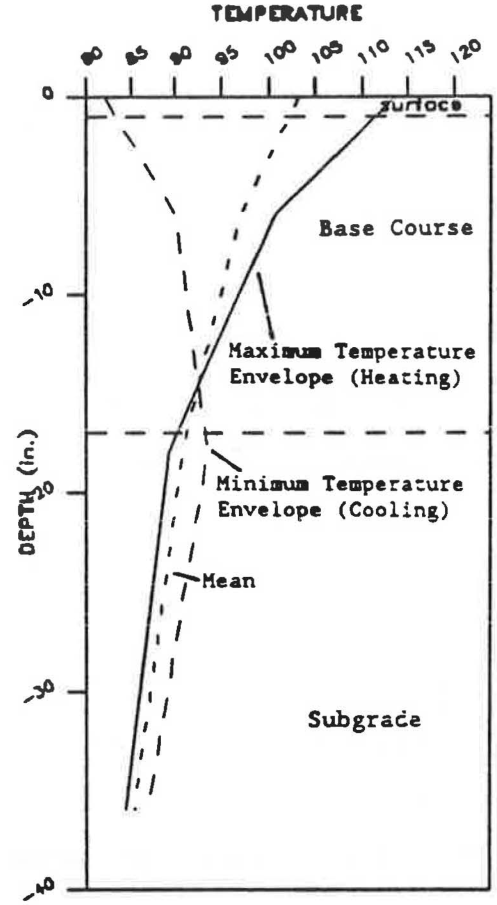



**FIGURE 3 Temperature variation with depth.**

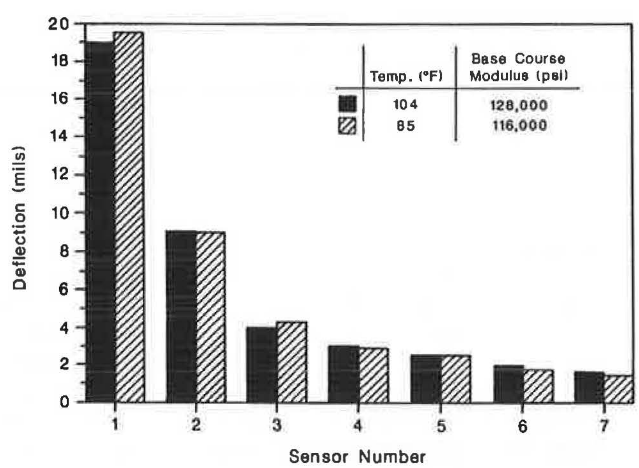



**FIGURE 4 Comparison of deflection basins at two different temperatures.**

## COMPARING PREDICTED AND MEASURED RESULTS

The base course moduli backcalculated by the program are compared with the predicted results from the simplified model. The moduli from LOADRATE are referred to as "measured" moduli because they are calculated from the deflection basins.

Typical results from the September tests are discussed. For that test, the base course temperature varied from 85°F to

104° Fahrenheit in the same day. For the model to predict moduli at different temperatures, a reference modulus at a known temperature is required as one of the inputs. The base course mean temperature for the day, which was 94°F, is selected as the reference temperature. As the system can be expected to come to equilibrium at the mean daily temperature, the reference modulus was chosen to correspond to this temperature. The reference modulus is obtained by calculating the modulus values at 94°F from each modulus at different temperatures and then averaging them. The material properties used are those of limestone, with an elastic modulus of 10 × $10^6$ psi, Poisson's ratio of 0.17, and linear thermal coefficient of 5 × $10^{-6}$°F. Other factors needed are the values of $K_1$ and $K_2$ in Equation 2. The constant $K_1$ can be obtained from LOADRATE and $K_2$ is 0.33, which was the value used when the program was developed.

The results of the prediction are plotted in Figure 5. The predicted moduli and the measured results showed a similar trend of increase as the temperature increases. The prediction results of other tests were also plotted against the measured results (Figure 6). The points cluster along the 45-degree line, which indicates that the model predictions and the actual values are in agreement. The standard deviation of 5200 psi is made up of random errors due to measurement, systematic errors due to the backcalculation procedure used, and errors due to the effects of suction change that are not accounted for in the predictions.

To isolate the moisture effects on the base course moduli, deflection data with identical base course temperatures were analyzed. The result is presented in Table 3. Because the range of moisture content variations of granular materials is small, the initial volume fraction ($C_w$) is assumed to be 0.13 for all of the calculations. It can be seen that for all the test sections, the base course moduli in different months but with the same base course temperature varied by less than 7 percent. Thus, the effects on the modulus of the base course due to changes of suction were too small to be measured reliably by the backcalculation method used.

