Compaction Specification for the Control of Pavement Subgrade Rutting

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Soil compaction is a primary measure for controlling permanent deformations of pavement subgrade materials. Major parameters in any compaction specification include the compaction moisture content, compacted density, and depth of compaction. An analytical procedure for predicting subgrade rut depth (permanent deformation) based on the resilient and permanent deformation characteristics of the subgrade is presented. Rut depths associated with a range of values for the major compaction parameters are evaluated for highway pavements using this new procedure. The analytical results suggest a new criterion for compaction moisture content that minimizes subgrade rutting. Contour plots illustrating the trade-offs among compaction level, compaction depth, and natural subgrade conditions are also presented

Accurate assessment of pavement performance throughout its service life is an essential component of pavement design. One of the key factors governing the performance of flexible pavements is the permanent deformation or rutting of the pavement layer materials.

The subgrade is often responsible for much of the permanent deformation in flexible pavements. In many cases where the in situ soil can withstand a specific vehicle-pavement-traffic combination without failure or excessive deformation, it can be used directly as the subgrade material. If, on the other hand, the in situ soil is not suitable or is below the required elevation, imported subgrade materials may be required to support the pavement structure. The compaction process used in placing this imported subgrade soil then becomes an important step in the design process.

A primary objective of compaction for highway and airfield pavements is minimization of the deformations of the subgrade soil, especially those caused by the initial load repetitions. Current subgrade compaction specifications from different highway agencies are summarized in table 1. These specifications are largely empirical, relying heavily upon previous engineering experience. The data in table 1 indicate some disagreement between use of the AASHTO T-180 (modified Proctor compaction energy) and the AASHTO T-99 (standard Proctor compaction energy) test specifications.

One quantitative criterion for comparing existing empirical compaction specifications or for developing new specifications is the rut depth at the top of the subgrade layer. Rut depth magnitude can be evaluated either by structural analysis of the layered pavement system or by statistical analysis of past performance data. The present study is an example of the first approach.

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In this study, a nonlinear analytical methodology for calculating subgrade rut depth is presented and used in a series of analytical studies to evaluate the influence of various compaction parameters on subgrade rutting. Four specific compaction parameters are explicitly considered: (a) compaction moisture content; (b) compacted density (defined here as the percent compaction relative to the modified Proctor maximum density); (c) compaction depth; and (d) natural subgrade condition. A widely used empirical compaction specification for highways is evaluated using this methodology. Finally, some guidelines for more rational compaction specification for cohesive subgrade soils are drawn from the analysis results.

SUBGRADE RUTTING MODEL

In pavement structures subjected to cyclic loading, the cumulative permanent vertical strain after N cycles of loading, $\varepsilon_{pc}(N)$, can be calculated as the summation of the incremental permanent strains developed in each cycle:

$$\varepsilon_{pc}(N) = \sum_{I=1}^{N} \varepsilon_p(I) \quad (1)$$

in which $\varepsilon_p(I)$ is the incremental permanent strain for the Ith loading cycle. Equation 1 is represented graphically in figure 1, where linear behavior is assumed. Because of the plastic nature of pavement and subgrade materials, the loading modulus, E_{lo}, is in general not equal to the unloading resilient modulus, M_r.

A relationship between E_{lo} and M_r (*10*) can be developed based on the following the typical relationship between $\varepsilon_{pc}(N)$ and N suggested by Monismith (*8*) and Barksdale (*3*):

$$\varepsilon_{pc}(N) = aN^b \quad (2)$$

in which a and b are empirical material constants determined from a plot of log $\varepsilon_{pc}(N)$ vs. log N. The incremental permanent strain caused by the Nth load repetition is obtained by differentiating Eq. 2:

$$\frac{d\varepsilon_{pc}(N)}{dN} = \varepsilon_p(N) = abN^{b-1} \quad (3)$$

The resilient vertical strain due to unloading during the Nth cycle, $\varepsilon_r(N)$, is commonly assumed to be independent of the number of cycles (*10*), i.e.:

$$\varepsilon_r(N) = \varepsilon_r \quad (4)$$

Dividing Eq. 3 by ε_r:

$$\frac{\varepsilon_p(N)}{\varepsilon_r} = \frac{ab}{\varepsilon_r} N^{b-1} \quad (5)$$

