Abridgment

Predicting Permanent Deformation of Asphalt Concrete From Creep Tests

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Pavement rutting is the result of channelized traffic that causes differential surface deformation in the areas of intensive load applications under wheel paths. The amount of pavement rutting depends on the following parameters:

1. The distribution, particularly transverse, of the traffic loads, i.e., the channelized traffic;
2. The stresses, which depend on the response characteristics of the layer materials, induced in the pavement system; and
3. The permanent strains, which depend on the permanent deformation characteristics of the layer materials, induced as the result of the stresses.

The general approach to the determination of the permanent deformation characteristics of pavement materials under repeated loading has been to test the material under conditions as nearly representative of field conditions as possible (1, 2, 3, 4). The test procedures include using the actual stresses (actual stress levels for axial and confining stresses) induced by wheel loads of varying intensity and duration, temperatures, and moisture conditions. The effects of each parameter on the permanent strains can be obtained by using a well-planned experimental design. Since the relationships are derived for the permanent strains of the paving materials under simulated field conditions, these predictions should be very reliable. The disadvantage to this approach is that, when the number of parameters involved is too large, the experimental program becomes much too cumbersome and too expensive to be of practical use.

This paper presents an alternative approach for predicting the permanent deformation characteristics of asphalt concrete under repetitive loading. This approach uses a simplified testing procedure in which only a relatively small number of creep tests are needed for the characterization of the constitutive equation for predicting permanent strains (5).

CREEP AND RECOVERY BEHAVIORS OF ASPHALT CONCRETE

Asphalt concrete exhibits creep under sustained loading and partial recovery on unloading. When the applied stress is small, the creep strain is approximately linearly proportional to it. Traditionally, the time-dependent behavior of a linear viscoelastic material can be characterized by means of a constant-stress creep test. If the material is a strictly linear viscoelastic material, the creep compliance $J(t)$ thus determined and the linear superposition principle together allow the prediction of the time-dependent behavior of the material under any type of loading. This approach, at least the concept, is also applicable to the description of the time-dependent behavior of a certain class of nonlinear viscoelastic materials (6).

However, asphalt concrete is not a linear viscoelastic material, even at small stress levels. For example, the recovery, as shown in Figure 1 (7), indicates that the material exhibits permanent strain that depends on the duration as well as the intensity of the loading. The recovery curves shown in Figure 1 cannot be predicted with reasonable accuracy by using linear viscoelastic theory. Similarly, the use of linear viscoelastic theory to predict the creep behavior of asphalt concrete under multistep loading gives poor agreement with the test results.

The results shown in Figure 1 suggest that the creep behavior may be represented by a generalized nonlinear Kelvin model as shown in Figure 2. In this model the nonlinear dashpot may contribute to the irrecoverable strain, while the series of Kelvin models (Kelvin chain) may contribute to the power-law creep behavior (6). Therefore, the total creep strains ϵ_T are separated into two parts, the irrecoverable strains ϵ_p due to the nonlinear dashpot and the completely recoverable strains ϵ_v due to the Kelvin chain. These strains can be characterized from a series of uniaxial compressive creep and recovery tests on asphalt samples prepared in the laboratory. The following results are obtained:

$$\epsilon_p(t) = A(\sigma)t^{\alpha} \qquad (\alpha = 0.4) \qquad (1)$$

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Figure 1. Creep and recovery of constant-stress creep tests (t_1 = 100 s).

