COMPRESSIVE STRESS PULSE TIMES IN FLEXIBLE PAVEMENTS FOR USE IN DYNAMIC TESTING

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Traffic moving over a pavement structure results in a large number of rapidly applied stress pulses being applied to the material comprising each layer. The most realistic method to characterize this stress condition is through the use of dynamic tests such as the repeated load triaxial test or fatigue tests. In this investigation the shape and duration of the compressive stress pulse resulting at different depths beneath the surface are studied for several flexible pavement systems and for vehicle speeds varying between 1 and 45 mph. A comparison is made of the compressive stress pulses caused by a vehicle moving over a layered pavement system at a speed of 1 mph using both linear and nonlinear elastic finite element theory. Viscous effects and inertia forces are neglected in both theories. Because the normalized stress pulses calculated using the linear elastic theory are found to agree closely with those calculated using the nonlinear theory, linear elastic finite element theory is used throughout the remaining portion of the study.

The results of this investigation show that the shape of the compressive stress pulse varies from approximately a sinusoidal one at the surface to more nearly a triangular pulse at depths below approximately the middle of the base. Typically, the compressive pulse time also varies almost inversely with vehicle speed up to at least a speed of 45 mph. Pavement geometry and layer stiffness for spring and summer temperatures do not have a significant influence on the stress pulse times for conventional pavement constructions. For vehicle speeds up to 45 mph, the calculated stress pulse times were empirically corrected for viscous effects and inertia forces using the results of field measurements made at the AASHO Road Test. Finally, curves are presented from which approximate compressive stress pulse times can be selected for use in dynamic testing.

•AS traffic moves along the highway pavement structure, large numbers of rapidly applied stress pulses are applied to each element of material below and for some distance out to the sides of the wheelpath. Typically, these stress pulses last for only a short period of time, and the magnitude and duration of the pulse vary with the type of vehicle and its speed, the type and geometry of the pavement structure, and the position of the element of material under consideration.

To evaluate material properties in the laboratory, the best approach available at the present time is to simulate as closely as possible the field loading condition using a dynamic test. Dynamic bending tests have been used to evaluate fatigue resistance of stabilized surface and base materials (1, 2). Repeated load triaxial tests have also been used by a number of investigators (3, 4, 5). This test gives the dynamic modulus and the permanent rutting (strain) characteristics of both stabilized and unstabilized pavement materials. These results can be used in either theoretical analyses (6, 7) or in direct comparison with the effects of varying basic parameters such as compaction density, gradation, water content, or amount of stabilizing agent.

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In performing the repeated load triaxial test, a cylindrical specimen of material to be tested is placed inside a conventional triaxial cell and usually subjected to a uniform chamber pressure. A large number of repeated axial loads are then applied to the specimen through the piston of the cell by either a pneumatic, hydraulic, or mechanical loading system (1, 2, 3, 4, 5). In the field, both the confining pressure and axial stress would vary as a wheel load moves over the surface. However, for convenience, most investigators have maintained the confining pressure a constant although it can and probably should be varied (5). The obvious advantage of the repeated load test over tests that use a single, slowly applied loading is that the rapidly applied, repetitive stress condition used in repeated load tests much more closely approximates the dynamic loading conditions that actually occur beneath the surface of a pavement system.

The purpose of this paper is to investigate the shape and duration of the axial stress pulse that should be used in performing a dynamic repeated load test. Factors studied that influence the stress pulse are the geometry and stiffness of the pavement structure, the vehicle speed, wheel configuration, rotation of principal stress axes, and material nonlinearity. The stress pulses directly beneath the wheel loading for a range in pavement geometries and layer stiffnesses are determined by using linear elastic layered theory neglecting inertia and viscoelastic effects. The results obtained using the elastic layered theory are compared with the results from a nonlinear theory and are shown to give good agreement. Finally, curves are presented that can be used to select appropriate stress pulse times for dynamic testing for vehicle speeds varying from 1 to 45 mph.

CALCULATION OF THE STRESS PULSE USING ELASTIC LAYERED THEORY

As the velocity of the vehicle increases, field measurements (8) have shown that the stresses and deflections in a layered pavement system become less because of inertia forces and viscous effects. The solution of the general layered system problem considering both viscous effects and inertia forces is very complicated, and this problem has not yet been completely solved. Viscous effects can at least be partially accounted for by testing the pavement materials by using approximately the same transient stress conditions as those that occur in the field caused by the moving vehicle.

To approximately evaluate the shape and duration of the stress pulse that should be applied to a specimen, elastic finite element theory was used neglecting inertia forces and viscous effects. For most of the investigation a single static, circular load of 9,000 lb was applied normally to the surface of the layered system. Shear stresses between the tire and pavement surface were assumed to be negligible. The pressure exerted by the tire on the surface was assumed to be 79.6 psi uniformly distributed over a circular area having a radius of 6 in. The elastic layered pavement system was idealized by using 221 rectangular, ring-shaped finite elements as shown in Figure 1. The size of the elements were increased with increasing distance from the loading as the stress gradients decreased. Each layer was assumed to extend in the lateral direction a large but finite distance, and the interfaces between layers were assumed to be rough.

