# Characterization of Saturated Granular Bases Under Repeated Loads

LUTFI RAAD, GEORGE H. MINASSIAN, AND SCOTT GARTIN

The behavior of typical granular materials with different gradation was investigated under saturated, undrained, repeated triaxial loading conditions. Of particular interest is the comparative behavior of open-graded and dense-graded base courses and the influence of fines content on the dynamic response. The effect of aggregate gradation on the cyclic stress-strain behavior, pore pressure, damping, resilient modulus, compressibility, and permeability is investigated. Results indicate that saturated granular materials will develop excess pore water pressure under undrained repeated triaxial loading. This could lead to a decrease in resilient modulus and a potential increase in volume compressibility. Open-graded aggregates are more resistant to pore pressure buildup than dense-graded aggregates and are therefore less likely to induce damage in pavements under saturated conditions. In this respect, the estimated damage per repetition could be as much as 70 to 100 times more for pavements with dense-graded bases.

It is estimated that more than 90 percent of the major pavements in the United States are periodically exposed to surface water infiltration resulting in saturation and flooding of underlying pavement layers (*1*). Cedergren (*2*) used data from several field test sections and estimated that relative damage for wet sections varies from 5 to 70,000 times in comparison with dry sections. According to Markow (*3*), pavement wetting and subsequent drying are associated with the following periods:

1. The time during rainfall in which the pavement sublayers may be increasing in moisture content and could possibly reach saturation;
2. The time during which the sublayers are sufficiently wet or saturated to influence material properties, structural response, and performance; and
3. The time during which any excess moisture, not significantly affecting pavement behavior, is drained off.

Estimates of pavement wetness duration can be determined using data and relationships presented by Markow (*3*) and Moulton (*4*). Results show that, for a variation of base permeability in the range of 10 ft/day and 1,000 ft/day, the period of excessive moisture during which pavement performance could be adversely affected ranges between 1 and 28 days. Other field data (*1*) show that the period of saturation following a rain can range from 5 to 20 days, except for pavements with excellent drainage properties. During saturation, pavement sublayers could experience excess pore water pressure as a result of repeated traffic loads. An increase in pore water pressure reduces the effective stresses and, consequently, the strength and stiffness of the underlying soil layers. Consolidation settlement could result as the excess pore water pressure dissipates following a sequence of repeated loads. In recent years, more states have built permeable base pavements, which allow rapid drainage of infiltrated moisture. Performance data nationwide indicate that properly designed and constructed permeable bases significantly reduce pumping, faulting, and pavement cracking (*5*). Laboratory studies on pavement models reported by Dempsey (*6*) conclude that open-graded unbound granular bases are much less susceptible to pumping and channeling. Additional analyses performed by Raad (*7*) on dynamic pore water pressure generation and dissipation in granular pavement layers support such findings.

## OBJECTIVES

Although a qualitative assessment of the behavior of saturated unbound granular layers in pavements has started to emerge, a mechanistic evaluation is essentially lacking. This study evaluates the behavior of saturated unbound granular bases under repeated triaxial load conditions. Specifically, the dynamic response of saturated granular base materials under controlled-strain repeated triaxial loading conditions will be investigated. The test aggregate gradations vary from open graded to dense graded. The influence of gradation on cyclic stress-strain behavior, pore pressure generation, damping, resilient modulus, and volume compressibility will be determined.

## LABORATORY INVESTIGATION

### Materials

Four materials (G1–G4), representing a range of gradation from open graded to dense graded, were used. All aggregates were crushed sedimentary river deposits of igneous origin. A summary of aggregate type, gradation, classification, dry density, compaction moisture content, permeability, and volume compressibility associated with excess pore pressure dissipation is presented in Table 1. A comparison of the grain size distribution is shown in Figure 1.

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L. Raad and G. H. Minassian, University of Alaska Fairbanks, Fairbanks, Alaska 99775. S. Gartin, Materials Section, Alaska Department of Transportation and Public Facilities, Anchorage, Alaska 99507.

TABLE 1 Summary of the Properties of Tested Aggregates

| | Aggregate Type | | | |
|---|---|---|---|---|
| Sieve | G1 | G2 | G3 | G4 |
| 3/4" | 100 | 100 | 100 | 100 |
| 3/8" | 50 | 70 | 72 | 65 |
| #4 | 8 | 40 | 51 | 50 |
| #8 | 5 | 23 | 36 | 34 |
| #40 | 0 | 10 | 16 | 20 |
| #200 | 0 | 0 | 0 | 10 |
| $\gamma_d$(pcf) | 106.9 | 120.7 | 121.9 | 121.4 |
| m (%) | 4.08 | 4.34 | 3.99 | 4.05 |
| $K_T$ (cm/sec) | 0.00333 | 0.00107 | 0.00075 | 0.00061 |
| $K_C$ (cm/sec) | 0.0227 | 0.0104 | 0.0114 | 0.00094 |
| $K_{av}$ (cm/sec) | 0.0087 | 0.0033 | 0.0029 | 0.00076 |
| $m_v$ | $3.77 \times 10^{-3}$ | $27.6 \times 10^{-3}$ | $3.51 \times 10^{-3}$ | $5.98 \times 10^{-3}$ |
| AASHTO A-1-a Classification | A-1-a | A-1-a | A-1-a | A-1-a |
| Unified Classification | GP | GW | GW | GP-GM |

Note:
$\gamma_d$ = dry density
m = compaction moisture content
$K_T$ = permeability as measured in the triaxial set-up
$K_C$ = permeability as measured using constant head permeability test
$K_{av}$ = average permeability (i.e., logarithmic average of $K_T$ and $K_C$)
$m_v$ = volume compressibility associated with excess pore pressure dissipation

