FACTORS INFLUENCING THE RESILIENT RESPONSE OF GRANULAR MATERIALS

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This investigation is concerned with better defining those properties of granular base materials that contribute to the resilient response of pavement structures and includes a study of the influence of aggregate density, aggregate gradation (percent passing No. 200 sieve), and degree of saturation on the resilient response of two aggregates representative of those used in the construction of asphalt concrete pavements. Tests, carried out in triaxial compression, consisted of applying repeated axial stresses with realistic stress histories at a fixed frequency and at a load duration representative of that expected in the field. For both granular materials, the resilient modulus increased considerably with an increase in confining pressure and only slightly with an increase in axial stress. Poisson's ratio increased with a decrease in confining pressure and an increase in repeated stress. The resilient modulus and Poisson's ratio were also affected to lesser degrees by density, percent passing the No. 200 sieve, and degree of saturation. An analysis of a conventional asphalt concrete pavement over a sandy clay subgrade indicated that reasonable changes in the modulus or Poisson's ratio of the granular base layer can result in considerable changes in the response of the pavement structure to load.

• OVER the years highway engineers have devoted considerable effort toward improving the pavement design process. With the advent of large electronic computers, renewed interest has developed in the use of multilayer analysis as a part of the design procedure to evaluate the response of the pavement structure to load. In such analyses, nonlinear elastic and viscoelastic as well as elastic response characteristics can be used to represent the response of the materials comprising the pavement structure. To consider the influence of granular materials on the response of asphalt pavement structures to load within such a framework, it is necessary to determine their deformation characteristics under loads representative of those occurring in the field.

A number of investigations have, in recent years, examined the resilient response of granular materials (1, 2, 3). From these investigations, it would appear that the following factors may have a significant influence on the stress-deformation characteristics under short-duration repeated loads: (a) stress level (confining pressure), (b) degree of saturation, (c) dry density (or void ratio), (d) fines content (percent passing No. 200 sieve), and (e) load frequency and duration.

These studies also indicate that granular materials possess distinctly nonlinear stress vs. strain behavior with the resilient modulus increasing with an increase in

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confining pressure or sum of principal stresses. [Resilient modulus, M_R, is defined as the quotient of repeated axial stress, σ_d, in triaxial compression divided by the recoverable axial strain, ϵ_a, i.e., $M_R = \sigma_d/\epsilon_a$ (in psi).] Little information is available, however, for the effect of stress level on Poisson's ratio for such materials. In addition, most of the investigations have not considered the effect of material variables on the response of the pavement structure to load.

Accordingly, the purpose of this investigation has been to (a) ascertain the significant properties of granular materials at times of loading corresponding to moving vehicles, and (b) determine the influence of each factor on the response of flexible pavements using numerical techniques and results of laboratory tests, with the overall objective of adding to the required body of knowledge necessary for improved pavement design and evaluation.

Editor's Note: This paper as originally prepared included an Appendix containing seven tables and three figures. Because of space limitations, these have not been printed here. This Appendix is available in Xerox form at cost of reproduction and handling from the Highway Research Board. When ordering, refer to XS-34, Highway Research Record 345.

MATERIALS

Two aggregates were used in this investigation: one was a well-graded, subangular, partially crushed gravel and the other a well-graded crushed rock. Both materials have been extensively used in prior studies (2, 4, 5).

To investigate the effects of aggregate characteristics on resilient response, a number of factors were included:

1. Density—three levels termed low, medium, and high (based on ASTM D 2049 64T).
2. Aggregate gradation—three levels (Fig. 1) termed coarse, medium, and fine and based on percent passing the No. 200 sieve as follows: coarse, 2 to 3 percent; medium, 5 to 6 percent; and fine, 8 to 10 percent. [The aggregate gradation was maintained constant above the No. 30 sieve with the grading curve lying in the middle of the limits for a ¾-in. maximum Class 2 aggregate base (State of California, 1969). Aggregate gradings for both aggregate types are included in Table A1 of the Appendix.]
3. Degree of saturation—dry, partially saturated, and saturated.

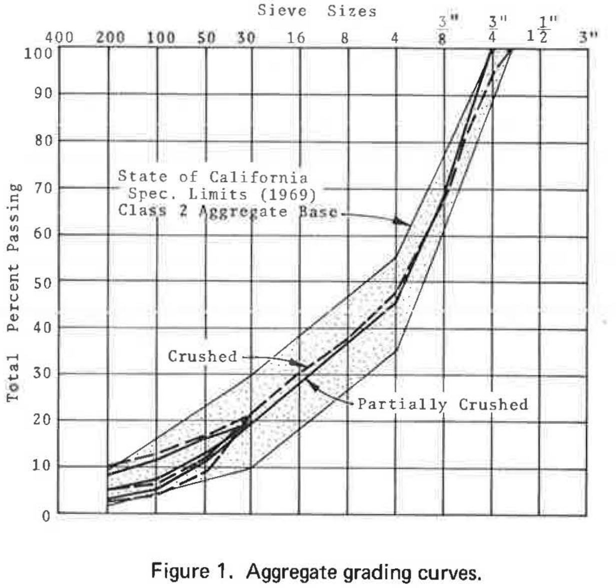


Figure 1. Aggregate grading curves.

EQUIPMENT AND PROCEDURES

Equipment

Measurements of resilient response were made in a conventional triaxial cell on specimens nominally 4 in. in diameter by 8 in. in height. Repeated axial stresses were applied using a pneumatic loading system reported earlier (2).

Axial and radial strains for all specimens were measured using small displacement transducers (LVDT's) (6). Transient and static pore pressure measurements were obtained in the saturated tests with a device similar to that described by Chan and Duncan (7) that permitted both the transient and static values to be determined.

Sample Preparation

For tests on dry materials, specimens were prepared using vibratory compaction. Variations in density were obtained by changing the number of layers and the vibratory load. All layers were vibrated for 15 sec.

Partially saturated specimens were prepared in a similar manner with the exception that, before compaction, a specific amount of water was added to the oven-dried aggregate and then blended thoroughly. The material was placed immediately in layers into the mold and vibrated to obtain the desired density. At the completion of the test, the water content was determined. This value, together with the initial density, was used to calculate the degree of saturation.

Saturated specimens were also prepared in the manner described for the dry materials with the following changes in procedure. Once the specimen was compacted and completely sealed, de-aired water was allowed to percolate slowly up through the specimen until all entrapped air had been removed. Back pressure techniques were used to ensure complete saturation.

After fabrication, dual LVDT's were clamped onto each specimen outside the membrane to measure radial strains at the quarter points and axial strains over the middle 4 in.

Experimental Procedures

Before testing the specimens over the range of indicated material variables, preliminary tests were conducted to establish the influence of number of stress repetitions and stress sequence on the resilient properties of granular materials. The influence of stress repetitions was ascertained by subjecting a series of specimens to 25,000 load applications and observing variations in resilient modulus, M_R, and Poisson's ratio, υ, over the duration of the test. (Resilient Poisson's ratio, υ, is defined as the quotient of the recoverable radial strain, ϵ_r, divided by the recoverable axial strain, ϵ_a, i. e., $\upsilon = \epsilon_r/\epsilon_a$.) Two stress sequences (one an increasing, the other a decreasing sequence) were used to evaluate the influence of this factor, the difference in response between the first and last stress condition providing an indication of the effect of stress sequence.

