Rut Depth Prediction and Test Procedures for Permanent Deformation in Asphalt Pavements

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The rutting mode of pavement distress is a major problem on heavily traveled flexible pavement truck routes, and several groups have developed procedures using layer theory and the permanent deformation characteristics of the layer materials to evaluate it. One such analytic procedure is that developed by Barksdale (1), Monismith and others (2), and McLean and Monismith (3). This uses elastic layer theory and a permanent deformation law determined from laboratory repeated load tests for each layer material. Another procedure, that developed by Moavenzadeh and others (4), uses accumulative linear viscoelastic deformations. Recently, Brademeyer (5) has revised this model to include an exponential law that accounts for the nonlinearities of the accumulated permanent deformations, and Hufford and Lai (6) have developed a viscoplastic law for asphalt concrete based on laboratory incremental creep-creep recovery tests. Many of these developments are incorporated into the VESYS IIM rutting structural subsystem (7), which has been verified by comparing the predicted rutting with measured rutting at the Pennsylvania State University test facility (8).

This paper summarizes the analytic methods and the testing procedures that form the basis for the current version of the VESYS IIM rut depth model.

ANALYTICAL DEVELOPMENT OF VESYS II(M) RUT DEPTH MODEL

The permanent deformation ϵ_p of a material specimen subjected to a single stress pulse can be expressed in terms of the following functional relationship:

$$\epsilon_p = f(\sigma, \xi, T, M) \qquad (1)$$

where σ, ξ, T, and M represent the stress, time duration of loading, temperature, and moisture respectively. The total strain response $\epsilon(t)$ is illustrated in Figure 1. (The definitions given in this figure assume that the plastic strain is dependent on the state of stress and independent of time, but that the viscous strain is dependent on both the state of stress and the time of loading.) A haversine load pulse of amplitude A and duration d, which is repeatedly applied to a typical flexible pavement, is shown at repetition N_j in Figure 2a. The interaction of the strain components is shown in Figure 2b. The increment of the permanent deformation $R_p(N_j)$ that is due only to the N_jth pulse is composed of the permanent viscous and plastic strains, provided, however, that sufficient time is allowed between repetitions for the complete rebound of the recoverable viscoelastic deformation. As N increases, $R_p(N_j)$ becomes smaller, but the deflection amplitude $R_\delta(d/2)$ is assumed to remain constant. $R_p(N_j)$ may be expressed as a varying fraction of the deflection amplitude as

$$R_p(N_j) = R_\delta(d/2)f(N_j) \qquad (2)$$

where $f(N_j)$ is a function of the ratio of the incremental permanent deformation to the deflection amplitude. Most of the work cited above has shown that $R_p(N_j)$ can be reasonably represented by a monotonically decreasing logarithmic function of the number of previously applied loads:

$$f(N) = \mu_{sys}(N)^{-\alpha_{sys}} \qquad (3)$$

where μ_{sys} and α_{sys} represent the rutting characteristics of the total pavement system. The pavement rutting characteristics are computed in the VESYS IIM model by using layer theory in conjunction with a laboratory determined permanent deformation law for each pavement layer. Integration of equation 2 over N cycles gives the total accumulated permanent deformation. The model accounts for real-world variability by treating the elastic and viscoelastic moduli, the load amplitude and duration, and the load repetitions N as random variables that are described by their means and variances. The rut depth is computed and summed over specified incremental analysis periods in order to include changes in the environment and traffic rate.

The current laboratory test procedure requires con-

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Figure 1. Strain response to a stress pulse.

