IMPROVED FRAMEWORK FOR PREDICTING PERMANENT DEFORMATION IN ASPHALT LAYERS

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When permanent deformation in asphalt pavements is predicted by elastic analysis and repeated-load triaxial testing, problems arise in the tension zone because of tensile stress in both horizontal directions. This stress situation cannot be directly reproduced in the triaxial test. An approach is suggested to deal with this problem in particular and with pavement materials characterization in general. It recognizes that strains developing in any particulate material depend on the combination of mean normal stress and octahedral shear stress. These stress invariants are functions of the principal stresses but are independent of their directions. Triaxial tests can be more flexibly used by reproducing the appropriate values of these stress invariants rather than the in situ principal stresses. Measurement of vertical and lateral strains during the test permits the evaluation of corresponding strain invariants that can be used to calculate the in situ vertical strain, which is of interest in rut depth prediction. Elastic analysis indicates that the suggested approach should lead to better predictions of permanent deformation in high temperatures and thick layers. The very high tensile stresses associated with lower temperatures and thinner layers still, however, present a problem because only one tensile stress can be applied in the triaxial test.

•OVER the last few years, increasing attention has been directed to problems of developing suitable, analytically based procedures for the prediction of permanent deformation in flexible pavements (1, 2, 3, 4, 5), particularly the asphalt layer. At the present time the most promising approach is based on linear or nonlinear elastic analysis of the structure and the results of repeated-load triaxial, or creep, testing of materials. Relationships between the imposed stresses and the resulting permanent strains are applied to the in situ stress situation, and the total permanent surface deformation is arrived at by summation of vertical permanent strains throughout the depth of the structure.

The repeated-load triaxial test programs associated with this work have concentrated on trying to reproduce the in situ principal stress conditions occurring beneath the center line of the applied wheel load, and this approach seems reasonable for the compressive stress conditions encountered in the upper part of the asphalt layer and in the unbound layers of the pavement. However, for the lower part of the asphalt layer, where tensile horizontal stresses develop in both the lateral and longitudinal directions, approximations and assumptions have had to be made because tensile stress can only be applied in one direction in the triaxial test. A comparison of stress conditions in the two situations is shown in Figure 1.

The approach previously adopted (3, 4) is shown in Figure 2. The in situ vertical strain at any point is equated to the appropriate axial or radial strain in the triaxial test depending on the position in the layer being considered. Using this approach, Morris et al. (4) and McLean and Monismith (3) obtained different permanent strain

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Figure 1. Stress conditions.

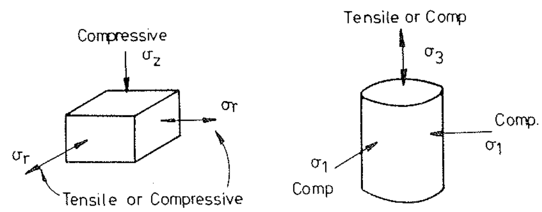


Figure 2. Previous approach for determining vertical permanent strain.

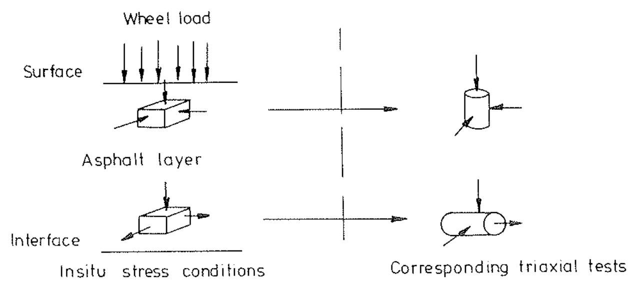
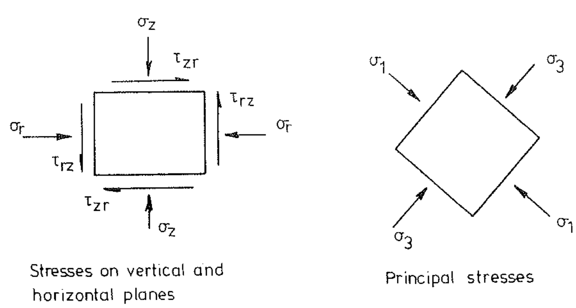


Figure 3. General in situ stress situation.



variations with depth. This suggests that the method may not be so sound as their predictions for permanent deformation at the surface suggest. Furthermore, even if the disparity of stress conditions in the tension zone shown in Figure 2 is ignored, and Morris (6) has indicated that there may be some justification for this, the procedure is only valid for locations on the center line of the wheel load where the principal planes are vertical and horizontal.