For the dry and partially saturated specimens the results of the preliminary experiments indicated that, so long as the stresses are representative of those found in a pavement structure, the resilient response determined after 50 to 100 axial stress repetitions could be used to properly characterize the behavior of granular materials, and that one sample could be used to determine the resilient response for stresses of different intensities. For saturated granular materials, the resilient response under a given stress level was susceptible to change because of potential increases in the static pore pressure (causing a reduction in $\overline{\sigma}_3$). The studies indicated, however, that, if the sample were conditioned in a drained state with 1,000 to 2,000 axial stress repetitions, the potential for increases in the static pore pressure was reduced. Furthermore, if the principal stress ratio did not exceed 6 to 7, the resilient response after 50 to 100 axial stress repetitions would provide a reasonable indication of that for a material subjected to a complex stress history, and the response due to stresses of different intensities could thus be measured in any sequence on a single sample.

Accordingly, the data reported here were obtained from specimens that had been conditioned for 1,000 repetitions before testing to minimize the effects of uneven contacts at the sample ends or initial imperfections in the sample. Fifty to 100 repetitions of each combination of axial and radial stresses were then applied to the specimen—stresses that covered the range expected in typical pavements.

Moreover, one frequency, 20 repetitions per min, and one stress duration, 0.1 sec, were used. It should be noted that no observable influence on resilient modulus was obtained for durations in the range 0.10 to 0.25 sec.

TEST RESULTS

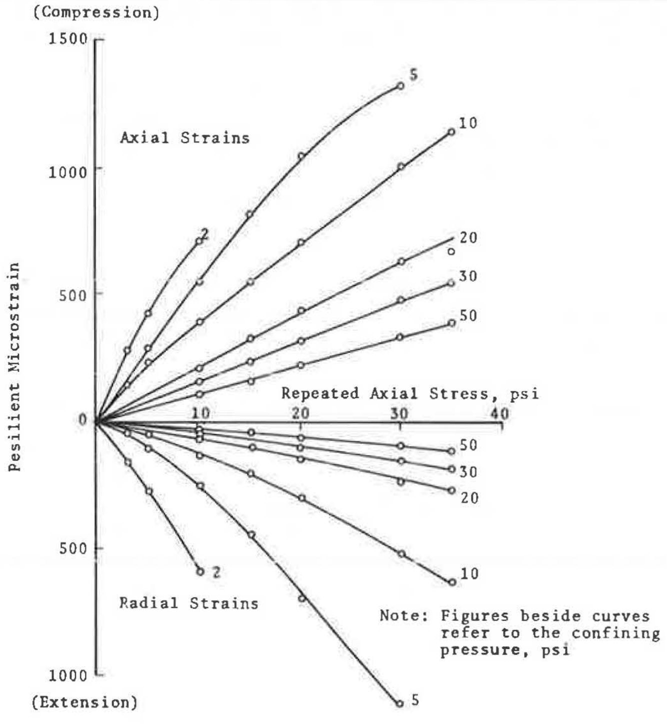
Influence of Stress Level

Dry and Partially Saturated Series—All specimens were conditioned at a confining pressure of 10 psi and a deviator stress of 15 psi and then subjected to a range in stresses. (After testing a sample at each stress level, it was retested at its initial stress state to determine the extent of the changes in the material during the period of test. The difference between the initial and final strain states was normally less than 5 percent.) An example of the results for a dry specimen is shown in Figure 2. It will be noted that the resilient axial and radial strains vary not only with the repeated axial stress but also with the confining pressure, σ_3. Nonlinearities in the stress vs. strain relationships are apparent in all cases with greater degrees of nonlinearity at small values of σ_3. For axial strains, a slight softening occurred at low axial stress levels, while at higher stress levels specimens exhibited a stiffening type of response. These same patterns were observed on the majority of the specimens tested. For radial strains a softening pattern was always observed. It is possible that some of this nonlinearity was due to insensitivity in the measuring devices and test equipment at the low stress levels; however, this could not be verified.

The effect of the axial stress on the resilient modulus is shown in Figure 3. In this figure it will be noted that the modulus generally increases with increasing axial stress (or principal stress ratio) for principal stress ratios greater than 2. [Although the specimens were tested at principal stress ratios ranging from 1.25 to 7.0, there is evidence that this trend will continue to principal stress ratios of 9 to 11 (2, 6).]

The effect of confining pressure and sum of principal stresses on the modulus is shown in Figures 4 and 5 [in the more conventional manner (2, 8)]. These results emphasize the importance of properly accounting for the stress state and its variation within the base layer so that realistic measures of the modulus can be obtained.

Figure 6 shows the variation in Poisson's ratio with stress level for the sample whose data were presented in Figure 2. The general trends observed in this figure were also obtained from tests on other specimens although the absolute values were dependent on aggregate type, density, and gradation.



Note: Figures beside curves refer to the confining pressure, psi

Figure 2. Variation in axial and radial strains with axial stress (partially crushed aggregate, low density, coarse grading, dry).

To simplify the relationship between Poisson's ratio and stress, it was determined (Fig. 7) that the variation in Poisson's ratio could be approximated by a third-degree polynomial curve (fitted to the data using least squares techniques) of the form

$$\upsilon = A_0 + A_1\left(\frac{\sigma_1}{\sigma_3}\right) + A_2\left(\frac{\sigma_1}{\sigma_3}\right)^2 + A_3\left(\frac{\sigma_1}{\sigma_3}\right)^3$$

This form of the relationship was representative for all the test series.

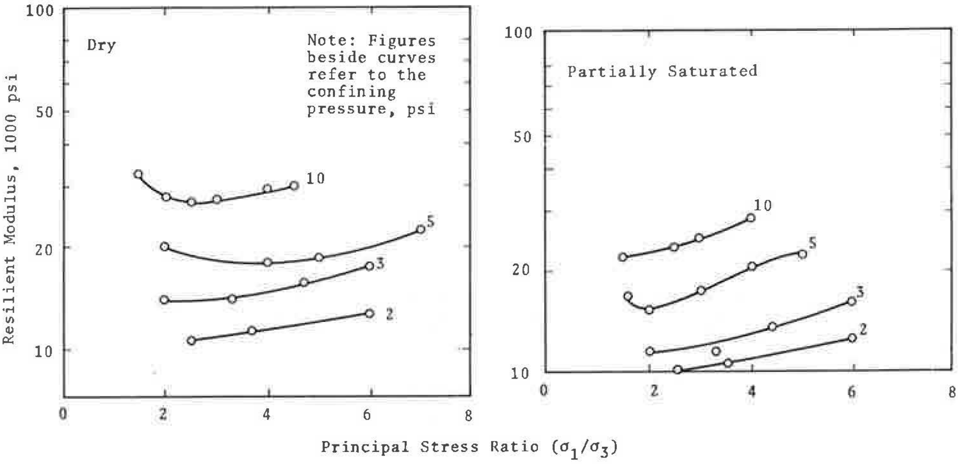


Figure 3. Variation in secant modulus with principal stress ratio (partially crushed aggregate, low density, coarse grading).

