COEFFICIENTS OF RELATIVE STRENGTH FOR IOWA GRANULAR BASE MATERIALS

K. L. Bergeson and J. M. Hoover, Department of Civil Engineering and Engineering Research Institute, Iowa State University

The purpose of this investigation was to use the consolidated-undrained triaxial test to relate untreated and asphalt-treated Iowa granular base materials to those used in the AASHO Road Test. The primary objectives were to (a) obtain a measure of the relative behavior of Iowa materials from different aggregate sources for comparison with 2 AASHO Road Test materials also subjected to the same triaxial test technique and (b) develop a laboratory triaxial test technique and form of analysis to indicate a granular materials variability for ascertaining an assigned coefficient of relative strength. Results indicated that volumetric strain-axial strain relations were appropriate evaluation parameters for determining coefficient of relative strength at what was termed minimum volume failure criteria; minimum volume is considered as a point of "proportional limit" when viewed in conjunction with a stress-strain diagram.

•PERFORMANCE of a flexible pavement structure is related to the physical properties and supporting capacity of the various structural components. The AASHO Interim Guide for the Design of Flexible Pavement Structures, based on the pavement performance-serviceability concept developed from the AASHO Road Test, uses the physical properties and supporting capacity of granular base materials through an evaluation of the coefficient of relative strength of the materials. The term "coefficient of relative strength" implies that materials vary in their physical properties and, thus, affect the supporting capacity of the pavement structure. The coefficients developed from the AASHO Road Test are indicative of a material's variance.

The purpose of this investigation was to use the consolidated-undrained triaxial test to relate untreated and bituminous-treated Iowa granular base materials to those used in the AASHO Road Test. The primary objectives were to

1. Obtain a measure of the relative behavior of Iowa materials from different aggregate sources for comparison with 2 AASHO Road Test materials also subjected to the same triaxial test technique, and
2. Develop a laboratory triaxial test technique and form of analysis to indicate a granular materials variability for ascertaining an assigned coefficient of relative strength (CORS).

MATERIALS

Twenty-one materials of varying aggregate types and sources were studied. All untreated aggregates and bituminous-treated field mixes were furnished through cooperation of the Iowa State Highway Commission (ISHC).

Bituminous-treated, field-mixed samples were obtained by ISHC personnel from construction batch plants immediately following mixing with asphalt. Aggregates used for all laboratory mixes were obtained by sampling prior to batching or from stockpiled

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materials. Asphalt cement for the laboratory mixes, penetration grade 120 to 150, was also furnished by the ISHC.

Samples of AASHO Road Test base material, obtained from the road test site, were provided in a limited quantity. The base material included a hard dolomitic limestone, recommended by the ISHC for use in an untreated condition, and a coarse-graded gravel, recommended for use in a bituminous-treated condition.

SPECIMEN PREPARATION

All 4-in. diameter by 8-in. high cylindrical test specimens were prepared by a vibratory compaction procedure using an electromagnetic vibrator operating at a constant frequency of 3,600 cycles/min and an amplitude of 0.368 mm, a surcharge weight of 35 lb, and a vibration duration of 2 min. This procedure, previously reported by Hoover et al. (1), minimizes aggregate degradation and segregation while producing uniform densities comparable to other methods. Figure 1 shows the specimen preparation procedure.

Bituminous-Treated Materials

Laboratory- and field-mixed materials were molded and tested in a similar manner. The major difference was in the initial preparation and combining with asphalt of the laboratory mixes of known gradation and then molding as a 1-step operation. The field-mixed samples, by contrast, had to be reheated from a previously mixed condition and relatively unknown gradation and asphalt content.

Aggregates for the laboratory-mixed materials were blended and adjusted, if needed, to meet ISHC recommended gradations within ±2 percent of each sieve fraction. Test specimens were molded at the asphalt content recommended by the ISHC.

