curacy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

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Permanent Deformation Characterization of Bituminous Mixtures for Predicting Pavement Rutting

J. BRENT RAUHUT

A general overview of rutting models available for predicting rutting in flexible pavements, the permanent deformation characterizations used by these rutting models or subsystems, and the general limitations of these characterizations is given. Discussed in detail are VESYS and DEVPAV. The most intensive development of a rutting model has been for the VESYS subsystem through support of the Federal Highway Administration. Since numerous researchers are involved in its further development and implementation, the published results of permanent deformation testing by a number of researchers have been transformed to the VESYS material characterization parameters ALPHA(1) and GNU(1). The relationships between these and other significant variables such as deviator stress, temperature, resilient modulus, and confining stress are reviewed and summarized. ALPHA(1) and GNU(1) were found to generally decrease with increasing deviator stress or temperature; the increase in ALPHA(1) dominated the effect on permanent strain predictions. ALPHA(1) increases with increasing confinement, and GNU(1) appears to decrease. Both parameters appear to increase as the material stiffness increases.

The advent of pavement models capable of making predictions of permanent deformations in pavement materials has created a need for characterizing materials in terms of permanent strains that result from repeated wheel loadings. A number of researchers have studied this problem both in the laboratory and through theoretical studies and comparisons with field measurements, and several procedures have been applied with varying degrees of success.

Virtually all models that offer predictions of rutting in pavements use elastic-layer theory to arrive at predictions of stresses or strains and then use these predictions and characterizations of the permanent deformation potential of pavement materials to arrive at predictions of rutting on a pavement surface. All of these procedures are limited (a) because the models are not as yet developed to the level of complexity imposed by the real physical system and (b) because of shortcomings in the characterizations of the permanent deformation potentials of the pavement materials. This does not imply that the characterizations are not useful but simply means that further development and improvements are needed to increase the confidence level in their predictions. The same is certainly true of fatigue-life predictions and, to a lesser extent, of most other outputs from analytical models used for pavement analysis and design.

The purposes for this paper are twofold. The first is general in nature and is intended to offer a brief overview of available pavement models developed for predicting rutting in flexible pavements and the characterizations used for permanent deformation potential of bituminous mixtures. The second is to update the state of knowledge of those characterization parameters used specifically by the VESYS rutting prediction subsystem. The former should be useful to researchers interested in flexible pavement models and the latter to the Federal Highway Administration of the U.S. Department of Transportation, state departments of transportation, and private and academic researchers working to improve and implement VESYS.

RUT-PREDICTION MODELS AND THEIR MATERIAL CHARACTERIZATIONS

A number of general approaches to the permanent deformation characterization of bituminous materials have been applied; they may be classified as follows:

1. Creep compliance characterization: These compression tests are generally run with one long-term static load but have also been run incrementally with specified load and unload durations (1) and with repetitive static loads. Characterization is in terms of a creep modulus as a function of load duration.
2. Repetitive-load test characterization: Many cycles of stress are applied for very short intervals (usually 100 000 or more cycles at 0.06- to 0.2-s load durations) in a factorial format to take into account the effects of stress state and sample temperature. Characterization is in terms of permanent strain as a function of cycles of loading.
3. Regression model characterization: Rutting is predicted on the basis of parameters such as stress and material stiffness. Permanent deformation potential is implicitly considered through its correlations with the significant parameters used.

The creep compliance test characterization is used by Shell in its design procedures (2) for predicting rutting, whereas multiple-regression model characterizations are used by Meyer and Haas (3,4) in their computer programs OPAC and WATMODE. Most other procedures used repetitive-load test characterizations, and the remainder of this paper will be limited to this type of characterization. However, discussions of the Shell procedure, OPAC, and WATMODE may be found in Rauhut, Roberts, and Kennedy (5,6).