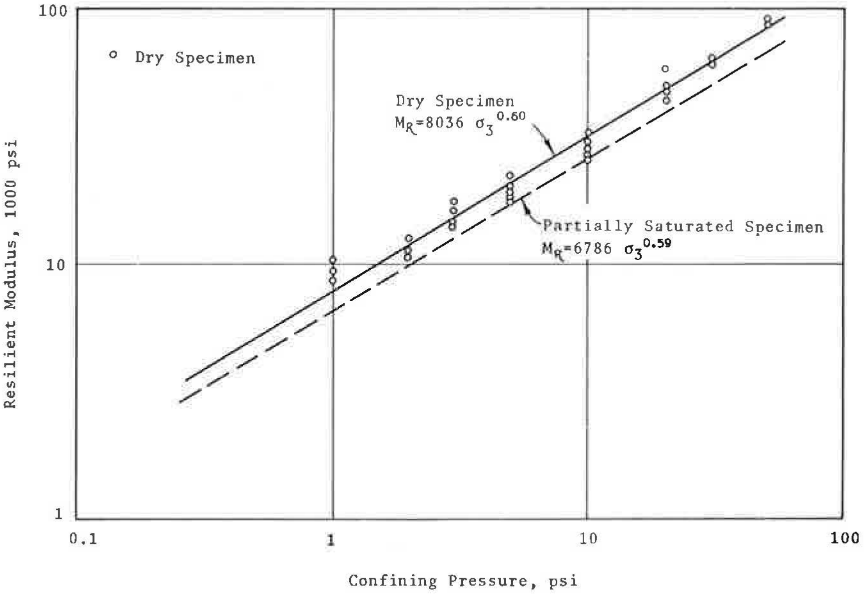


Figure 4. Variation in secant modulus with confining pressure (partially crushed aggregate, low density, coarse grading).

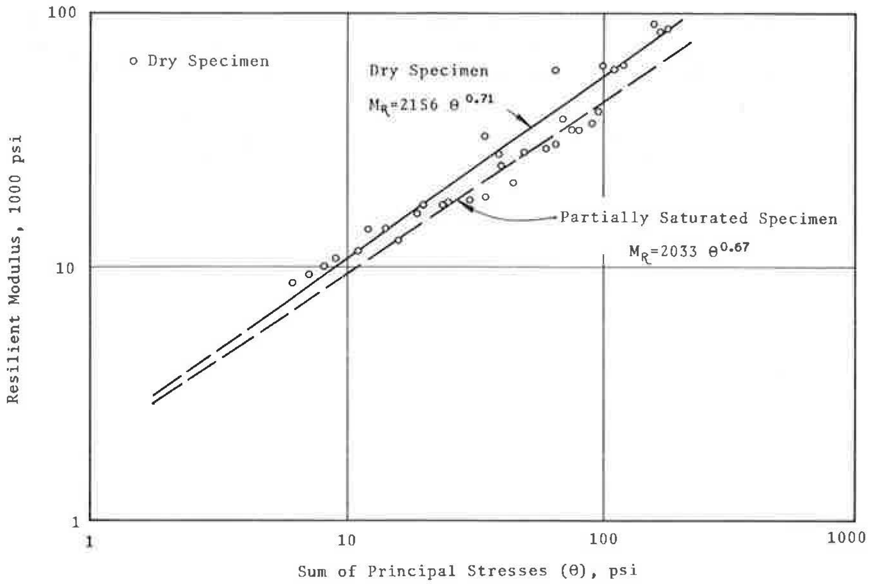


Figure 5. Variation in secant modulus with sum of principal stresses, $\theta = \sigma_1 + 2\sigma_3$ (partially crushed aggregate, low density, coarse grading).

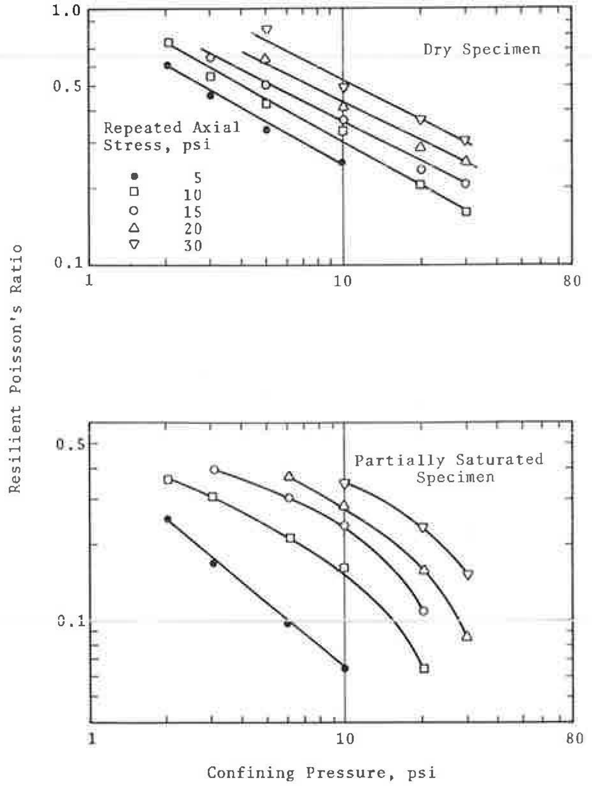


Figure 6. Variation in secant Poisson's ratio with stress level (partially crushed aggregate, low density, coarse grading).

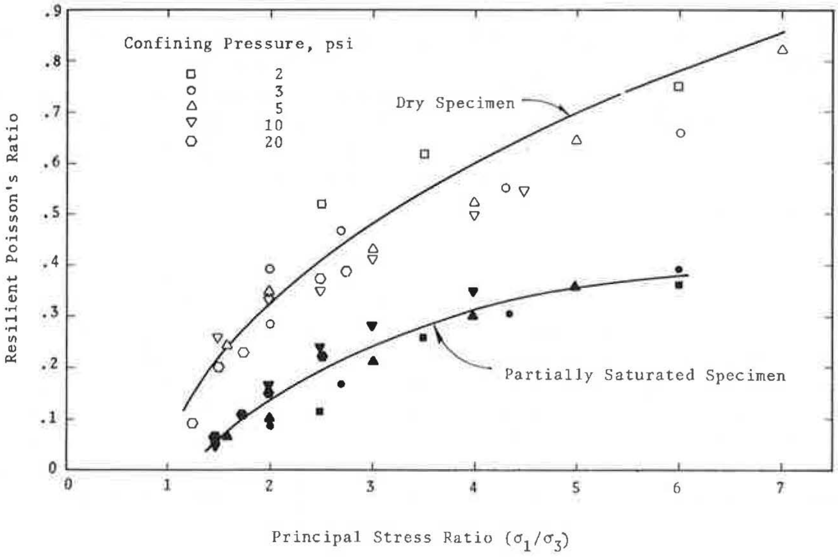


Figure 7. Secant Poisson's ratio as a function of principal stress ratio (partially crushed aggregate, low density, coarse grading).