AASHO coarse-graded gravel material, as obtained from the test road, was separated into individual sieve fractions, blended, and adjusted to within 1 standard deviation from the AASHO mean gradation for bituminous-treated base material as given in the road test report (11, Table 37, p. 74). Test specimens were molded at 5 percent asphalt content.

All bituminous-treated specimens were air-cured at about 75 F for a minimum of 7 days prior to testing.

Untreated Materials

Seven materials were selected for use in an untreated condition, as representative of the various aggregate types. Each was blended and adjusted in the same manner as the laboratory-mixed, bituminous-treated materials. A moisture-density curve was established for the adjusted blend, and test specimens were molded at optimum moisture. When compaction was complete, all specimens were wrapped in 2 layers of Saran Wrap with a taped layer of aluminum foil and placed in a curing room at about 75 F and 100 percent relative humidity until testing.

AASHO crushed-limestone material was blended and adjusted to within 1 standard deviation from the mean gradation for untreated crushed limestone base material as given in the road test report (11, Table 31, p. 68). Test specimens were molded at 6 percent moisture content.

TESTING PROCEDURE

This investigation utilized the consolidated-undrained triaxial test for all specimens. All testing was conducted at a deformation rate of 0.01 in./min. Pore pressure, volume change, and axial load readings were taken at vertical deflection intervals of every 0.01 to 0.2 in., every 0.025 to 0.4 in., and every 0.05 to 0.6 in. deflection. Specimen volume changes were measured to a precision of 0.01 in.^{3}. Both positive and negative pore pressures could be measured.

A minimum of 4 tests were performed within each mix type (field mix, 4 percent laboratory mix, 5 percent laboratory mix, and selected untreated mixes) at 10-, 20-, 30-, and 40-psi lateral pressure.

Figure 2 shows the bituminous-treated materials test procedure. The test procedure for the untreated materials was similar except that specimens (a) could not be saturated and (b) were not heated but maintained at room temperature.

METHOD OF ANALYSIS

Failure Criterion

Results of this investigation were analyzed on the basis of 2 criteria of failure.

1. Minimum volume (MV) is defined as that point of loading at which the specimen has consolidated to its smallest volume during triaxial shear. As the specimen is loaded, volume decreases to some minimum value, and pore pressure in the undrained specimen increases to its maximum positive value. It is believed that at this point failure has begun and may be considered a "proportional limit" when viewed in conjunction with a stress-strain curve. On further axial loading volume increases, an interparticle sliding or crushing or both will begin. Pore pressure will also decrease. Further illustrations of this concept are presented by Fish and Hoover (2) and Ferguson and Hoover (3).
2. Maximum effective stress ratio (MESR) is defined as that point in a triaxial shear test at which the effective stress ratio $(\bar{\sigma}_1 - \bar{\sigma}_3)/\bar{\sigma}_3$ is at a maximum. Effective stresses are intergranular stresses corrected for pore pressures. At MESR the specimen volume has increased substantially, and negative pore pressure normally exists. Further illustrations of this concept are presented by Fish and Hoover (2) and Best and Hoover (4).

Calculations

An IBM 360/65 computer program was used to determine stress, strain, volume change, and pore-pressure conditions at each data point in the shear portion of the triaxial test. This program was also capable of producing plots of effective stress ratio, percentage of volume change, and pore pressure versus percentage of axial strain. Values of cohesion, friction angle, modulus of deformation (2), and Poisson's ratio were determined from each series of tests and output of the appropriate failure criterion.

Statistical Analysis

An IBM 360/65 computer program capable of generating correlation coefficients among a large number of variables, having an equally large number of observations of each variable, was used as one means of analyzing the large volume of triaxial test results. The correlation coefficients were output in matrix form.

The coefficient of correlation is a good measure of linear correlation between 2 variables. It must be emphasized, however, that the correlation coefficients developed are indicative of linear trends only. A low correlation coefficient means only that no significant linear trend exists; consequently, a nonlinear relation may exist. The coefficient may vary from +1 to -1. A positive value indicates positive linear correlation; a negative value indicates negative linear correlation.