The principle of superposition was used to calculate the shape and duration of the stress pulse and its variation with depth as a vehicle moves at a constant speed over the surface of a pavement system. The superposition approach used to solve this problem can be conceptually visualized as allowing the vehicle to remain stationary and the element to move past under the vehicle. If it is assumed that zero time corresponds to the instant that the wheel is directly above the element for which the stress pulse is desired, then the half of the theoretically symmetrical stress pulse corresponding to the vehicle moving away from the point can be readily constructed by plotting at the corresponding times the appropriate stress quantities calculated at a number of points out from the loading along a horizontal plane passing through the element under consideration. The time at which the stress is plotted simply corresponds to the distance out from the axis of symmetry of the loading to the point being considered divided by the vehicle speed. The finite element computer program used in this study (9)

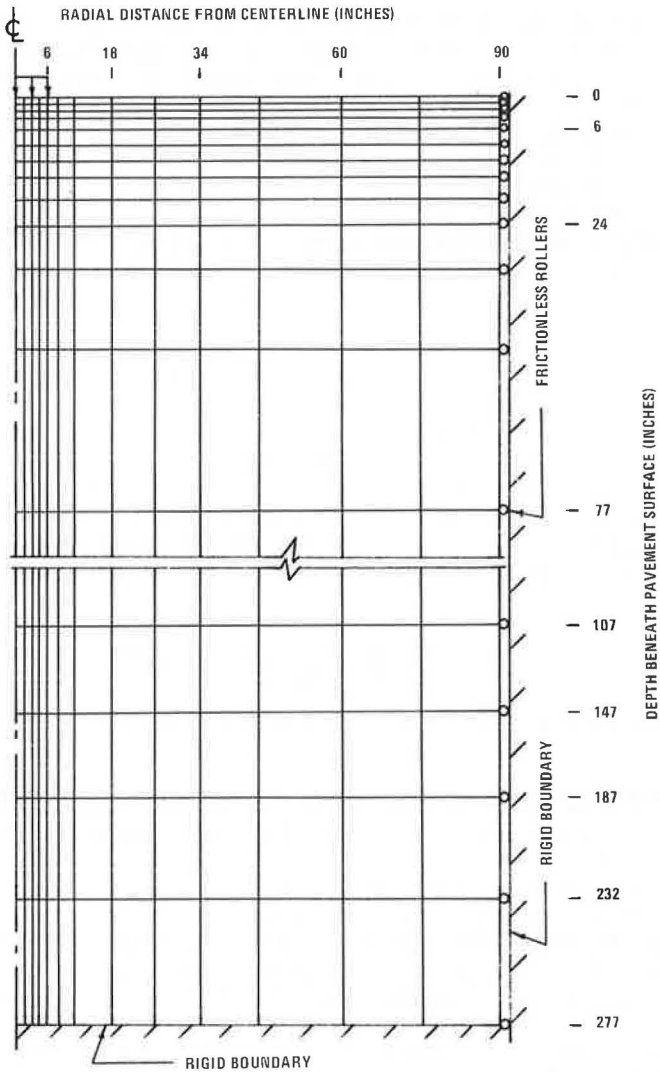

Figure 1. Finite element idealization of pavement system.

calculates the stress state at the center of each finite element. To more accurately construct the stress pulse, the values of stress in between the element centers were estimated by interpolating along a horizontal plane. To do this, a third-degree parabola was passed through the known stress points using Lagrange's interpolation formula (10). All numerical calculations were performed on the UNIVAC 1108 computer at the Georgia Institute of Technology.

COMPARISON OF LINEAR AND NONLINEAR ELASTIC THEORY

To evaluate the effect of material nonlinearity on the shape of the stress pulse, the stress pulses obtained using the linear elastic layered theory were compared with those calculated using a nonlinear elastic theory. The comparison was made for a layered pavement system consisting of 4 in. of asphalt concrete surfacing, 15 in. of crushed stone base, and a silty clay subgrade.

The asphalt concrete was assumed to have a modulus of elasticity of 100,000 psi in compression and 90,000 psi in tension. Several approximations were made in characterizing the granular base. When subjected to a compressive stress state, the granular material was assumed to behave isotropically and have an elastic modulus equal to

$$E_r = 15{,}000\ \sigma_3^{0.5} \tag{1}$$

where

E_r = resilient modulus (psi), and
σ_3 = confining pressure (psi).

Consider now the behavior of the lower part of the base when subjected to radial (lateral) tensile stresses. A certain amount of radial tensile stress can be applied before slip of the material occurs. For stress levels below those required to cause slip, the tensile stresses are resisted by frictional stresses developed between the granular particles caused by the vertical compressive stresses that exist in the base. The lateral tensile stress that can be developed before slip occurs depends on both the magnitude of the normal stress and the coefficient of friction between the particles of stone. For this study a coefficient of friction of 0.6 was used, which corresponds to a friction angle of approximately 31 degrees. When the base was subjected to tensile stresses less than that required to cause slip, a vertical elastic modulus of 10,000 psi and a lateral modulus of 8,000 psi were assigned. When slip did occur, a vertical modulus of 6,000 psi and a radial modulus of 600 psi were used. These values of moduli are probably conservative because, as soon as slip does occur, passive pressure in the surrounding soil further out will be developed, which will result in a rapid increase in stiffness in the radial direction. Furthermore, recent studies (13) indicate that an unstabilized granular material in an unconfined condition can have a vertical modulus of elasticity of 5,000 psi or more.

