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Rutting Evaluation of Subgrade Soils in Ohio

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The results of several previous investigations have led to the conclusion that rutting criteria should be included in any pavement design methodology that attempts to achieve the goal of improved pavement serviceability. Moreover, in some practical cases, it is necessary to estimate the rutting expected to occur in a pavement system during a certain period. Therefore, it is necessary to develop a scheme for the estimation of rutting. Because it is the foundation of the pavement, the subgrade makes a considerable contribution to its rutting. The objective of this research was to study the rutting in subgrade soils experimentally. The rate-process theory approach was used for the analysis of the results. Five types of silty soils were obtained from four different construction sites in Ohio, and laboratory-prepared samples were used for uniaxial dynamic testing. A direct general relationship that relates rutting to the dynamic modulus and the applied stress level was developed. On the basis of that relationship, a scheme for the estimation of subgrade permanent deformation is proposed and design nomographs for the soils studied were developed. The findings of this study are limited to the types of soils (silty and clayey) tested; further studies should indicate their applicability to other materials also.

In recent years, extensive studies have been carried out to develop various rational pavement design schemes and material-characterization techniques for use in evaluating pavement-component responses to loading and environmental conditions.

The analysis of permanent deformation (i.e., rutting) in a pavement system is an important element of many of the proposed rational pavement design schemes that require detailed consideration of the progressive accumulation of plastic strains in each layer of a pavement subsystem and its supporting layers.

It has been estimated in the AASHTO Road Test that, in some cases, the subgrade layer contributes up to 19 percent of the total pavement system rutting.

Therefore, rutting in the subgrade may be critical, especially for subgrades subjected to saturation for long periods and for weaker subgrades in which excessive permanent deformations are unavoidable. Hence, subgrade rutting should be considered in any new design methodology.

In rational design systems, the soil properties are described by the subgrade modulus or modulus of resilience (M_R), which is dependent on the deviatoric stress, which, in turn, is influenced by load intensity and pavement geometric characteristics. The M_R is also greatly dependent on the type of soil. From the pavement designer's viewpoint, although the knowledge of modulus versus stress and modulus versus type of soil relations are required, this information is not entirely sufficient. To estimate pavement rutting, there are two additional basic requirements: (a) a determination of environmental effects and (b) a determination of the properties affecting soil rutting under repeated loading.

Thus, the problem is to develop a mechanistic procedure for estimating the amount of rutting that will occur in a selected or designed pavement structure to be constructed in an area that has known climatic characteristics.

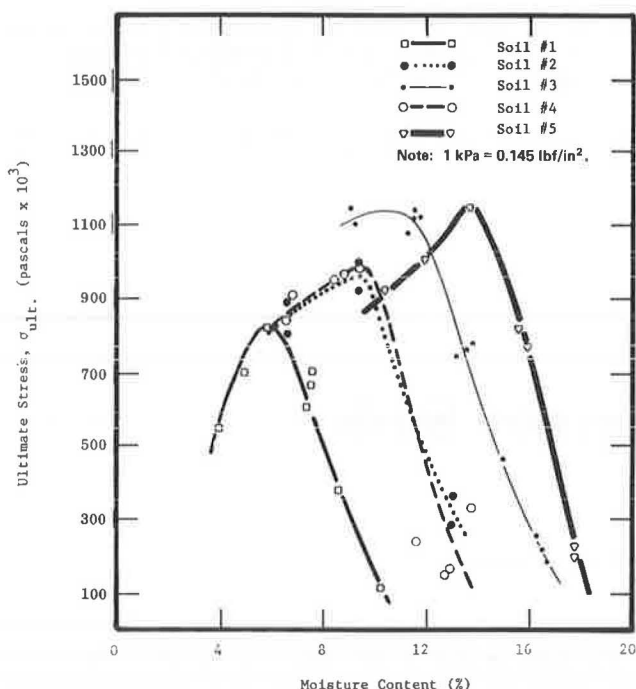
One approach to the estimation of subgrade rutting involves limiting the vertical compressive strain at the subgrade surface to some tolerable level that is associated with a specific number of load repetitions (1). By controlling the material characteristics and the pavement thickness so that the strain level is not exceeded, a permanent deformation that is less than or equal to the prescribed limit is ensured. The suggested limiting criteria depend on the method of analysis, the stiff-

Table 1. ASTM standards (soil properties and soil classifications).

Soil No.	County	Project No.	Location	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Specific Gravity ^a	Soil Classification		
								Unified	AASHTO	FAA
1	Auglaize	39-75	Greenville Road	18.6	13.2	5.4	2.720	SM	A-4	E-3
2	Carroll	2-75	0-542	23.2	12.8	5.4	2.705	SM	A-4	E-6
3	Licking	239-75	0-21 N (top layer)	23.9	17.7	6.2	2.631	ML-CL	A-4	E-6
4	Licking	239-75	0-21 N (bottom layer)	NA	NA		2.691	SM	A-2-4	E-2
5	Hamilton	461-75	I-275	33.6	17.5	16.1	2.670	CL	A-6	E-7

^aThis test was conducted according to Massachusetts Institute of Technology recommendations.

Figure 1. Unconfined-strength curves.



nesses, and the Poisson's ratios for each sublayer. The material characteristics considered in a pavement design should be within the same range as those used in the limiting analysis; otherwise, the resulting analysis will have little significance.

A second approach is to estimate the rutting that results from repeated traffic loading over the design period. For subgrade rutting, Majidzadeh and others (2) and Monismith and others (3) have established the relation

$$\epsilon_p/N = AN^m \quad (1)$$

where

ϵ_p = permanent strain,
 N = number of stress repetitions, and
 A and m = rutting parameters; $A = \epsilon_p$ at $N = 1$, and m is the slope of the straight-line relationship between $\log(\epsilon_p/N)$ and $\log N$.

Majidzadeh based this finding on a relationship between the creep strain versus time and plastic strain versus number of load applications relationships. Mitchell and others (4) had proposed a similar relationship for creep, based on the rate process theory. Experimental studies (2, 5, 7) have supported the validity of this relationship for a practical wide range of soil types, applied dynamic stresses, and environmental conditions.