TABLE 1 EXAMPLES OF COMPACTION LEVELS SPECIFIED BY VARIOUS HIGHWAY AGENCIES

Agency	Specified Compaction Level
Federal Highway Administration (4)	90% AASHTO T-99
AASHTO (1)	95% AASHTO T-99
Asphalt Institute (2)	95% AASHTO T-180 (top 12 in.) 90% AASHTO T-180 (below)
Maryland State Highway Administration (7)	95% AASHTO T-180 (top 12 in.) 92% AASHTO T-180 (below)
Indiana State Highway Administration (5)	95% AASHTO T-99
Colorado State Highways (9)	95% AASHTO T-99 or 90% AASHTO T-180

Note: AASHTO T-99 = standard Proctor test
AASHTO T-180 = modified Proctor test

For convenience, Eq. 5 can be simplified by defining two new material parameters:

$$\mu = \frac{ab}{\varepsilon_r} \tag{6}$$

$$\alpha = 1 - b \tag{7}$$

Eq. (5) then becomes:

$$\varepsilon_p(N) = \varepsilon_r \mu N^{-\alpha} \tag{8}$$

On the other hand, as shown in figure 1:

$$\varepsilon_p(N) = \varepsilon_t(N) - \varepsilon_r \tag{9}$$

in which $\varepsilon_t(N)$ is the total loading vertical strain developed during the Nth load cycle. By assuming linear stress-strain behavior during loading and unloading with different moduli E_{lo} and M_r, the total and resilient strains in the vertical or z-direction can be represented respectively as

$$\varepsilon_{t_z} = \frac{1}{E_{lo}(N)}[\sigma_z - \nu(\sigma_x + \sigma_y)] = \frac{\sigma_z^*}{E_{lo}(N)} \tag{10}$$

and

$$\varepsilon_{r_z} = \frac{1}{M_r}[\sigma_z - \nu(\sigma_x + \sigma_y)] = \frac{\sigma_z^*}{M_r} \tag{11}$$

in which $\sigma_z^* = \sigma_z - \nu(\sigma_x + \sigma_y)$ and ν is assumed the same for both loading and unloading. Combining Eqs. 8, 9, 10, and 11:

$$\varepsilon_p(N) = \frac{\sigma_z^*}{E_{lo}(N)} - \frac{\sigma_z^*}{M_r} = \frac{\sigma_z^*}{M_r}\mu N^{-\alpha} \tag{12}$$

Rearranging Eq. 12:

$$E_{lo}(N) = \frac{M_r}{1 + \mu N^{-\alpha}} \tag{13}$$

Based on Eqs. 1 and 13, the following procedures can be used to calculate rut depth:

(1) Determine the stress-dependent unloading (resilient) modulus, M_r;

(2) Use M_r in a multilayer elastic solution to calculate the pavement recovery deformation during unloading, δ_{unlo} (constant for all N);

(3) For a specific load cycle N, determine $E_{lo}(N)$ using Eq. 13;

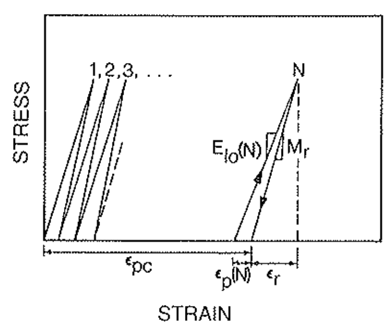

FIGURE 1 Strains developed during cyclic loading.

(4) Use $E_{lo}(N)$ in a multilayer elastic solution to calculate the pavement deformation during loading at cycle N, $\delta_{lo}(N)$;

(5) Determine the incremental permanent deformation at load cycle N, $\delta_p(N) = \delta_{lo}(N) - \delta_{unlo}$;

(6) Repeat steps 3 to 5 for various N values;

(7) Determine the total accumulated rut depth at load cycle N by numerical integration of the values obtained in step 5.