Although at the present time the approximations that were made concerning the granular base have not been fully justified experimentally, it is believed that these assumptions are certainly more nearly valid than assuming that a granular base behaves as an isotropic, elastic material when subjected to tensile stress components. Furthermore, using this approach, good agreement was found between calculated and measured subgrade stresses on one of the unstabilized granular bases at the AASHO Road Test (14). Certainly, the behavior of granular bases needs considerable further study.

The resilient modulus of the silty clay subgrade was assumed to be a function of only the deviator stress (11) with $E_r = -1{,}090(\sigma_1 - \sigma_3) + 16{,}000$ when $\sigma_1 - \sigma_3$ is less than 12.4 psi, and $E_r = 43.6\ (\sigma_1 - \sigma_3) + 2{,}350$ when $\sigma_1 - \sigma_3$ is greater than 12.4 psi. The resilient modulus, E_r, and the deviator stress, $\sigma_1 - \sigma_3$, are both measured in psi in these expressions.

The nonlinear problem was solved numerically by gradually increasing the surface loading in 50 increments using an anisotropic finite element computer program (9, 14). The corresponding elastic layered system was then solved using the same moduli for the asphalt concrete as used in the nonlinear analysis and a modulus of 35,000 psi and 12,000 psi for the base and subgrade respectively. The moduli used in the elastic analysis for the base and subgrade were approximately the equivalent values determined in those layers from the nonlinear analysis.

The comparison between the linear and nonlinear theory for half of the theoretically symmetrical, vertical compressive stress pulse is shown in Figure 2. Stress pulses shown in this and all subsequent figures are for a vehicle speed of 60 mph as evaluated from elastic theory. Although the absolute values of the vertical compressive stresses were different, the stress pulses were found to be very similar when normalized by the peak value of the vertical stress. Because of the good agreement between the calculated linear and nonlinear normalized stress pulses, all subsequent theoretical calculations were performed using the linear finite element theory.

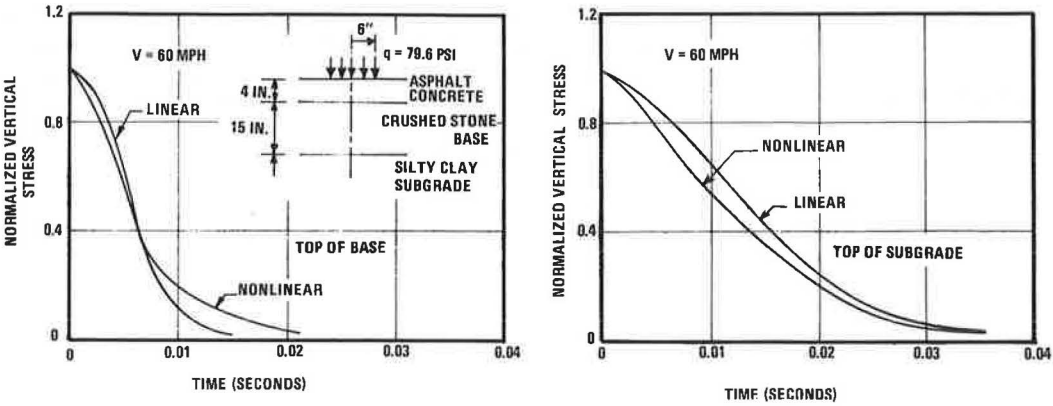

Figure 2. Comparison of theoretical linear and nonlinear vertical compressive stress pulses at two depths—4-in. surfacing and 15-in. base.

FACTORS INFLUENCING THE SHAPE AND DURATION OF THE STRESS PULSE

As a wheel load moves along the surface in the direction of an element of material, the orientation of the principal stress axes is gradually rotated (Fig. 3). At the instant the wheel is directly above the element, the principal stress axes are oriented vertically and horizontally with the principal compressive stress acting in the vertical direction. A typical comparison of half of the vertical and principal compressive stress pulses is given for two depths in Figure 4 for a system having a 4-in. asphalt surfacing and a 15-in. base. The principal normalized stress is seen to be greater than the vertical stress at all times except when they are equal at the instant the load is over the element. Therefore, the principal stress pulse has a longer duration than does the vertical stress pulse with this difference becoming greater with depth.