Khedr (5) and Majidzadeh and others (6), in correlating the parameter A in Equation 1 to the modulus of resilience at a constant applied stress, have established the relationship

$$A = K|E^*|^S \quad (2)$$

where

$|E^*|$ = dynamic modulus of resilience (i.e., magnitude of dynamic modulus) and

K and S = parameters that depend on applied dynamic stress.

Their findings that the parameter m is almost constant is also supported by a statistical analysis of m -values by Bayomy (7).

In this study, the variation of A with stress level was investigated for different types of silty soils in various as-compacted and saturated conditions. The purpose was to develop a rutting estimation scheme for the subgrade that considers most of the possible influencing factors.

SOILS TESTED

In the laboratory phase of this study, five soils were obtained from four different locations in Ohio. Each soil was brought from the field, oven dried, and sieved through a 12.7-mm (0.5-in) sieve. The grain-size distribution was determined for each soil by using both the washing method and hydrometer analysis. Standard soil identification and classification tests were carried out; the pertinent properties are summarized in Table 1 (7, 10). Figure 1 shows the unconfined-strength curves for these soils. The samples measured 70.6 mm (2.78 in) in diameter and 145-152 mm (5.7-6.0 in) in height and were compacted by using drop-hammer compaction.

Uniaxial dynamic tests were performed on the laboratory-prepared soil samples. To avoid the effects of aging, the dynamic modulus (M_R) was determined after the first 2000 cycles were applied. Rutting curves (permanent deformation versus number of load repetitions) were measured for each sample before and after saturation to determine the corresponding subgrade rutting parameters (i.e., A and m).

ANALYSIS OF RESULTS

The parameter A is dependent on soil type and structure, moisture content, dry density, and dynamic stress level. In previous research (5, 6, 7), $|E^*|$ has been shown to represent soil structure, moisture content, and dry density. And, according to Equation 2, A is a function of dynamic modulus and applied stress. The relationship between E^* and the applied stress (σ_{ap}) is discussed in the following section.

Figure 2. Relationship between E^* and σ_{apl} for different types of soil.

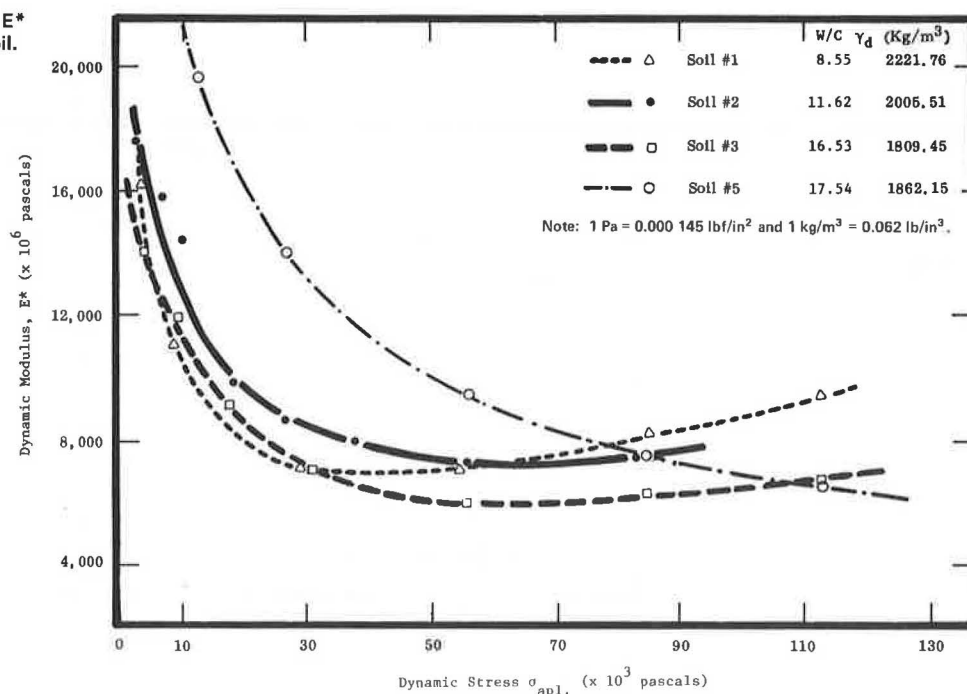
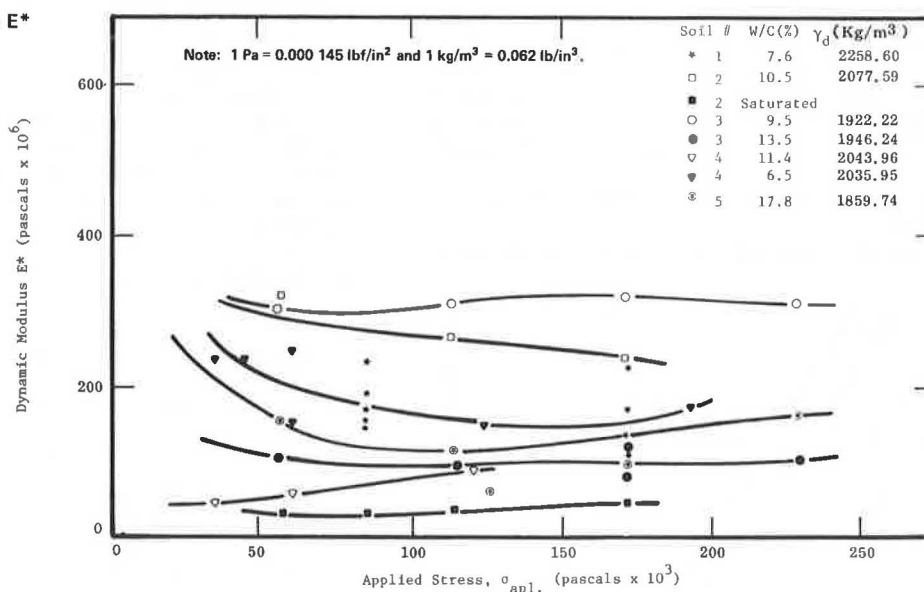


Figure 3. Relationship between E^* and σ_{apl} .