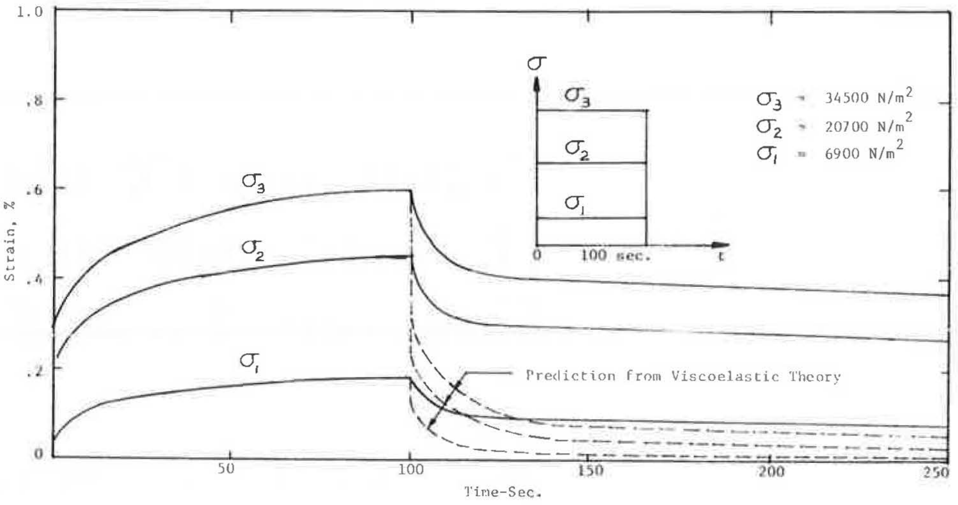


Figure 2. Generalized nonlinear Kelvin model.

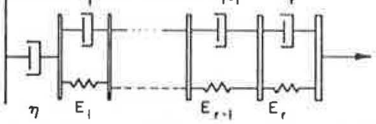
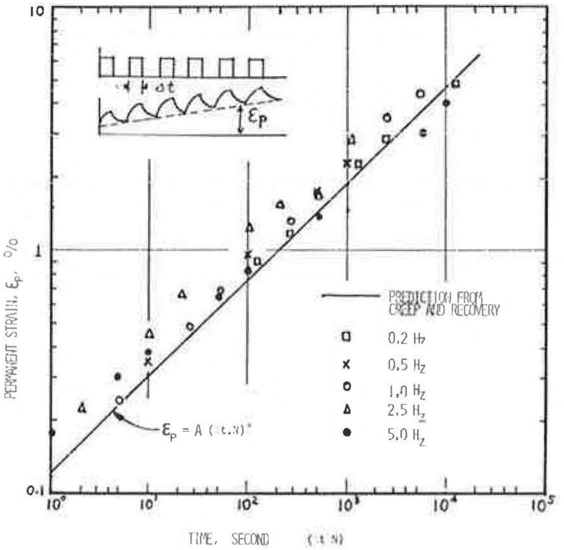


Figure 3. Accumulative permanent strains versus effective loading time.



and

$$\epsilon_v(t) = B(\sigma)t^\beta \qquad (\beta = 0.115) \tag{2}$$

Thus, under a constant-stress creep and recovery test, the total creep strain $\epsilon_T(t)$ and the recovery strain $\epsilon_r(t)$ can be predicted as follows:

$$\epsilon_T(t) = B(\sigma)t^\beta + A(\sigma)t^\alpha \qquad (t < t_1) \tag{3}$$

and

$$\epsilon_r(t) = B(\sigma)[t^\beta - (t - t_1)^\beta] + A(\sigma)t_1^\alpha \qquad (t > t_1) \tag{4}$$

where t_1 is the duration of the loading time.

It has been shown (7) that under a time-dependent stress input the recoverable strain can be predicted by using the superposition principle (for linear behavior), but that the irrecoverable strains can be more accurately predicted by using a strain-hardening theory. Thus,

$$\epsilon_T(t) = \int_0^t (t - \xi)^\beta [\partial B(\sigma)/\partial\sigma]\,\dot{\sigma}(\xi)d\xi + \int_0^t \dot{\epsilon}_p(\xi)d\xi \tag{5}$$

where the permanent strain rate can be determined from equation 1 and

$$\dot{\epsilon}_p = \alpha A t^{\alpha-1} \tag{6}$$

It t is eliminated from equations 1 and 6, $\dot{\epsilon}_p$ becomes

$$\dot{\epsilon}_p = \alpha(\epsilon_p)^{(\alpha-1)/\alpha}(A)^{1/\alpha} \tag{7}$$

Equations 6 and 7 can be used to predict the creep of asphalt concrete under multistep loading. The predictions reported by Lai and Hufferd (5) are much more accurate than the predictions using strictly linear viscoelastic theory.