Figure 3 shows in two dimensions an element oriented vertically from the pavement. The indication is that, in general, the principal stresses do not act vertically and horizontally. Since the rut depth prediction always requires that the vertical in situ permanent strain be determined, some procedure, independent of the directions of the principal stress, is required if the triaxial test is to be used for this purpose. Such an approach uses stress invariants, which are functions of the principal stresses but are independent of the orientation of the axes. Corresponding strain invariants can be determined from the laboratory tests, and better estimates of the in situ vertical strain can be obtained.

Although it is true that the maximum permanent deformation occurs beneath the center of the wheel load, in practice this is not a fixed location and, particularly in the transverse direction, the deformation occurring off the axis is important.

STRESS INVARIANTS

In a three-dimensional stress system at a point where the principal stresses are σ_1, σ_2, and σ_3, considerations of equilibrium indicate the following three stress invariants:

$$I_1 = \sigma_1 + \sigma_2 + \sigma_3 \quad (1)$$

$$I_2 = \sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_3\sigma_1 \quad (2)$$

$$I_3 = \sigma_1 \sigma_2 \sigma_3 \quad (3)$$

So that the in situ stress conditions in a test system can be reproduced, the values of I_1, I_2, and I_3 are required even if their component principal stresses differ.

An easier physical interpretation of a three-dimensional stress system is obtained by considering the applied stresses to be divided into those causing volume change and those causing shear distortion. Appropriate stress functions for mean normal stress are

$$p = \tfrac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad (4)$$

and for octahedral shear stress are

$$\tau\,\mathrm{oct} = \tfrac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2} \quad (5)$$

τ oct is a function of I_1 and I_2, but $p = \tfrac{1}{3}I_1$, and hence these two parameters are also invariants.

If these two stress functions alone are used, the invariant I_3 is not considered. However, this is the normal procedure when particulate materials are dealt with, and I am not aware of evidence to suggest that I_3 is a significant parameter. In addition, its physical meaning is difficult to define.

The approach suggested by Freeme (7), based on plasticity theory, goes some way toward solving the problem but concerns only the shear stress function and ignores mean normal stress, which is of considerable significance for particulate materials.

If, for simplicity, the in situ stress condition beneath the center of a single wheel load is considered, then $\sigma_1 = \sigma_z$ = vertical stress, and $\sigma_2 = \sigma_3 = \sigma_r$ = horizontal stress. Hence, the normal and shear stress invariants can be written as

$$p = \tfrac{1}{3}(\sigma_z + 2\sigma_r) \quad (6)$$

and

$$q = (\sigma_z - \sigma_r) = \left(3/\sqrt{2}\right)\tau\,\mathrm{oct} \quad (7)$$

The deviator stress q has been introduced in keeping with soil mechanics practice (8). In the conventional triaxial compression test, the vertical stress is σ_1 and the confining stress is σ_3. However, the in situ conditions in the tension zone dictate that tensile vertical stress needs to be applied in the triaxial test. Therefore, when a conventional positive sign for compression is used, the lateral stress becomes the major principal stress σ_1, and the axial stress becomes σ_3 as shown in Figure 1.

Hence, for the triaxial test, the values of p and q may be defined as follows:

$$p = \frac{1}{3}(2\sigma_1 + \sigma_3) \quad (8)$$

and

$$q = (\sigma_1 - \sigma_3) \quad (9)$$

The triaxial test program should be planned so that the combinations of p and q that are applied to the test samples are the same as the in situ combinations for the point concerned.