However, when the fluctuation of the suctions is large, as in the case of FM1235, the effects of suctions on the modulus values are apparent. In Figure 7, the month of October is used as the reference, and all the other moduli are predicted from the October modulus. The deflection readings were collected from different months in which there was a wide spread of base course temperatures. The base course modulus for each month was the mean value of the moduli backcalculated from 10 deflection basins taken at the same spot. The solid line in the figure denotes the predicted moduli without considering the suction effects. The dotted line, calculated by considering both temperature and suction variations, yields a much better prediction.

The same method is used to fit the base course moduli of SH7, where the suction readings were obtained by thermal moisture sensors. The result is plotted in Figure 8, which shows a good agreement between the predicted and measured results.

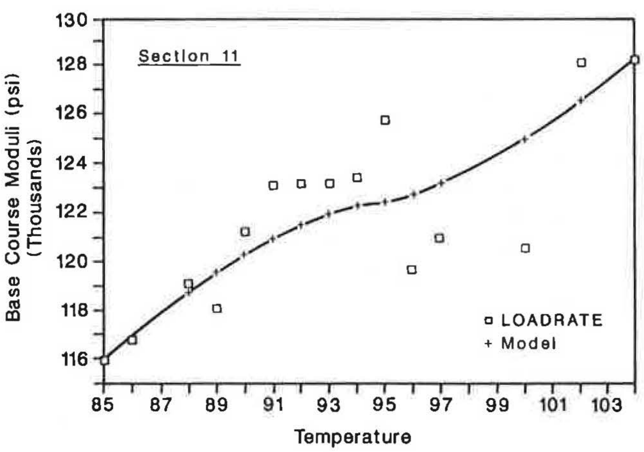



**FIGURE 5 Comparison of base course moduli from LOADRATE and the model (Section 11 TTI Annex).**

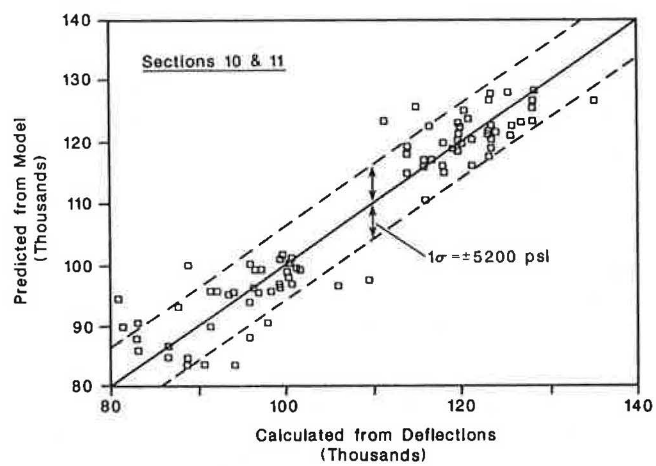



**FIGURE 6 Predicted versus backcalculated results (TTI Annex).**

TABLE 3 MOISTURE EFFECTS ON BASE COURSE ELASTIC MODULI

| Site | E (psi) | $K_1$ | θ (psi) | Δsuction (psi) | Δθ (psi) | Measured change of modulus | Predicted change of modulus |
|---|---|---|---|---|---|---|---|
| FM1235 | 110,000 | 33,700 | 34.8 | -59 | +7.7 | +7,000 | +8,032 |
| FM1983 | 74,000 | 21,800 | 39.1 | -15 | +2.0 | -2,900 | +1,261 |
| SH7 | 110,000 | 36,000 | 28.5 | -2 | +0.25 | +5,000 | +321 |
| FM491 | 46,000 | 15,300 | 27.8 | -10 | +1.3 | -3,000 | +717 |
| FM497 | 49,000 | 17,700 | 21.1 | -1 | +0.13 | -3,400 | +101 |

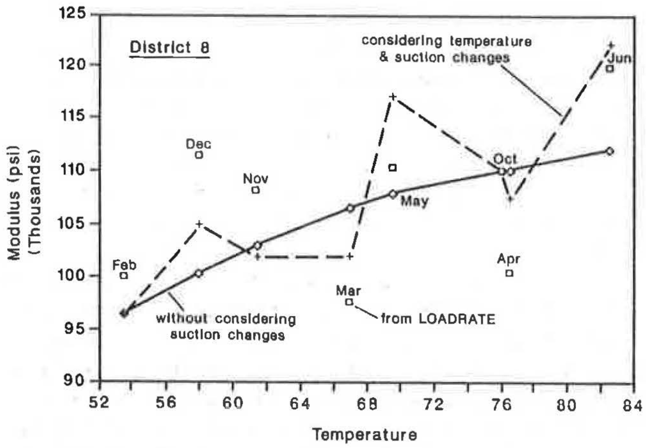



FIGURE 7 Comparison of base course moduli from LOADRATE and the model (FM1235).