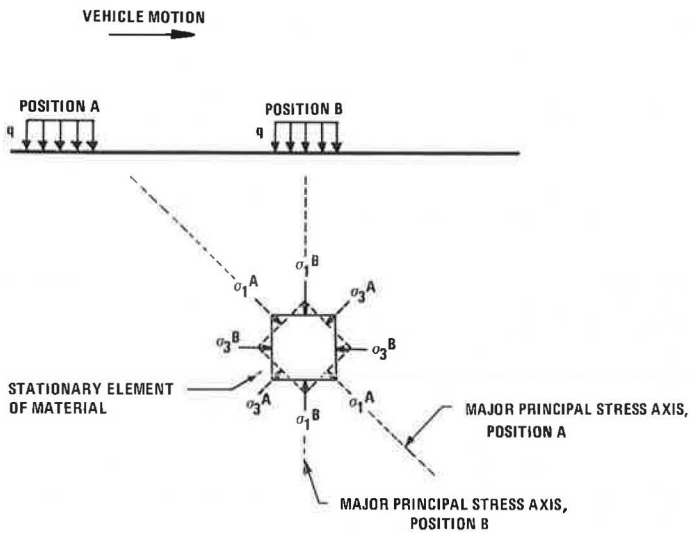

Figure 3. Rotation of principal stress axis of an element as a vehicle moves over the surface.

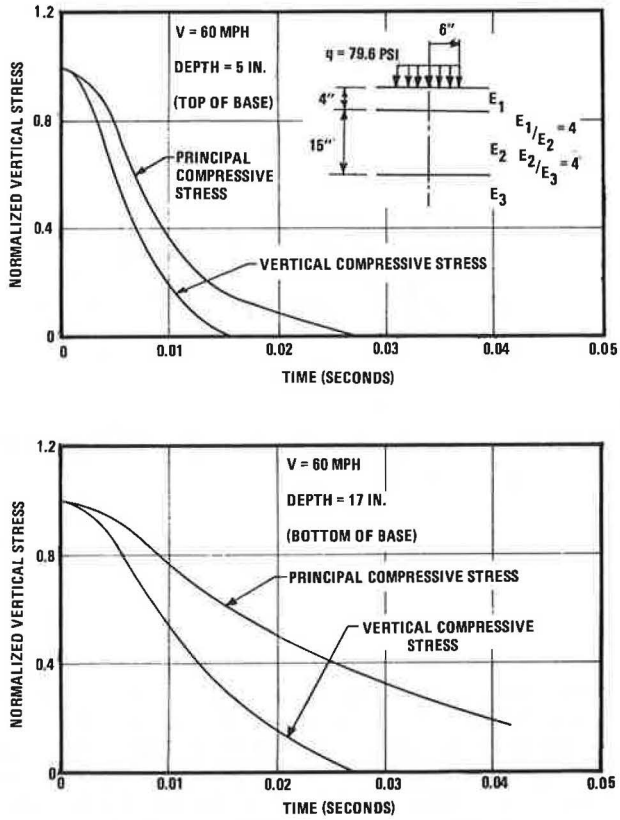

Figure 4. Comparison of vertical and principal compressive stress pulses for two depths—4-in. surfacing and 15-in. base.

The actual stress pulse shape is approximated in this investigation using either an equivalent sinusoidal or triangular stress pulse as shown in Figure 5. The reason for choosing these simplified equivalent pulse shapes is that all commonly used pneumatic, hydraulic, and mechanical loading systems can usually be made to apply one or both

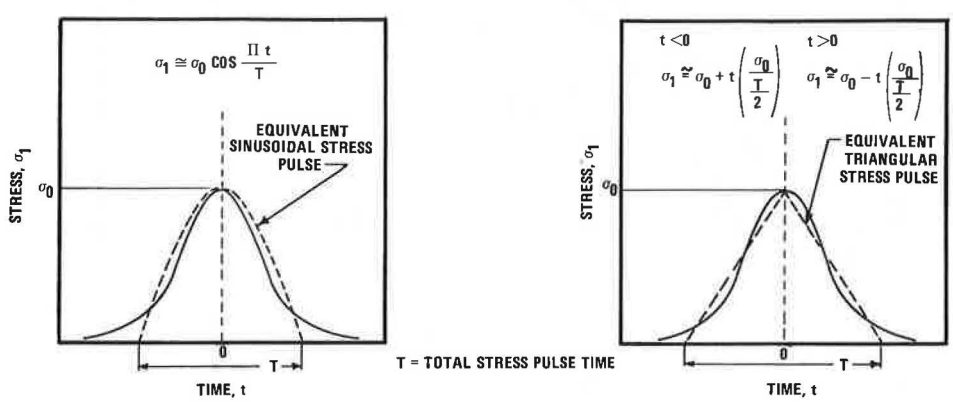

Figure 5. Equivalent sinusoidal and triangular stress pulses.

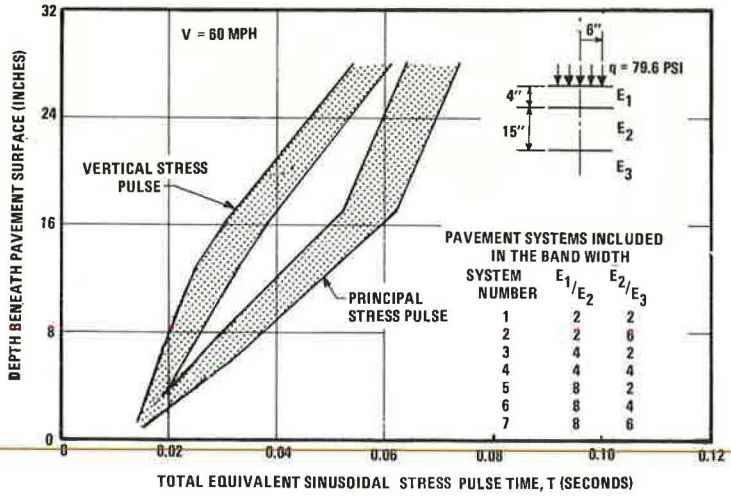

Figure 6. Variation of theoretical vertical and principal compressive stress pulse with depth—4-in. surface and 15-in. base.