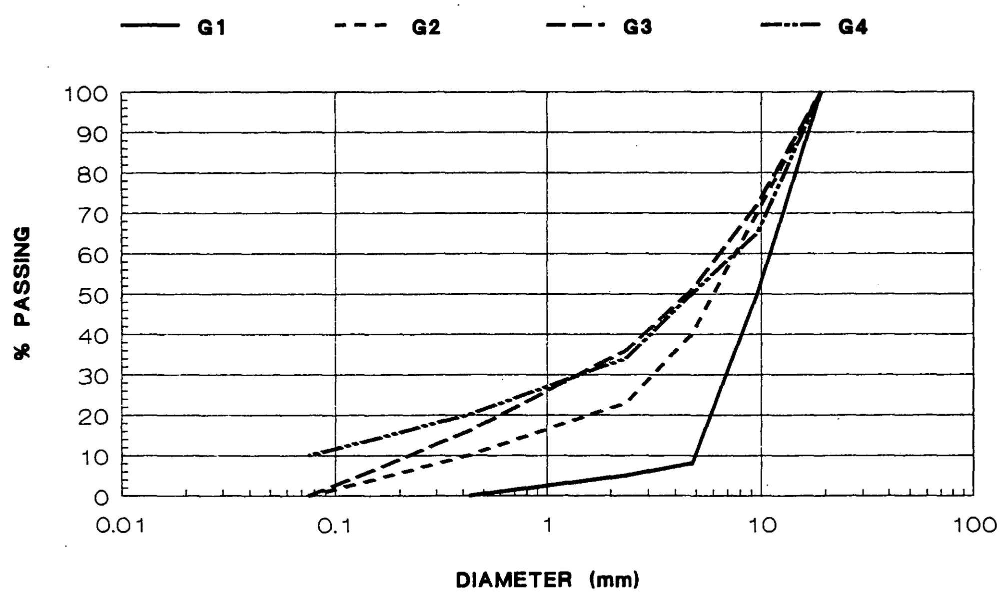

FIGURE 1 Gradations of aggregates used in the study.

### Specimen Preparation

Cylindrical specimens, 4 in. in diameter and 8 in. high, were prepared using vibratory compaction. Specimens were compacted in four layers, each subjected to 0.92 psi surcharge and vibrated at 60 Hz for 45 sec using a vibrating table. A 0.035-in.-thick rubber membrane was used to encase the compacted specimen. Before mixing and compaction, the portion of the specimen retained on the No. 8 sieve was soaked for 24 hr to attain a saturated surface dry condition. This procedure facilitated the back-water pressure saturation of the specimen required in the saturated undrained repeated load testing phase.

### Resilient Testing

The compacted specimen was tested to determine the stress-dependent resilient modulus relationship under repeated triaxial loading conditions. The specimen was subjected to the required confining pressure using water as a confining medium. Repeated deviator stress pulses were applied using MTS closed-loop hydraulic testing equipment. Specimen conditioning and resilient testing were performed according to AASHTO Method T274-82. Following that, the specimen was subjected to a controlled-strain repeated load testing under a confining pressure of 5 psi, using the same cyclic strain that would be used after saturation during undrained loading. This allows a comparison of resilient modulus values under controlled-stress and controlled-strain loading conditions.

### Saturation and Permeability Testing

After the completion of resilient testing, the specimen was subjected to a flow of carbon dioxide gas under 1 psi pressure for a period of 1 hr. This was followed by gradual backpressuring of deaired water through the specimen, which would help dissolve the carbon dioxide and achieve a high degree of saturation. During the saturation process, an effective confining pressure of 5 psi was maintained (i.e., the difference between the cell pressure and the back-water pressure was kept at 5 psi). Saturation was assumed to be complete when a $\beta$ value (the ratio of the change in pore water pressure to the change in cell pressure) of 0.94 or larger was attained. After saturation, the specimen's permeability was determined for three different hydraulic head values, and the average permeability was reported. Permeability was also determined in a constant-head permeability setup according to AASHTO Method T215-70.

### Controlled-Strain Repeated Load Testing

Controlled-strain undrained repeated load triaxial tests were conducted on saturated specimens under an initial effective 5 psi confining pressure. Each specimen was tested under a given controlled-strain haversine pulse having a duration of 0.10 sec and a frequency of 60 cpm. The peak cyclic strain value used in these tests varied between 0.05 and 1.0 percent. The applied strain cycles were repeated until the specimen liquefied (i.e., the average excess pore water pressure in a given loading cycle became equal to the initial effective confining pressure) or until the total number of strain applications reached 1,500. Stresses, strains, and pore water pressure were monitored during the controlled-strain testing phase. At the end of this phase, the specimen was allowed to drain until an effective confining pressure of 5 psi was attained, and the volume compressibility associated with the corresponding pore pressure dissipation was measured.

## RESULTS

### Cyclic Stress-Strain and Damping Characteristics

The mechanistic behavior of the aggregates under repeated triaxial loading can best be illustrated through the variation of stress-strain characteristics with the number of strain repetitions. A schematic representation of the stresses and strains during a given cycle is presented in Figure 2. A typical variation of the stress-strain curve with number of repetitions is shown for Aggregate G3 when subjected to repeated strain cycles of amplitude equal to 0.25 percent (Figure 3). The cyclic stress-strain loop seems to stabilize with number of load repetitions for the moist condition (i.e., as compacted moisture content), whereas in the case of saturated undrained loading, the stress-strain loops tend to "collapse," indicating significant softening. This is shown further in Figures 4 and 5 where a significant decrease in deviator stress, total strain modulus, and resilient modulus occurs with increasing number of repetitions. This is caused by the increase in pore pressure ratio (i.e., the ratio of excess pore water pressure in the specimen to the initial applied effective pressure), thereby resulting in

