# Dynamic Characterization of Cement-Treated Base and Subbase Materials

HANI LOTFI and MATTHEW W. WITCZAK

## ABSTRACT

In recent years, the resilient modulus has been introduced for evaluating pavement material response. A comprehensive laboratory evaluation of resilient modulus, $M_r$, of five cement-treated base (subbase) materials used by the Maryland State Highway Administration are presented in this paper. A total of 84 specimens, having factorial mix combinations of material type, gradation, cement content, density level, and curing period, were used to investigate their influence on the $M_r$ response. In addition, the static modulus test was performed on each specimen to determine its static modulus, E, as well as the unconfined compressive strength, $q_u$. It has been found that the cement content, material type, and gradation are the major influence on modulus response. The water needed for cement hydration, as well as the optimum moisture content needed for maximum density, were found to affect the results. The resilient modulus becomes more independent on repeated axial deviator stress when the cement content and/or curing period increase. The test results suggest that different relationships between resilient modulus and unconfined strength exist for the cement-treated dense-graded aggregate (DGA) and soil cement materials. Separate equations were therefore developed and presented. For design of flexible pavements, new layer coefficient-resilient modulus nomographs were developed. As for rigid pavement, a more precise evaluation of the composite modulus of subgrade reaction is presented.

In the past, most pavement design schemes were highly empirical and, as such, relied heavily on the use of empirical, material characterization test techniques. In the past 20 years, however, design technology has been greatly improved by the functionally based performance aspect of the AASHTO Road Test. In addition, the knowledge and implementation of design procedures based on elastic layered analysis has also been improved.

The resilient or dynamic modulus test is a relatively recent method used for the laboratory evaluation of all stabilized pavement materials. The resilient modulus of pavement materials has slowly but surely been incorporated into several rigid and flexible pavement design procedures.

For the design of rigid pavements, the composite modulus of subgrade reaction, $k_c$, is normally used. Its value can be estimated from Figure 1, which is based on subbase (base) thickness and the resilient modulus or stiffness of the subbase type used (1). In using this plot, general ranges of resilient modulus are recommended for several subbase types. The recommended range for cement-stabilized base material is from 0.5 to 1.0 million psi and for soil cement, the range is from 0.4 to 0.9 million psi (1).

For flexible pavement design practice, the estimation of the structural layer coefficient, $a_i$ and the use of material equivalencies or substitution ratio (SR), based on the modulus is presented by Van Til et al. (6). A general interpretation of material substitution ratios is

$$SR = a_i/a_s \qquad (1)$$

where $a_s$ is the layer coefficient for the standard (reference) material and $a_i$ is the layer coefficient for any other material in the $i^{th}$ layer (5).

Thus, the resilient modulus can be used directly in both rigid and flexible pavement design procedures. One current and major limitation of the above use with cement-treated materials is that only suggested ranges of resilient modulus for all cement-treated material are generally available. In addition, the range of modulus values suggested is quite large, which allows for considerable engineering judgment for estimation of a design modulus to be used in determining either the $k_c$ or $a_2$ values. The current study was therefore conducted to develop a more precise evaluation of the modulus based on the material type, cement content, and other variables of material stabilization.

## STUDY OBJECTIVES

The primary objective of this study was to determine the resilient modulus of typical cement-stabilized base/subbase material types used by the Maryland State Highway Administration (MSHA). The materials investigated in this study were classified as follows: cement-stabilized dense-graded aggregate (DGA), which includes limestone (LS) and MSHA (MS); and cement-stabilized soil, which includes types A-2, A-3, and A-2-4.

The objectives in this laboratory study included:

1. Evaluation of the typical limits of resilient modulus, $M_r$, values that exist for different cemented material types used by the MSHA;
2. Investigation of the feasibility of predicting the $M_r$ from the properties of the mix;
3. Evaluation of the factors that affect the $M_r$ response of cement-stabilized material;
4. Investigation of whether accurate correlations between $M_r$ and the unconfined compressive