of these simplified wave forms. The sinusoidal and triangular stress pulses were visually fitted to the calculated data. A sophisticated numerical curve-fitting technique was not believed to be justified because at the present time it is not possible to predict with an certainty what effect the length of time that a portion of the stress pulse stays on the sample will have on the overall physical response of a specimen. Furthermore, the uncertainties associated with calculations made involving asphalt concrete and

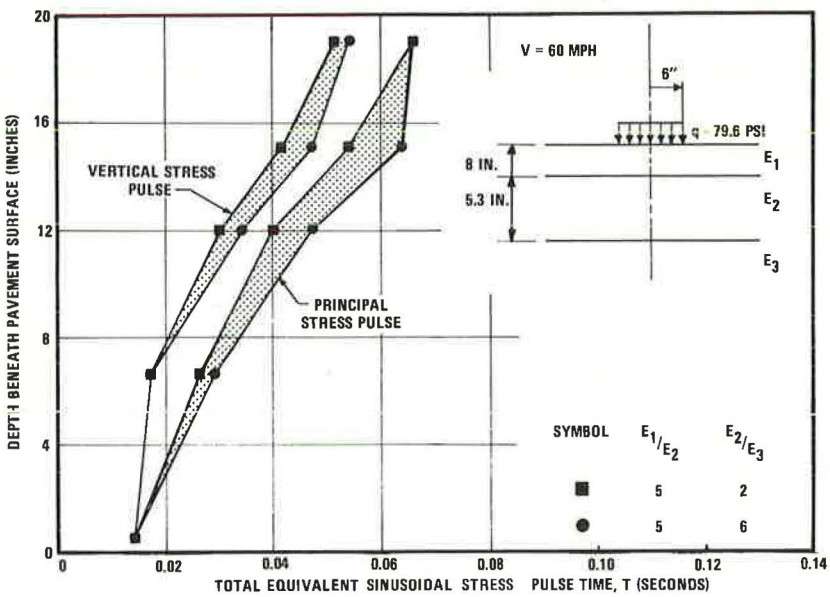

Figure 7. Variation of theoretical vertical and principal compressive stress pulse time with depth—8-in. surface and 5.3-in. base.

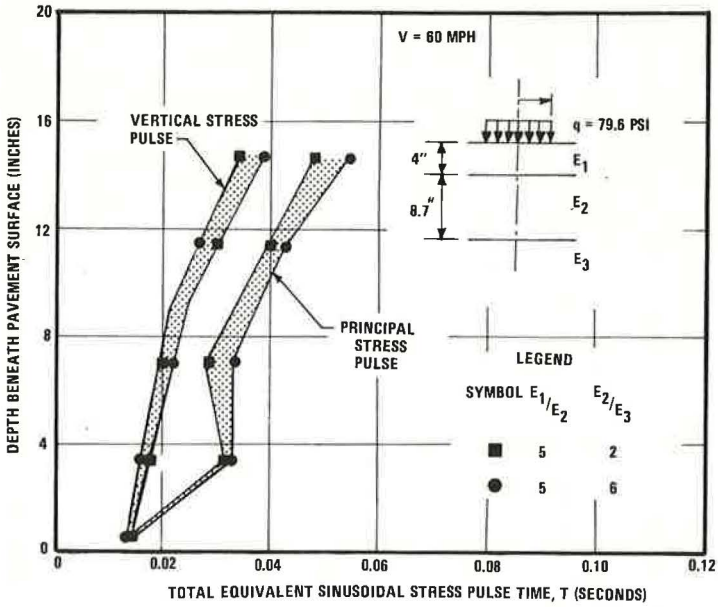

Figure 8. Variation of theoretical vertical and principal compressive stress pulse time with depth—4-in. surface and 8.7-in. base.

unstabilized granular bases using elastic layered theory do not justify a high degree of precision. Undoubtedly the technique used accounts for some of the scatter in the results shown in Figures 6 through 8.

The effect of depth, pavement geometry, and layer stiffness on the equivalent sinusoidal vertical and principal stress pulse times is shown in Figures 6 through 8 for a 9,000-lb, single-wheel loading. These figures show that the total stress pulse time for both the principal and axial stress pulses increases significantly with depth beneath the pavement surface. For example, the vertical stress pulse time in a typical pavement consisting of a 4-in. asphalt concrete surfacing overlying a 15-in. granular base would increase by a factor of approximately 2.7 in going from the surface down to the top of the subgrade. These results clearly indicate that the variation in pulse time with depth should certainly be considered in conducting an experimental testing program. The principal stress pulse time becomes greater with depth than does the vertical compressive stress pulse. After a certain depth, however, the difference in the two equivalent stress pulse times apparently becomes approximately constant or may even decrease with further increase in depth, depending on the pavement geometry.