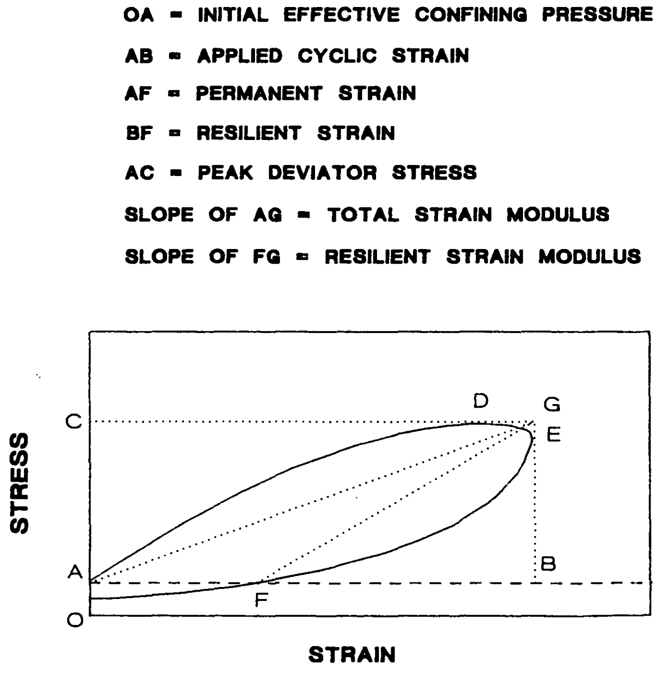

FIGURE 2 Stress-strain loop.

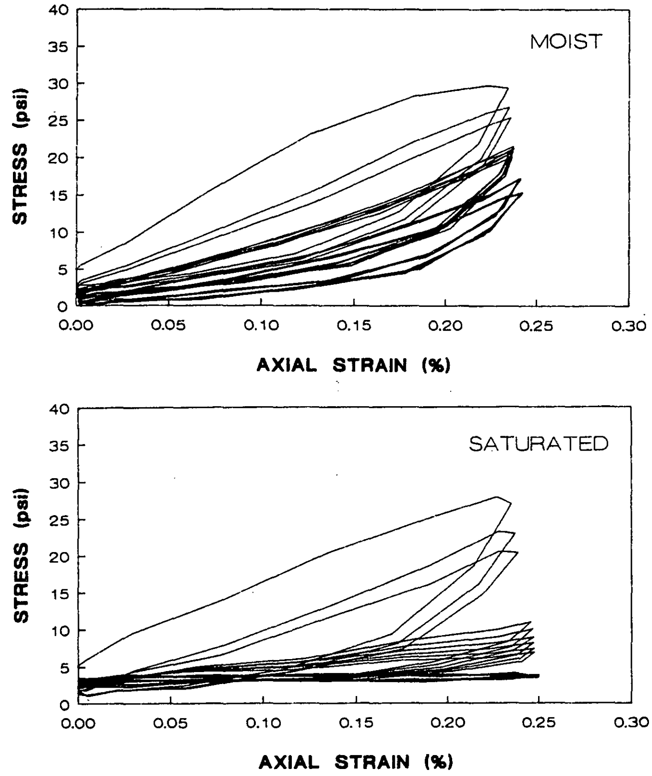

**FIGURE 3** Cyclic stress-strain behavior of Aggregate G3.

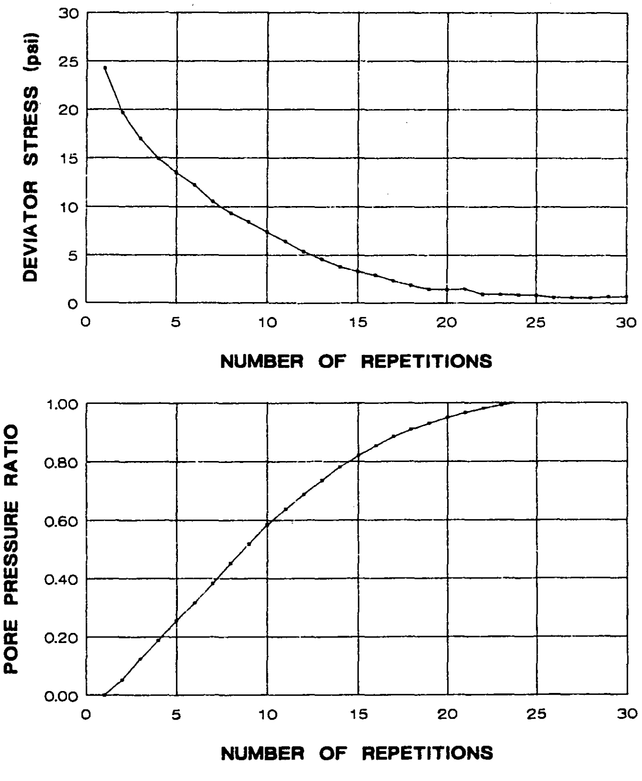

**FIGURE 4** Variation of deviator stress and pore pressure ratio with number of repetitions for Aggregate G3 (saturated condition).

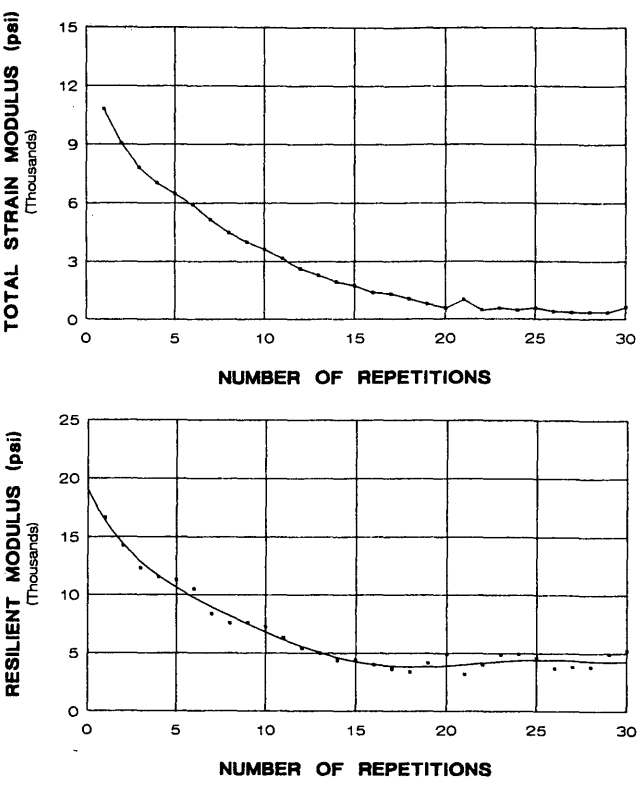

**FIGURE 5** Variation of total strain modulus and resilient modulus with number of repetitions for Aggregate G3 (saturated condition).

a decrease in effective stresses and gradual softening and collapse of the stress-strain curve.