COMPUTER SOLUTION ALGORITHM

The computer program ERHAP (Evaluation of Rutting for Highway and Airfield Pavements) follows the procedure described in the preceding section to calculate the rut depth at the top of the subgrade layer for flexible pavement systems. The unloading deformation is computed from the cyclic stresses and the resilient modulus using the following equations to represent the stress dependency of the pavement layers:

For cohesive soils:

$$M_r = k_1 \, \sigma_d^{-k_2} \tag{14}$$

For cohesionless soils:

$$M_r = k_1 \, \theta^{k_2} \tag{15}$$

in which k_1 and k_2 are material coefficients, σ_d is the cyclic deviator stress, and θ is the bulk stress.

Stress states cannot be computed without specification of the moduli for the various soil layers in the pavement, and the moduli cannot be determined without knowledge of the existing stress states. Consequently, the solution must be obtained through an iterative procedure. Starting with an initial assumed value of modulus for each stress dependent layer, stress states due to a specific load configuration are evaluated using multilayer linear elastic theory. Updated moduli values are obtained from these computed stresses using Eqs. 14 and 15. The process is repeated until the differences between the calculated stresses at successive iteration cycles are within a specified tolerance level.

The computer program BISAR (*11*), developed by the Shell Oil Company, is incorporated in ERHAP as a subprogram for calculating the stresses at the mid-depth of each layer. The BISAR program is based on multilayer linear elastic theory and is capable of analyzing stresses, strains, and deformations for multiple load conditions.

For rut depth calculation, ERHAP again employs the BISAR program as a subprogram to compute the vertical deformation at the top of the subgrade soil. The nonlinear resilient moduli, calculated iteratively as described above, are used as unloading moduli for the calculation of the unloading recoverable deformation, δ_{unlo}. The value of the loading modulus is determined at each load cycle for each subgrade layer using Eq. 13, and the incremental loading deformation $\delta_{lo}(N)$ is calculated by BISAR. Note that the stress dependence of the loading modulus is incorporated through the M_r material parameter in Eq. 13. The incremental permanent deformation $\delta_p(N)$ is then:

$$\delta_p(N) = \delta_{lo}(N) - \delta_{unlo} \tag{16}$$

Values of $\delta_p(N)$ are calculated at various values of $N = N_i$ and the cumulative permanent deformation or rut depth, RD,

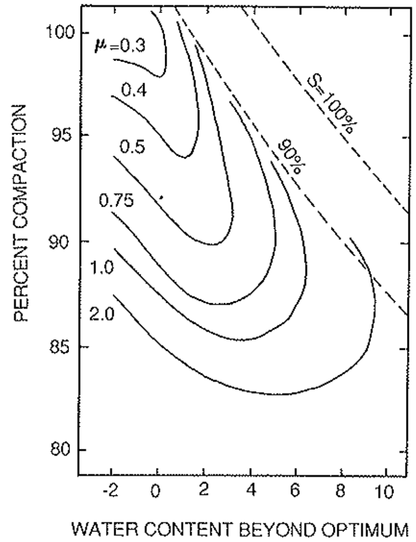

FIGURE 2 Values of μ at different dry density-compaction moisture combinations (soaked condition).

is evaluated at the final load cycle by numerical integration:

$$RD = \sum_{i=1,2,3} \frac{\delta_p(N_i) + \delta_p(N_{i+1})}{2} (N_{i+1} - N_i) \tag{17}$$

INFLUENCE OF COMPACTION PARAMETERS ON SUBGRADE RUTTING

The permanent deformation at the top of the subgrade is used in this study as the principal criterion for evaluating compaction specifications for subgrade soils. The soil parameters μ, α, and CBR for a typical cohesive soil at different compaction conditions are shown in figures 2 through 4 (*6*). Other soil properties are summarized in table 2. The μ and α parameters will in general be functions of soil type, moisture content, and compacted density. The influence of stress level on these parameters for this soil is negligible (*6*). The μ and α coefficients are used as input to ERHAP to calculate rut depths for different compaction conditions. The CBR values are used

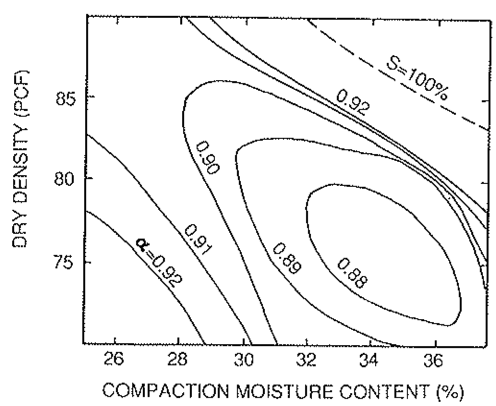

FIGURE 3 Values of α at different dry density-compaction moisture combinations (soaked condition).