Strains measured in the triaxial test need to be translated to the in situ situation by equating the appropriate invariants, the same approach that was used for stresses. Here again the physical interpretation is helpful. The mean normal stress p causes volume change, the corresponding strain invariant is the volumetric strain v, and the octahedral shear stress causes a corresponding shear strain. These strains are defined for conditions in the triaxial test as

$$v = 2\epsilon_1 + \epsilon_3 \quad (10)$$

and

$$\gamma\,\mathrm{oct} = \left[\left(2\sqrt{2}\right)/3\right](\epsilon_1 - \epsilon_3) \quad (11)$$

and for the in situ situation as

$$v = \epsilon_z + 2\epsilon_r \quad (12)$$

and

$$\gamma\,\mathrm{oct} = \left[\left(2\sqrt{2}\right)/3\right](\epsilon_z - \epsilon_r) \quad (13)$$

where γ oct is the octahedral shear strain. Both ϵ_1 and ϵ_3 must be determined in the triaxial test so that v and γ oct may be calculated. Then, solving equations 12 and 13 for ϵ_z, which is the required in situ strain, gives

$$\epsilon_z = \frac{4}{3}\epsilon_1 - \frac{1}{3}\epsilon_3 \quad (14)$$

IN SITU STRESS CONDITIONS

The extent to which the suggested approach can be used to reproduce the tension zone stress conditions was investigated by using the BISTRO computer program to analyze a range of pavement structures (9). The structures are shown in Figure 4, and some details of them are given in Table 1.

For the asphalt layer, two thicknesses were chosen to represent the range likely to occur in practical situations in which permanent deformation of this layer could be expected to be significant. Temperature conditions below 25 C were not considered since little permanent deformation is likely below this level. Structures with 40 C penetrating to a depth of 300 mm are rather unrealistic, but systems 9 to 12 recognize that temperature gradients do occur. Clearly other combinations of temperature and layer thickness are possible, but sufficient data emerged from those selected to arrive at certain conclusions.

The two subgrade conditions represent the range likely to occur in practice. The granular subbase was excluded from systems 9 to 12 because the earlier calculations showed that support conditions did not have a large effect on stresses in the asphalt layer. This conclusion is indirectly supported by McLean and Monismith (3).

Each system was loaded with a single, standard 40-kN wheel load having a contact pressure of 500 kPa. For all systems the variation of vertical and horizontal stress with depth on the center line of the load was evaluated. Based on these basic data, the variation of both p and q with depth was calculated.

Figures 5 and 6 show stress distributions for two of the systems that were analyzed. The variation of mean normal stress is similar to that for horizontal stress. A zone is shown near the top of the layer where the horizontal stress is greater than the vertical stress. This causes the deviator stress to assume a negative value relative to the situation lower in the layer. Horizontal stress changes from compressive to tensile at 100 mm in Figure 5 and at 300 mm in Figure 6. This defines the top of the tension zone.

Corresponding values of p and q from all the systems analyzed fall within the black area shown in Figure 7. These combinations, representing the range of likely practical conditions, only occupy a small part of Figure 7. The changing stress conditions moving down through a layer are shown in Figure 7 from bottom right to top left on the p-q relationship. The extremities are all for the 100-mm layer; values for the 300-mm layer generally fall within the square formed by the dotted lines through ±1000 kPa on both axes.

This area is enlarged in Figure 8 so that variations due to differences in the various structures can be identified. Layer thickness is the variable having most influence on the shape and position of the p-q relationship. Increasing the temperature or the strength of subgrade support tends to increase the nonlinearity of the relationship and shorten its length.

The primary purpose of this investigation was to check whether all points within the black zone of Figure 7 could be reproduced in the triaxial test. The limitation of the test for compressive values of p is provided by the capacity of the cell. Triaxial cells are generally designed for pressures up to about 1000 kPa, but special-purpose, high-pressure cells are available so that all points having compressive values of p can be accommodated.

The test limitations in the tension zone are provided by the situation of a uniaxial tension test, i.e., $\sigma_1 = 0$. This condition is represented by

$$q = -3p \tag{15}$$

and is shown in Figure 7. This limitation is more severe than any other occurring in the compression zone, because only points to the right of this line can be reproduced in the triaxial test. However, the more detailed Figure 8 shows that systems 4 and 8 terminate only slightly to the left of the line, $q = -3p$. In addition, design calculations

Figure 4. Pavement systems analyzed.