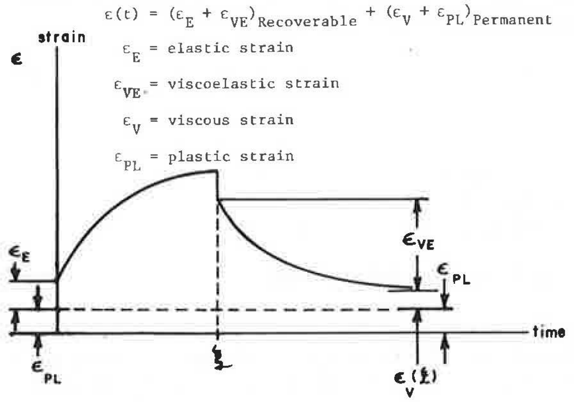
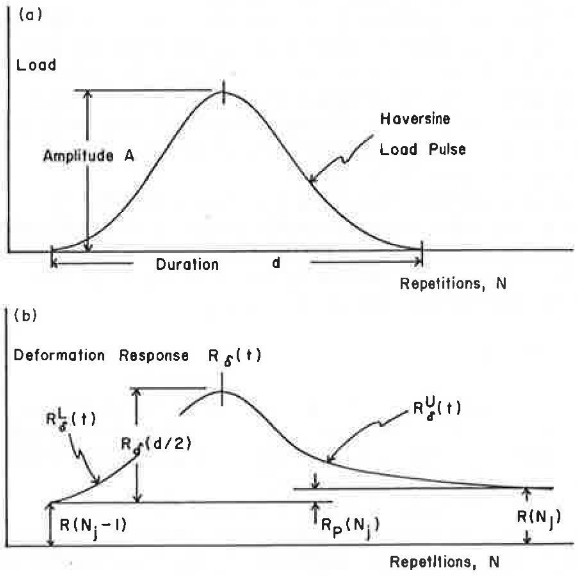


Figure 2. Response to haversine load pulse at N_jth repetition.



tinuous repeated load tests in which a haversine load of duration d and a rest period (unload time) are applied repeatedly for a certain number of cycles N. The accumulated viscoelastic, viscous, and plastic strains remaining at the end of selected cycles are measured. Typical continuous repeated test results for asphalt concrete are given in Figure 3. The intercept, slope, and resilient strain amplitude give the material permanent deformation characteristics μ_K, α_K, for layer K:

$$\epsilon_p(N) = (\mu_K/e)N^{-\alpha_K} \qquad (4)$$

where e = general viscoelastic haversine response at peak loading (resilient strain).

VERIFICATION OF THE VESYS IIM MODEL

Rut depths predicted using the VESYS IIM model on different pavement sections at the Pennsylvania State University test track facility compare favorably with the measured values, as indicated in the following table.

Time (months)	Rut Depth (cm) Section 6 Observed	Predicted	Section 9 Observed	Predicted
1	0.08	0.18	0.08	0.52
9	0.19	0.32	0.53	0.97
15	0.47	0.51	1.02	1.36

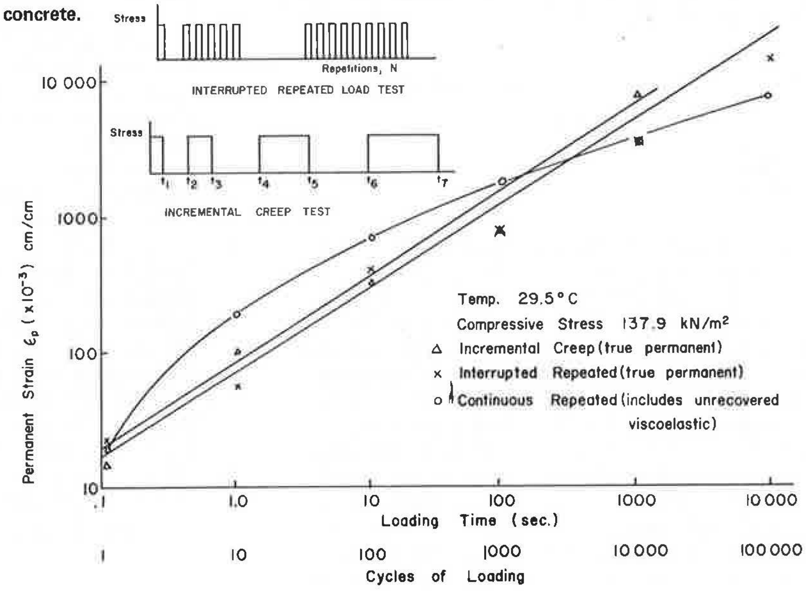
That the early values of predicted rut depth are greater than the observed values may be attributed to an interpretation of the laboratory continuous repeated curve (Figure 3) as having a straight line slope that is somewhat larger than that which might actually occur were sufficient time allowed for complete viscoelastic strain recovery. A general functional relationship between stress and strain that separates the recoverable from the nonrecoverable components in equation 1 can be given as

$$\epsilon(t) = [D_0 + D\phi(t)]\sigma + [\Psi_0 + \Psi(\xi)]F(\sigma) \qquad (5)$$

where

D = retarded viscoelastic compliance,

Figure 3. Permanent strain plots for asphalt concrete.