Dynamic Modulus | E^* |

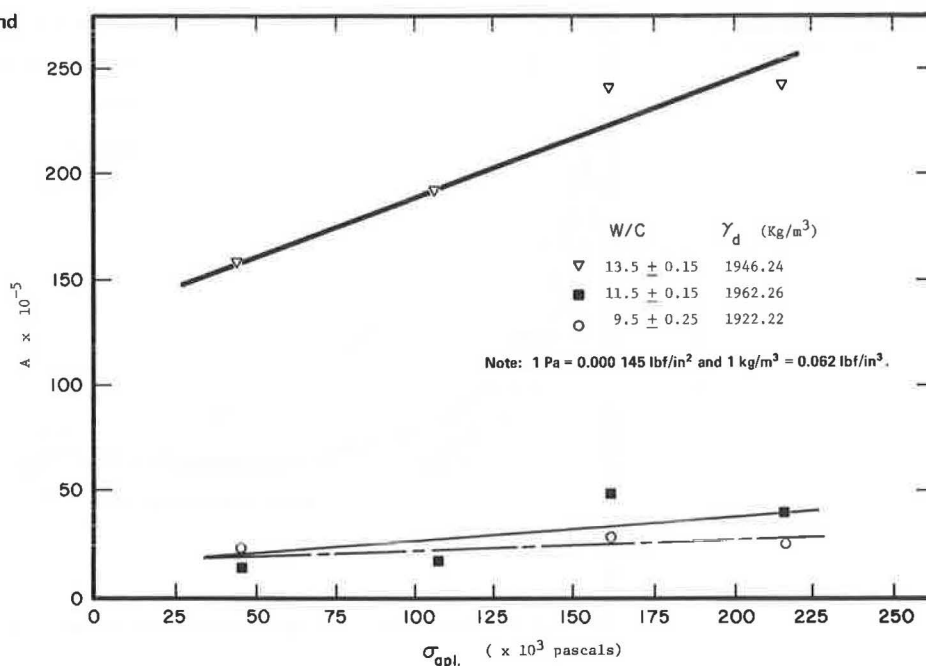
Figures 2 and 3 show the general relationship between E^* and σ_{apl} for the soils used. The dynamic modulus generally is found to decrease rapidly with an increase in applied dynamic stress up to a certain level; then there is a slight increase in E^* until, finally, it tends to converge to a steady value in the higher range of applied stresses. These results generally agree with the relationships proposed by Majidzadeh and others (2) and by Seed and others (8).

For the range of applied stresses considered in this study, the E^* -values were found to be almost constant above approximately 55.2 kPa (8 lbf/in²). The consistency of E^* in this range for each moisture content and dry density for all soils supports the choice of E^* as a representative material characteristic in that its value

reflects such material properties as dry density, moisture content, and soil structure. Therefore, the dynamic modulus (i.e., E^*) is a material property that is dependent on soil type, applied stress, and moisture content.

In the Dynaflect in situ measurement of M_s , the stresses in the subgrade under Dynaflect dynamic loading are considerably lower than those under the 40.5-kN (9000-lbf) design wheel load. Because of the stress dependency of the soil modulus, the dynamic modulus calculated from field Dynaflect measurements should be adjusted to represent the actual traffic loading conditions. The measured modulus values are higher than those under actual in situ support conditions. The laboratory dynamic modulus or field-adjusted dynamic modulus is then incorporated into the rational pavement design models.

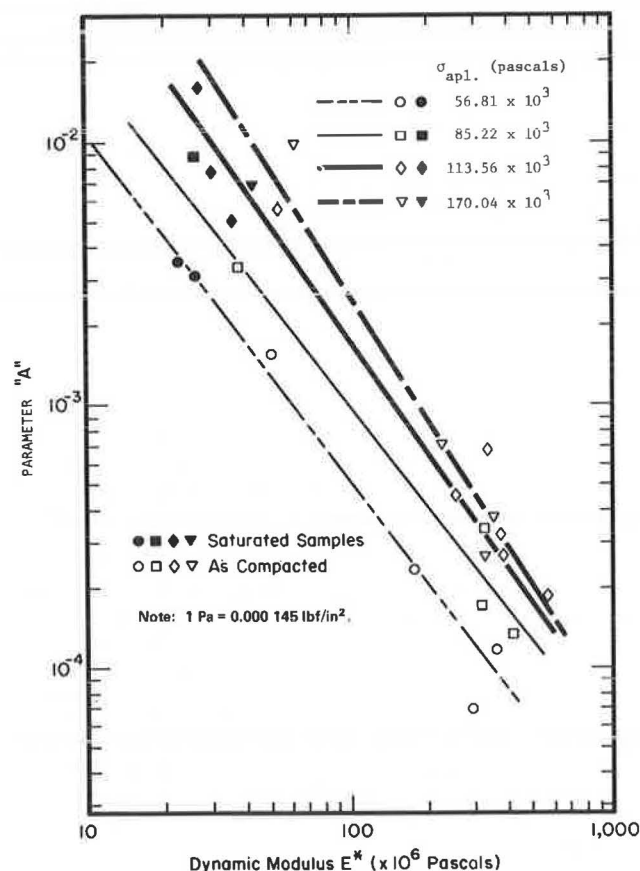
Figure 4. Relationship between A and σ_{apl} (soil no. 3 Licking County; top layer).



Parameter A

The experimental data indicate that the rutting parameter A and dynamic modulus E^* are interrelated. The general relationship observed is that A increases as E^* decreases and is dependent on σ_{apl} . Although the variation of A is greatly dependent on σ_{apl} in the wet range of soil conditions, this dependency may not have much signifi-

Figure 5. Relationship between A and $|E^*|$ at different applied stresses (soil no. 2).



cance on the dry side of optimum, as shown, for example, for soil no. 3 in Figure 4.

Figure 5 shows the relationship between A and E^* on a log-log graph at a constant σ_{apl} for soil no. 2. This straight-line relationship is consistent with Equation 2. As can be seen in this figure, these straight lines at different stresses are not generally parallel, and there are greater deviations in the wet range (low E^* values). Unconfined ultimate compressive strength (σ_{ult}) was thought to be the missing factor. To include this factor in the relationship between A , E^* , and σ_{apl} , Figure 6 shows the linear relationship between $\log [A/\exp(\sigma_{apl}/\sigma_{ult})]$ and $\log E^*$

Figure 6. Rutting master curve: soil no. 2.