Damping in soils is the energy lost during a complete cycle of applied shear stresses (*8,9*). The energy loss is equal to the area enclosed by the cyclic shear stress-shear strain loop. The damping ratio reflects the damping characteristics of a soil and could be used for dynamic response analysis of pavements. With reference to Figure 2, the damping ratio is given by

$$D = \frac{1}{\pi} \frac{\text{area of Loop ADEF}}{\text{area of AGB}} \qquad (1)$$

The variation of damping with number of repetitions is illustrated for Aggregate G3 and strain level 0.25 percent in Figure 6. In the case of moist aggregate, the damping response remains a relatively stable response under repeated loads. This was typical for all the aggregates tested. However, under saturated conditions, an unstable response seems to be associated with a critical pore pressure ratio in the range of 0.60 to 0.70. For the higher values, the stress-strain loop would collapse with increasing repetitions, leading in many cases to unstable response of damping and resilient behavior. In general, the gradation of the aggregates and the degree of saturation do not seem to have a significant effect on the damping ratio. However, the cyclic strain level seems to have the predominant influence. An increase in cyclic strain from 0.05 to 0.5 percent will result in an average increase in damping ratio from about 3 to 15 percent. This is smaller than the damping

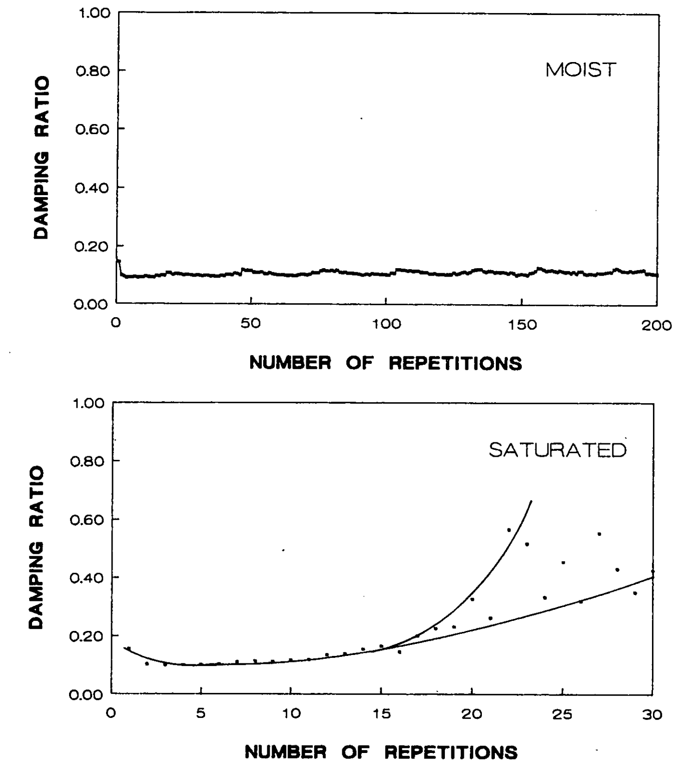

**FIGURE 6 Variation of damping ratio with number of repetitions for Aggregates G3.**

ratio reported for sands by Seed and Idriss (*8*). For the same range of cyclic strains, the ratio for sand varies, on the average, between 12 and 22 percent.

### Pore Pressure Generation

The generation of excess pore water pressure of saturated granular layers could be a major cause of fast deterioration of pavement structures. This could be related to the following failure mechanisms:

1. An increase in pore pressure reduces strength and stiffness of the underlying granular layers and results in increased surface deflections and loss of pavement serviceability.
2. In the case where pore pressure ratio increases and reaches unity, liquefaction will occur and result in the possible pumping of underlying soil through pavement cracks and joints. Excess pore water pressure could also be a major cause of channeling and erosion as reported by Dempsey (*6*).
3. The dissipation of excess pore water pressure results in the settlement of granular layers, causing additional loss of pavement support and surface cracking.

A comparison of pore pressure ratio increase for all aggregates (Figure 7) illustrates the superior behavior of open-graded Base G1 compared with G2, G3, and G4. The pore pressure ratio reaches unity and causes liquefaction in all aggregates except G1, where the rate of pore pressure development decreases with number of repetitions and the pore pressure ratio remained well below unity even after 1,500 repetitions. Note that in Aggregate G4, with 10 percent fines content, the rate of pore pressure increase is generally greater than in Aggregate G3, with similar gradation but with no fines. In both aggregates, however, the number of repetitions required to cause liquefaction remains essentially the same.

The influence of cyclic strain level on pore pressure development is shown in Figures 8 and 9. Results indicate that, for all values of cyclic strains, Aggregate G1 is more resistant to the development of pore pressure compared with other more densely graded aggregates. In other words, for the same cyclic strain level, it would require more cyclic strain repetitions to achieve the same pore pressure ratio for G1 aggregate than the rest of the tested aggregates. An increasing fines content generally increases the rate of pore pressure generation, particularly for cyclic strains that are smaller than 0.10 percent (Figure 9).