Saturated Test Series—These specimens were conditioned at 1,000 to 2,000 repetitions in a drained condition and at the same stress conditions used in the dry and partially saturated series. Tests were conducted in both the drained and undrained conditions with resilient axial and radial strains measured after 50 to 100 repetitions. In all instances, drained and undrained stress-strain pairs were nearly the same. For the undrained tests, pore pressure measurements were also recorded throughout the test. Generally, static pore pressure (back pressure) remained relatively constant over the duration of a particular test. Transient pore pressure (that due to the repeated load) developed almost instantaneously and was generally of the order of 5 to 10 percent of the repeated load. For example, for one series of undrained tests, the transient pore pressures were as follows:

Back Pressure (psi)	Repeated Axial Stress (psi)	Sustained Radial Stress (psi)	Transient Pore Pressure (psi)
45	10	10	0.9
45	15	15	1.3

Generally, the variation in radial and axial strain with stress level was similar to that observed for the dry and partially saturated tests, except the relationship between the axial stress and axial strain was slightly more linear than that observed for the dry and partially saturated test series (Fig. A2, Appendix).

Influence of Mix Variables

To permit a reasonable comparison of data, it was necessary to adopt simple and realistic indexes that could be used to define the effect of each variable. For the resilient modulus, the least squares equations relating the modulus to the confining pressure, $\sigma_3\left(M_R = K_1\sigma_3^{K_2}\right)$, and the sum of principal stresses, $\theta\left(M_R = K_1'\sigma^{K_2'}\right)$, for all samples tested were determined. The coefficients K_1, K_2, K_1', and K_2' determined in this manner are summarized in Tables A2, A3, and A4 of the Appendix for the dry, partially saturated, and saturated test series. In addition, least squares techniques were used to develop relationships between Poisson's ratio and the principal stress ratio, σ_1/σ_3, for each sample. An example of this has already been shown in Figure 7. Because this relationship generally possessed the same shape for all samples, it was concluded that a mean value for Poisson's ratio could be determined. This value also appears in Tables A2, A3, and A4 where the mean value corresponds to the average of Poisson's ratio at σ_1/σ_3 of 2.0 and 5.0.

Density

Generally, the coefficients K_1 and K_1' were found to increase with increasing density, while K_2 and K_2' remained relatively constant or decreased slightly. The effects are shown for the partially crushed aggregate (dry test series) in Figure 8. Similar trends were found to exist for the partially saturated and saturated test series. For the crushed aggregate, K_1 also tended to increase with density (Fig. A3 of the Appendix). In one instance, however, K_1 was shown to decrease with increasing density (coarse grading, dry test series). The relationship was checked and no experimental error could be found. A possible explanation for this was the inconsistent interaction between

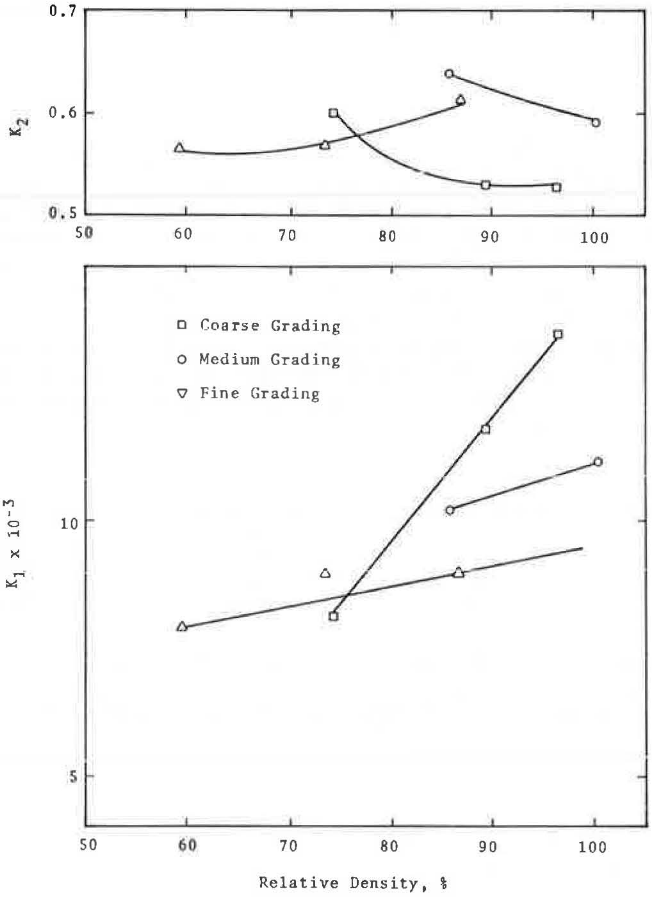


Figure 8. Variation of constants K_1 and K_2 in relationship $M_r = K_1 \sigma_3^{K_2}$ with relative density (partially crushed aggregate, dry test series).

K_1 and K_2 as the density increases. For the partially crushed aggregate (Fig. 8), as K_1 increased, K_2 tended to remain constant or decrease slightly. This was also shown to be the case for the crushed aggregate (Fig. A3) for the fine and medium gradings. For the coarse grading, however, K_2 increased. Had K_2 decreased in the manner shown for the other test series, K_1 would probably have increased.

When examined in terms of the resilient modulus, the effect of density was found to be greater for the partially crushed aggregate than for the crushed aggregate. For the partially crushed aggregate (Fig. 9), the modulus increased with relative density. In addition, the effect of density decreased as the percent of fines increased. For the crushed aggregate (Fig. 10), relative density had only a small influence on the modulus. Once again, as the fines content increased, the influence decreased. It is interesting

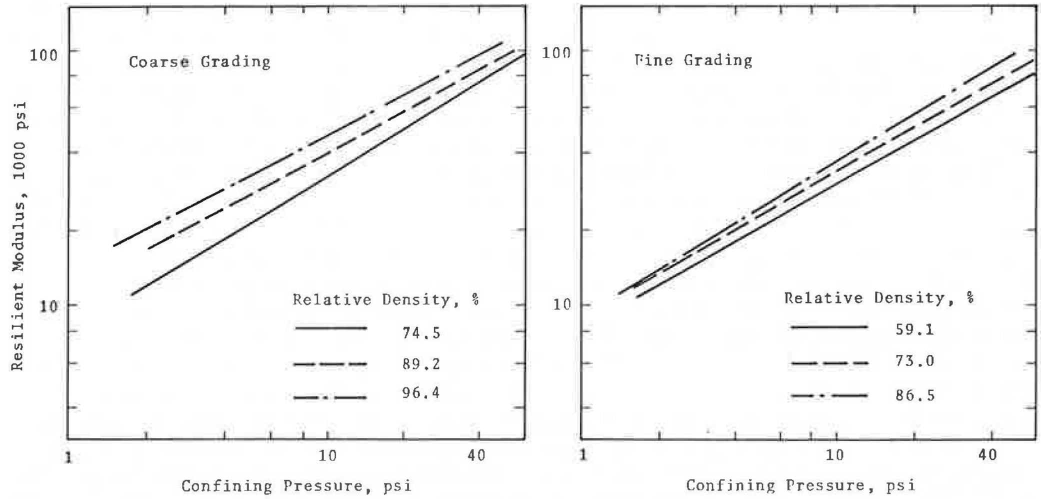


Figure 9. Effect of density on relationship between resilient modulus and confining pressure, σ_3 (partially crushed aggregate, dry test series).