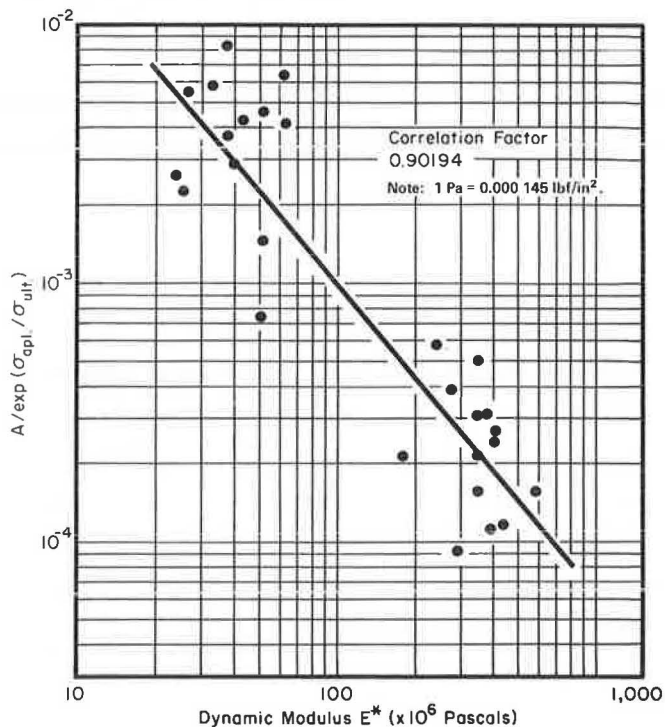


Table 2. Constants for rutting master curve and test of linearity for soils used.

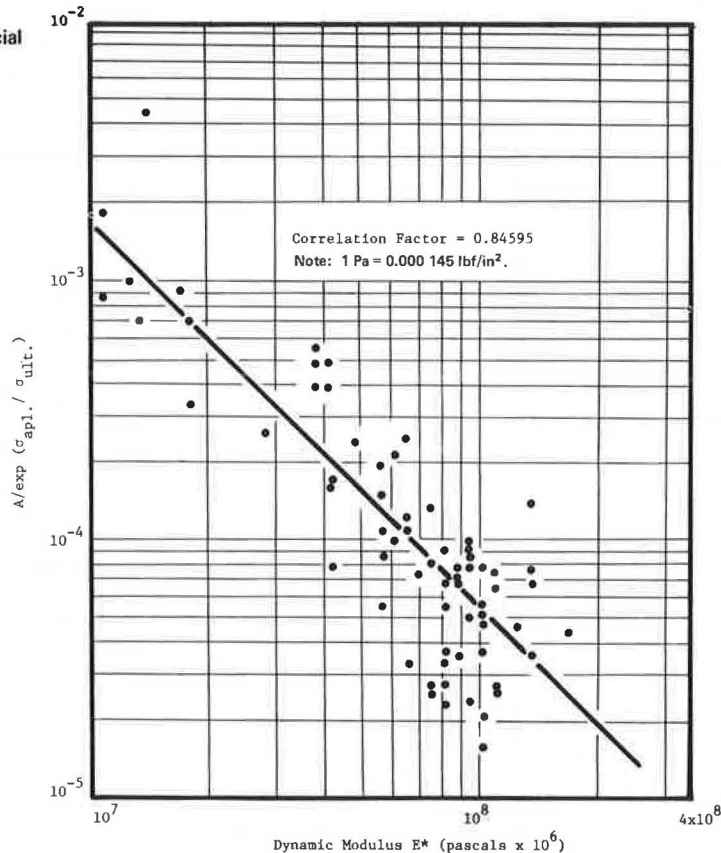
Soil No.	County	No. of Samples (N)	R	C	rs	CORR	Critical CORR	F*	
								Calculated	0.05, 1, n-2
1	Auglaize	47	2.812×10^6	1.180	12.580	0.759 26	0.285	61.250	4.06
2	Carroll	27	3.897×10^6	1.200	10.728	0.901 94	0.374	109.042	4.24
3	Licking	15	7.736×10^{11}	1.830	14.959	0.972 51	0.497	226.740	4.67
4	Licking	15	8.347×10^{16}	2.730	15.959	0.950 70	0.497	103.390	4.67
5	Hamilton	33	4.507×10^2	0.757	8.072	0.708 87	0.344	31.311	4.16
6 ^b	Franklin	19	1.458×10^9	1.644	12.835	0.841 41	0.444	41.214	4.45
7 ^b	Cuyahoga	27	4.932×10^5	1.170	7.974	0.777 37	0.374	38.179	4.24
8 ^a	NA	72	1.307×10^5	0.910	7.885	0.806 40	0.230	130.137	3.99
9 ^a	NA	73	3.111×10^7	1.473	11.713	0.845 95	0.269	178.672	3.99

*Null hypothesis is $\log R = C = 0$, and decision is reject if F calculated $> F_c$ (from table); i.e., accept linearity.

^bUndisturbed field samples of natural silty clay (Khedr data (5)).

^cLaboratory-prepared samples of artificial clay (Khedr data (5)).

Figure 7. Rutting master curve: artificial clay samples.



for soil no. 2: Thus, this relationship can be written in the form

$$A = RE^{*-C} \exp(\sigma_{apl}/\sigma_{ult}) \quad (3)$$

where R and C are material constants and independent of the variables involved. The results found for the other types of soils were considered consistent with this analysis.

Equation 3 represents a master curve for each type of soil by which the A can be directly determined for any soil condition when obtaining the constants R and C . For the soils considered in this study, these constants and the correlation coefficients (CORR) were obtained for each relationship (see Figure 6). The CORR-values were compared with the critical coefficients for a 0.05 level of significance and were accepted, as shown in Table 2. To verify the linearity of the proposed relationship, a statistical F-test was conducted for all relationships; it was found that the linearity is valid.