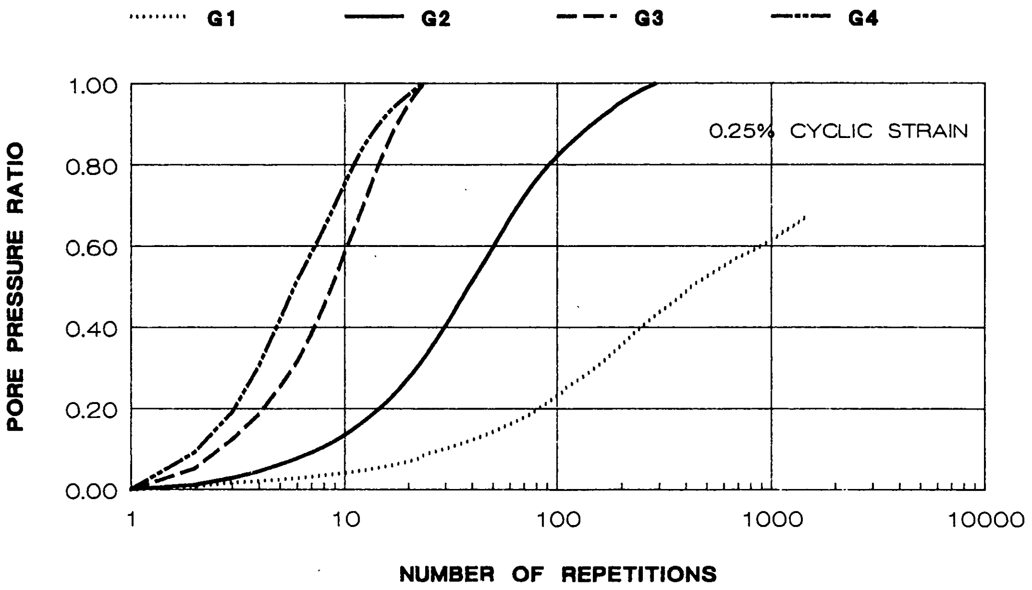

**FIGURE 7 Variation of pore pressure ratio with number of repetitions.**

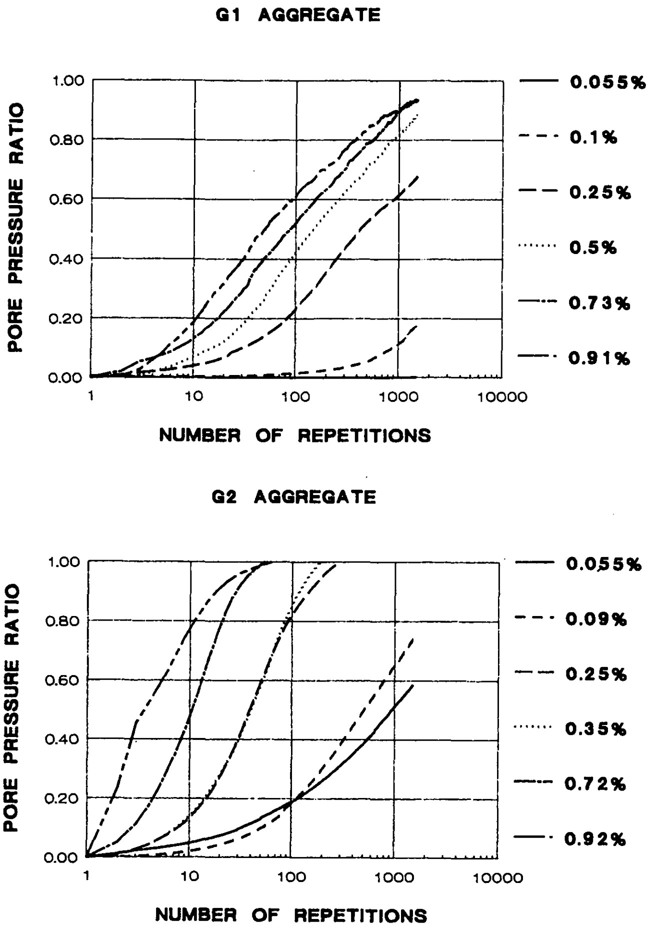

**FIGURE 8** Variation of pore pressure ratio with number of repetitions for Aggregates G1 and G2.

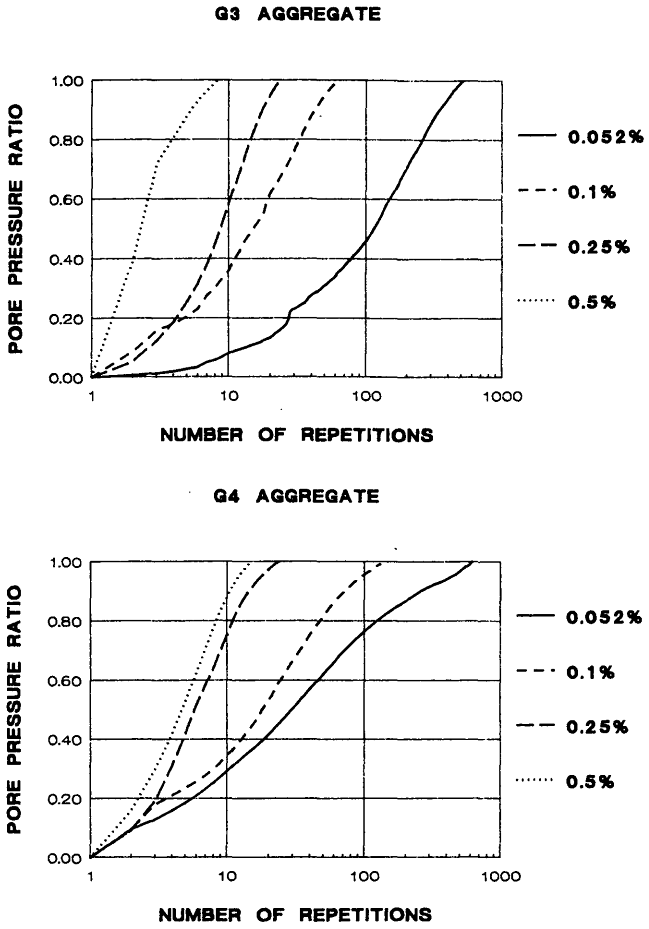

**FIGURE 9** Variation of pore pressure ratio with number of repetitions for Aggregates G3 and G4.

The relative performance of the various granular bases under saturated conditions could be estimated by comparing the percent damage induced for a given load repetition. In this case the pavement damage associated with a pore pressure ratio equal to 0.60 was considered. Damage induced was assumed to be linear with load repetitions as proposed by Miner's damage theory. The percent damage caused per load repetition for different strain levels is summarized in Table 2. Aggregate G1 has the lowest damage factors. They ranged between 0.1 and 0.5 percent for Aggregate G1 and 10 percent and 35 percent for the more dense-graded Aggregates G3 and G4.