Correlation matrices were produced separately for the field mixes, 4 percent laboratory mixes, 5 percent laboratory mixes, and the untreated mixes at 10-, 20-, 30-, and 40-psi lateral pressure.

Flow charts indicating variables used for the correlation matrices at minimum volume and maximum effective stress ratio failure criteria are shown in Figures 3 and 4 respectively. Definitions of the variables shown in the flow charts are as follows:

Name	Abbreviation	Number
Asphalt content	AC	1
Optimum moisture content	Opt. MC	1
Sand equivalent	S. Eq.	2
Percentage passing No. 200 sieve	-No. 200	3

Figure 1. Specimen preparation.

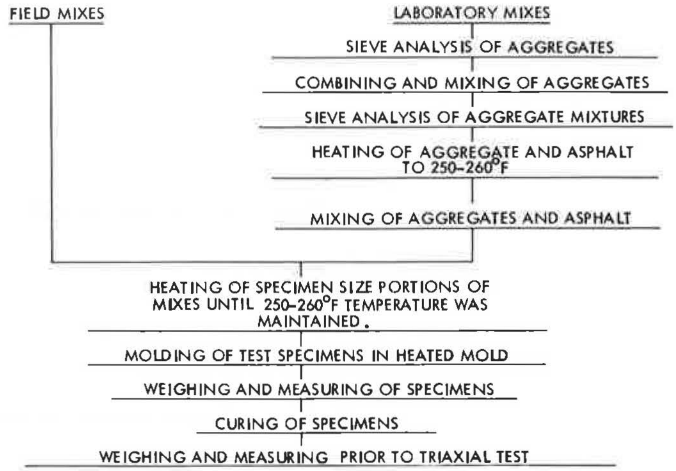


Figure 2. Test procedure for bituminous-treated materials.

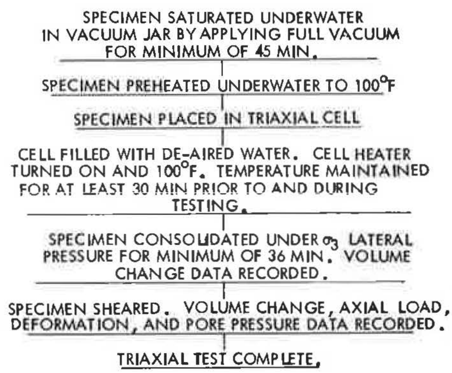


Figure 3. Variables used at minimum volume conditions for correlation determinations.

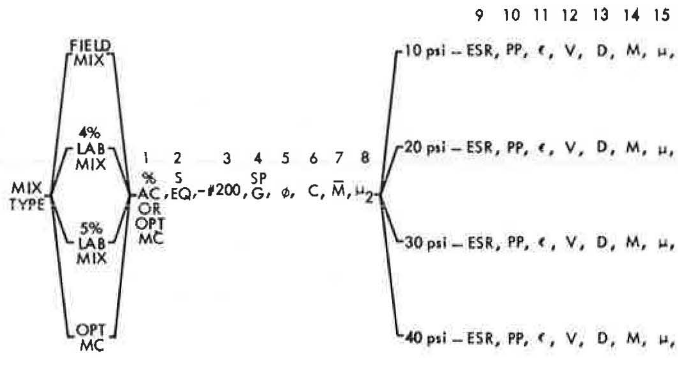
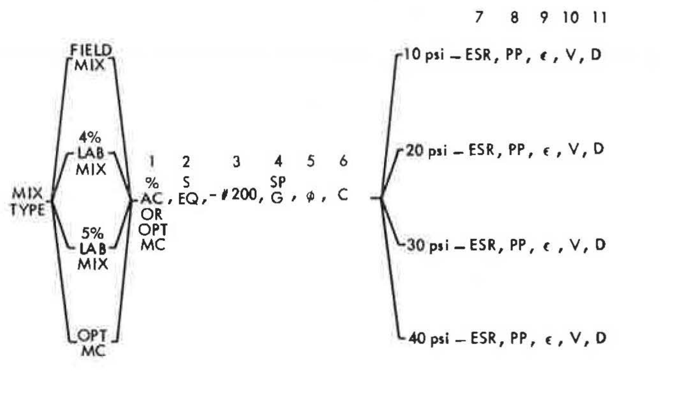