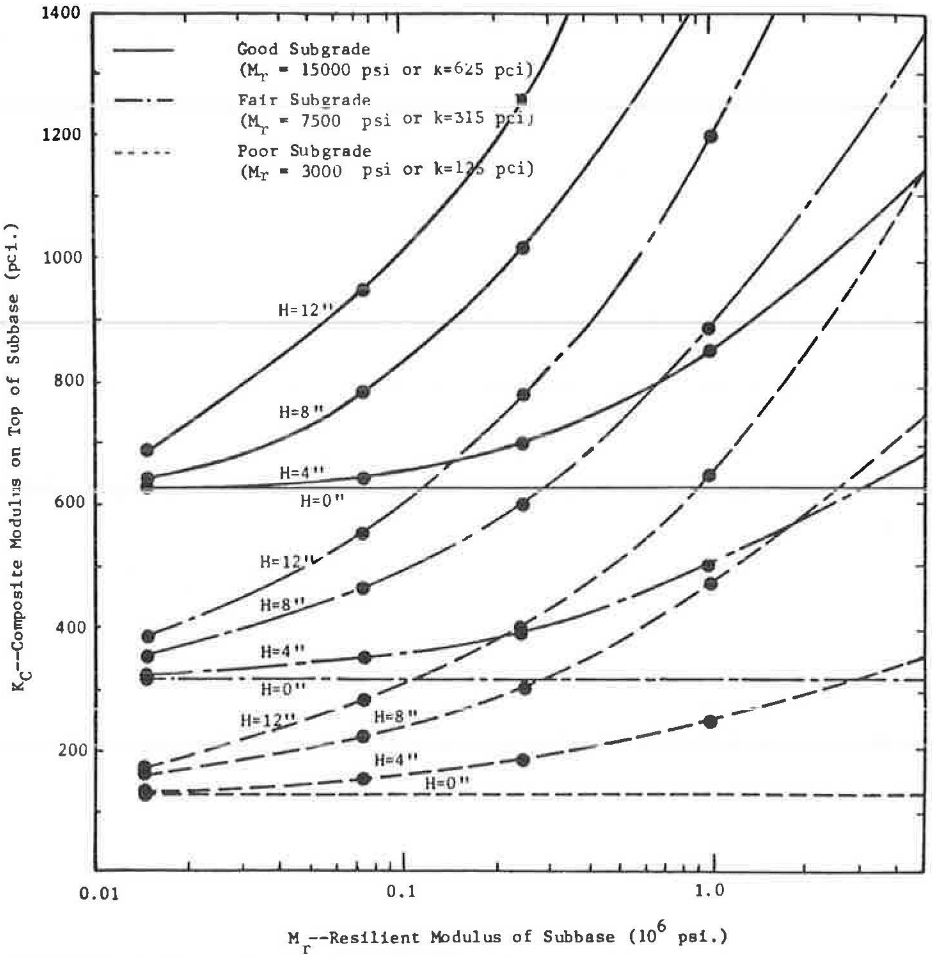


FIGURE 1 Resilient and composite moduli relationship for various subbase thicknesses and subgrade conditions [modified from AASHO Interim Guide (1)].

strength, $q_u$, and the static modulus, E, existed for cement-stabilized materials;

5. Evaluation of specific values of layer coefficient ($a_i$) and SR based on the modulus for use in the design of flexible pavements; and
6. Evaluation of typical values of the composite modulus of subgrade reaction ($k_c$) based on the modulus for use in design of rigid pavements.

## EXPERIMENTAL WORK

Numerous laboratory tests were conducted in this study. They were grouped into routine tests (sieve analysis, specific gravity, and Atterberg limits); preliminary tests (density levels and optimum cement content); and evaluation tests (unconfined compressive strength, static, and resilient modulus). The material factors that influenced the modulus response and that were investigated in this study were the material type, the cement content (3, 4.5, and 6 percent for the DGA and optimum, +1.5 and +3 percent for soils), the density levels (100 and 97 percent of AASHO T-180 density for the DGA and AASHO T-134 for soils), the DGA gradation (upper and lower limits of the MSHA gradation specification), and the curing period (7 and 28 days).

For the determination of compaction energy required for the 97 percent density level, three compaction tests of three different compactive energies were performed on each combination of DGA type (limestone and MSHA) and gradation (upper and lower) for the DGA materials, and performed on each combination of soil type (A-2, A-3, and A-2-4) and cement content (optimum, +1.5 and +3 percent) for the soil materials. The optimum cement content used in preparing the soil specimens was the cement content that yielded unconfined compressive strength of 450 psi (specimen size: 4-in diameter x 4.6-in. height). For the determination of the optimum cement content, each soil type was mixed with four different cement contents--around the optimum--and from each combination of soil type and cement content, three identical specimens were prepared and tested to find the average $q_u$ (unconfined compressive strength) of each combination. For each soil type, a $q_u$-cement content relationship was plotted from which the optimum cement content was determined. A comprehensive discussion of the test procedures and results is presented by Lotfi (3).

For the laboratory evaluation of typical $M_r$ values, 48 specimens of cement-treated DGA were tested with the University of Maryland's MTS Systems Corporation. These specimens were prepared in accordance with a factorial mix combination of two DGA types, two gradations, two density levels, three cement contents, and two curing periods. In addition, 36 specimens of soil cement were also tested from a factorial mix combination of three soil types, two density levels, three cement contents, and two curing periods. On the basis of the testing program noted, a total of 84 specimens (4-in. diameter x 8-in. height) were tested to determine $M_r$ values. Each $M_r$ test specimen was tested at a factorial combination of five stress levels (ranging from 40 to 320 psi); three repetition levels (200, 300, and 400) and three frequencies (4, 8, and 16 Hz). Immediately after the evaluation of the $M_r$ value, each specimen was tested on a universal compression machine to determine the unconfined compressive strength, $q_u$, and the static modulus, E, to investigate the $M_r$-$q_u$ and $M_{r-E}$ relationships.