VESYS RUTTING-PREDICTION SUBSYSTEM

The VESYS rutting-prediction subsystem uses a characterization derived from repetitive-loading compression tests to define fraction of predicted total strain that is permanent as a function of number of load cycles. The two parameters used are called ALPHA(1) and GNU(1); these parameters and their use are derived and explained in full elsewhere (7,8). They are also reviewed briefly below.

When permanent strain is plotted versus load cycles on log-log paper, a straight line may be drawn tangent to the curve to approximately predict permanent strain over the range of loadings of interest (usually to a portion of the curve that represents the highest range of loading numbers). ALPHA(1) is one less the slope of this line and thus represents primarily the rate at which permanent strain is increasing. GNU(1) is the product of the intercept value of permanent strain after the first load cycle and the slope divided by the average resilient strain; thus GNU(1) is the more complex parameter and is less prone to predictable behavior than is ALPHA(1). In general, increasing ALPHA(1) or decreasing GNU(1) individually results in reduced rutting predictions.

As with any slope-intercept representation of a function, a region on the graph may be reached by means of a variety of combinations of two parameters; therefore they may vary somewhat according to some relationship and still give reasonable results. In this case, neither variable is directly a slope or an intercept but, rather, are both functions of the slope and therefore somewhat interdependent.

Originally, one set of these parameters was used in VESYS IIM to characterize the bituminous material in the pavement structure for the entire year. An improved version called VESYS A (9) included a capability for separate seasonal characterizations, and a version called VESYS IIA added additional layers so that surface and bituminous base layers could be characterized separately.

At the present stage of development, selection of values of ALPHA(1) and GNU(1) requires previous knowledge of the expected stress state so that the effects of this important parameter on the characterization parameters may be considered. An approximation of the stress state may easily be obtained with elastic-layer solutions, but the effects of the stress state are difficult to apply both because of the limited data developed to date and because of the sensitivity of ALPHA(1) and GNU(1) to stress state and a number of material characteristics. I have previously attempted to assemble the results of all known permanent test results in terms of ALPHA(1) and GNU(1) (7,9) to alleviate this problem. More recent additional data will be added subsequently in this paper.

It should be kept clearly in mind that the permanent deformation potential of a bituminous mixture [characterized by ALPHA(1) and GNU(1)] varies daily and seasonally much as its dynamic modulus or stiffness does. As for stiffness, average values of ALPHA(1) and GNU(1) are used for discrete periods of time called "seasons" and are made consistent with average pavement temperatures in the bituminous layer. However, there is a further assumption or averaging effect for ALPHA(1) and GNU(1) that involves the average stress state throughout the depth of the bituminous layer. Whereas the material stiffness is not strongly stress dependent, the permanent deformation potential is very stress dependent and varies greatly from the top to the bottom of the pavement (7,10). To select average values of ALPHA(1) and GNU(1) in terms of stress state requires averaging across the upper zone of lateral compression and a lower zone of lateral tension.

While both repetitive-load triaxial and indirect tensile testing have been conducted to approximate the stress state in the tension zone of a bituminous layer, it is my opinion that such testing has not really as yet been successful. The reasons for this are that

1. No test has been devised that truly simulates the stress state in the lower or tensile zone of a bituminous layer and
2. Important lateral deformations that would contribute heavily to the vertical deformations called rutting in the bituminous layer are generally sufficient to mobilize substantial passive resistance to the lateral deformation; this phenomenon has not been accounted for in any test procedure I know of.

The shortcomings in the material characterizations are mentioned here simply because the VESYS model is being discussed first, not because they are unique to VESYS. They are just as applicable to the other models discussed subsequently since they all use essentially the same test technique for characterization.

My associates and I have attempted on two occasions to obtain generalized definitions of ALPHA(1) and GNU(1) through multiple regressions. The first attempt (7) used deviator stress, temperature, and percentage of asphalt content as independent variables. The resulting equations explained less than 50 percent of the variance of the dependent variables and were considered unacceptable for general application. A recent attempt that used a much broader data base met with little more success, although several likely equation forms were tested.