Figure 4. Variables used at maximum effective stress ratio conditions for correlation determinations.



Name	Abbreviation	Number
Specific gravity	Sp. G.	4
Angle of internal friction	ϕ	5
Cohesion	$\underline{C}$	6
Average modulus of deformation (2)	$\overline{M}$	7
Poisson's ratio (2, Eq. 21)	μ_2	8
Effective stress ratio	ESR	9
Pore pressure	PP	10
Axial strain	ϵ	11
Volumetric strain	V	12
Density	D	13
Modulus of deformation	M	14
Poisson's ratio (2, Eq. 13)	μ	15

In addition to the variables gathered from the triaxial tests, the following properties, as determined by the ISHC, were included as variables for the correlation matrices: specific gravity, sand equivalent, and percentage passing the No. 200 sieve for the field mixes.

The AASHO materials were not included as a part of any of the correlation matrices since they were considered strictly as control samples.

The primary purpose of this phase of analysis was to determine which pair, or pairs, of variables exhibited a significant degree of correlation and was consistent among the various materials. The value of these variables could then be compared to the value of the same variables of the AASHO control mixes, and ranked accordingly, in order to obtain the coefficient of relative strength (CORS).

RESULTS

Minimum Volume Criteria

Investigation of correlation matrices developed for the various mix types (field, 4 percent laboratory, 5 percent labortory, and untreated) at minimum volume failure conditions indicated that the highest degree of correlation was obtained between volumetric strain (defined as the percentage ratio of unit volume change to original volume at start of shear phase of triaxial test) and axial strain (defined as the percentage ratio of axial deformation to original axial length at start of shear phase). Volumetric strain and axial strain referred to here are at the point of minimum volume failure criteria.

The correlations between volumetric strain and axial strain (V-ϵ) were consistent for all lateral pressures within each mix type and among mix types. Figures 5 through 7 show the V-ϵ regression lines for the various mix types at 10-psi lateral pressure. Figure 8 shows the combined V-ϵ regression line for the untreated materials at 10-, 20-, and 30-psi lateral pressure.

Least squares linear regressions were performed on values of volumetric strain and axial strain within the mix types of each lateral pressure. Results are given in Table 1.

Slopes of the volumetric strain-axial strain lines, as determined by regression, remained relatively consistent among treated mixes within a given lateral pressure though there appeared to be a decrease in slope with increase in lateral pressure for the treated mixes.

Slopes of volumetric strain-axial strain lines for the untreated mixes were considerably greater than for treated mixes and appeared to increase with lateral pressure.

The volumetric strain-axial strain regression lines for the 10-, 20-, and 30-psi lateral pressures for untreated and treated mixes, shown in Figure 9, were used for qualitative observations. It can be shown that, when Poisson's ratio is 0, volumetric strain is equal to axial strain and lateral strain is 0. It can also be shown that, when Poisson's ratio equals 0.5, volumetric strain is 0 (incompressible) and axial strain equals twice the lateral strain. These conditions are shown in Figure 9.

Figure 5. Volumetric strain versus axial strain for 4 percent laboratory mix at minimum volume and 10-psi lateral pressure.