### Permeability and Compressibility

The influence of base permeability on the drainage of granular layers in pavement structures has been recognized by a number of investigators (*1–3*,*5*). An increase in base permeability can significantly decrease the drainage time and therefore reduce the exposure of the pavement to additional load repetitions during the period of base soaking. This would decrease the pavement damage associated with excess moisture conditions. However, under dynamic loading conditions, dissipation of the excess pore pressure generated in the granular base depends on both its permeability and compressibility.

**TABLE 2 Percent Damage per Repetition for the Tested Aggregates**

| | Damage per Repetition (%) | |
|---|---|---|
| Aggregate Type | Cyclic Strain 0.25% | Cyclic Strain 0.50% |
| G1 | 00.10 | 00.50 |
| G2 | 00.17 | 04.00 |
| G3 | 10.00 | 35.00 |
| G4 | 15.00 | 20.00 |

This can be illustrated by examining the following one-dimensional equation for pore pressure generation and dissipation (*7,10*):

$$\frac{\partial u}{\partial t} = \frac{K}{\gamma_w m_v} \frac{\partial^2 u}{\partial Z^2} + \frac{\partial u_e}{\partial N} \frac{dN}{dt} \tag{2}$$

where

$\gamma_w$ = density of water,
$u$ = average cyclic excess pore water pressure,
$K$ = permeability,
$m_v$ = compressibility,
$\frac{\partial u_e}{\partial N}$ = rate of generation of excess pore water pressure under undrained loading conditions, and
$\frac{dN}{dt}$ = frequency of load applications.

The right-hand side of the equation represents the sum of contributions of two components: (*a*) the pore pressure generation term, $\frac{\partial u_e}{\partial N} \frac{dN}{dt}$, and (*b*) the pore pressure dissipation term, $\frac{K}{\gamma_w m_v} \frac{\partial^2 u}{\partial Z^2}$.

The ratio $K/m_v$ is a parameter that influences the dynamic pore pressure dissipation. A higher $K$ and a lower $m_v$ would reduce the time required for dynamic pore pressure dissipation in the granular layer.

Permeability values for the aggregates used in this study are summarized in Table 1. Permeability measurements using the triaxial test setup yielded lower values than those obtained using the constant head apparatus. This could probably be attributed to the higher effective confining pressure applied on the specimens in the triaxial cell. The logarithmic average of the measured permeability values ranges from $0.87 \times 10^{-2}$ cm/sec for Aggregate G1 to $0.76 \times 10^{-3}$ cm/sec for Aggregate G4.

Volume compressibility, $m_v$, associated with the dissipation of excess pore water pressure, depends on the pore pressure ratio and cyclic strain level (Figure 10). For pore pressure ratios less than 0.60, $m_v$ maintains essentially a constant value. However, for higher pore pressure ratios, $m_v$ increases and reaches a maximum value for pore pressure ratio equal to 1. This is consistent with similar findings by Seed et al. (*11*). Furthermore, the limited data obtained in this study indicate that for a pore pressure ratio equal to 1, higher cyclic strains will result in higher values of $m_v$. Maximum measured compressibility values are summarized in Table 1. Well-graded aggregates, G2 and G3, have lower compressibility than open-graded aggregate, G1. However, Aggregate G4, with 10 percent fines, maintains the highest compressibility.

## Resilient Properties

Results of the variation of resilient modulus, $M_R$, with the applied stress state expressed in terms of the sum of principal stresses $\Theta$ are shown in Figures 11 and 12. In this case, the relationship is defined as $M_R = k\Theta^n$, where $k$ and $n$ are material parameters. As expected, the most dense-graded aggregate, G3, exhibits the highest resilient modulus, whereas the open-graded aggregate, G1, has the lowest. For example, assuring a $\Theta$ of 30 psi, the resilient modulus of G1 is 18,000 psi compared with 26,000 psi for G3, an increase of about 44 percent. These modulus values, however, were determined for moist-when-compacted specimen conditions. Under saturated undrained loading conditions, the resilient modulus decreases as a result of the increase in pore water pressure and the corresponding decrease in effective stresses. Such a decrease is illustrated by the variation of modular ratio with respect to pore pressure ratio (Figures 13 and 14). The modular ratio is defined as the ratio of the resilient modulus under saturated undrained loading to the resilient modulus for moist-compacted conditions, under the same cyclic strain level.

Although the variation of the resilient modulus with applied stress for the moist-compacted condition depends on aggregate gradation, the modular ratio decreases with increase in pore pressure ratio, and this decrease is essentially similar for all aggregate gradations considered.