RUTTING SUBSYSTEM OF MONISMITH AND OTHERS

The design subsystem presented by Monismith and others (11) estimates the amount of permanent deformation or rutting that results from repeated traffic loading. Relationships between applied stress and permanent strain defined by repeated-load triaxial compression tests are used for fine-grained soils, granular materials, and asphalt concrete. Stresses resulting from the wheel loads are estimated through use of one of the ELSYM computer programs as a structural model. The stresses in turn permit estimation of permanent deformation in each layer of a specific pavement by

1. Computing the permanent strain at a number of points within the layer, the depth being sufficient to define the strain variations with depth, and
2. Estimating the deformation by summing the products of the average permanent strains and the corresponding differences in depths between the

locations at which the strains were determined; total rut depth is estimated by summing the contributions from each layer.

While this is a fairly straightforward method and indicates promise, the material characterizations used are quite complex and are dependent on a very detailed test program for specific materials used in order to arrive at the values of the many parameters considered. Few data are currently available for use with this procedure.

The consideration of discrete increments of depth in the bituminous layer and the characterization of materials in terms of stress state offer the opportunity to consider variations in stress state throughout the layer and, thus, the variation of permanent strain with stress. If properly characterized, this would allow the effects of lateral tension to come into play. In general, it is my opinion that this offers some theoretical advantage over the current generation of VESYS subsystems, but it would require a very large research commitment to sufficiently develop the approach and to broaden the material characterization data base for general use, even for research.

Similar procedures have also been developed and applied by Singh and Hamdani (10), Barksdale (12), and Huschek (13).

DEVPAV

DEVPAV is a finite-element program that has been under development by Kirwan and others (14) for some years in Ireland. In addition to the usual loading information, it uses permanent deformation characterizations for the various layers that were apparently developed by multiple regressions on repetitive-loading compression test results for each specific material considered. The following equation was given for a dense bituminous macadam tested at the University of Nottingham:

$$\epsilon_n (\%) = [0.0015(0.68 + 0.0008 T^2 \operatorname{Log}_{10} N)^{1.9} \nabla]^{1.75} \quad (1)$$

This equation is in terms of number of applications N, the applied stress ∇ (kPa), and the temperature T. This is an interesting development because this equation is in the form of a constant times stress to a power in lieu of the constant times number of applications to a power used in the VESYS system. This characterization, like those used by Monismith and others (11), appears to be more complete than those for VESYS.

PERMANENT DEFORMATION MATERIALS CHARACTERIZATIONS

The use of stress state and pavement temperature directly in the material characterization, as reported by several researchers and discussed above, offers a rather direct application of these important parameters to rutting predictions. This is, in effect, the object of studies by me and by others to define the relationships of the VESYS parameters ALPHA(1) and GNU(1) to stress state and material temperature. If these relationships are established, ALPHA(1) and GNU(1) may be easily expanded to input arrays as functions of distress and temperature and their values selected internal to the computations. This would require modifications to the computer programs to generate ALPHA(1) and GNU(1) rather than simply obtain them directly from input arrays.

Recent Permanent Deformation Test Results

I have for some years transformed all repetitive-load permanent deformation test data available into the ALPHA(1)-GNU(1) characterization in order to gain as much insight as possible about relationships between these material variables and other significant variables, especially deviator stress and material temperature (7,9). Since ALPHA(1) and GNU(1) are not independent of each other, their relationship to each other has also been studied and reported (7). My intent here is to expand the published data to include results of more recent testing and to add relationships between ALPHA(1) and GNU(1) and resilient modulus.