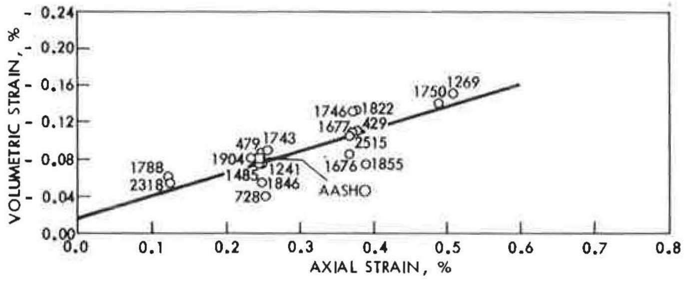


Figure 6. Volumetric strain versus axial strain for 5 percent laboratory mix at minimum volume and 10-psi lateral pressure.

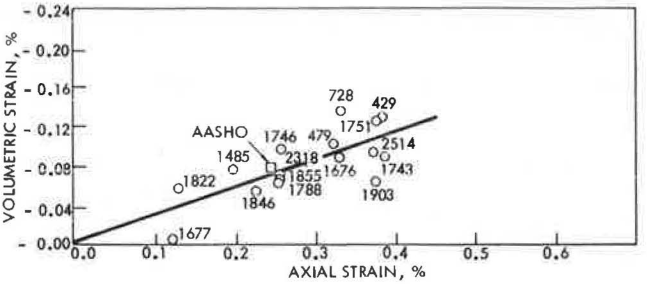


Figure 7. Volumetric strain versus axial strain for field mix at minimum volume and 10-psi lateral pressure.

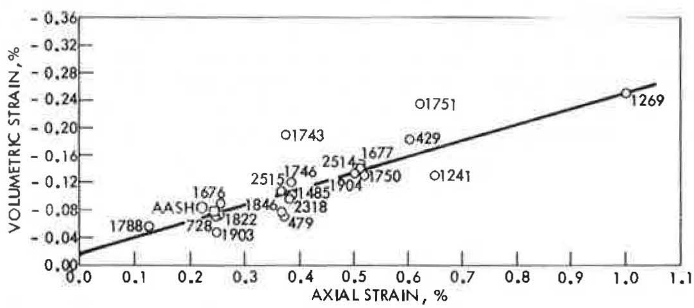


Figure 8. Volumetric strain versus axial strain for untreated mix with optimum moisture content at minimum volume and 10-, 20-, and 30-psi lateral pressures.

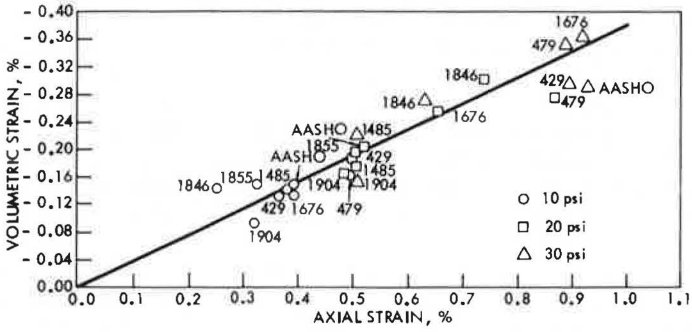
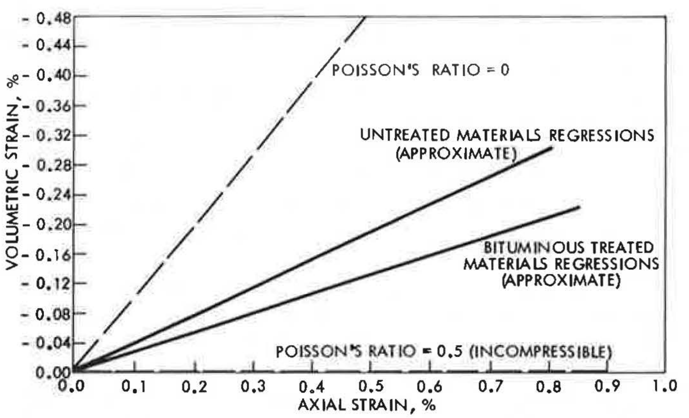


Table 1. Regression results.