## RESULTS

### Factors That Influence the Resilient Modulus

### Loading Conditions

Three loading factors were investigated in this study: the deviator stress level, the loading frequency, and the number of load repetitions. It is well understood from the literature that the stabilized materials usually exhibit linear (stress-independent) elastic properties. In this study, it was found that the stabilized materials became more stress-independent as the cement content and the curing period are increased. The other load factors, loading frequency, and load repetitions were found to have little, if any, influence on the modulus response.

### DGA Gradation

Two gradations were used in this study, the upper and lower limits of gradations (4). The percent of fines (passing sieve No. 200) of the upper gradation was 10 percent, and the percent of fines for the lower gradation was 0. In this study, it was found that the modulus of the cement-treated DGA, having the upper limit of gradation, is higher than the modulus of that having the lower limit of gradation by a factor of 1.5 for the limestone material and 2.0 for the MSHA material.

### Material Type

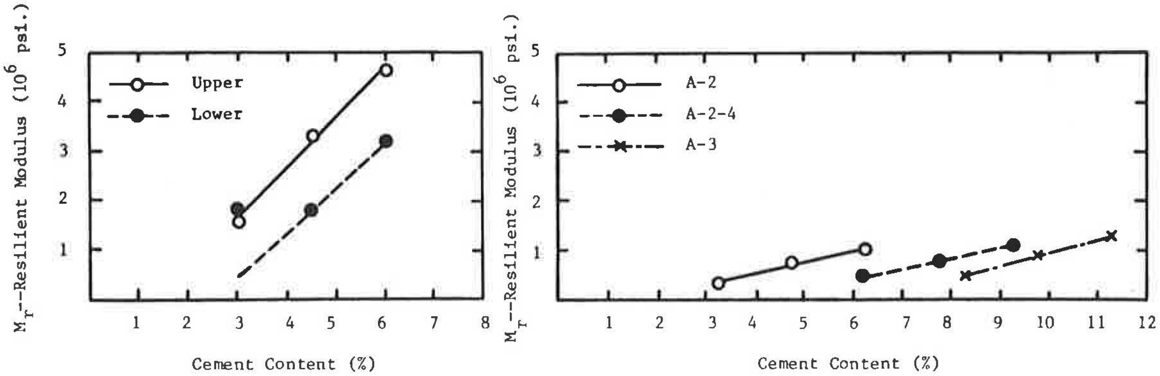
Two broad material categories were tested in this study. They were the cement-treated base (DGA) and soil cement. The $M_r$ values of the cement-treated DGA were found to range from about $5 \times 10^5$ to $5 \times 10^6$ psi (after a 7-day cure period). In general, the lower value is obtained with the lower limit of gradation mixed with 3 percent cement, while the higher value results from mixing the upper limit of gradation with 6 percent cement content. The $M_r$ values of the LS type were found to be higher than the MS type by an average factor of 1.5.

The $M_r$ values of soil cement were found to range from $2.5 \times 10^5$ to approximately $1.4 \times 10^6$ psi--after a 7-day cure period--and from about $5 \times 10^5$ to $2 \times 10^6$ psi--after a 28-day cure period. The lower $M_r$ values are obtained when the soil is mixed at its optimum cement content and the higher values of $M_r$ are obtained when the soil is mixed at a cement content higher than the optimum value. This important trend was found to be independent of the soil type investigated when mixed with its optimum cement content.

### Cement Content

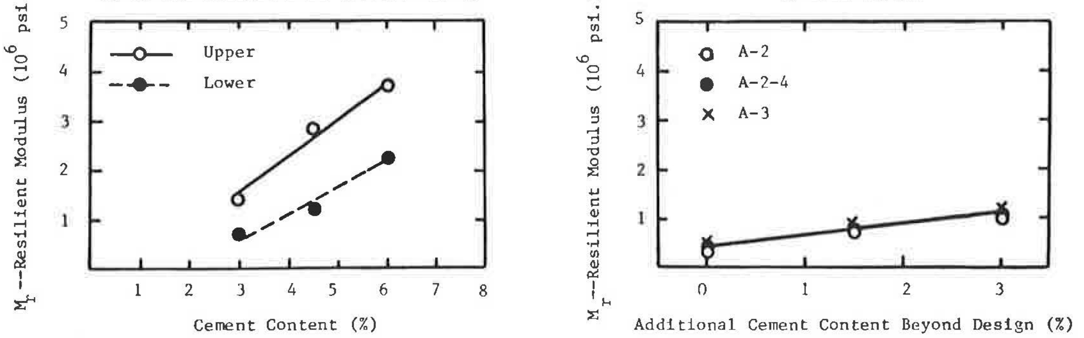
Three values of cement content were used for each material type to study their respective influences on the resilient modulus. Cement contents of 3.0, 4.5, and 6.0 percent were used to stabilize the DGA, and the optimum cement contents, of +1.5, and +3.0 percent were used to stabilize the soil cements.