In pavement design, the mechanistic evaluation of the granular layers is often needed. Mechanistic design procedures use limiting criteria in terms of pavement response parameters

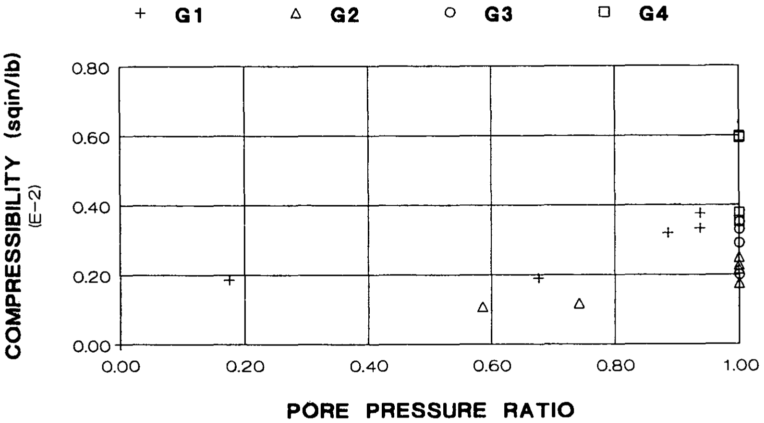

**FIGURE 10 Compressibility versus pore pressure ratio.**

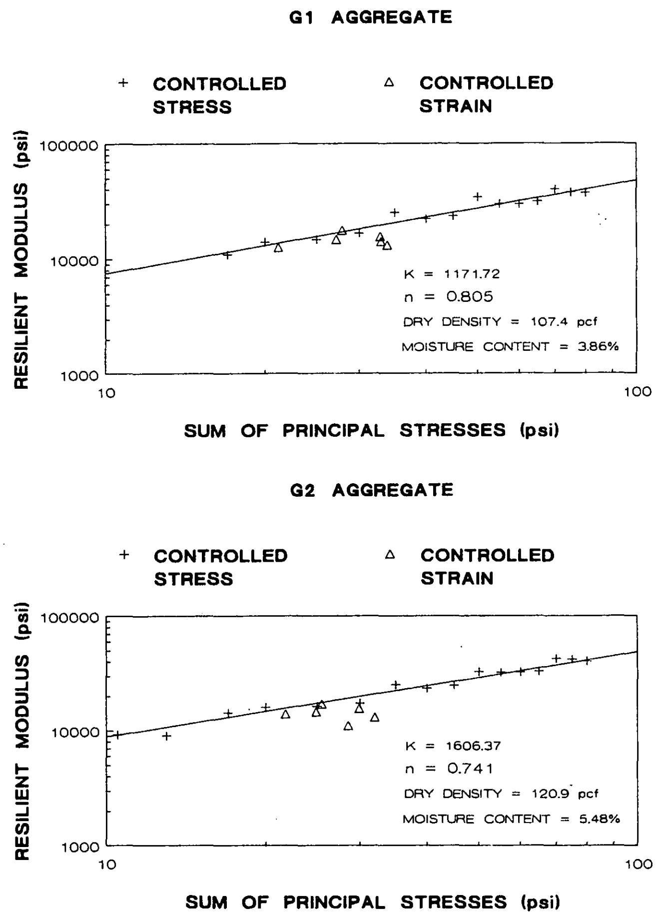

**FIGURE 11** Resilient moduli for Aggregates G1 and G2.

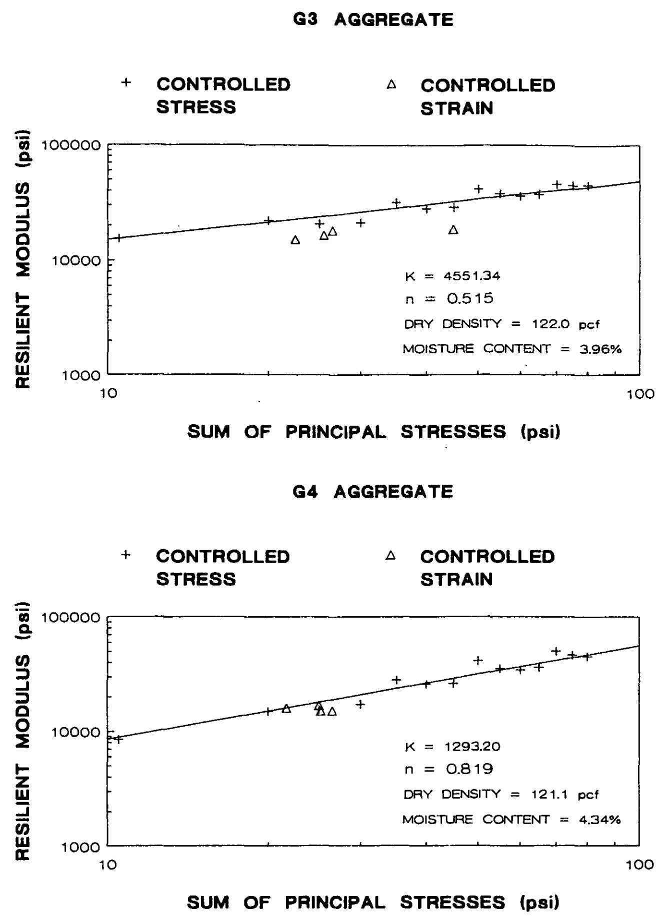

**FIGURE 12** Resilient moduli for Aggregates G3 and G4.

to minimize the damage induced by repeated traffic loads. Although the development of these criteria for saturated granular bases is beyond the scope of this paper, the following general approach could be considered:

1. Determine the duration and frequency of occurrence for periods that correspond to near-saturation conditions in the pavement.
2. Estimate traffic loading and repetitions within each period.
3. Determine the resilient modulus of the granular layers by using the appropriate modular ratio (Figures 13 and 14).
4. Compute stresses and strains in the granular layer and apply limiting criteria to estimate critical number of load repetitions.
5. Use the reduced resilient modulus (Step 3) to determine the stresses and strains on the underside of the pavement surface layer and assess its fatigue behavior.