Mix	Lateral Pressure	Intercept	Slope	Correlation Coefficient
Field	10	-0.016	-0.243	0.855
	20	-0.012	-0.234	0.841
	30	-0.030	-0.190	0.948
	40	-0.022	-0.228	0.931
4 percent laboratory	10	-0.017	-0.243	0.816
	20	-0.026	-0.203	0.943
	30	-0.050	-0.179	0.973
	40	-0.048	-0.186	0.986
5 percent laboratory	10	-0.006	-0.267	0.722
	20	-0.010	-0.241	0.860
	30	-0.049	-0.167	0.881
	40	-0.060	-0.191	0.945
Optimum moisture content	10	-0.094	-0.118	0.400
	20	-0.028	-0.321	0.903
	30	-0.023	-0.353	0.899
	40	-0.012	-0.377	0.966

Note: AASHO values were not included in the regressions.

Figure 9. Volumetric strain and axial strain characteristics based on minimum volume criteria.



Untreated materials exhibited greater slopes than treated materials, indicating that at a given value of axial strain the amount of volume decrease is greater for the untreated materials. It also indicates that both materials exhibited a limited amount of lateral strain although volume was decreasing. Treated materials underwent more lateral strain, at a given axial strain, than untreated materials.

The variation in slopes between the untreated and treated materials can be attributed to test temperature (the treated materials were tested at 100 F), density difference from untreated to treated condition, degree of saturation, or asphalt content. If the temperature difference at testing is assumed to be the cause of the deviation, that should allow the asphalt-treated specimens to undergo volume decrease without lateral strain easier than if they were tested at room temperature. This, however, would only tend to lessen the deviation since temperature, if it is contributing, is tending to equalize and not cause the variance.

Dry densities of the untreated specimens were generally higher than those of treated specimens of the same material. This is probably due to the asphalt increasing specimen volume by separation of soil particles with a film of asphalt and fines, thereby decreasing the specimen weight. Also, the cohesive property of asphalt does not allow so much freedom for particle reorientation during compaction as water in the untreated specimens. If density is thus assumed to cause the deviation in volumetric strain at a given vertical strain, it can be reasoned that the less dense specimen of a given material would normally have a greater void ratio and consequently should be able to undergo a volume decrease without lateral strain easier than denser specimens. This again would tend to equalize the deviation and not contribute to it.

All field- and laboratory-mixed bituminous-treated materials were vacuum saturated. As previously indicated, the untreated material specimens could not be saturated. The latter was due to complete disintegration of the specimens under vacuum saturation and severe flotation removal of fines when capillary saturated. Calculated degree of saturation of the untreated materials ranged from less than 60 to near 95 percent saturation. Theoretically, materials at a low percentage of saturation should undergo a greater volumetric strain than materials at a higher percentage of saturation. No correlation was found between calculated degree of saturation and volumetric strain. Instead, untreated materials of high saturation exhibited both high and low volumetric strain. Similar data were noted for the low degree of saturation in untreated materials.

Thus, by the process of elimination it can be concluded that the primary cause of deviation in regression slopes of the treated materials to the untreated materials is the asphalt itself. It should not be concluded, however, that density and temperature have no effect whatsoever. Instead, the effect of these variables would appear to decrease the deviation. This behavior can possibly be explained by the fact that the cohesive properties of the asphalt tend to lock the individual particles together in a matrix of asphalt and fine material. During the initial shear portion of a test, when the specimen is being further consolidated, the particles are less able to reorient themselves into a more compact state without a greater amount of lateral strain than the untreated specimens, even though the latter are less dense initially.