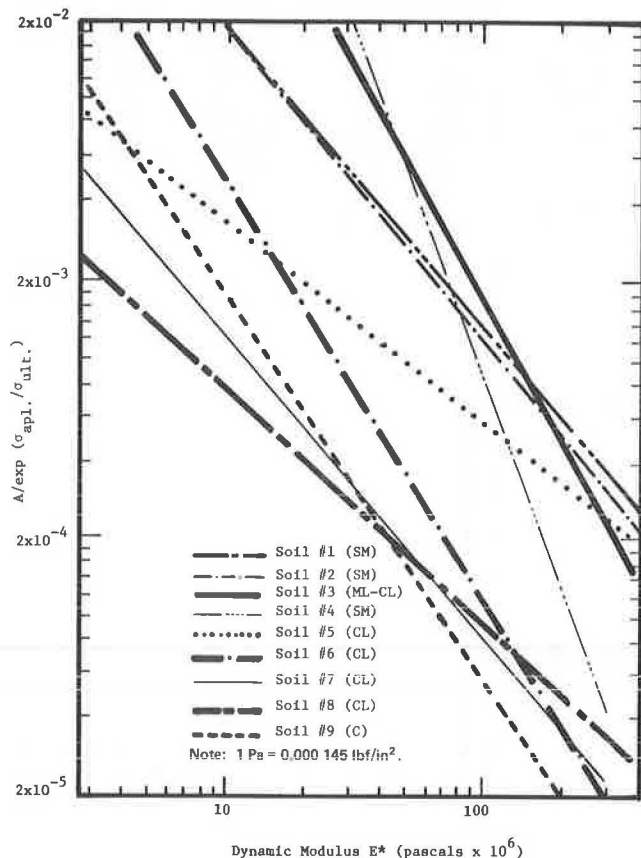
The applicability of the model for other types of subgrade material was also investigated. Test data for undisturbed field samples from Cuyahoga and Franklin counties (soils no. 6 and 7), as well as for two groups of laboratory-prepared samples (soils no. 8 and 9) made of artificial kaolin clay and silty clay (5), were reasonably consistent with this model. Figure 7 shows the master curve for the artificial clay samples. The proposed relationship appears to be general and is applicable for all soils in the silty or clayey categories. Further studies are recommended for soils in the wet and saturated conditions, to be validated in bulk media as well as for other types of granular materials that might be used as subgrades or subbases in pavement subsystems.

The variation of soil effect on A is summarized in Figure 8, which represents all of the relationships for the soils investigated by straight lines on a log-log graph.

If Equation 3 is written in the form

$$(1/C) \{ \log[A/\exp(\sigma_{apl}/\sigma_{ult})] \} = (1/C) \log R - \log E^* \quad (4)$$

Figure 8. Rutting master curves: different types of subgrade soil.



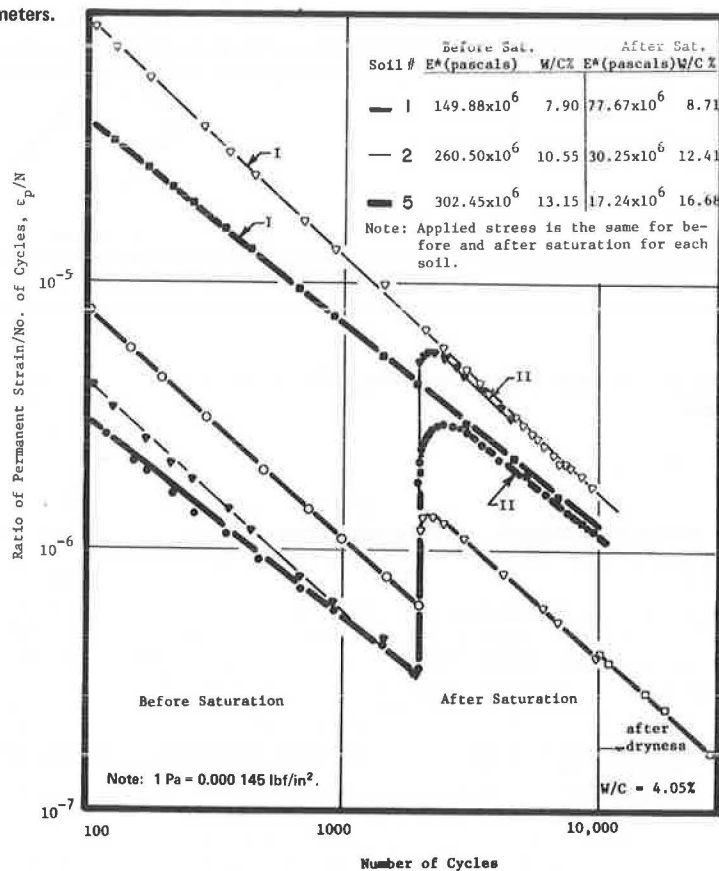
the master lines are translated into parallel lines that have a unit slope and an intersection with the vertical axis of

$$rs = (1/C) \log R$$

where rs equal rutting sensitivity: rs is believed to reflect the sensitivity of the rutting phenomenon to the changes in environmental conditions represented by the changes in E^* and $\sigma_{ult.}$

To evaluate environmental effects, samples of soils no. 1 (Auglaize County, A-4 or E-3) and no. 2 (Carroll County, A-4 or E-6) were subjected to 200 cycles, brought to saturation, and then retested for another 8000 cycles. The effect of saturation is shown in Figure 9. The analysis of all saturated samples showed a jump in the measured rutting depth ($\log \epsilon_p/N$ versus $\log N$ relation) that occurs on saturation. This jump depends on the applied stresses and the increase in moisture content. It was found that saturated samples of these soils followed the proposed rutting model as well. Moreover, the samples behaved almost as if the tests had been started in a saturated condition. This means that the new parameter (A_{sat}) is the governing one (5), as is shown by the coincidence of lines I and II in Figure 9. It is seen that there is an increase in the value of A and that this is associated with a decrease in E^* . If the new values of A for the saturated samples are plotted on the A versus E^* log-log graphs, it is found that the relationship is valid in the saturated region. Thus, it is concluded that the variation of A on saturation of the soil follows the generalized master rutting equation proposed here.

Figure 9. Effect of saturation versus dryness on rutting parameters.



Parameter m

The parameter m in Equation 1 is the absolute value of the slope of the $\log(\epsilon_p/N)$ versus $\log N$ straight line. An overall look at the m-values shows that they are almost constant—all values except those for a few points in soil no. 5 are between 0.83 and 0.94. A one-way analysis of variance in m-means with a multiple comparison was conducted by using the Statistical Package for Social Sciences program (9) to determine if there is a significant difference in these values. Three techniques (Tukey (B), Tukey, and Scheffé) were used. The results obtained by using the Tukey (B) and Tukey techniques show no significant differences in their means for soils no. 1, 2, 3, and 4, although there is a difference in the means for soil no. 5. The results obtained by using the Scheffé technique showed no significant differences in the means for all the soils. From an engineering point of view, we can conclude that there is no significant difference in the mean values and that m is an almost universal constant for the group of soils considered in this study and ranges between 0.85 and 0.90 (see Figure 10).