## SUMMARY AND CONCLUSIONS

An attempt has been made to study the behavior of typical granular materials with different gradations under saturated undrained repeated triaxial loading conditions. Of particular interest is the comparative behavior of open-graded and dense-graded base courses and the influence of fines content on the dynamic response. The influence of gradation on cyclic stress-strain behavior, pore pressure generation, damping, resilient modulus, compressibility, and permeability was determined. Limiting criteria expressed in terms of repeated resilient strains and stresses and the allowable number of load repetitions were developed to provide an improved mechanistic evaluation of saturated unbound granular layers in pavement structures. Results of this study lead to the following conclusions:

1. Dynamic loading of saturated granular layers induces excess pore pressure, thereby reducing the effective stresses and the corresponding frictional resistance in these layers.
2. Aggregate gradation has a major influence on the excess pore pressure generated. Open-graded aggregates with permeability greater than $8 \times 10^{-3}$ cm/sec seem to be more resistant to pore pressure generation than dense-graded and less permeable aggregates.
3. Volume compressibility depends on excess pore pressure generated during a dynamic loading sequence. However, for pore pressure ratios less than 0.60, the compressibility remains essentially unchanged. The most influential gradation component on compressibility is percent fines (i.e., percent passing No. 200 sieve). For example, Aggregate G4 with 10 percent fines has a maximum compressibility of $6 \times 10^{-3}$ in²/lb compared with $3.5 \times 10^{-3}$ in²/lb for Aggregate G3, which

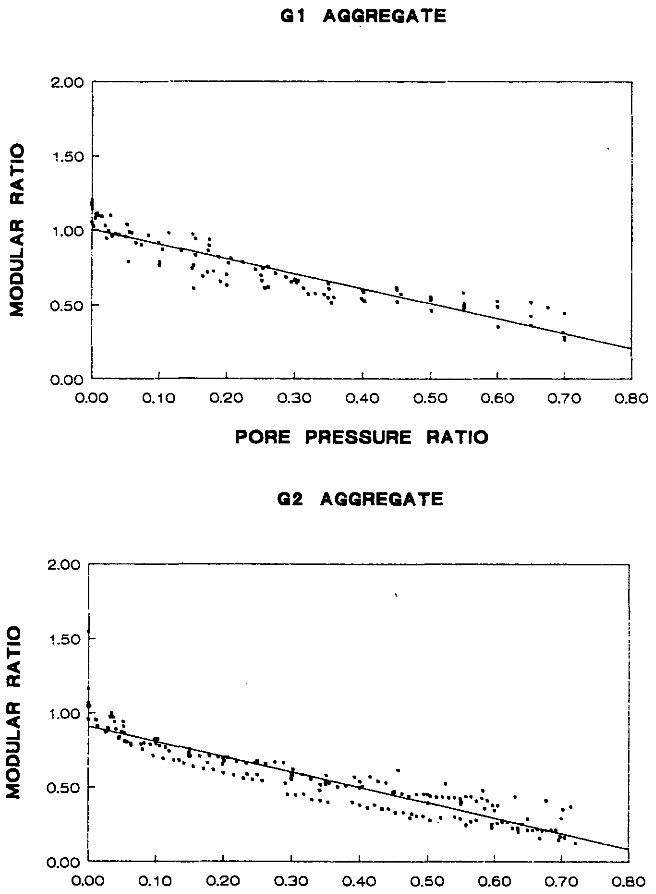

**FIGURE 13 Change of modular ratio with pore pressure ratio for Aggregates G1 and G2.**

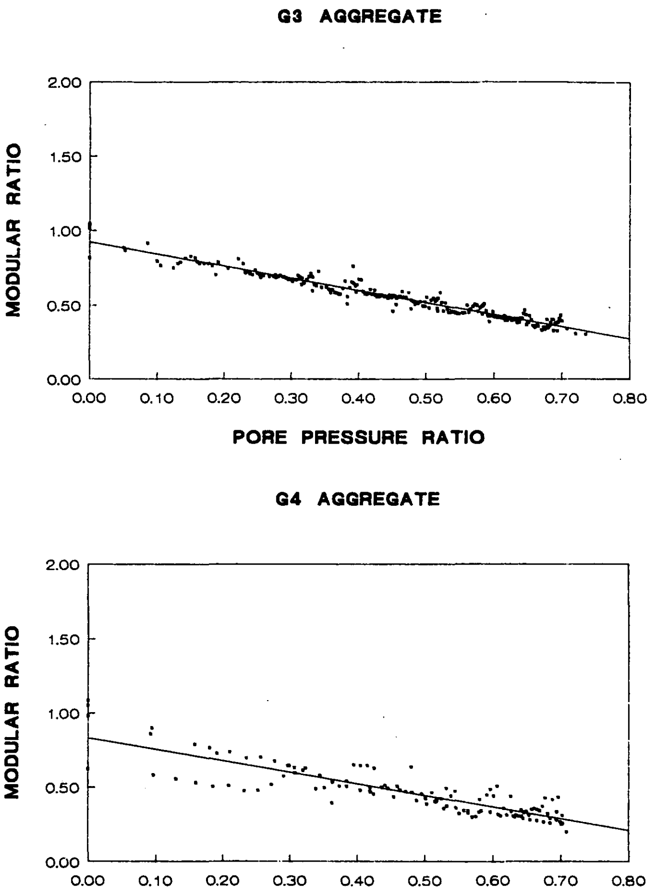

**FIGURE 14 Change of modular ratio with pore pressure ratio for Aggregates G3 and G4.**

has similar gradation but no fines. A higher compressibility indicates larger settlement of pavement layers after the dissipation of excess pore pressure.

4. The damping ratio for all aggregates tested increases with increasing cyclic strain and varies on the average between 3 and 15 percent, independent of degree of saturation and gradation.

5. The resilient modulus decreases with increasing pore pressure ratio. The decrease is similar for all gradations considered and varies essentially between 0 and 70 percent.

6. The open-graded aggregate seems to resist higher stresses and strains associated with a given number of load repetitions compared with other more dense-graded aggregates. In this respect, the estimated damage per repetition, under saturated conditions, could be as much as 70 to 100 times more for pavements with dense-graded bases than those with open-graded bases.

## ACKNOWLEDGMENTS

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