Figure 9 shows that more solid materials such as concrete mixtures will have slopes of volumetric strain-axial strain approaching the line representing Poisson's ratio equal to 0. Such materials exhibit very little lateral strain on loading, while stability is primarily dependent on individual material properties. The other extreme is fluids and fluid mixtures that are nearly incompressible and will have slopes of volumetric strain-axial strain approaching Poisson's ratio of 0.5. Fluids are entirely dependent on lateral restraint to support loads.

From the data shown in Figure 9, one can imagine a succession of lines beginning at Poisson's ratio equal to 0 and representing materials that derive stability from individual material properties and continuing to the line representing Poisson's ratio equal to 0.5 and representing materials deriving their stability primarily from lateral restraint. As the slope of this line decreases, stability becomes more dependent on some form of lateral restraint. Asphaltic concrete is a fluid-solid mixture (Fig. 9) and is more dependent on lateral restraint for stability than on individual material properties.

In a study of cement-treated granular base materials, Ferguson and Hoover (3) advanced the hypothesis that the stability of untreated granular bases may be a function of lateral restraint existing prior to loading and of its ability to increase the restraint through resistance to lateral expansion. The results of this study appear to confirm this hypothesis, extending it to include bituminous-treated base materials.

A study of the shear strength parameters of cohesion and friction angle at minimum volume for the 7 materials used in the treated and untreated condition revealed that the addition of asphalt generally reduced the angle of friction and slightly increased cohesion but did not substantially alter overall shear strength characteristics. This indicates that strength alone does not account for the differences in stabilities of bituminous-treated and untreated base materials.

A mechanism that may account, in part, for the stability differences and may not be so nearly dependent on strength is suggested. Under similar field conditions bituminous-treated materials will exhibit more lateral strain per given amount of vertical strain than untreated materials. This would give rise to greater lateral support from adjacent material for the bituminous-treated materials and, hence, greater stability by virtue of being more able to undergo lateral strain.

A study by Csanyi and Fung (5) concluded that there was no direct relation between performance of an asphaltic mix and its stability regardless of the method used to determine stability. This indicates that, although asphaltic mixes may meet stability requirements and may not fail in terms of shear, they may fail in performance from rutting and channeling. It, therefore, seems that some measure of rutting potential is needed that would also be a measure of strength. The volumetric strain-axial strain characteristics of a particular material would seem to satisfy these requirements. A material that has a high value of volumetric strain-axial strain at minimum volume must undergo more densification and decrease in volume before reaching the condition where lateral strain will provide additional support. This material will have begun to fail in performance as a result of densification, which is the beginning of rutting. A material having a low value of volumetric strain-axial strain will need to densify very little before reaching the condition of additional lateral support.

The discussion given above also indicates that compaction and sufficient lateral support are variables that affect the stability of bituminous-treated base materials to a large degree. Nichols (6) concluded in a flexible pavement research project in Virginia that deflections and performance seemed more closely allied with compaction than with pavement design characteristics. Arena et al. (7) concluded in a compaction study that sections of pavement rolled under pressures of 85 psi had rutted far less after 3 years of exposure to heavy traffic than those rolled at 55 to 75 psi. This indicates that compaction of an asphalt-treated material is a critical factor contributing to the stability of that material and substantiates the use of minimum volume criteria and volumetric strain-axial strain characteristics as a means of evaluating stability and performance.

CORS Based on Volumetric Strain-Axial Strain

CORS were determined at 10-, 20-, and 30-psi lateral pressures. AASHO bituminous-treated gravel and untreated crushed stone were assigned CORS of 0.34 and 0.14 respectively in accordance with the AASHO Interim Guide for the Design of Flexible Pavement Structures. Each material was ranked according to its value of volumetric strain-axial strain (V-ϵ), at minimum volume, on triangular charts of 10-, 20-, and 30-psi lateral pressure. Figure 10 shows the chart used for 10-psi lateral pressure. It is readily noted that the final development of these charts relied on a straight-line relation between only 2 points of control, i. e., the 2 AASHO samples recommended and supplied to the project. The charts are used as follows:

1. Volumetric strain and axial strain, as computed from the consolidated undrained triaxial shear test data at the point of minimum volume during shear, are respectively entered from the left and right sides of the chart; and
2. At the intersection of the values given above, a line is projected down and to the left, to the CORS scale.