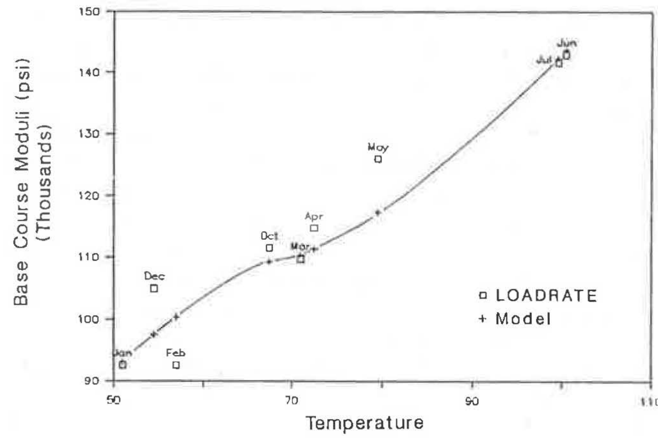



FIGURE 8 Comparison of base course moduli from LOADRATE and the model (SH7).

## COMPARATIVE STUDY

In this section, an example is presented to illustrate the application of the thermal and moisture models. The models are used to convert the base course moduli at different temperatures and suctions to those at a reference condition so that a comparative study can be performed.

Consider two low-volume roads, A and B. The base course modulus of road A backcalculated from a deflection basin is 60,000 psi. The temperature and suction of the base course when the deflection data were taken were 50°F and −10 psi, respectively. The base course modulus of road B is found to be 70,000 psi at 110°F, and the suction was −100 psi. The properties of the base course materials are summarized in Table 4. The problem is to find out which pavement is stronger by comparing the base course modulus.

The temperature of 70°F and suction of −10 psi are selected as the reference condition. Assuming that the dry unit weight of the base course for both roads is 120 pcf, the porosity, $n_{obs}$, can be calculated. The fraction of the total volume representing face-centered cubic arrays, obtained from Equation 10, is used in Equation 12 to obtain the change of bulk stress caused by temperature variation. The change of bulk stress due to suction is obtained from Equation 15. Equation 16 is used to calculate the change of modulus. The equivalent moduli at the reference condition are calculated for both roads. At first glance, it seems that road B is stronger than road A because the base course modulus is higher. However, because the base course temperatures and suctions at the time the moduli were obtained were not the same, a comparative study cannot be performed unless the equivalent moduli are calculated. It turns out that the modulus of road A is slightly higher than that of road B at the same temperature as shown in the table.

## CONCLUSION

Theoretical solutions to model temperature and moisture effects on granular materials are presented in this paper. The thermal model requires the properties of the soil particles and the modulus at the reference temperature as the input, whereas suction values are required in the moisture model. The variations of base course moduli due to temperature and suction

TABLE 4 COMPARISON OF BASE COURSE MODULI

| Road | Base Course temperature (°F) | Base Course modulus (psi) | Base Course suction (psi) | Base course material | Material properties | Calculated modulus at 70°F and 10 psi suction |
|---|---|---|---|---|---|---|
| A | 50 | 60,000 | -10 | Limestone | $K_1$ = 10,000 psi<br>K2 = .45<br>$\mu$ = .17<br>$\alpha$ = $8x10^{-6}$ /°F<br>E = $8x10^{-6}$ psi | 61,400 |
| B | 110 | 70,000 | -100 | Crushed stone | $K_1$ = 15,000 psi<br>K2 = .40<br>$\mu$ = .21<br>$\alpha$ = $6x10^{-6}$ /°F<br>E = $10x10^{-6}$ psi | 59,400 |

NOTE: The values of $K_1$ and $K_2$ are from Rada and Witczak (27).

changes predicted by the models agree well with the back-calculated moduli. Instead of using empirical temperature adjustment factors, the models can be used for comparative studies as illustrated in the example. Because the solutions are developed theoretically, the models are applicable to other problems in which the effects of temperature and moisture on granular soils are of concern.

The following conclusions can be drawn from this study:

1. The granular base course moduli of low-volume roads showed a trend of increase as temperature rises and suction becomes more negative, which can be explained as the result of an increase of the contact pressure between particles due to thermal expansion and suction changes.
2. The theoretical models presented in this paper predict very well the changes of the moduli of granular base course layer due to the changes of temperature and moisture.
3. The models can be applied to adjust the base course moduli of low-volume roads for temperature and moisture effects. They can also be used for comparative study of pavement conditions, as illustrated in the example. Furthermore, the moisture model can be used to predict pavement conditions at a certain time of year so the application of seasonal load zoning can be determined as early as possible.

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