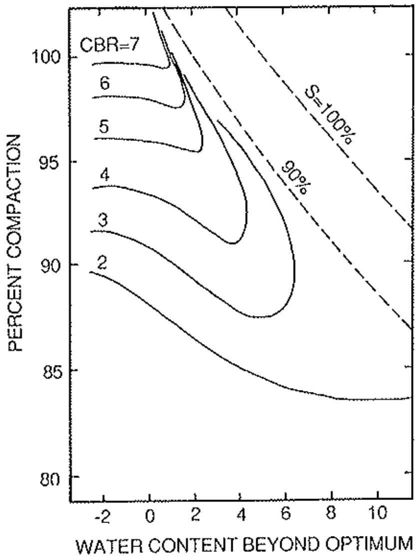

FIGURE 4 Values of CBR at different dry density-compaction moisture combinations (soaked condition).

to predict the nonlinear resilient modulus using the empirical relation (*6*):

$$\log M_r = 1.0016 + 0.0430(\text{CBR}) - 1.9557\left(\frac{\log \sigma_d}{\text{CBR}}\right) - 0.1705 \log \sigma_d \quad (18)$$

in which M_r is in ksi, δ_d is in psi, and CBR is in percent.

As the soaked CBR condition is the critical case for evaluating subgrade strength in highway pavement design, values of μ and α at the soaked condition were accordingly used in all analyses reported here. Note that even if a flexible pavement section is located in a dry environment, the permanent deformation that occurs during a short wet season is substantial and will often control the design.

As noted earlier, there is wide variation among the compaction specifications of different highway agencies. The Asphalt Institute compaction specification (*2*) was chosen for investigation in this study because it is the most comprehensive, i.e., all four major compaction parameters are considered: compacted density, compaction moisture content, depth of compaction, and natural subgrade condition. The Asphalt Institute compaction criteria for cohesive soils require a density not less than 95 percent of the AASHTO T-180 (modified Proctor) density for the top twelve inches of subgrade and 90 percent for below. The compaction moisture content must be within one to two percentage points below the modified Proctor optimum water content.

Typical highway loads are represented in the analyses by a standard 18-kip single axle load (18 KSAL) with one million repetitions. This loading condition was used in conjunction with the AASHTO flexible pavement design procedures in all cases analyzed. A schematic pavement section is shown in figure 5. This pavement section, together with the standard highway loading, was used to investigate the influence of the various compaction parameters.

TABLE 2 PROPERTIES OF COHESIVE SOIL USED IN STUDY (*6*)

Soil description:	"EPK" Kaolinite (available from The Feldspar Corp., Spruce Pine, N.C.)
USCS Class:	ML
Plastic Limit:	41.9%
Liquid Limit:	48.2%
Clay content:	34% (particles smaller than 0.002 mm.)

Compaction Water Content

As shown in figure 3, each compaction level has an associated compaction water content at which μ is minimized. Conceptually, this should also represent the optimum condition for minimizing subgrade rutting. The relationship between compaction level and water content for minimizing μ can be represented by the regression equation:

$$w_o = 32.1 - 0.332(PC) \qquad (R^2 = 0.97) \qquad (19)$$

in which w_o is the percentage point difference between the compaction moisture content and the modified Proctor optimum moisture content and PC is the relative compaction in percent based on the modified Proctor maximum dry density.