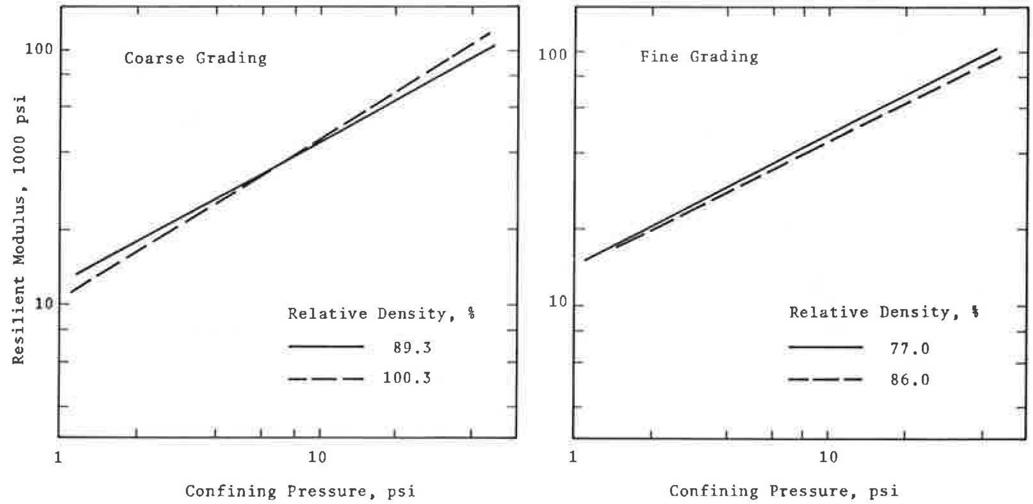


Figure 10. Effect of density on relationship between resilient modulus and confining pressure, σ_3 (crushed aggregate, dry test series).

to note that, despite the irregularity in K_1 (decreased with increased density) for the coarse grading, the modulus was relatively unaffected by density.

The level of density also affected Poisson's ratio. Although the influence was not always clear, the value in most cases decreased slightly with increasing density. For example, Figure 11 shows the influence of density on the partially crushed aggregate at two levels of fines content. In many cases the close coincidence of the curves in Figure 11 (coarse grading) was found to exist; however, there were cases in which there was an obvious decrease in Poisson's ratio with increasing density, as shown in Figure 11 (fine grading—mean values of 0.49, 0.45 and 0.34).

Aggregate Gradation (Percent Passing No. 200)

In all cases, the regression constants K_1 and K_2 (also applicable to K_1' and K_2') were affected by the fines content (Table A5 of the Appendix). The manner in which K_1 changed depended on the aggregate type. For the partially crushed aggregate, K_1 generally decreased as the fines content was increased. For the crushed aggregate, however, K_1 increased with increasing fines content. The reason for this is not apparent at this time, but, because the same trends were also observed for the partially saturated and saturated test series, it was concluded that this was a real aspect of the materials tests. Although the effect of gradation on K_2 was not as well defined, it would appear that K_2 decreased slightly as the fines content increased. The influence of gradation on the resilient modulus was not well defined (Fig. 12). However, over the range of confining pressures encountered in field pavements (0 to 10 psi), the resilient modulus of the partially crushed aggregate decreased as the fines content increased, while for the crushed aggregate, the modulus increased with increasing fines content.

Poisson's ratio was also influenced by the fines content. In most instances, as the fines content increased, the mean value for Poisson's ratio was reduced. An example of the manner in which Poisson's ratio varied with grading for partially crushed and crushed aggregate is shown in Figure 13. Regardless of aggregate type, there was a noticeable reduction as the percent of fines increased and the reduction appeared to be a function of the aggregate type (i. e., a greater reduction for the crushed aggregate).

Aggregate Type—For the dry test series, the coefficient K_1 was always larger for the crushed aggregate than in the partially crushed material, regardless of aggregate

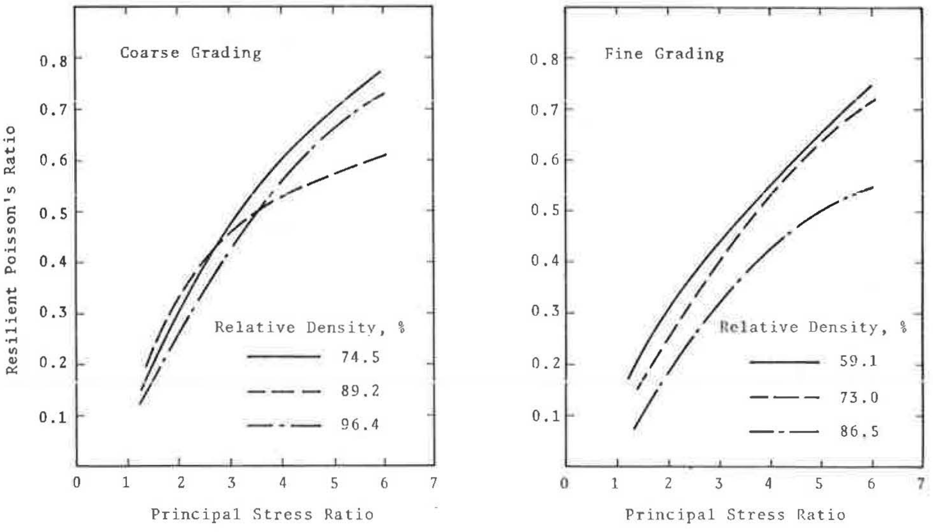


Figure 11. Effect of density on the relationship between resilient Poisson's ratio and principal stress ratio, σ_1/σ_3 (partially crushed aggregate, dry test series).

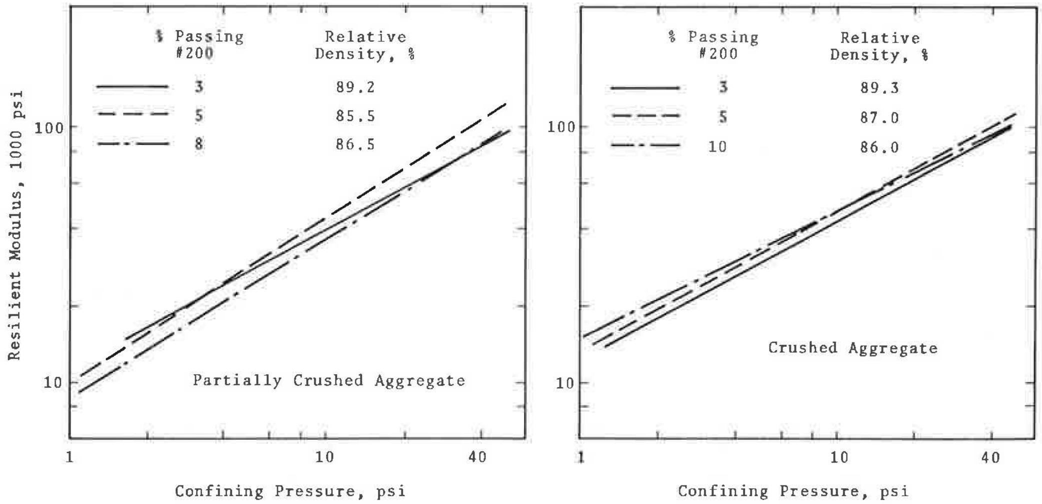


Figure 12. Effect of aggregate gradation (percent passing No. 200) on the relationship between resilient modulus and confining pressure, σ_3 (dry test series).