To validate this conclusion, data from previous Ohio State University research (5) were analyzed for variations in m. The mean values were calculated, and it was found that they lie within the same range. These results are summarized below.

Soil Number	No. of Samples	Mean	SD
1	26	0.888	0.0249
2	19	0.886	0.0416
3	19	0.900	0.0289
4	18	0.859	0.0782
5	35	0.845	0.0596
6	18	0.860	0.0584
7	27	0.865	0.0375
8	83	0.862	0.0455
9	81	0.876	0.0580

The parameter m was also investigated for saturated samples of soils no. 1 and 2, and it was noted that the

m-values are almost the same, whether calculated separately for a saturated condition or as a continuation of a presaturation test.

To determine the effect of saturation on the m, the values were plotted against E^* for both before and after saturation (Figure 11). As shown in this figure, there is no pronounced change in m on saturation, although some samples did show slight decreases. A t-test on the difference in the means before and after saturation was conducted; the results, summarized below, showed that, statistically, there is no significant difference in the mean m-values, and it was concluded that there is no significant change in this parameter on saturation.

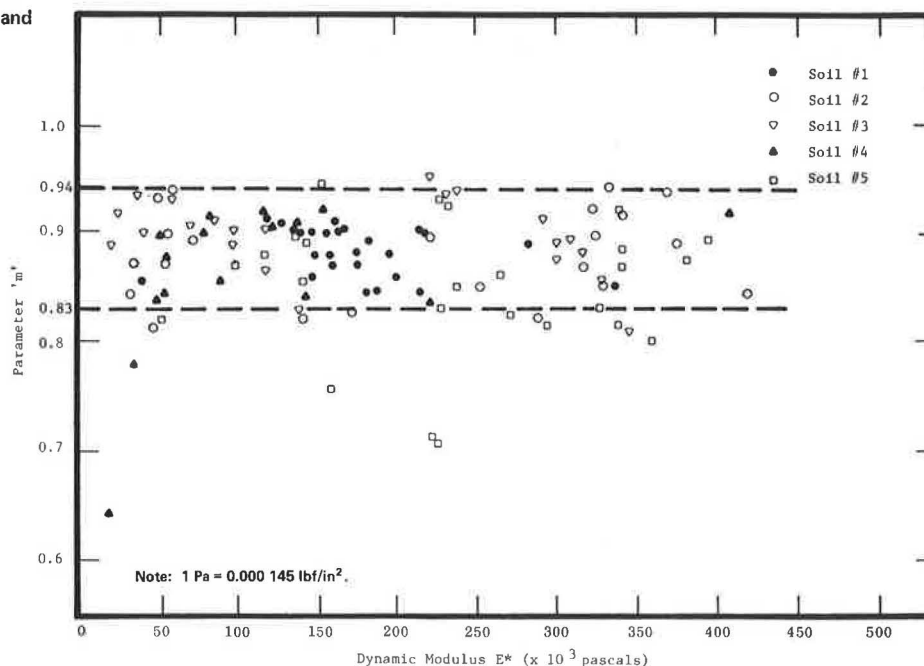
Item	Value	Item	Value
Number		SD	
Before	26	Before	0.024
After	27	After	0.028
Mean value		t	
Before	0.885	Calculated	-0.820 26
After	0.891	Critical	$\pm 1.998 8$

DEVELOPMENT OF DESIGN GUIDELINES FOR RUT-DEPTH DETERMINATION

The parameters A and m must be considered for a full evaluation of subgrade permanent deformation. The experimental relationship found in this study and the determination of m for various types of subgrade soils can help the pavement design engineer to determine the amount of rutting in the subgrade at any stage of pavement service life. A systematic procedure is developed here to give a quick and reasonably accurate estimation of the rut depth. This procedure is summarized by the block diagram in Figure 12 and illustrated by the numerical example given below:

Assume a subgrade soil similar to that of Auglaize County (soil no. 1, $R = 2.812 \times 10^6$, $C = 1.18$, and $m = 0.888$) and a soil condition that gives (1 MPa = 145 lbf/in² and 1 mm = 0.04 in)

Figure 10. Relationship between m and E^* for all soils.



Soil at	E^* (MPa)	$\beta = \sigma_{api}/\sigma_{ult}$	h (mm)
Compaction	103.4	0.2	762
Saturation	55.2	0.4	762

Determine the rut depth at compaction and at saturation by assuming $N = 10\ 000$ cycles for both conditions.

At compaction,

$$\text{Equation 3} \rightarrow A = 2.812 (10^6)(103.41 \times 10^6)^{-1.18} \times e^{0.2} = 1.1986 \times 10^{-3}$$

$$\text{Equation 1} \rightarrow (\epsilon_p/N) = AN^{-a}$$

$$\epsilon_p = AN^{1-a} = 1.976 \times 10^{-3} (10\ 000)^{1-0.888} = 3.362\ 72 \times 10^{-3}, \text{ and } d_r = \epsilon_p \times h = 3.362\ 72 \times 762 = 2.5624\ \text{mm} (0.1009\ \text{in}).$$

At saturation,

$$\text{Equation 3} \rightarrow A = 2.812(10^6)(55.2 \times 10^6)^{-1.18} \times e^{0.4} = 3.0734 \times 10^{-3}$$

$$\text{Equation 1} \rightarrow \epsilon_p = 3.0734 \times 10^{-3}(10\ 000)^{1-0.888} = 8.6222 \times 10^{-3}, \text{ and } d_r = 8.6222 \times 10^{-3} \times 762 = 6.57\ \text{mm} (0.2587\ \text{in}).$$

Based on the values determined for m for each soil group and by using the equations developed above, a rut-depth determination nomograph was developed for each category of soils that have the same m . These nomographs are shown in Figure 13.

The above example can be solved directly by using these nomographs as discussed below.

Following the line \rightarrow in Figure 13, this subgrade is expected to have a rut depth (d_r) of 2.56 mm (0.1009 in) after a service life of $N = 10\ 000$ cycles. For the saturated condition where $E^* = 55.2$ MPa and $\beta = 0.4$, the rut depth is determined by following the line \rightarrow , which gives $d_r = 6.5$ mm (0.256 in) for the same N -value.