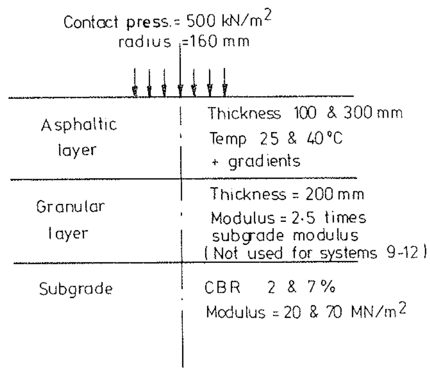


Table 1. Information from pavement analyses.

System Number	Temperature (deg C)	Subgrade (percent)	Thickness of Layer (mm)	Depth (percentage of layer thickness): Compression Zone	Depth (percentage of layer thickness): Limit for Triaxial Testing	Depth (percentage of layer thickness): To $\sigma z = \sigma r$	Minimum Thickness of Lowest Sublayer (percentage of layer thickness)	Number of Sublayers of Approximately Equal Thickness
1	25	2	100	52	59	48	84	1
2	40	2	100	55	68	47	64	1
3	25	7	100	54	66	46	68	1
4	40	7	100	67	95	44	10	10
5	25	2	300	52	70	22	60	2
6	40	2	300	53	75	20	50	2
7	25	7	300	53	73	18	54	2
8	40	7	300	58	88	12	24	4
9	40 to 30	2	100	55	62	50	76	1
10	40 to 30	7	100	60	71	50	58	2
11	40 to 20	2	300	67	77	10	46	2
12	40 to 20	7	300	67	77	0	46	2

Figure 5. Stress distributions through a 100-mm layer.

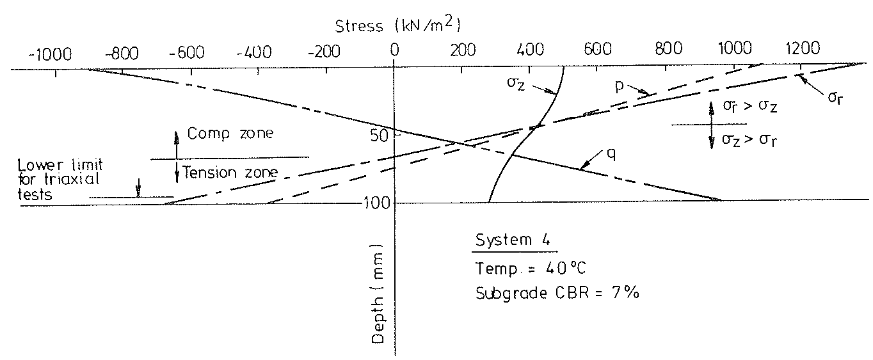


Figure 6. Stress distributions through a 300-mm layer.

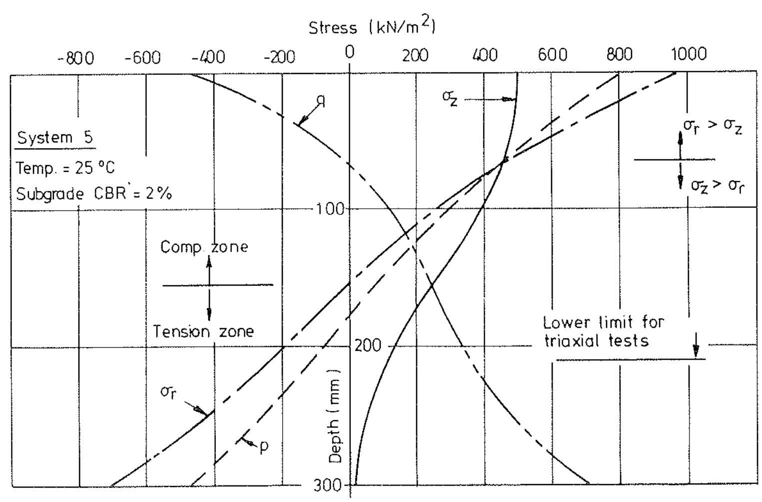


Figure 7. In situ relationship between p and q.