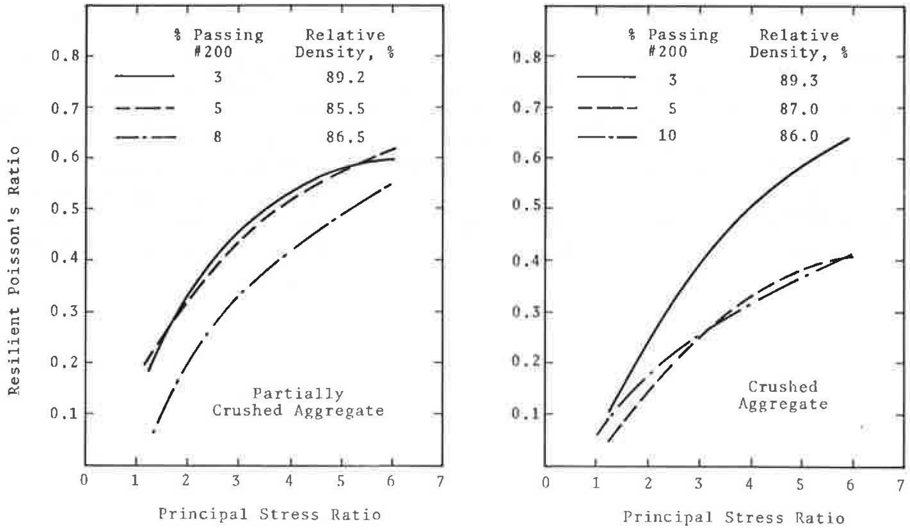
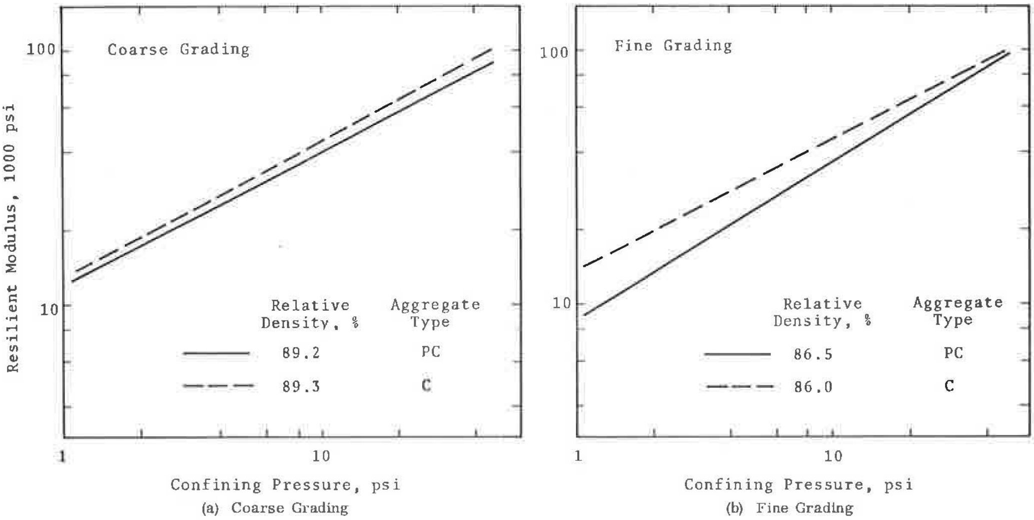


Figure 13. Effect of aggregate gradation (percent passing No. 200) on the relationship between resilient modulus and confining pressure, σ_3 (dry test series).

gradation (Table A5 of the Appendix). The percent change in K_1, however, appeared to be a function of the aggregate gradation. For the coarse grading the difference was about 5 percent (12,338 vs. 11,752), while for the medium and fine grading the differences were 31 and 64 percent respectively. The actual effect on the modulus was not nearly as great (Fig. 14) because there were also differences in K_2, but the influence of aggregate gradation is still apparent. The observations noted for the dry test series also held for the partially saturated series, in spite of the fact that all comparisons could not be made at equivalent levels of degree of saturation. For this series, however, there was not the large influence of gradation as the fines content increased.



(a) Coarse Grading

(b) Fine Grading

Figure 14. Effect of aggregate type (partially crushed vs. crushed) on the relationship between resilient modulus and confining pressure, σ_3 (dry test series).

Poisson's ratio also varied as a function of aggregate type. For the dry test series, the mean value was generally greater for the partially crushed aggregate. The actual variation for the specimens whose modulus data are shown in Figure 14 is shown in Figure 15. Although the patterns are similar, Poisson's ratios for the crushed aggregate were generally lower than those for the partially crushed aggregate.

Degree of Saturation—In all cases, K_1 decreased from the dry to partially saturated tests series (Table A6 of the Appendix) where the comparisons were made on the basis of total stresses. (For the dry test series, the cell pressure is approximately equal to

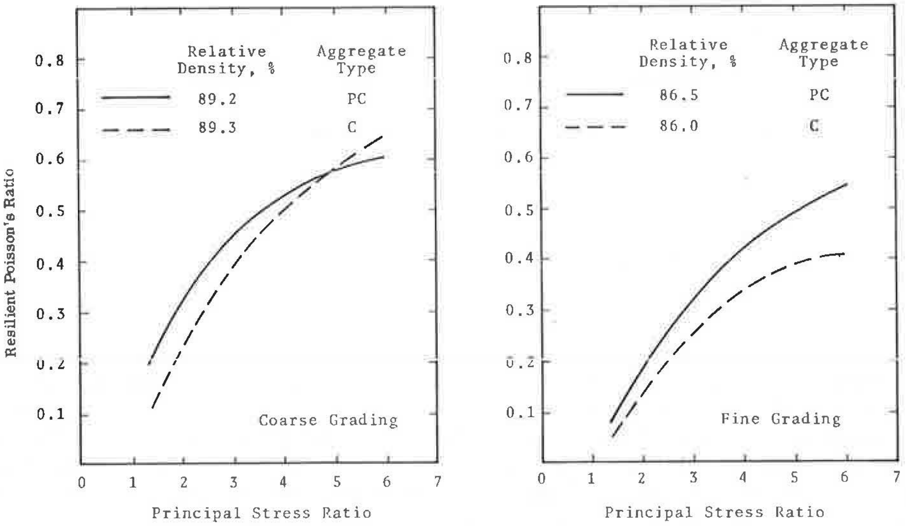


Figure 15. Effect of aggregate type (partially crushed vs. crushed) on the relationship between Poisson's ratio and principal stress ratio, σ_1/σ_3 (dry test series).

the total stress—and in this case only, the effective stress. For the partially saturated test series, the cell pressure is equal to the total stress and is not the same as the effective stress. Pore pressure measurements were not attempted; hence, effective stresses cannot be properly defined in the tests for partially saturated materials.) Figure 16 provides an indication of this effect for each aggregate at two levels of grading—coarse and fine.