SUMMARY AND CONCLUSIONS

1. The rutting model— $\epsilon_p/N = AN^{-a}$ —is applicable to the fine-grained soils investigated in this study.

2. The dynamic modulus $|E^*|$ is an appropriate measure that reflects the moisture content, the dry density, and the soil structure as far as the rutting process is concerned.

3. The parameter m was found to be constant and to vary between 0.85 and 0.90 and have a grand mean of 0.872, which could be considered in the evaluation of subgrade rutting potential. There is no statistically significant change in this parameter before and after saturation conditions.

4. The parameter A was established as a function of E^* , σ_{api} , and σ_{ult} by using the relationship $A = RE^{*-c} \exp(\sigma_{api}/\sigma_{ult})$, where R and C are material constants that can be determined experimentally. This equation accounts for the variation of A with type and structure of soil, environmental changes, and stress level.

5. The effect of saturation was found to result in an increase in the value of A associated with a decrease in E^* for a specific applied stress. This behavior was found to follow the above relationship.

6. The relationship proposed here includes all of the factors that might affect the variation of A while m is constant and, therefore, represents a master curve that could be used to determine A (which is a key parameter for the determination of the rut depth of fine subgrade materials).

7. A rutting sensitivity is introduced and defined as $rs = (1/C) \log R$. As far as rutting is concerned, this index may reflect the material sensitivity to changes in environmental conditions represented by E^* and σ_{ult} .

8. A proposed system for estimating subgrade rut depth is presented. This system is summarized by a block diagram. Nomographs have also been developed for the determination of rut depth; an example is given.

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Figure 11. Effect of saturation on m : (soil no. 1, Auglaize County).

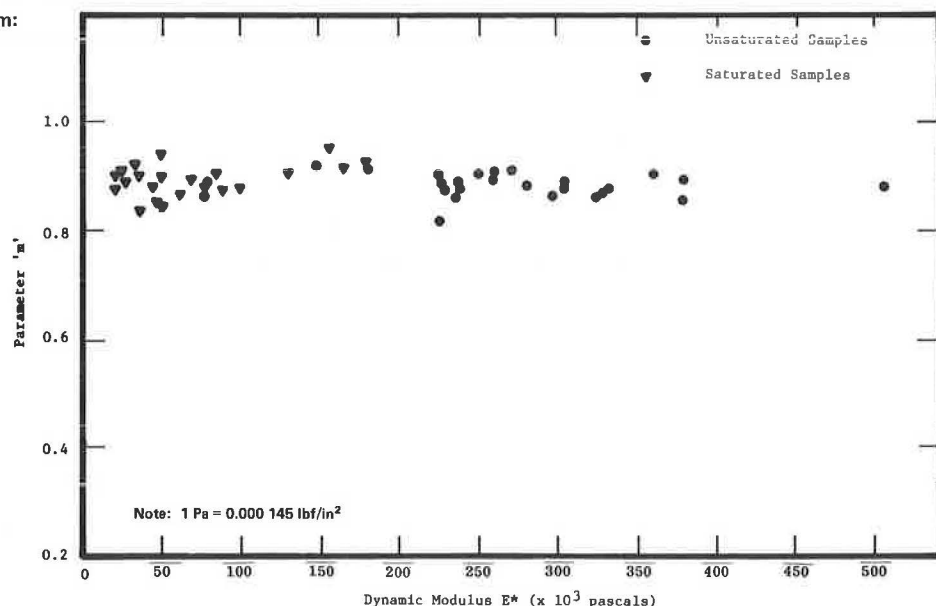


Figure 12. Proposed scheme for estimation of subgrade rutting.