The primary sources of new information on permanent deformations in bituminous mixtures are the following:

1. A factorial of 42 compression tests on cylindrical specimens run by Barksdale (15,16) on base mixtures used in Georgia [these samples were compacted by the 50-blow Marshall procedure and included variations in air content (4.5-6.0 percent), asphalt content (4.2-5.5 percent), deviator stress, lateral stress, and temperature; the load duration was 0.06 s with a loading frequency of 45 cycles/min],
2. A factorial of compression tests for a particular sand-asphalt mixture reported by Singh and Hamdani (10) [this mixture had an asphalt content of 7 percent and was tested with a loading frequency of 60 cycles/min; this factorial included three levels of deviator stress and three levels of temperature, and the lateral stress was held constant at 138 kPa (20 psi)], and
3. Tests on a dense bituminous macadam reported by Brown and Bell (17) (these test results are for a single temperature and a mixture with 4.7 percent asphalt content and 5.7 percent voids; these results are reported to show the effects of changing lateral pressure with deviator stress and temperature constant).

Although reported previously with deviator stress and temperature as independent variables (9), the results of tests by Rauhut that have resilient modulus as the independent variable are also discussed briefly again. Each set of test results is discussed separately below and then summarized in combination. The general trends or relationships developed through previous studies and reported in Rauhut (9) are also listed below:

1. GNU(1) and ALPHA(1) both decrease as stress increases. The decrease in ALPHA(1) generally dominates to cause an important increase in permanent deformation as stress increases.
2. It appears that the mechanisms that affect permanent deformation differ above and below some temperature on the order of 15.6°C (60°F) to 21.1°C (70°F). Below 15.6°C, (a) GNU(1) increases with temperature and (b) ALPHA(1) increases slightly with temperature for the higher stress levels but decreases at the lower stress level. Between 15.6 and 21.1°C, (a) GNU(1) decreases with increasing temperature and (b) ALPHA(1) decreases with increasing temperature.

Georgia Base Mixture

ALPHA(1) and GNU(1) are first displayed as functions of deviator stress in Figure 1 for Georgia black base (15) and sand asphalt (10). The general decrease in ALPHA(1) as deviator stress increases (noted in previous studies) is indicated in Figure 1a, although there appears to be an increasing trend at the lower deviator stresses. And although the results for GNU(1) are somewhat scattered, it

appears to increase at lower deviator stresses and to decrease at higher ones (see Figure 1b). Most other test data indicate a decrease in GNU(1) as deviator stress increases over the full range of deviator stress.

Figure 1. Plots of ALPHA(1) and GNU(1) versus deviator stress for Georgia black base and sand asphalt.

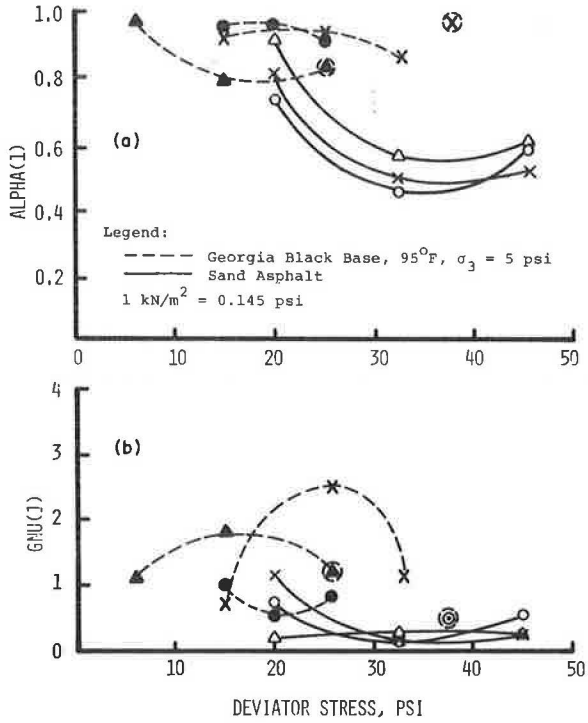
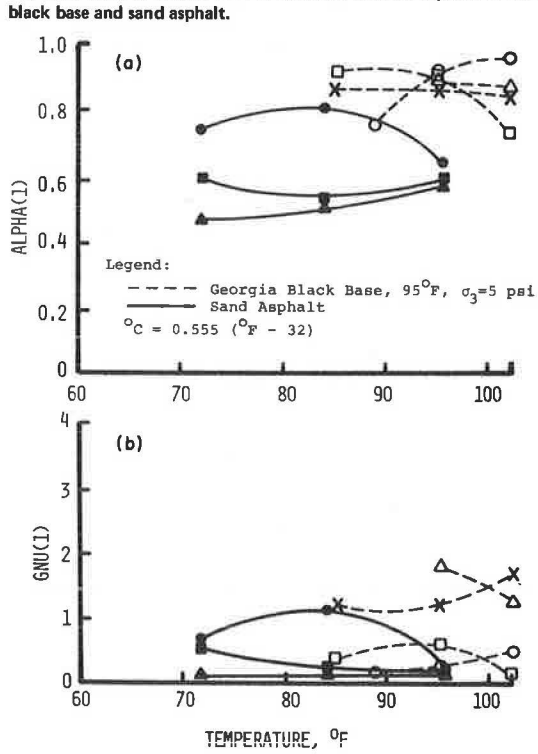