As shown in Figure 2, the modulus generally in-



a) Cement Treated Base (D.G.A.--L.S.)

c) Soil Cement



b) Cement Treated Base (D.G.A.--M.S.)

d) Soil Cement

**FIGURE 2** Effect of cement content on the modulus of various cemented materials.

creases linearly with increasing cement content, at least in the range of the 3-percent increase. However, different rates are noticed for different materials and gradations. The regression equations representing the relation between cement content and modulus for different materials and gradations are given in Table 1. These relations were developed by taking the average value between modulus at 97- and 100-percent density levels. The relatively large increase in modulus attributed to a 1-percent increase in cement content for each cemented material is given in Table 2. This clearly indicates the sensitivity of cement content to the modulus. It can be observed that the increase in $M_r$ for the DGA (upper gradation) is greater than the increase in $M_r$ for soils by a factor ranging from 3.4 to 4.2, while for the DGA (lower gradation), this factor ranges from 2.3 to 3.8.

TABLE 1 Cement Content–Resilient Modulus Relationship

| Material | Regression Equation |
|---|---|
| DGA–LS Upper limit | $M_r{}^a = 1.445 + 1.023C^b$ |
| DGA–LS[c] Lower limit | $M_r = -2.430 + 0.933C$ |
| DGA–MS Upper limit | $M_r = -0.785 + 0.763C$ |
| DGA–MS Lower limit | $M_r = -0.968 + 0.517C$ |
| Soil (A-2) | $M_r = -0.379 + 0.235C$ |
| Soil (A-3) | $M_r = -1.477 + 0.241C$ |
| Soil (A-2-4) | $M_r = -0.948 + 0.222C$ |

[a] $M_r$ represents the resilient modulus in $10^6$ psi.
[b] C is the percent of cement content.
[c] The 3 percent cement content was not used in regression.

TABLE 2 Increase in Modulus-Cement Content Influence

| Matreial | $\Delta M_r{}^a$ ($10^6$ psi) |
|---|---|
| DGA–Upper limit | 0.75–1.00 |
| DGA–Lower limit | 0.50–0.90 |
| Soil-cement | 0.22–0.24 |

[a] The change in $M_r$ is due to a 1.0-percent increase in cement content.

In contrast to the DGA cement-treated base materials, Figure 2(d) shows that for each soil mixed with its optimum cement content, the modulus is almost the same and the increase in modulus attributed to the increase of cement content beyond the optimum value, is also identical. These results are logical when the common basis for selecting the optimum cement content for all soil cement material (i.e., 450-psi strength) is considered.

### Density Level and Moisture Content

Two density levels were used in preparing the specimens: 100 percent of AASHO T-180 for DGA materials and 97 percent of AASHO T-134 for soil materials. All specimens were molded at a moisture content equal to the optimum value needed for the 100-percent density level. In contrast to what one would normally expect, 45 percent of the results showed that the reduction of the density level will cause an increase in the modulus response. One possible explanation for this can be found in Felt (2), who noted that the moisture content needed for cement hydration is not the same as that needed for maximum density. It was also stated that the compressive strength reaches its maximum value at moisture contents slightly less than the optimum moisture content for sandy soils. As the moisture used in the case of the 97-percent density level is less than the optimum moisture content of that density level, the compressive strength and, therefore, modulus, which is strongly related to compressive strength, can be found to be greater than the modulus at the 100-percent density level. For the materials not affected by that phenomenon, the reduction in modulus caused by the reduction in density level from 100 to 97 percent ranges from 0.6 to 0.85 with an average of 0.7.

### Cure Period

All the specimens were tested after both 7- and 28-day cure periods, but the DGA 28-day period results were not used in the analysis because a preliminary analysis of results indicated that a variable but significant damage to the specimens occurred from modulus testing after the 7-day tests. During the cure period, specimens were kept in a room with 100-percent humidity and a temperature of 70° F.

For the soil cement samples, the results of this study showed that the modulus at 28 days is higher than that at 7 days by a factor ranging from 1.25 to 1.55; this factor was found to be dependent on the soil type and the optimum cement content. The higher the optimum cement content, the higher the factor of modulus increase. A linear regression analysis between the modulus at 28 days and that at 7 days, for all soil cement specimens, showed that their relation could be represented by the equation:

$$M_{r28} = 0.1887 + 1.093\ M_{r7}, \qquad r = 0.868 \qquad (2)$$

where $M_{r28}$ and $M_{r7}$ are the resilient moduli at 28 and 7 days, respectively.

### $M_r$ Predictive Equations

Because of the relative difficulty, expense, and laboratory time associated with performing direct laboratory resilient modulus tests, predictive equations were developed from which the modulus response can be determined either from the properties of the mix or from common properties such as the unconfined compression test or the static modulus test. The prediction of the $M_r$ response from the properties of the mix was presented in Table 1. It should be emphasized that the equations in Table 1 can be specifically used for the materials tested in this project. However, more general predictions of the $M_r$ response can be obtained by regressing the $M_r$ values against each of the unconfined compression strength, $q_u$, and/or the static modulus E.