BEHAVIOR OF ASPHALT CONCRETE UNDER REPEATED LOADING

Equation 5 can be used to predict the creep behavior of asphalt concrete under repeated loading. For repeated loading with variable stress amplitude, but constant duration of loading (aT) and recovery (1 - a)T in each load application, the recoverable and irrecoverable strains at any instant of time can be calculated from equations 6 and 7. For example, the strains at the end of the loading portion in the Nth cycle (t = NT + aT) are

$$\epsilon_v = B(\sigma_{2N})(aT)^\beta + (T)^\beta \sum_{i=0}^{N-1} B(\sigma_{2i})[(N + a - i)^\beta - (N - i)^\beta] \tag{8}$$

and

$$\epsilon_p = (aT)^\alpha \left[\sum_{i=0}^{N} A(\sigma_{2i})^{1/\alpha}\right]^\alpha \tag{9}$$

The strains at the end of the recovery period in the Nth cycle [t = (n + 1)T] are

$$\epsilon_v = (t)^{\beta} \sum_{i=0}^{N} B(\sigma_{2i})[(N + 1 - i)^{\beta} - (N + 1 - i - a)^{\beta}] \qquad (10)$$

and ϵ_p is the same as that given by Anderson and Lai (8). Some useful results from equations 8, 9, and 10 are discussed briefly in the following.

Effect of Duration of Loading

Equation 9 shows that the permanent strain under repeated loading is dependent on the duration of loading time. When the stress amplitude is the same throughout the test period, this reduces to

$$\epsilon_p = A(\sigma)(aTN)^{\alpha} = A(\sigma)(aT)^{\alpha}(N)^{\alpha} \qquad (11)$$

This power-law relation is suitable for representing the accumulative permanent strain induced under repeated stress cycles. Figure 3 compares the test results and the values calculated using equation 11. This power law relationship has also been reported by Brown and Snaith (4), in which it is also shown that the total permanent strain is dependent on the total effective duration of loading (aTN) rather than on the total number of repetitions (N).

Effect of Rest Period

The effect of the rest period on the total permanent deformation is contributed by the ϵ_v part of the strain. As shown in equation 10, the accumulated permanent strain due to ϵ_v is dependent on β, the ratio of the rest period to the loading period. Equation 9 indicates that the magnitude of ϵ_p is independent of the rest period. For longer rest periods, the contribution of ϵ_v to the total cumulative strain is small, particularly if β is small.

Effect on Mixed Stress Amplitude

Since the contribution of the ϵ_v part of the total permanent strain is small, the discussion of the effect of mixed stress amplitude is concentrated on the ϵ_p part. Equation 9 indicates that, under a constant loading duration in each cycle, the total accumulated strain is independent of the sequence in which the different stress amplitudes are applied, so long as the combination of the various stress amplitudes in the entire period is the same.

CONCLUDING REMARKS

The approach discussed here is applicable to a rich-mix asphalt concrete. For asphalt concrete with a low asphalt content, the total permanent strain due to repeated loading cannot be considered as due solely to viscous flow, and hence equations 10 and 11 alone are no longer sufficient to describe the permanent deformation. It is more likely that the following equation would give a better prediction

$$\epsilon_p = A(\Delta tN)^{\alpha} + \gamma(N)^{\xi} \qquad (12)$$

The first term in this equation is the same as equation 11, and the second term is considered to be due to the time-independent plastic deformation or friction, as against the viscous flow. Three of the four coefficients in equation 12 (A, α, and γ) can be determined from the creep and recovery test results, and the fourth coefficient ξ can be determined from a repetitive loading test.

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