Figure 2. Plots of ALPHA(1) and GNU(1) versus temperature for Georgia black base and sand asphalt.



Three of the four curves in Figure 2a for temperature approximate the trends from previous studies that showed ALPHA(1) decreasing as temperature increased, but the fourth, at a higher lateral pressure, increases as temperature increases. It is not clear why the increased lateral pressure would have this effect, but it appears likely that the higher lateral pressure may have caused more vertical rebound (and thus less measured vertical permanent strain) as the mix became less stiff at higher temperatures.

The curves in Figure 2b indicate that two of the test series displayed the anticipated downward trends in GNU(1) as temperature increases, whereas the other two increased as temperature increases. The increase in GNU(1) with temperature for the mix tested at 207-kPa (30-psi) lateral pressure is consistent with the increase in ALPHA(1) just discussed for this same test series.

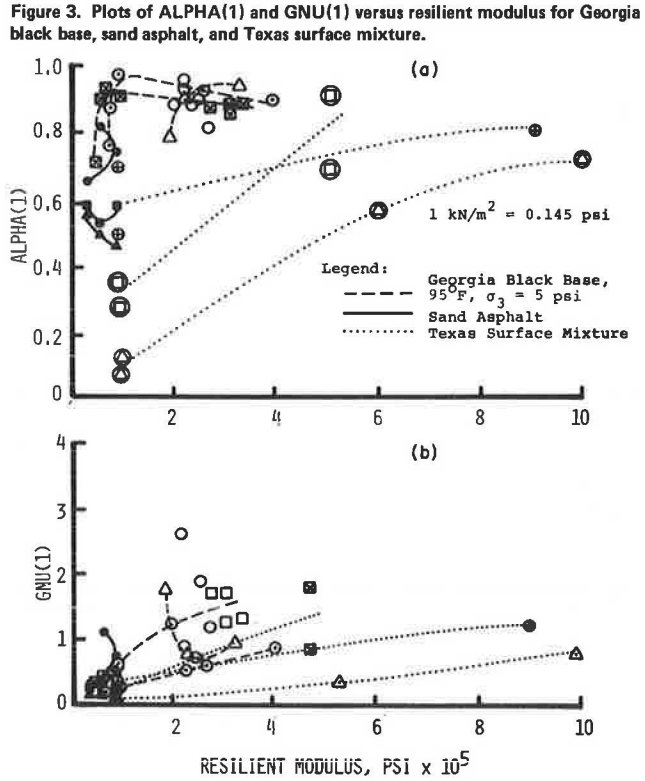
To summarize, Barksdale's test results (15) displayed, in general, the same trends as other previous test results, but some of the test series indicate different trends. These differing trends may indicate a factor or factors not accounted for or yet explained, or they may be test related.