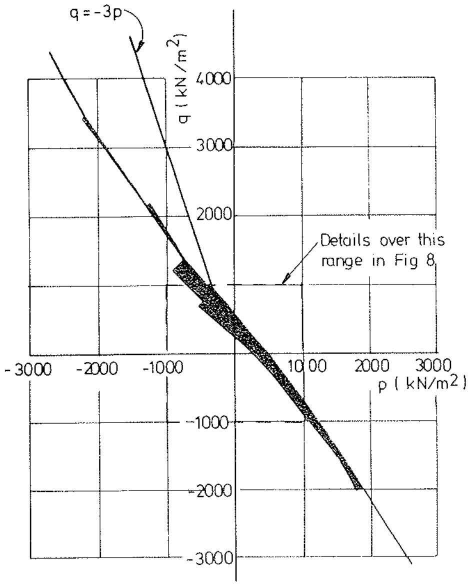
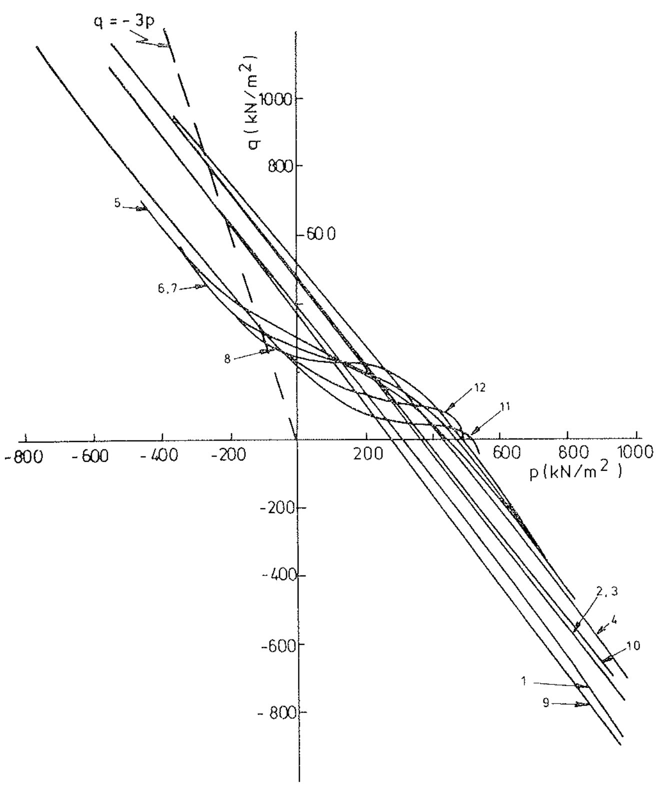


Figure 8. Relationships between p and q for various conditions.



for permanent deformation do not necessarily require details right down to the bottom of the layer.

IMPLICATIONS FOR DESIGN CALCULATIONS

Figures 5 and 6 and Table 1 show the extent of the compression zone and the depth of the surface zone in which the horizontal stress exceeds the vertical stress. This latter zone has been identified because the definitions of major and minor principal stress are reversed both in situ and in the triaxial test. This, however, has not been done here because interest is mainly focused on the problems of the tension zone.

For design calculations to predict permanent deformation, the asphalt layer is subdivided into a number of sublayers. The position of the center of the lowest of these is dictated by the lowest point for which stress-strain data are available from the triaxial test. If Figure 5 is used as an example, this lowest point is 5 mm from the bottom, and hence 10- × 10-mm sublayers could be used for analysis. This would provide detailed information on the variation of permanent deformation with depth.

The case shown in Figure 6 is not so good because the lowest sublayer would need to be 180 mm thick. The remaining 120 mm could be either treated as one layer or subdivided into thinner ones.

Table 1 gives the thickness of the lowest sublayer and the suggested number of sublayers of approximately equal thickness for all the systems investigated.

For conditions in which the layer is thin and the temperature low or the subgrade support weak, no subdivision of the layer is possible. Fortunately these are conditions in which the contribution of the asphalt layer to permanent deformation is likely to be minimal. In these cases, the stress conditions at the center of the layer and the corresponding strains represent the average situation for the whole layer. If layers are thick, temperatures are high, and subgrade support is strong, more sublayers are possible, although in several cases only two can be used, one for average conditions in the tension zone and one for the compression zone. However, further subdivision is possible for the latter.