Figure 6 shows that, for a 4-in. surfacing and 15-in. base and a reasonably wide range in layer stiffnesses, the total stress pulse times did not change drastically with changes in layer stiffness. Considering the uncertainties associated with using the elastic layered theory, it was deemed justifiable to investigate only two reasonable variations in layer moduli for the other two systems studied, and to use only the average total pulse times in summarizing the results of this investigation.

The shape of the stress pulse also varies significantly with depth (Fig. 9). Near the surface the pulse shape can be reasonably accurately approximated as a half sinusoid. With increasing depth, however, the pulse flattens out significantly so that, for elements located in the subgrade, the pulse can, in general, be more accurately approximated by a triangular pulse shape. For the pavement system shown in Figure 6, which has a 4-in. asphalt surfacing and 15-in. base, the sinusoidal shape pulse gives a reasonably good approximation to the stress pulse above a critical depth somewhere between the middle and top portion of the base; below this level the triangular pulse is

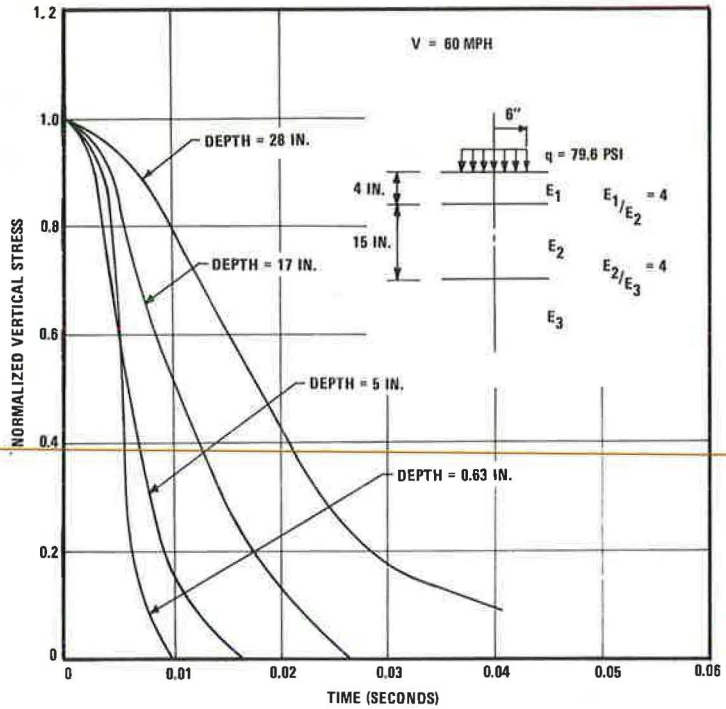

Figure 9. Variation of calculated vertical compressive stress pulse shape with depth—4-in. surface and 15-in. base.

probably more appropriate. For the system with a 4-in. surfacing and 8.7-in. base (Fig. 8), the approximate depth for change in shape of the stress pulse is in the vicinity of the top of the base. The critical depth of the stress pulse shape for the system with the 8-in. asphalt surface and 5.3-in. granular base (Fig. 7) is in the lower part of the asphalt layer.

All of the stress pulses shown are for a vehicle speed of 60 mph and a single-wheel loading. A single-axle, dual-wheel loading causes a change in the pulse shape and peak stress in the lower part of the base and subgrade. The equivalent pulse times for points located beneath the center of the dual-wheel assembly for practical purposes can be assumed to be the same as for a single-axle loading, although a slight decrease in equivalent pulse time does apparently occur. Neglecting inertia forces and viscous effects, the effect of vehicle speed would be to simply compress the time scale of the stress pulse in an inverse proportion to the vehicle speed. Thus, if the pavement performs as an elastic system, an increase in vehicle speed would tend to linearly decrease the stress pulse time, and a decrease in speed would linearly increase the stress pulse time. In going from a creep speed to speeds of 45 to 60 mph or more, however, inertia forces and viscous effects would be expected to probably influence the stress pulse and result in a nonlinear scaling law. These effects are empirically considered in the next section by adjusting the stress pulse times to agree with measured pulse times.

COMPARISON WITH EXPERIMENTALLY MEASURED STRESS PULSES

To investigate the influence of inertia and viscous effects, the theoretically calculated stress pulses were compared with the pulse times measured in the field during the AASHO Road Test. A reasonably good evaluation of the elastic theory can be obtained because most of the significant variables for this study are documented in the