### $M_r$-E Relationship

Two linear regression models were developed, one for each material type, to predict $M_r$ from E. These equations are as follows:

$$\text{(DGA)} \quad M_r = 0.185 + 4.41E, \qquad r = 0.937 \qquad (3)$$

$$\text{(Soils)} \quad M_r = 0.303 + 2.07E, \qquad r = 0.707 \qquad (4)$$

with $M_r$ and E in $10^6$ psi. Based on these models, it can be concluded that the dynamic (resilient) modulus ($M_r$) is higher than the static modulus (e) by a factor of approximately 5.0 for the DGA and factor ranges from 2.5 to 5.0 for soils.

### $M_r$-$q_u$ Relationship

For the prediction of $M_r$ based on $q_u$, two semilogarithmic regression models were developed. They are as follows:

$$\text{(DGA)} \quad \log M_r = -0.141 + 0.000529\, q_u, \quad r = 0.842 \quad (5)$$

$$\text{(Soils)} \quad \log M_r = -0.659 + 0.001135\, q_u, \quad r = 0.905 \quad (6)$$

with $q_u$ in psi and $M_r$ in $10^6$ psi. The $q_u$ values are based on specimen sizes of 4-in. diameter and 8-in. height. By using the results of the unconfined compression test that was performed on a specimen that had a 4-in. diameter and a 4.6-in. height for the optimum cement content determination, it was found that the $q_u$ values based on the 4.6-in. specimen height are higher than those based on the 8-in. specimen height by a factor of 1.51. By applying the factor of 1.51 to Equations 5 and 6, the $M_r$-$q_u$ relationships based on the 4.6-in. specimen height become

$$\text{(DGA)} \quad \log M_r = -0.141 + 0.00035\, q_u \quad (7)$$

$$\text{(Soils)} \quad \text{Log } M_r = -0.659 + 0.000752\, q_u \quad (8)$$

By combining the two materials, the regression model that represents all the material tested was found to be

$$\log M_r = -0.403 + 0.000755\, q_u, \quad r = 0.873 \quad (9)$$

Equations 7, 8, and 9 are shown in Figure 3, with the $M_r$-$q_u$ relationship presented by Van Til in NCHRP Report 128 (6). In this report, it can be seen that the NCHRP relationship is generally consistent with the model developed in this study for all cemented material that is represented by Equation 9. However, Figure 3 also shows that each type of cemented material group, soil cement, and cement-treated base should be represented by a separate equation rather than one relationship for all cemented materials (i.e., Equations 7 and 8 should be used instead of Equation 9).

### Layer Coefficient and Substitution Ratio

The Van Til nomograph yields the layer coefficient values, $a_2$, based on either the $q_u$ or the $M_r$ value (6). Figure 4 shows the relation between $a_2$ values based on the $q_u$ and that based on $M_r$. From this figure, it is obvious that if the Van Til nomograph is directly used without modification, the $a_2$ values based on $M_r$ are quite different from those based on the $q_u$ parameter by a factor that ranges from 0.5 to 1.3 for soil cement and from 1.5 to 2.0 for cemented DGA.

Because of the extreme difference in $a_2$ values generated by the Van Til nomograph between the use of $M_r$ or $q_u$ values, the $a_2$-$q_u$ relationship of that nomograph was used as the base or standard correlation. As a consequence, a specific $M_r$-$a_2$ nomograph for each material tested in this study (soil cement and cemented DGA) was developed as shown in Figure 5.

The cement content, material type, and the DGA gradation are the factors of major influence on the layer coefficient of the cement-stabilized materials. For cement-treated DGA material, the values of $a_2$ range from 0.2 to 0.45, and for soil cement, the values of $a_2$ range from 0.15 to 0.25. Figure 6 shows the typical values of both layer coefficient and substitution ratio for each material at different cement contents. The substitution ratios were calculated from Equation 1 by using the value of $a_2$ of an unbound MSHA-DGA limestone, as found by a companion part of this project, equal to 0.143. Layer coefficient predictive equations for each material type and gradation were also developed and are given in Table 3.