From figure 4, a different PC vs. w_o relationship is found to maximize CBR. This relationship can be represented by the regression equation:

$$w_o = 39.6 - 0.392(PC) \qquad (R^2 = 0.99) \qquad (20)$$

Both CBR and μ affect rutting magnitude. To investigate the relative importance of these two parameters, rut depth was calculated at different values of w_o for two pavement sections, one resting on a uniform subgrade with PC = 95 percent and the other on a subgrade with PC = 90 percent. One million 18-KSAL load repetitions were assumed in each case. As is clearly shown in figure 6, the compaction moisture content corresponding to the minimum μ-value produces less rutting than does the compaction moisture content corresponding to the maximum CBR. Consequently, the relation-

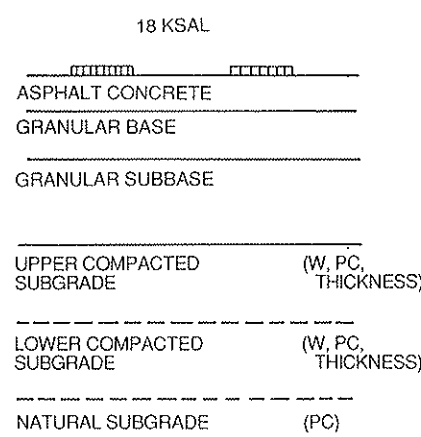

FIGURE 5 Pavement section schematic for rut depth analyses.

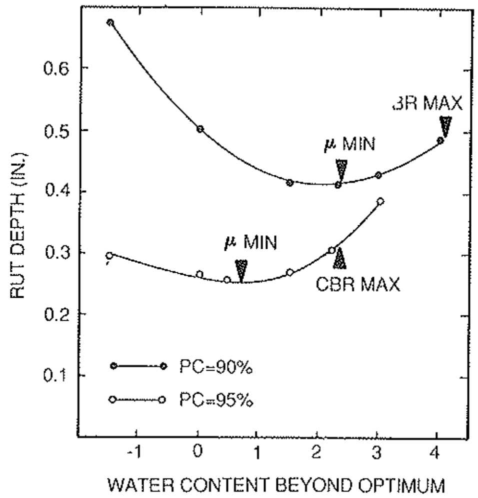

FIGURE 6 Influence of compaction moisture content on rut depth at different compaction levels.

ship between compaction moisture content and percent compaction given in Eq. 19 is the more suitable criterion for compaction moisture control.

The reduction in rutting resulting from this proposed compaction moisture criterion can be illustrated by calculating the rut depth at the top of a subgrade compacted to the Asphalt Institute's minimum compaction level requirements (95 percent for the top twelve inches and 90 percent below). For compaction moisture contents based on Eq. 19 (w_o = 0.6 percentage points for PC = 95 percent and 2.3 points for PC = 90 percent; see Eq. 19), the calculated rut depth is 0.382 inches. For comparison, rut depths were calculated at the same compaction levels but at a variety of uniform moisture contents. A normalized rut depth factor RF is defined as

$$RF = \text{(Computed Rut Depth)} / 0.382 \text{ in.} \quad (21)$$

The relation between RF and w_o is shown in figure 7. The RF values are always greater than one, implying that the lowest rut depth is obtained by varying w_o with PC as proposed in Eq. 19. Compacting wet of optimum as specified by Eq. 19 reduces the rut depth by 35 percent from that obtained using the Asphalt Institute specification of 1.5 percentage points dry of optimum (i.e., $w_o = -1.5$).

Compaction Level

Rut depths corresponding to five different compaction levels and three different thicknesses for the top subgrade layer were calculated. The five compaction combinations considered were as follows:

1. As specified by the Asphalt Institute (95 percent compaction for the top layer and 90 percent below)
2. Three percentage points dry of specifications (92 percent compaction for the top layer and 87 percent below)
3. Five percentage points dry of specifications (90 percent compaction for the top layer and 85 percent below)
4. Two percentage points wet of specifications (97 percent compaction for the top layer and 92 percent below)
5. Five percentage points wet of specifications (100 percent compaction for the top layer and 95 percent below)

The three different thickness values (d_1) considered for the top subgrade were 6, 12, and 24 inches; recall that the Asphalt Institute specifies 12 inches. The AASHTO design procedure was used to determine the required thicknesses for the pavement layers. In this procedure, the total pavement thickness is dependent on the compaction level of the top subgrade layer. The μ, α, and CBR values for each subgrade layer were taken from figures 2, 3, and 4 while M_r was calculated from Eq. 18.