Until design calculations using the approach suggested in this paper have been attempted, it will be difficult to decide how many sublayers are really necessary. Clearly a large number provide greatest accuracy in predicting permanent strain. However, because the permanent strain variation with depth is not yet well-established, the minimum number of layers required for a particular design situation cannot be specified. It is also necessary in this context to know the importance of the asphalt layer in relation to the rest of the structure insofar as the potential for permanent deformation is concerned.

DISCUSSION OF RESULTS

The results have shown that, although the suggested approach can deal with the tension zone to a limited extent, which, in many cases, may be adequate for design calculations, there are still situations of high tensile stress that cannot be reached because of the limitations of the triaxial test. For a better understanding of the seriousness of this limitation, information is required from laboratory testing on the relative importance of mean normal stress and shear stress. If one of the stresses can be shown to have much more effect on permanent strain than the other, then this one at least can be applied at the correct level, and the other approaches can be used if they are compatible with the limitation represented by the line, $q = -3p$, shown in Figure 7.

Any study of the relative importance of p and q must recognize the fundamental fact that volume change occurs during shear for particulate materials. In other words volumetric strain is a function of both p and q, and the same is likely to be true of shear strain. Hence, the proposed test program should investigate the effects of p and q independently.

In all the foregoing discussion of stress levels for laboratory testing, the values of p and q have been taken to be those occurring beneath the center of the load. Any point in the pavement is subjected to stress pulses as the wheel moves along, and these p and q values are therefore based on the peak values of such pulses. The actual stress path taken to reach these peak values will depend on the shapes of the three principal stress pulses.

In laboratory testing, it is normal to pulse the vertical and confining stresses mutually in phase or to apply a constant confining stress in conjunction with a cyclic vertical stress. Figure 9 shows the different stress paths that can result.

P represents a point on the p-q relationship for the particular structure and can be considered to be lying on one of the curves in Figure 8. O represents the starting point and is the stress condition due to overburden pressure, which will be quite near zero for the asphalt layer. If the vertical and confining stresses are pulsed in phase, the stress path is the line OP (case a, Figure 9). If a constant cell pressure is applied and P is still to represent the peak stress condition, then case b in Figure 9 represents the stress path. The essential difference is that the mean level of $p(p_m)$ increases, and this will increase the stiffness of the material and reduce permanent deformation. A better situation, involving constant cell pressure, is represented by case c, in which p_m is the same as for case a. This results from the application of a cell pressure equal to the mean of the cyclic alternative.

The above points were illustrated by the results of work by Brown and Snaith (10), who also investigated the effect of different compressive pulse lengths in a preliminary way. They concluded that for the conditions selected there was only a negligible effect on permanent strain. The approximate relative pulse lengths and corresponding stress paths they used are shown in Figure 10. Unequal stress pulses produced a slightly higher value of p_m and a correspondingly higher permanent strain (10).

It would seem, therefore, that for a given peak value of q, the mean value of p must be correctly reproduced in the laboratory test.

A reasonable correlation exists between the permanent strains developed in creep tests and those from repeated load tests (5, 10). An alternative approach that eliminates problems of stress path is to carry out confined creep tests in which appropriate values of vertical and confining stress are applied to represent a point such as P in Figure 9. The corresponding strains and their variation with time can then be monitored, and the information can be used as indicated in this paper.

The tension zone gives rise to another advantage of using creep tests inasmuch as fatigue cracking failure is likely under repeated-load conditions and its incidence is clearly undesirable when permanent deformation is investigated.

Stress levels from three previous investigations compared with those suggested in Figures 7 and 8 are shown in Figures 11 and 12.

The zones used by Morris et al. (4) in their factorial experiment are shown in Figure 11. There is a gap between their tension and compression tests, and the stress conditions for the thick layer in their test track fall partly in this gap. This would seem to be undesirable for predicting in situ permanent deformation. The two zones, however, fall within the limits established here.

The tests carried out by Brown and Snaith (10) were not specifically related to in situ stress conditions and fall mainly outside the proposed testing zone (Figure 11). Their unconfined tests at low stress levels, however, do accommodate conditions near the center of the layer. This is the gap in the tests of Morris et al. (4).