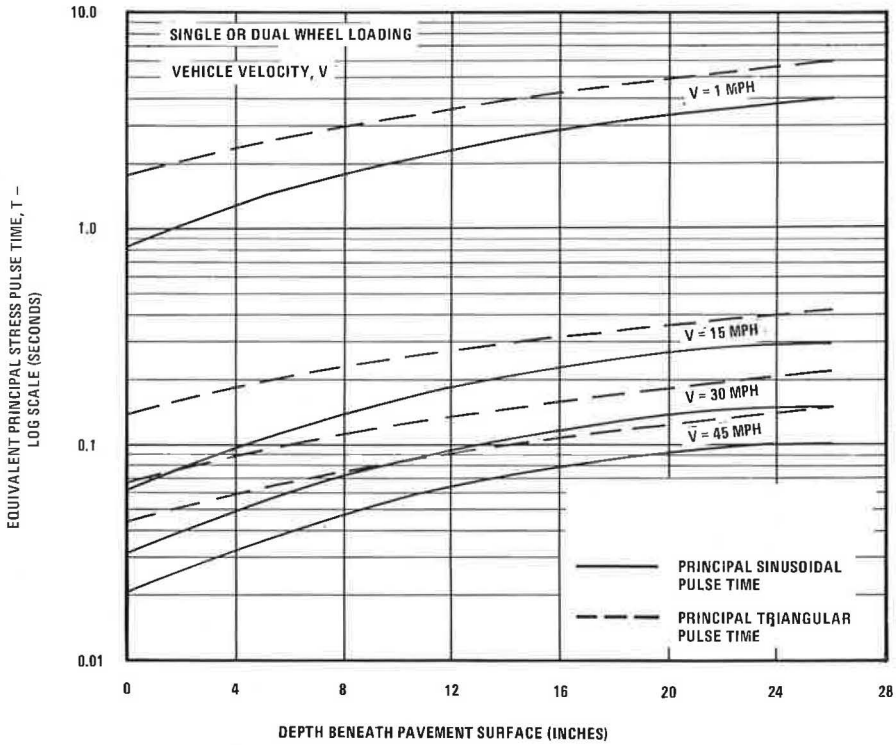

Figure 10. Variation of equivalent principal stress pulse time with vehicle velocity and depth.

literature (12). The following comparisons are made for a flexible pavement system consisting of a 5-in. asphalt concrete surfacing, 6-in. unstabilized crushed stone base, 12-in. sand-gravel subbase, and a compacted silty clay subgrade. Peak vertical pressures and the corresponding leading and tailing distances to zero pressure were measured at the top of the subgrade embankment.

Only the results of the measurements made using a 22.4-kip single-axle, dual-wheel loading moving at a creep speed were compared with the elastic theory. Inertia forces and viscous effects in the field measurements were minimized by making this comparison using the values measured for a creep vehicle speed. The average distance from zero pressure to the peak pressure measured at the Road Test was 49.7 in. for these conditions. The corresponding average measured distance from the peak to zero pressure was 57.0 in. The distance from zero to peak pressure calculated for the AASHO Road Test conditions using the elastic finite element theory varies from a minimum value of 47.5 in. to a maximum of 57.0 in. depending on how the numerical results are interpreted. The extreme values of the theoretical results, therefore, agree closely with the extremes in the measured distances for the case of creep vehicle motion.

Because inertia forces and viscous effects are neglected when using the finite element theory, the calculated distance in which the pulse either builds up to a maximum or goes from the maximum value to zero does not vary with vehicle velocity. In the Road Test pavement system, however, these measured distances were found in the most extreme instance to increase by as much as 26 percent as the vehicle goes from a creep speed to a speed of 30 mph. To estimate the effects of inertia forces and viscous effects, all of the measured leading and tailing distances for both the 18- and 22.4-kip single-axle, dual-wheel loadings were averaged for each vehicle speed. Corresponding average correction factors to be applied to the creep distance were determined to be 1.11 and 1.13 for vehicle speeds of 15 and 30 mph respectively. By

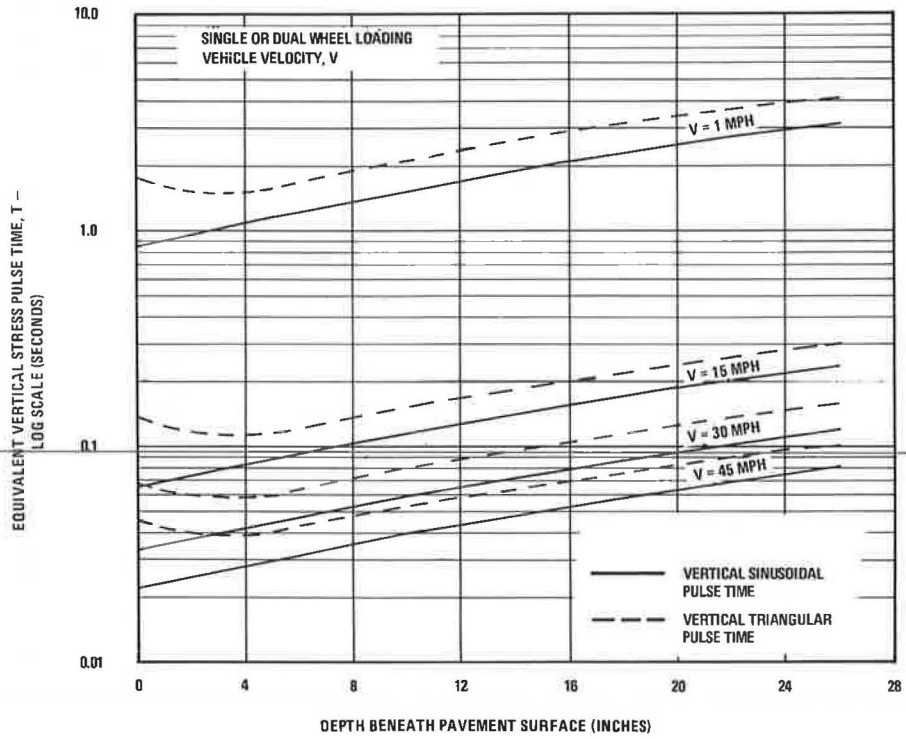

Figure 11. Variation of equivalent vertical stress pulse time with vehicle velocity and depth.