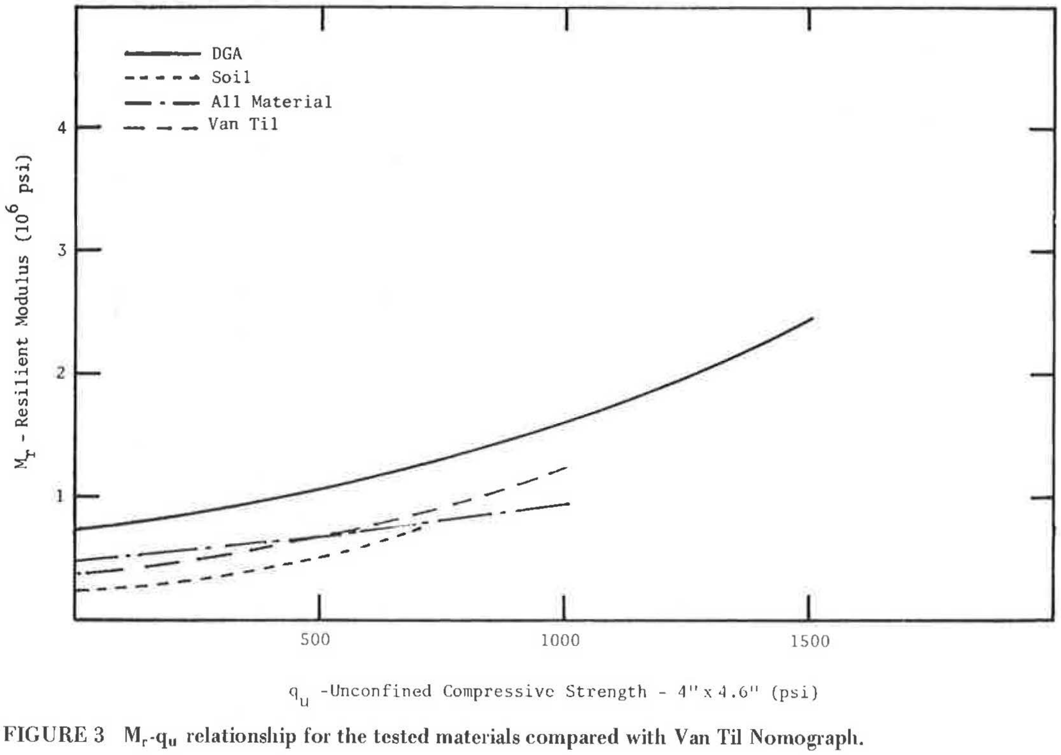


FIGURE 3 $M_r$-$q_u$ relationship for the tested materials compared