The unconfined creep tests discussed by Van de Loo (5) would fall on the same line, $q = -3p$, as most of the tests of Brown and Snaith (10). The major shortcoming of these tests (5) and Freeme's approach (7), however, seems to be that they ignore the effect of confining stress.

The zone suggested by McLean and Monismith (3) from analyzing an experiment carried out by Hofstra and Klomp (11) is shown in Figure 12. This was established from calculations involving dual wheel loads and includes stress conditions off the axis of symmetry. In these circumstances, the difficulty arises of vertical and radial stresses not being principal values (Figure 3), and it is not clear from this paper whether this has been taken into account. The suggested stress zone for testing is somewhat wider and shorter than that given in Figures 7 and 8 but can be entirely

Figure 9. Stress paths for repeated loading.

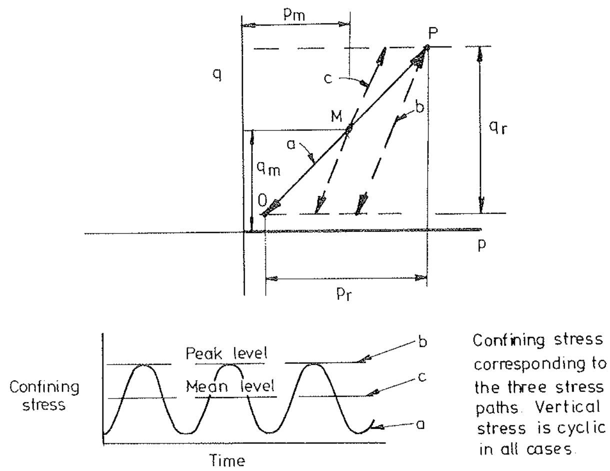


Figure 10. Varying relative pulse lengths and corresponding stress paths.

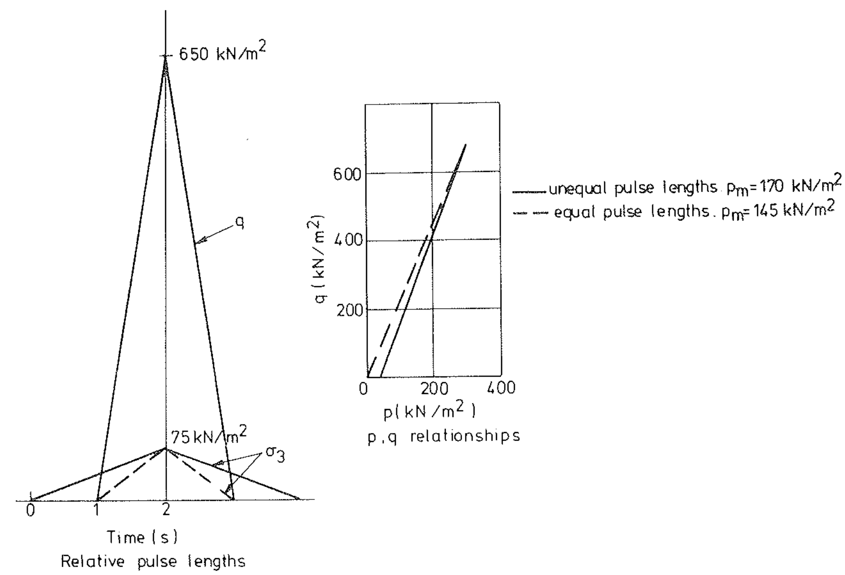


Figure 11. Stress conditions used by Morris et al. and Brown and Snaith compared with those from Figure 8.