Figure 3 provides graphs of these same test results for resilient modulus with the addition of data for Texas surface mixture (9). Although there is considerable scatter, it appears that ALPHA(1) increases rapidly as mixture stiffness increases in the range of very low mixture stiffness below about 690 000 kPa (100 000 psi) and then decreases at a slow rate as further increases in stiffness occur. GNU(1) appears to generally increase as stiffness increases.

Sand Asphalt for Desert Use

The sand asphalt data in Figure 1 also indicate general decreases in ALPHA(1) and GNU(1) with increasing deviator stress. However, the trends

Figure 3. Plots of ALPHA(1) and GNU(1) versus resilient modulus for Georgia black base, sand asphalt, and Texas surface mixture.



with temperature for this material (Figure 2) were less clear. The increases in permanent deformation with temperature across this range of 25-40°C (72-96°F) were not dramatic, so it is hypothesized that the effects of interactions between ALPHA(1) and GNU(1)--to decrease ALPHA(1) and to increase GNU(1) individually results in increased permanent strain--are not readily discernible in the graphs.

The graphs for sand asphalt in Figure 3 of ALPHA(1) and GNU(1) versus resilient modulus do not show any discernible trends. It should be noted that the resilient modulus was quite low at all temperatures, ranging from 572 000 kPa (83 000 psi) at 25°C (72°F) to 173 000 kPa (25 000 psi) at 40°C (96°F).

Dense Bituminous Macadam

Figure 4 indicates the effect of increasing both confining and vertical pressures to maintain a constant deviator stress and an increasing lateral stress [temperature = 30°C (86°F), asphalt = 4.7 percent, voids = 5.7 percent (17)]. As might be expected, the permanent strain was considerably decreased by the increase in lateral resistance, and ALPHA(1) reflected this as an increasing trend. GNU(1) decreased with increasing confinement for the lower deviator stress but increased for the higher deviator stress.

It appears, based on these limited data, that the dominant effect of lateral confinement is reflected in changes in ALPHA(1); trends for GNU(1) are more erratic.

Texas Surface Mixture

Graphs of trends for variations in ALPHA(1) and GNU(1) with deviator stress and temperature are given in Appendix A of Rauhut and Jordahl (9), and

Figure 4. Plots of ALPHA(1) and GNU(1) versus lateral stress for dense bituminous macadam.

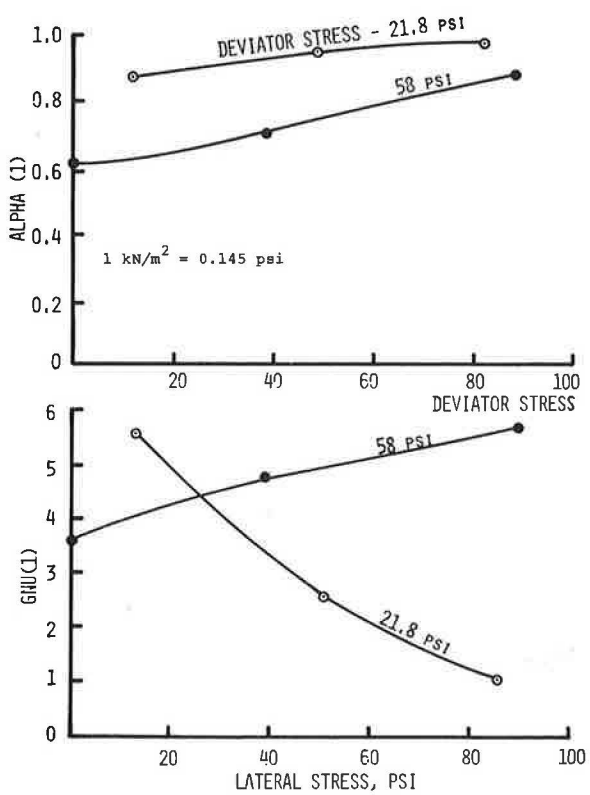
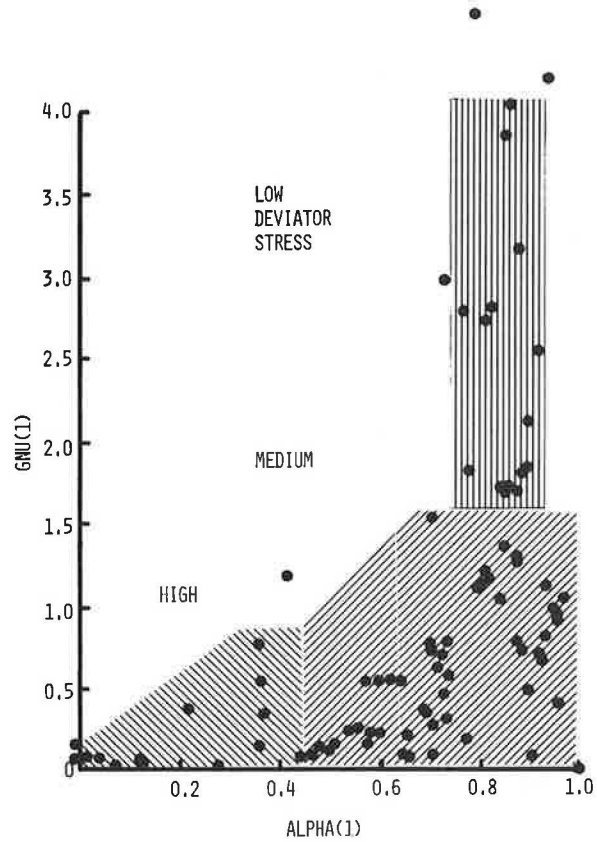