When the data were plotted in the conventional manner (Fig. 17), the modulus associated with the partially saturated test series was the lowest. This may be because of the manner in which the data are compared; data for the dry and partially saturated specimens were compared on the basis of total stresses, whereas data for the dry and saturated specimens were compared using effective stresses.

It appears that, if all results were defined in terms of total stresses, the value of K_1 would steadily decrease with increasing degree of saturation (or water content) as shown in Figure 16. The data presented by Kallas and Riley (9) tend to substantiate this hypothesis. Although there were inherent differences in the dry density (mean values of 126.6 pcf for water content of 2.4 percent and 132.2 pcf for

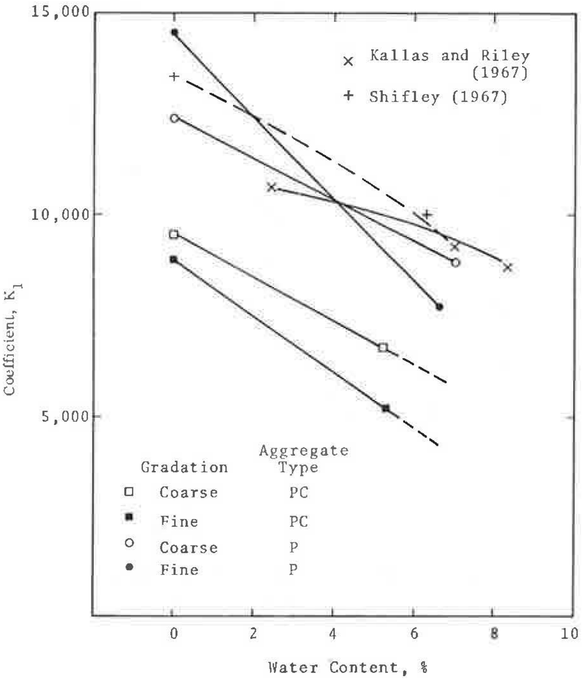


Figure 16. Variation in regression constant, K_1, with water content in relationship $M_r = K_1 \sigma_3^{K_2}$.

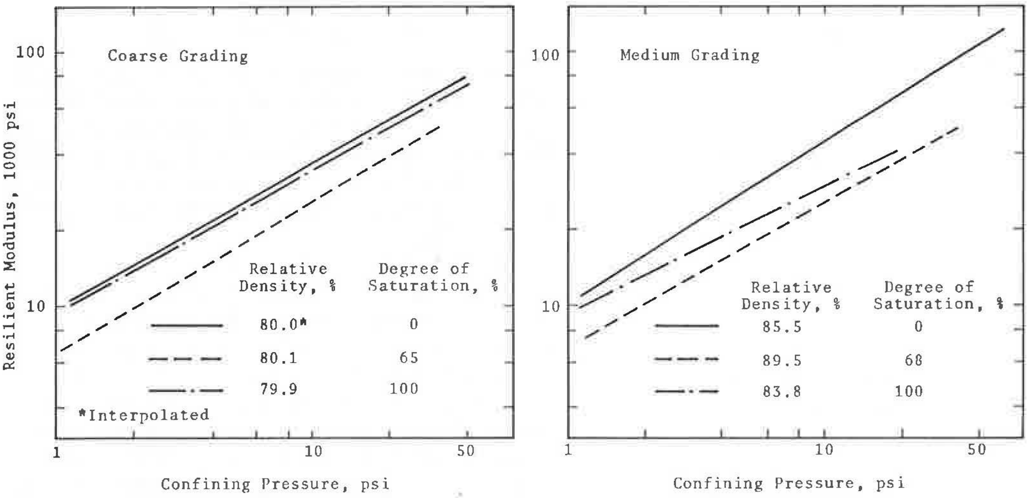


Figure 17. Effect of degree of saturation on the relationship between resilient modulus and confining pressure, σ_3 (partially crushed aggregate).

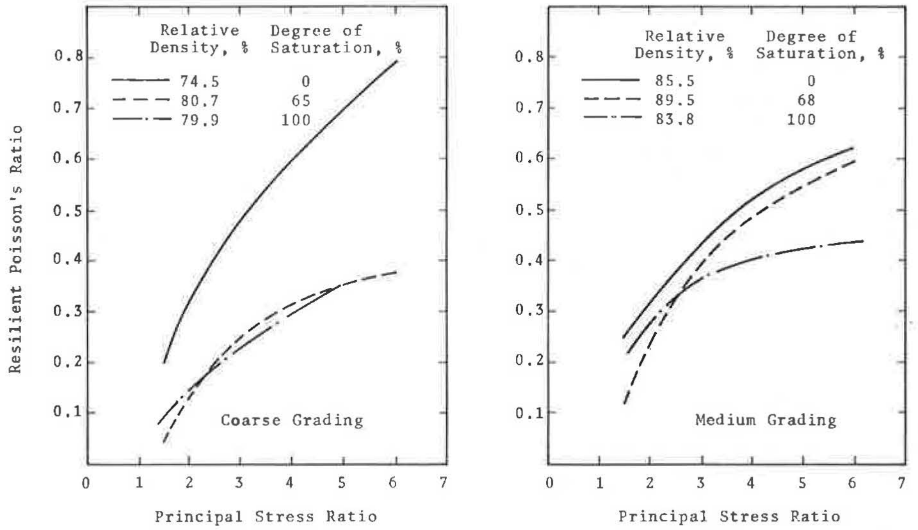


Figure 18. Effect of degree of saturation on the relationship between resilient Poisson's ratio and principal stress ratio (partially crushed aggregate).

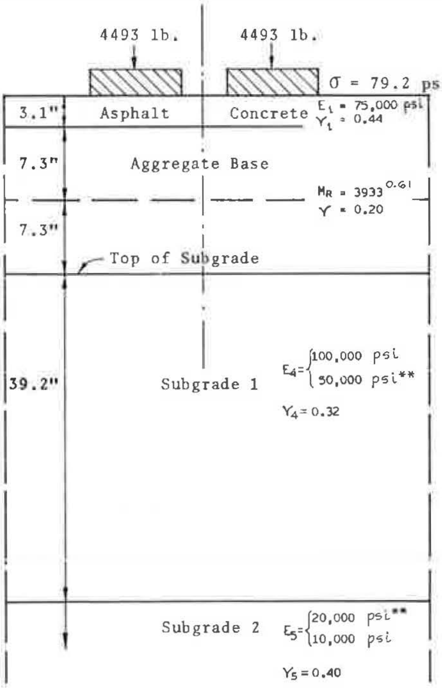


Figure 19. Layered system, loading conditions, and material properties; nonlinear analysis using layered theory.

water content of 6.3 percent) for their tests, the reduction in K_1 with increasing water content was very apparent.