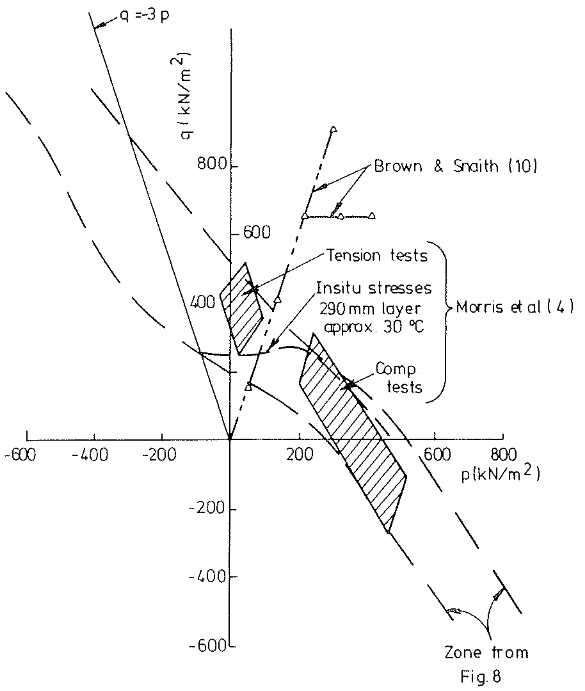
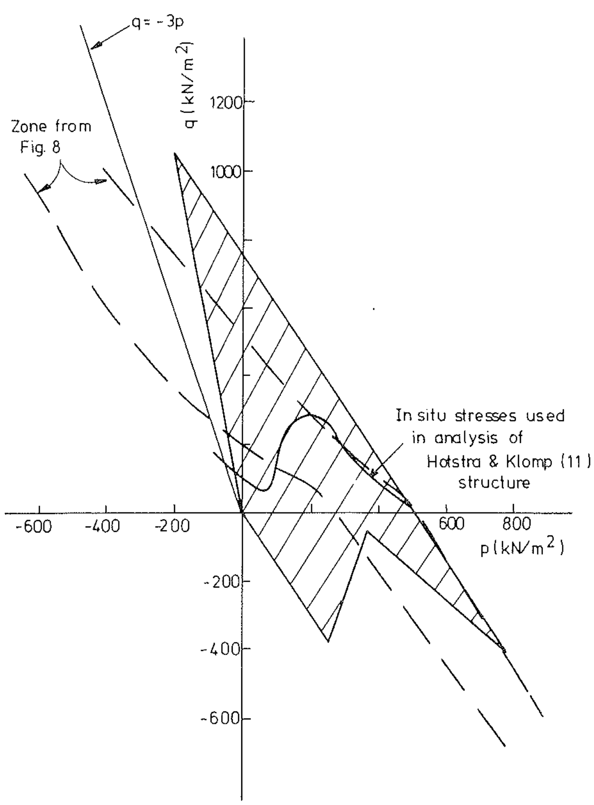


Figure 12. Stress ranges used by McLean and Monismith for analyzing Hofstra and Klomp experiment compared with those from Figure 8.



covered by the triaxial test. The stress conditions used by McLean and Monismith (3) in analyzing an experiment carried out by Hofstra and Klomp (11) fall within the testing zone. Although the stress zones used by other investigators are of the right order, the interpretation of their measured strains was not in line with the proposals in this paper. Use of equations 10 to 13 would produce a theoretically better answer, although it remains to be seen whether it would improve predictions of rut depth.

All discussions in this paper and others that have been referred to dealing with in situ stress conditions have relied on calculated values. The validity of such values, particularly in the detail with which they have been used, has not been completely established experimentally. Such confidence as has been built up in the use of linear or nonlinear elastic analyses has been based on tensile strain values at the bottom of the asphalt layer and on stresses and strains in the subgrade and surface deflection. The measurement of stresses in asphalt layers has only been attempted in a preliminary way (12). It is somewhat easier to measure strains in this layer, and validation of the theory could be obtained by this means. However, based on the assumptions in this paper, the relatively good predictions obtained for permanent deformation indicate that detailed validation of in situ stress conditions may not be necessary.

CONCLUSIONS

1. This paper outlines an improved approach to specifying stress conditions in laboratory tests of pavement materials. The approach is based on the stress invariants, mean normal stress, and octahedral shear stress.
2. This approach overcomes some of the inherent disadvantages of the triaxial test. In particular, the tension zone stresses in an asphalt layer can be reproduced more accurately under conditions when large permanent deformations are likely. Lower temperatures and thin layers, however, do still present a problem.
3. The stress conditions used in previous investigations are of the right order although the interpretation of strain measurements can be improved.

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