Figure 5. Relation between ALPHA(1) and GNU(1).



the summary of results of that study are given above. However, Figure 3 shows these same test results (dotted lines) plotted as a function of resilient modulus. For these tests and this surface material, ALPHA(1) and GNU(1) both generally increase as the resilient modulus increases.

Relationship Between ALPHA(1) and GNU(1)

The relationship between these two parameters has been studied in the past, and a plot from Rauhut and others (7) has been augmented to include results from testing reported above (see Figure 5). Virtually all of the new data fit the region occupied by previous test results. It appears that GNU(1) is generally in the range of 1.5 or less but may increase to higher values associated with relatively high values of ALPHA(1). Since rutting generally occurs during periods of higher pavement temperature [when ALPHA(1) would generally have relatively lower values], it appears probable that values of GNU(1) greater than 1.5 will not have much significance.

SUMMARY

The principal pavement models currently in use or under development for predicting rutting in flexible pavements have been discussed briefly. Also discussed have been some of their limitations, their materials characterizations, and the parameters on which their values depend.

The results of recent permanent deformation testing were reported, and the relationships between the VESYS material characterization parameters ALPHA(1) and GNU(1) and deviator stress, temperature, resilient modulus, and confining stress were

explored. The insights gained from past studies and from this more recent testing have been combined and are as follows.

1. ALPHA(1) and GNU(1) generally decrease as deviator stress or temperature increases; the decrease in ALPHA(1) dominates to result correctly in more predicted permanent strain.
2. ALPHA(1) increases as confinement increases to result in less predicted permanent strain. GNU(1) is also believed to decrease as confinement increases, but there are not sufficient data to strongly support this hypothesis.
3. Both ALPHA(1) and GNU(1) appear from the limited data to increase as material stiffness increases (predicted total strain would decrease), but ALPHA(1) may decrease for some mixes.

Some of the relationships between the material characterization parameters and other significant variables appear fairly clear; however, others are not as clear. This is believed to be partly the result of the sensitivity of these parameters to numerous material factors and properties, to stress state, and to test conditions. However, the interdependence and nature of these two parameters also affect the clarity of the trends.

The trends noted above for ALPHA(1) are consistent with the well-established increases in permanent strain and rutting in pavements that result from increased pavement temperature or from increased stresses caused by heavier axle loads. The trends for GNU(1) are not always consistent, but the net effect on rutting predictions is generally dominated by ALPHA(1).

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