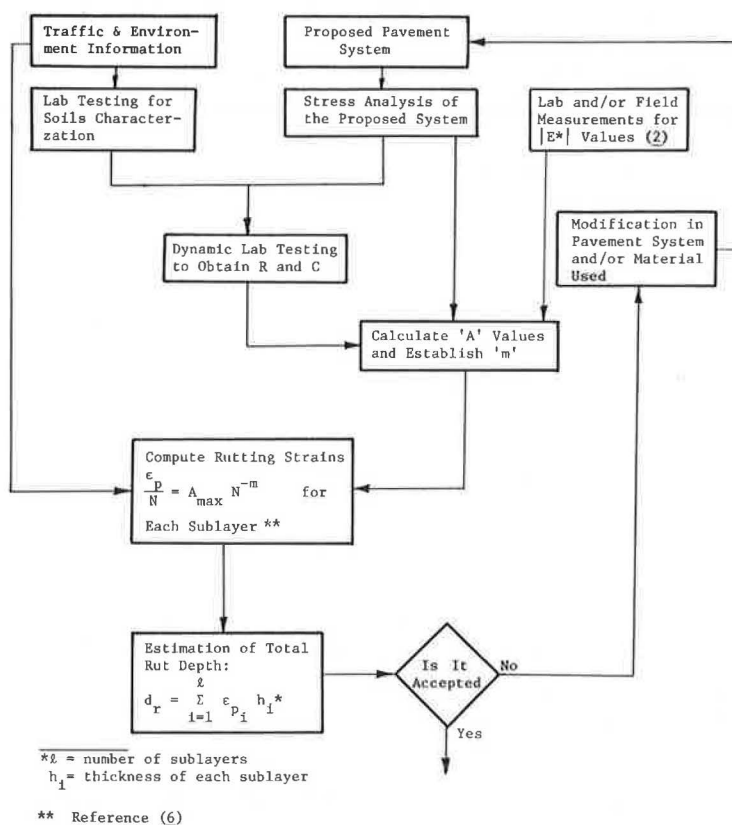
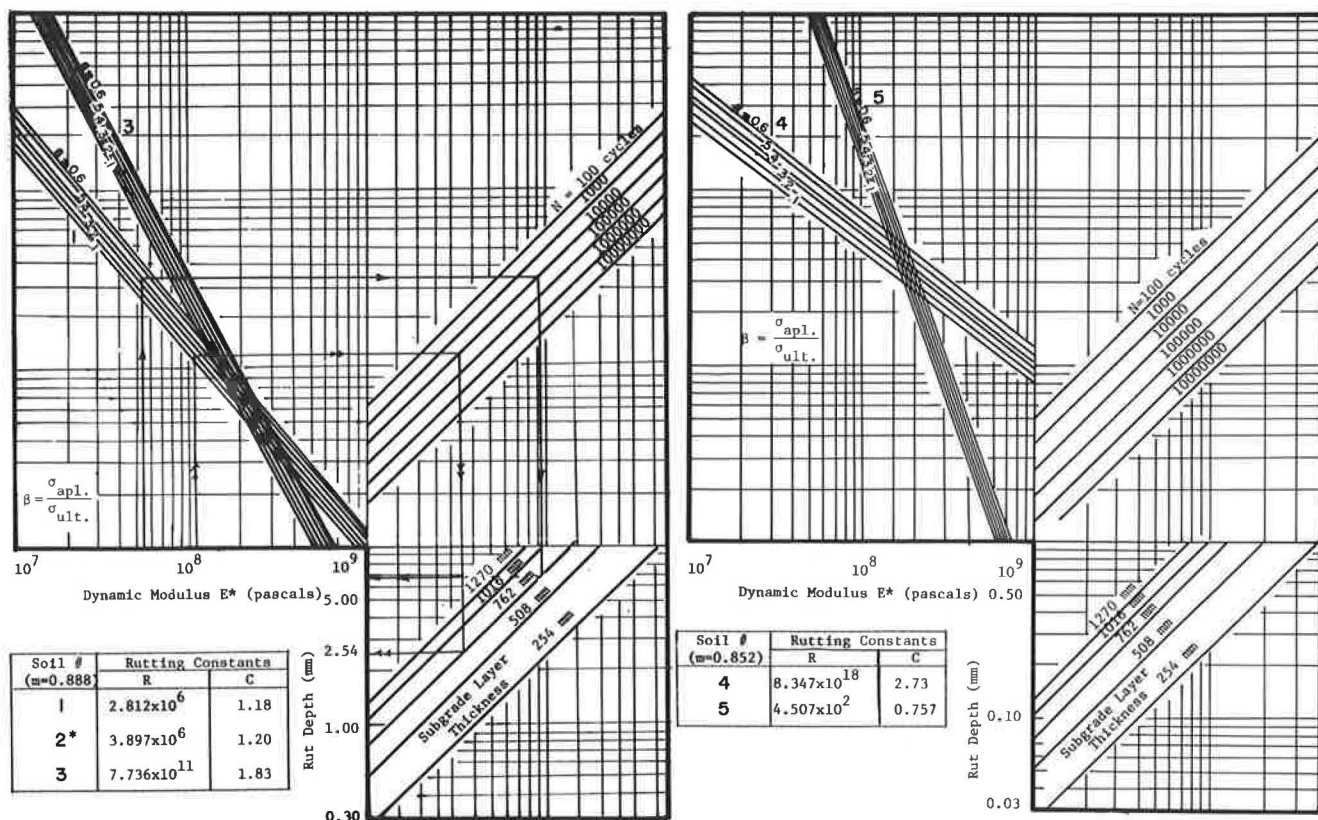


Figure 13. Rut-depth nomographs.



* Soil #2 almost coincides with Soil #1 in this graph

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Laboratory Testing of Cohesive Subgrades: Results and Implications Relative to Structural Pavement Design and Distress Models

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A thorough investigation of the distress and deformation properties of subgrade materials is under way at the National Danish Road Laboratory. Thus far, the program has concentrated on establishing sound laboratory relationships for cohesive subgrades with respect to resilient and permanent strain characteristics through the use of triaxial testing equipment. In the dynamic testing phase alone, more than 75 million repeated loads have been applied on a series of intact samples representing 12 test sites from 6 countries, and 4 new sites are being added. Although the results of the program thus far must be regarded as inconclusive from a predictive performance point of view, some basic relationships have emerged that are both sound and useful. First, the analysis of the data collected has indicated that the concept of equivalent axle loads is both misleading and irrelevant with respect to directly related subgrade-distress causes. A criterion based on a realistic requirement aimed at limiting the amount of permanent deformation in the soil itself has an extremely high axle-load exponent (mean value greater than 15). Second, the use of a constitutive relationship that can describe the progress of permanent subgrade strain is possible, but because of other uncertainties associated with natural variations, inhomogeneities, and difficulties inherent in the determination of material-characterization constants, the use of a permissible subgrade deviator stress is preferred; the suggested one is a function of a reference resilient modulus (M_0). As a result of the high load exponent hereby implied, this permissible stress is only slightly dependent on the number of load repetitions. On the other hand, the concept of a permissible resilient strain is shown to be poorly correlated with permanent strain and the number of repeated loads because of the various forms and degrees of nonlinear elastic response observed among the investigated subgrades. A fictive strain can, however, be used in lieu of the permissible-stress approach, although this will result in overly conservative designs if linear-elastic material behavior is assumed in the design technique.

The wealth of information and experience gained from the AASHO Road Test and subsequent smaller scale projects has, in a more or less direct manner, exerted

a great influence on flexible pavement design practice the world over. Based on this background, distress models have been empirically derived in accordance with various measures of serviceability. The question will now be raised as to the degree of validity of these models as applied to cohesive subgrades on a global scale, that is in general terms apart from the specific AASHO Road Test materials and structural systems, imposed traffic, climatic conditions, and subsequent interpretations. The following is intended to elucidate the results of research (which has thus far been limited to cohesive subgrades) that is intended to answer this question.

TERMINOLOGY AND NOMENCLATURE

The following notation and specific definitions are used in this paper.

- N = number of loads,
- σ = stress and is positive in compression,
- ϵ = strain and is positive in compression,
- $\sigma_{1,0}$ = vertical preload (static) stress,
- $\sigma_{3,0}$ = horizontal preload (static) stress,
- σ_{dyn} = superimposed dynamic deviator stress,
- $\sigma_{dyn,f}$ = σ_{dyn} at triaxial failure for $N = 100\ 000$,
- $\sigma_{dyn,p}$ = σ_{dyn} at ϵ_p permissible,
- ϵ_r = resilient axial strain,
- $\epsilon_{r,p}$ = ϵ_r permissible,
- ϵ_p = permanent axial strain,
- M_r = resilient modulus of elasticity (σ_{dyn}/ϵ_r),
- M_0 = reference value of M_r , and
- β = degree of failure ($\sigma_{dyn}/\sigma_{dyn,f}$).