Subgrade rut depth was calculated at one million 18-KSAL load repetitions for each of the 15 combinations of compaction

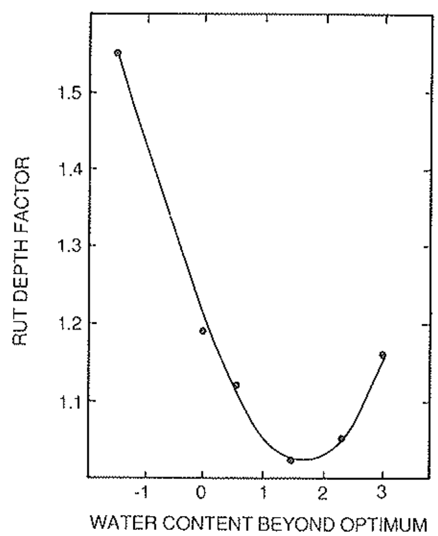

FIGURE 7 Influence of compaction moisture content on rut depth factor for Asphalt Institute compaction specification.

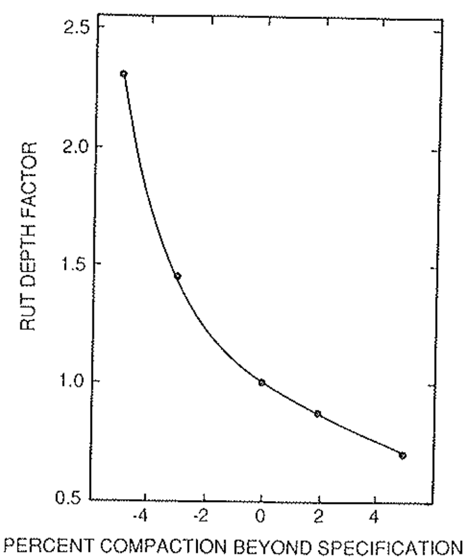

FIGURE 8 Influence of compacted density of top compacted subgrade layer on rut depth factor.

level and compaction depth (5 values of PC and 3 values of d_1). The normalized rut depth factors determined using Eq. 20 are summarized in figure 8 for d_1 = 12 inches. The rut depth factor increases significantly for negative PC_o values (PC_o is defined as the percentage point difference between the actual percent compaction and that specified by the Asphalt Institute). An increase in compaction level by 5 percentage points reduces RF from 1.0 to 0.7 while a decrease in compaction level by the same amount increases RF to 2.3.

The results to this point are all based on traffic levels of one million repetitions of the standard 18-KSAL vehicle. The influence of the number of load repetitions on the RF-PC_o relationship was investigated by analyzing repetition levels of 50 thousand and 20 million. The variation in normalized RD with PC_o for different numbers of repetitions is shown in figure 9; the normalization factor used in the denominator of Eq. 21 in these cases is the rut depth computed for the specified traffic conditions and based upon a pavement design and compaction conditions as specified by AASHTO and the Asphalt Institute. The normalization process largely compensates for the effect of load repetitions. Therefore, the analysis of a single repetition level may be sufficient for investigating the influence of the compaction parameters on the rut depth factor.

Depth of Compaction

The thickness of the upper compacted subgrade layer (d_1) specified by the Asphalt Institute is 12 inches. Contours of various PC_o-d_1 combinations producing the same subgrade rut depth are illustrated in figure 10. For example, a point on the RF = 1 contour represents a PC_o-d_1 combination that is equivalent to the Asphalt Institute specifications, at least in terms of subgrade rutting. The contours graphically illustrate the relative gains and losses in rut depth that result from any PC_o-d_1 combination.