D_0 = elastic compliance,
$\phi(t)$ = 0 as $t \rightarrow 0$ and 1 as $t \leftarrow \infty$,
$\Psi(\xi)$ = viscous plastic compliance as a function of duration of loading,
Ψ_0 = initial plastic compliance, and
$F(\sigma)$ = stress function associated with permanent deformation.

The application of equation 5 to the continuous repeated stress history of Figure 3 yields

$$\epsilon(t) = D[\phi(t) - \phi(t + \xi)]\,\sigma + [\psi_o + \psi(\xi)]\,F(\sigma) \tag{6}$$

which shows that the viscoelastic strains (ϕ terms) contribute to the total strain response $\epsilon(t)$. If, however, sufficient time were allowed between the load repetitions so that the viscoelastic strain could recover, then the true permanent deformation could be measured. This is demonstrated by applying equation 5 to the interrupted repeated load stress history (also shown in Figure 3), which yields

$$\epsilon(t) = \epsilon_p = [\psi_o + \psi(N\xi)]\,F(\sigma) \tag{7}$$

Equation 7 shows that the viscoelastic strains are completely eliminated, which suggests that the true permanent deformation law should be obtained from this type of test.

Because of the sophistication of the repeated load equipment required, the assumptions involving the selection of load duration and frequency, and the long time required to conduct continuous and interrupted repeated load tests, a simplified testing procedure is proposed. The simplified procedure uses the results from the incremental creep tests shown in Figure 3. A similar test procedure has also been suggested by Hufford and Lai (6).

The application of equation 5 to the incremental stress history gives

$$\epsilon(t) \cong \epsilon_p = [\Psi_o + \Psi(\xi)]\,F(\alpha) \tag{8}$$

and shows that the viscoelastic strains are eliminated in the same way as in the interrupted repeated test.

TEST PROGRAM AND RESULTS

Incremental creep tests for the duration of loading and unloading as shown below were conducted on asphalt concrete specimens at 13, 21, and 29°C (55, 70, and 85°F).

Pulse	Pulse Duration (s)	Rest Period After Pulse (s)
1	1.0	100
2	10.0	100
3	100.0	200
4	1000.0	1000

Interrupted and continuous repeated tests at these same temperatures were also conducted under haversine loading of 0.1-s duration and 0.9-s unloading. A typical result is illustrated by the comparative curves in Figure 3. In most cases, the continuous repeated tests gave curvilinear log-log plots especially at higher temperatures, but the plots of the interrupted and incremental creep tests gave straight lines. The excellent agreement between the interrupted repeated load and the incremental creep test results suggests the development of a fundamental incremental creep relation that includes the true permanent plastic and viscous components of strain.

This research also indicated that a master permanent strain-loading time curve could be constructed and that there is a time-temperature equivalence for the permanent deformation characteristics of asphalt concrete that can be expressed as

$$\epsilon_p(\xi, T) = \epsilon_p(\xi') \tag{9}$$

where

$\xi' = \xi/a_T$, the reduced loading time,
T = temperature, and
a_T = shift factor for permanent strain.

DISCUSSION AND CONCLUSIONS

1. The rutting predicted by the VESYS IIM structural subsystem is in good agreement with that observed on two experimental pavement sections. The numerous variations in the real system, the approximate nature of the model itself, and the variabilities and inaccuracies of the laboratory testing procedure all contribute to the differences encountered. The closeness of the predictions with observed values does, however, indicate the reasonableness of the VESYS IIM model used.
2. The close agreement between the results of the incremental creep tests and the interrupted repeated load tests and the log-log linear nature of these characteristics indicate that the simpler incremental creep test could be used in lieu of continuous repeated load tests to determine the rutting behavior of asphalt concrete at temperatures above 21°C (70°F).
3. A fundamental creep law that separates the recoverable from the nonrecoverable strain was developed. Such a law can be easily modified to include temperature and stress effects and can be included in any structural subsystem for the prediction of rutting.

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