with Van Til Nomograph.

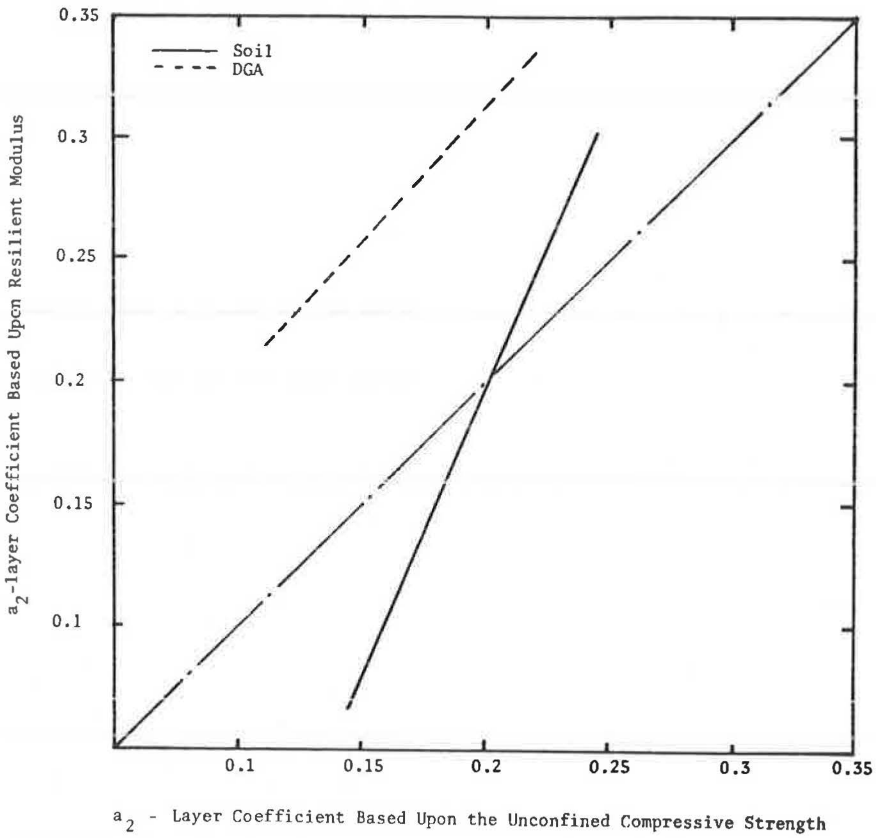
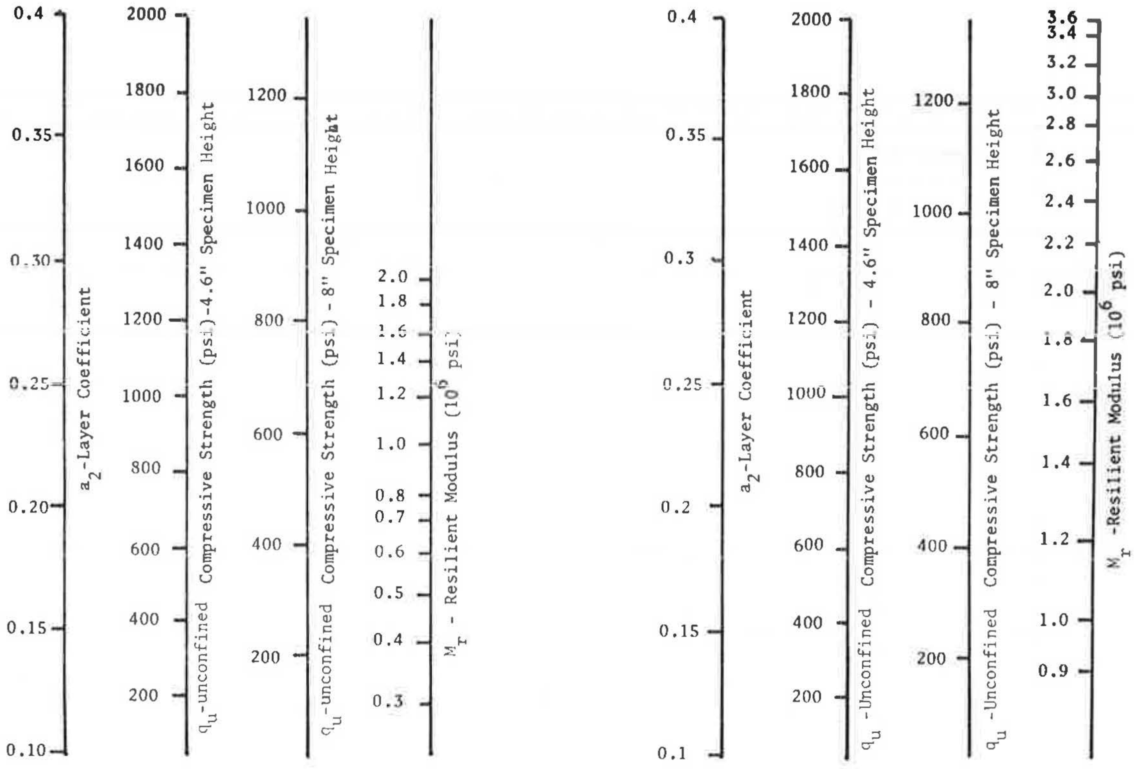