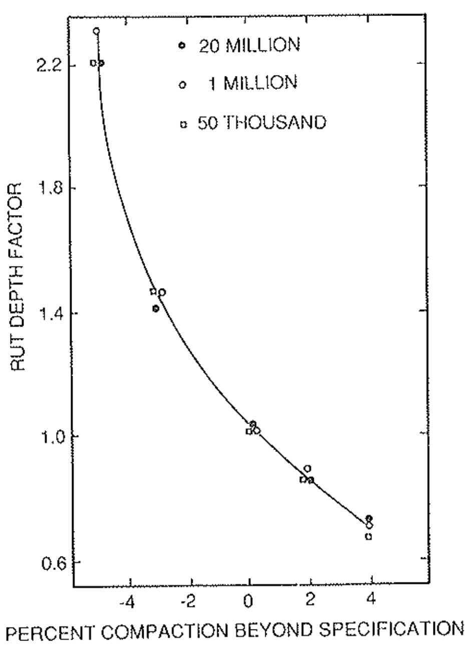

FIGURE 9 Variation of rut depth factor with compacted density for all repetition levels.

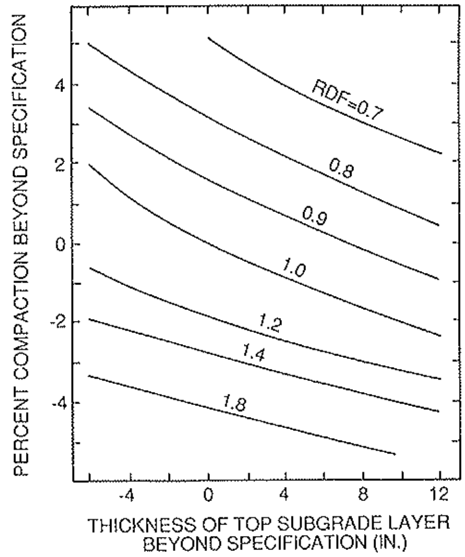

FIGURE 10 Combined influence of d_1 and PC_o on rut depth factor.

Natural Subgrade Condition

The Asphalt Institute compaction specification implicitly assumes an infinite thickness for the lower compacted subgrade layer. In effect, the Asphalt Institute specifications require that the natural subgrade have an in situ density corresponding to a compaction level of 90 percent. Clearly, this is not always the case. The influence of the natural subgrade condition on rut depth is illustrated through analyses of a pavement section composed of three subgrade layers. The top two layers are compacted layers and the bottom layer represents the natural subgrade. Three natural subgrade conditions were investigated: well compacted, defined as PC = 90 percent; moderately compacted, defined as PC = 87 percent; and poorly compacted, defined as PC = 85 percent.

It is clear that if the thickness of the middle subgrade layer is increased to the limit where the induced stresses at the bottom layer approach zero, then the natural subgrade condition will have no effect on rut depth. Alternatively, when the natural subgrade is well compacted (PC = 90 percent), the middle compacted subgrade layer is equivalent to the natural subgrade and only the top compacted subgrade layer influences rut depth. Figure 11 shows the trade-offs for the intermediate conditions where the natural subgrade is moderately to poorly compacted for different thicknesses of a middle subgrade layer (d_2) compacted to the specified 90 percent level. For example, a poorly compacted natural subgrade requires a 50-inch middle subgrade layer to achieve a RF of 1.0, while a moderately compacted natural subgrade requires only 36 inches for the middle subgrade layer.

Because of the relatively large layer thicknesses needed to overcome the influence of inferior natural subgrades, it is worthwhile investigating the compaction levels for the upper two subgrade layers required to achieve a rut depth factor of 1.0 at smaller d_2 values. Figure 12 illustrates computed rut

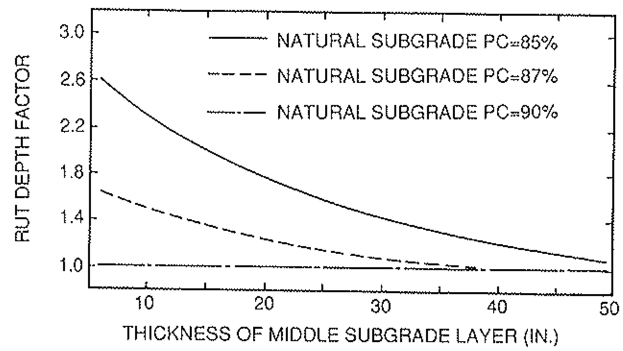

FIGURE 11 Influence of depth of middle compacted subgrade layer on rut depth factor for various natural subgrade conditions.

depth factors at different combinations of d_2 and subgrade compaction levels for a moderately compacted natural subgrade. For example, any point on the $RF = 1$ line in figure 12 represents a PC_o-d_2 combination that can be used with a moderately compacted natural subgrade as a substitute for the natural subgrade conditions implicitly assumed in the Asphalt Institute specifications.