extrapolating these results, a correction factor of approximately 1.14 was obtained for 45 mph. The theoretically calculated values of the pulse times for a creep vehicle speed are assumed to be reasonably good, considering how favorably the calculated distances compared with the leading and tailing distances measured at the AASHO Road Test. Therefore, the stress pulse times obtained using elastic layered theory were not corrected for creep vehicle speeds. The correction factors for greater vehicle speeds obtained from the AASHO Road Test field measurements were applied to the stress pulse times derived from elastic theory.

A tabulation was made of the corrected stress pulse times for the pavement systems shown in Figures 6 through 8. A study of these pulse times indicated that for conventional flexible pavement sections, including deep strength designs and spring and summer temperatures, the equivalent stress pulse times at a given depth do not change significantly with different flexible pavement constructions. This approximation made it possible to summarize the results of this investigation in Figures 10 and 11. These figures give the variation of both the equivalent sinusoidal and triangular stress pulse times with vehicle velocity and depth beneath the pavement surface. These stress pulse times have been empirically corrected for viscous and inertia effects as previously discussed. The stress pulse times given are for a point located directly beneath the center of the load for a single-wheel loading and beneath the center of the assembly for single-axle, dual-wheel loadings.

DISCUSSION OF RESULTS

The repeated load test should be performed to duplicate as closely as possible the same stress conditions that an element of material will be subjected to in the field. This is true if the results are to be used to directly compare the performance of

of different materials, or if the evaluated material properties are to be used in a layered system or other type of theoretical analysis. By simulating the field stress conditions in the laboratory, the effects of material viscosity and inertia are at least partly accounted for in the evaluated material properties. Because rate-of-loading effects are not considered in the presently used elastic layered theory, it is indeed important that the material properties at least partly reflect viscosity effects. An element of material in the field is actually subjected to repeated stress pulses of different magnitudes caused by the variation in the position of the wheel loading across the pavement and by the application of widely varying wheel loadings. At the present time probably the most realistic way to handle varying wheel loadings in performing the repeated load test is to convert the mixed traffic to an equivalent number of 18- or 20-kip single-axle loadings. Certainly further study is needed on the effects of varying loads on the specimen.

The results of this study indicate that, in general, for conventional pavements having an asphalt concrete surfacing up to a thickness of about 5 in., a sinusoidal stress pulse should be applied to specimens simulating elements of material in the asphalt surfacing and the upper part of the base. For the thicker deep-strength or full-depth asphalt pavements, a sinusoidal stress pulse is probably appropriate only for elements in the middle and upper parts of the asphalt. Below these depths, a triangular-shaped stress pulse more nearly approximates the actual one. More complicated stress pulse forms are not, at the present time, considered necessary because of the many uncertainties associated with the use of layered theory.

In conducting a repeated load test, the choice arises as to whether to use the vertical stress pulse or the principal stress pulse. Probably for measuring the dynamic modulus of elasticity, the principal stress pulse would be the most appropriate because the modulus is usually defined in terms of principal stress systems, and principal stresses are normally applied in a triaxial cell. On the other hand, if the plastic properties of the material are desired to study rutting, possibly the vertical stress pulse would be more appropriate because the displacements of the pavement system are usually desired in the direction normal to the pavement surface.

CONCLUSIONS

The repeated load triaxial test more closely simulates the stress conditions that an element of material beneath a flexible pavement system feels than does the CBR test, the Hveem stabilometer test, or the conventional triaxial test. Therefore, the repeated load test or similar tests should become more commonly used in the future to predict pavement performance. The vehicle speed and depth beneath the pavement surface are of great importance in selecting the appropriate axial compressive stress pulse time to use in dynamic testing. For conventionally used flexible pavement sections, including deep-strength asphalt concrete structures and spring and summer temperatures, the stiffness and depth of each layer have only a small influence on the duration of the stress pulse. The influence of these factors can be neglected at the present time for practical engineering purposes. In addition, the axial stress pulse duration for a single- and dual-wheel loading can be considered to be approximately the same although the duration of the stress pulse caused by the dual-wheel loading is slightly less. As a consequence of these simplifying relationships, the equivalent sinusoidal and triangular stress pulse times for vehicle speeds up to 45 mph can be given as a function of vehicle velocity and depth beneath the pavement surface (Figs. 10 and 11).

The stress pulse times given in this paper were obtained using a linear elastic layered theory. The theoretically calculated stress pulse times were empirically corrected for inertia and viscous effects by using data obtained from the AASHO Road Test. Nevertheless, as more reliable field data are obtained and more refined methods of analysis become available, the pulse times recommended in this paper should be reexamined and also extended to include vehicle speeds greater than 45 mph.

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