FIGURE 4 Relationship between layer coefficient based on the modulus and that based upon unconfined compressive strength.



(a) Cemented Soil

(b) Cemented DGA

FIGURE 5 Layer coefficient nomograph based on unconfined compressive strength.

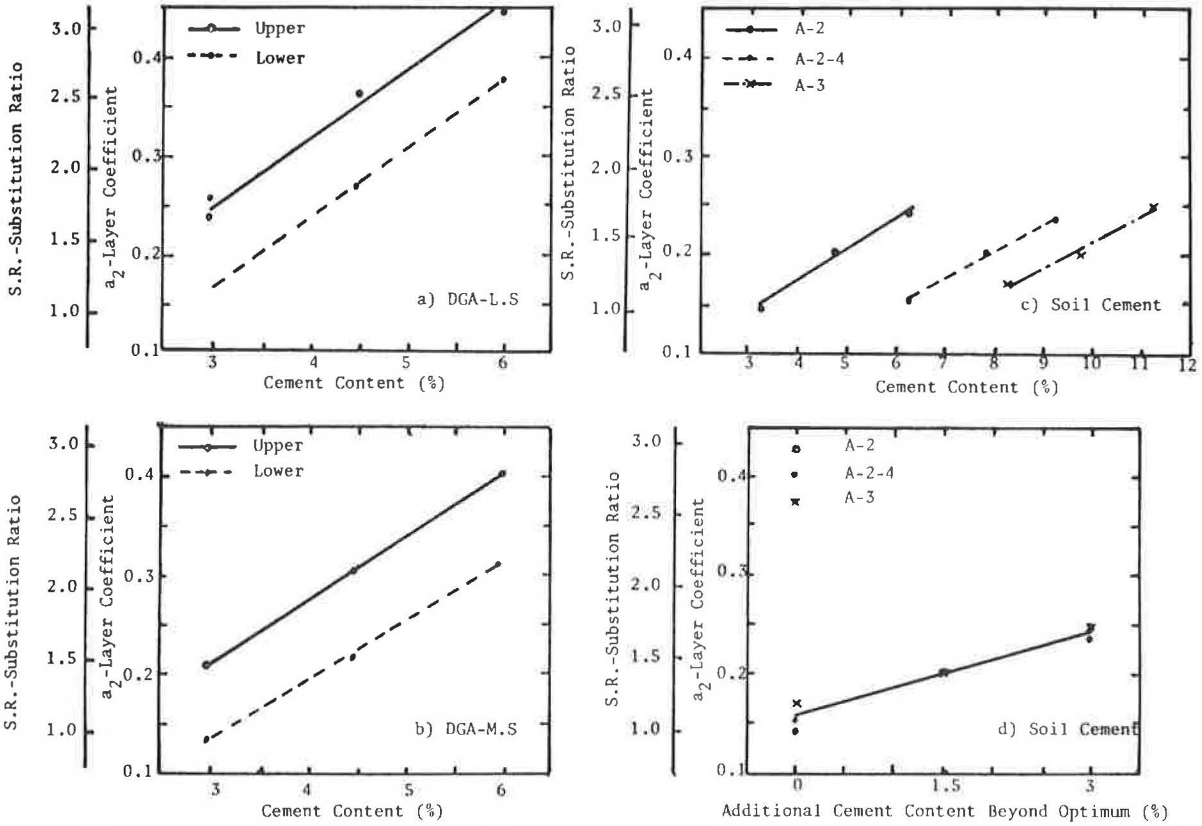


FIGURE 6 Effect of cement content on the $a_2$/SR of various cemented materials.

TABLE 3 Cement Content–Layer Coefficient Relationship

| Material Type | Regression Equation |
|---|---|
| DGA–LS Upper limit | $a_2 = 0.0305 + 0.0703C$[a] |
| DGA–LS Lower limit | $a_2 = -0.0650 + 0.0733C$ |
| DGA–MS Upper limit | $a_2 = 0.0163 + 0.0640C$ |
| DGA–MS Lower limit | $a_2 = -0.0508 + 0.0597C$ |
| Soil (A-2) | $a_2 = 0.0422 + 0.0313C$ |
| Soil (A-3) | $a_2 = -0.040 + 0.0253C$ |
| Soil (A-2-4) | $a_2 = -0.0168 + 0.0273C$ |

[a] C is the percent of cement content.

In general, the layer coefficient of the upper gradation is higher than that of lower gradation by a factor of 1.1 to 1.5. The layer coefficient of the limestone is higher than that of the MSHA type by an average factor of 1.25. The average SR values for cement-treated DGA and for soils were found to be 1.98 and 1.35, respectively. These values are similar to the 2.0 and 1.5 values used by the MSHA (see Table 4).

### Composite Modulus of Subgrade Reaction

In rigid pavement design, the $k_c$ values represent the composite modulus of subgrade reaction on top of a subbase-subgrade system. This value takes into consideration the subbase thickness, the resilient modulus of the subbase, and the subgrade support value. By using the typical modulus values shown in Figure 2, the $k_c$ values of different cement-treated materials can be determined from Figure 1 at three levels of subbase thickness (4, 8, and 12 in.) and three levels of subgrade conditions (good, fair, and poor). The values of $k_c$ of all possible combinations of material type, gradation, and cement content at different subbase thickness and subgrade conditions are presented in Lotfi (3).

## SUMMARY AND CONCLUSIONS

A comprehensive analysis of a laboratory evaluation of resilient modulus response for MSHA cement-treated material is presented in this paper. Based on the analysis of the modulus results, the following conclusions were reached:

1. The major factors that influence the $M_r$ response of cement-stabilized materials are the cement content, the material type, and the DGA gradation. The state of stress is of minor influence, especially at higher cement content and longer cure periods. The load frequency and number of repetitions are of extremely minor, if any, influence on the resilient modulus response.
2. The specific $q_u$-$M_r$ relationship presented for each cemented material type (soil cement and cement-treated DGA) should be used for the prediction of $M_r$, rather than one unique relationship for all cemented materials.
3. The dynamic (resilient) modulus of cement-treated DGA is higher than the static modulus by a factor of 5 although for soil content, the factor ranges from 2.5 to 5.0.
4. For layer coefficient determination, two nomographs were developed for soil cement and cement-treated DGA material, rather than one nomograph for all cemented materials. The factors of major influence on $a_2$ and SR are material type, cement content, and DGA gradations.
5. Design charts and summary tables were developed for each material type and DGA gradation for

TABLE 4 Typical SR Values for MSHA Cemented Materials

| | | SR | |
|---|---|---|---|
| Material Type | Cement Content (%) | Developed in this Project | Used by MSHA |
| DGA–LS | | | |
| Upper limit | 3 | 1.63 | 2.0 |
| | 4.5 | 2.55 | |
| | 6 | 3.10 | |
| DGA–LS | | | |
| Lower limit | 3 | 1.08 | |
| | 4.5 | 1.85 | |
| | 6 | 2.62 | |
| DGA–MS | | | |
| Upper limit | 3 | 1.47 | |
| | 4.5 | 2.10 | |
| | 6 | 2.81 | |
| DGA–MS | | | |
| Lower limit | 3 | 0.90 | |
| | 4.5 | 1.52 | |
| | 6 | 2.15 | |
| Average for DGA | | 1.98 | |
| Soil cement | Optimum | 1.08 | 1.5 |
| | Optimum + 1.5 | 1.40 | |
| | Optimum + 3.0 | 1.67 | |
| Average for soil | | 1.38 | |

the $k_c$ values. The factors that influence the $k_c$ values are cement content, material type, DGA gradation, subbase thickness, and subgrade condition.

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