SUMMARY AND CONCLUSIONS

A methodology for calculating the rut depth at any point throughout a pavement subgrade has been presented. This approach considers the stress dependency of the resilient modulus as well as the plastic behavior (as manifested by the difference between loading and unloading moduli) of cohesive soils. The approach can treat any loading configuration (single or multiple loads) and the effect of overburden stresses on the nonlinear moduli. A computer program based on the BISAR multilayer elastic analysis algorithms has been developed for performing these calculations.

A series of analytical studies was performed using the rutting model to provide guidance for more rational compaction specifications. Four major compaction parameters were considered in these studies: compaction moisture content; compaction level (percent compaction); depth of subgrade compaction; and the natural subgrade condition. Soil properties were based upon a single but typical cohesive soil type. The soaked condition was assumed in all analyses as it represents the critical case for rutting. Conclusions regarding the influence of each of the four compaction variables are as follows:

1. *Compaction Moisture Content.* For a given compaction level, there exists a specific compaction moisture content that minimizes subgrade rutting. The relationship between compaction level and moisture content for minimum rutting is given by Eq. 19 for the cohesive subgrade soil considered in this study.
2. *Compaction Level.* Results from this study confirm the reasonableness of the compaction levels recommended by The Asphalt Institute for highway loads. It was found that a decrease in compaction level from the specified values caused a significant increase in subgrade rutting while increases in compaction level beyond the recommended values produced negligible improvements. For example, calculated rut depth increased by 130 percent when the compaction level was decreased by 5 percentage points from the Asphalt Institute's recommendations; however, rut depth decreased by the comparatively smaller value of 30 percent when the compaction level was increased by 5 percentage points over the recommended values.
3. *Depth of Subgrade Compaction.* The thickness of the upper compacted subgrade layer was found to significantly influence rut depth. For example, increasing the thickness of the top subgrade layer from 6 to 24 inches reduced the computed rut depth by approximately 30 percent. Contours showing the variation of rut depth for different compaction level and compaction depth combinations are provided for highway loads.
4. *Natural Subgrade Condition.* The Asphalt Institute compaction specifications implicitly assume that the natural subgrade is compacted to 90 percent of the AASHTO T-180 maximum. In reality, this condition often does not occur. Contour lines have been developed to illustrate the combinations of compaction level and thickness for the middle subgrade layer that can be used to overcome the influence of moderately or poorly compacted natural subgrades.

The number of load repetitions was found to have a negligible influence on all of the general conclusions summarized above.

Although the results from these analyses have produced many interesting and useful observations regarding subgrade compaction criteria, it must be kept in mind that the analyses are all based upon properties for a single cohesive soil type. While it is expected that other cohesive subgrade soils will exhibit similar qualitative behavior, generally applicable quantitative conclusions will require additional studies that consider a range of cohesive soil properties.

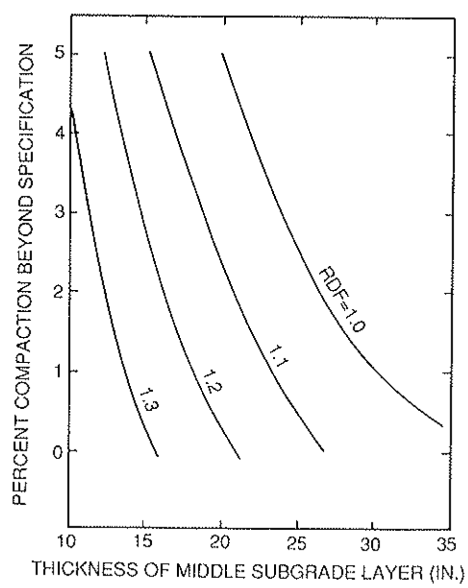

FIGURE 12 Combined influence of d_2 and PC_o on rut depth factor for moderately compacted natural subgrade.

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