The relationship between Poisson's ratio and the principal stress ratio (Fig. 18) was also affected by degree of saturation. In general, as the degree of saturation increased, Poisson's ratio decreased.

DESIGN IMPLICATIONS

To examine the influence of the aggregate characteristics on the response of a system, a sensitivity analysis was performed on the pavement structure shown in Figure 19. The thicknesses and material properties correspond to those found in Section 1 of the San Diego Test Road (6, 12).

Although there were a number of procedures in which such a structure could be analyzed (e.g., 2, 10, 11, and 12), the analyses performed here were conducted using a computer solution for the pavement system represented as a multilayer elastic structure (10). Using this approach, surface deflections and strains in the asphalt-bound layer have been determined. Changes in computed quantities corresponding to variations in moduli and Poisson's ratios provide an indication of the effect of these characteristics on pavement response.

Because some field measurements of deflection and strain were available, it was decided to use the axle load that had been used in the field measurements for the computations. As shown in Figure 19, this consisted of a set of dual tires with a load per tire of 4,493 lb and a contact pressure of 79.2 psi. The stress distribution was assumed to be uniform over the contact area, which was represented by two circular plates (4.25 in. radius spaced at a center-to-center distance of 11.2 in.).

The modular constant K_1' in the relationship $M_R = K_1'\theta^{K_2}$ was arbitrarily altered and calculations made for K_1' values of 3,433 and 4,433, while holding Poisson's ratio at 0.20. The results of these calculations are given in Table 1. As indicated, the change in K_1' resulted in changes in the predicted responses of varying degrees. For example, the surface deflection varied by ±0.0015 (7.5 percent) while the surface horizontal strains were altered by $\pm 59 \times 10^{-6}$ in. per in. (12 percent) and $\pm 42 \times 10^{-6}$ in. per in. (12 percent) in the longitudinal and transverse directions respectively. In terms of tensile strain, at the bottom fiber of the asphalt layer the change was on the order of $\pm 67 \times 10^{-6}$ in. per in. (14 percent).

Fixing the modular relationship at $M_R = 3{,}933\theta^{0.61}$, Poisson's ratio was varied from 0.2 to 0.5. The strains and displacements computed for each level of Poisson's ratio are given in Table 2. This change resulted in a decrease in the surface displacement from 0.0195 to 0.0150 (23 percent) in the surface compressive strains from 485 to 291×10^{-6} in. per in. (40 percent) and 360 to 228×10^{-6} in. per in. (37 percent) and an increase in the maximum tensile strain at the bottom of the asphalt layer from 491 to 515×10^{-6} in. per in. (4 percent).

Although not extensive, this analysis demonstrates the importance of properly defining the significant properties of the granular base layer. Small changes in either the modular relationship or Poisson's ratio can result in considerable changes in

TABLE 1

INFLUENCE OF BASE MODULUS ON PREDICTED DEFLECTIONS AND STRAINS

Type of Response	Predicted Response[a] (M_R =)			Measured Response	Comparison Ratio, Predicted/Measured (M_R =)		
	$3433\theta^{0.61}$	$3933\theta^{0.61}$[b]	$4433\theta^{0.61}$		$3433\theta^{0.61}$	$3933\theta^{0.61}$[b]	$4433\theta^{0.61}$
Total deflection, in.	0.021	0.0195	0.018	0.020	1.05	0.975	0.90
Surface plus base deflection, in.	0.015	0.0133	0.012	0.016	0.94	0.83	0.75
Horizontal microstrain							
Surface, longitudinal	544C	485C	433C	420C	1.39	1.15	1.03
Surface, transverse	402C	360C	323C	520C	0.77	0.69	0.62
	194T	160T	150T	130T	1.49	1.23	1.15
Maximum tensile	543	491	425				

[a] Modulus of subgrade layers No. 1 and 2 equals 50,000 and 20,000 psi respectively, and Poisson's ratio of base layer equals 0.20.
[b] Best estimate.

TABLE 2

INFLUENCE OF POISSON'S RATIO OF BASE IN PREDICTED DEFLECTIONS AND STRAINS

Type of Response	Predicted Response[a] (υ =)			Measured Response	Comparison Ratio, Predicted/Measured (υ =)		
	0.2[b]	0.35	0.5		0.2	0.35	0.5
Total deflection, in.	0.0195	0.0175	0.0150	0.020	0.98	0.88	0.75
Surface plus base deflection, in.	0.0133	0.0115	0.009	0.0160	0.83	0.71	0.56
Horizontal microstrain							
Surface, longitudinal	485C	402C	291C	420C	1.15	0.96	0.69
Surface, transverse	360C	303C	228C	520C	0.69	0.58	0.44
	160T	186T	202T	130T	1.23	1.43	1.55
Maximum tensile	491	497	515				

[a] Base modulus, $M_R = 3933\theta^{0.61}$, modulus of subgrade layers No. 1 and 2 equals 50,000 and 20,000 psi respectively.
[b] Best estimate.

critical responses of the pavement structure. If consideration were given to variations in moduli and Poisson's ratios for reasonable changes in density, aggregate gradation, aggregate type, and degree of saturation, the effect on the pavement structure could be considerably greater than that indicated here.

SUMMARY AND CONCLUSIONS

Considering the results of this study, the following points presented here should be emphasized:

1. Reasonable estimates of the resilient response of granular materials can be obtained after 50 to 100 axial stress repetitions for a material subjected to a complex stress history, and the response due to stresses of different intensities can be measured in any sequence on a single sample.
2. The resilient properties of untreated granular materials are affected most significantly by stress level. In all cases the modulus increased considerably with the confining pressure and slightly with the repeated axial stress. So long as shear failure does not occur, the modulus can be approximately related to the confining pressure, σ_3, or to the sum of principal stresses according to

$$M_R = K_1 \sigma_3^{K_2}$$

and

$$M_R = K_1' \theta^{K_2'}$$

Poisson's ratio increased with decreasing confining pressure and increasing repeated axial stress where the change in Poisson's ratio could be approximated as follows: $\upsilon = A_0 + A_1(\sigma_1/\sigma_3) + A_2(\sigma_1/\sigma_3)^2 + A_3(\sigma_1/\sigma_3)^3$.

3. The resilient properties of granular material were also affected by factors such as aggregate density, aggregate gradation (percent passing No. 200), aggregate type, and degree of saturation. At a given stress level, the modulus increased with increasing density, increasing particle angularity or surface roughness, decreasing fines content, and decreasing degree of saturation. Poisson's ratio, however, was slightly influenced by density, generally decreased as the fines content increased, and generally decreased as the degree of saturated increased.
4. Small changes in the modular relationship or Poisson's ratio for the granular base layer can result in significant changes in the response of the pavement structure.

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