Tables 2, 3, and 4 give the CORS determined for each material and mix type from charts similar to that shown in Figure 10. (Several CORS were determined as slightly negative values from the triangular charts but are given in Tables 2, 3, and 4 as 0.) The validity of the CORS thus determined can be fully ascertained only after extensive analysis of the pavement field performance where each material and mix type have been used.

However, it is obvious from data given in Tables 2, 3, and 4 that definite physical property and supporting capacity differences exist among the various materials and mix types. The CORS from untreated to either 4 or 5 percent laboratory mix show that an optimum asphalt content could be significantly less than 4 percent for some mixes or higher than 5 percent for other mixes. Comparison of untreated with treated CORS generally shows the benefit of addition of asphalt.

Three pairs of field and laboratory mixes each used the same aggregate source, i. e., mixes 1750-1751, 1903-1904, and 2514-2515 (respectively limestone-dolomite, gravel, and limestone). The variation of CORS due to asphalt content is apparent between the laboratory and field mixes for each of these materials (Tables 2 and 3). Table 3 gives little variance in CORS with asphalt treatment of these materials, probably because of the increase in lateral restraint, as later explained in this paper.

Comparison of the untreated 4 and 5 percent treated laboratory mixes with their respective field mixes is difficult, however. Major inconsistencies of comparison of the field mixes and their closest laboratory-mix asphalt content were noted during analyses. These inconsistencies were apparently related to gradation differences (extracted gradation varied from recommended gradation) and the effects of reheating the mixtures. A study by Hveem (8) indicates that asphalts harden and become more brittle (lowering of initial penetration) on cooling from an elevated temperature. Therefore, on reheating and cooling an unknown additional amount of brittleness may have been introduced in the field-mixed samples.

There was no discernible trend for the variation of CORS with aggregate type. Some gravels had a very low CORS, material 1260 in particular, while some had relatively high CORS. Material 1750, a dolomitic limestone, had a low CORS, while other dolomitic materials had high CORS. The traffic simulator study by Csanyi et al. (5) concluded that asphaltic mixes using softer aggregates tend to be displaced under traffic less than mixes with harder aggregates and that there is no direct relation between stability and trafficability of a particular mix. It would appear then that some mixes containing soft aggregates could perform better under traffic than those containing hard aggregates and vice versa.

The flexible pavement research study by Nichols (6) concluded that deflections and performance seemed more closely allied with compaction than with pavement design characteristics. From this it would seem that deflections would decrease and performance would increase with increasing density of the base course material. Figure 11 shows that, in general, CORS of the various materials increased with increasing density. A similar plot of density versus CORS of the field mixes was very erratic and was considered indicative of the effect of asphalt brittleness due to reheating and recooling.

Figure 12 shows a general trend for increasing CORS with increasing modulus of deformation (2) for the laboratory mixes only at 10-psi lateral pressure. This plot indicates that volumetric strain-axial strain at minimum volume is a measure of strength. A similar plot of modulus of deformation versus CORS of the field mixes was very erratic and was again considered indicative of the effect of asphalt brittleness.

Comparison of the CORS for each individual material and mix type from 10- to 20- to 30-psi lateral pressures shows less variation in value than originally anticipated. At least a partial reason for this behavior is that the range of volumetric strain-axial strain at minimum volume between untreated and treated materials increased with increasing lateral pressure. A similar increase occurred between the 2 AASHO materials, thus tending to provide similar CORS for the various materials of each of the 3 lateral pressures.

It can be reasoned that, as lateral restraint (pressure) is increased to a point of near total confinement, all materials will tend to behave similarly and their individual

Figure 10. Triangular chart for determining CORS at 10-psi lateral pressure.

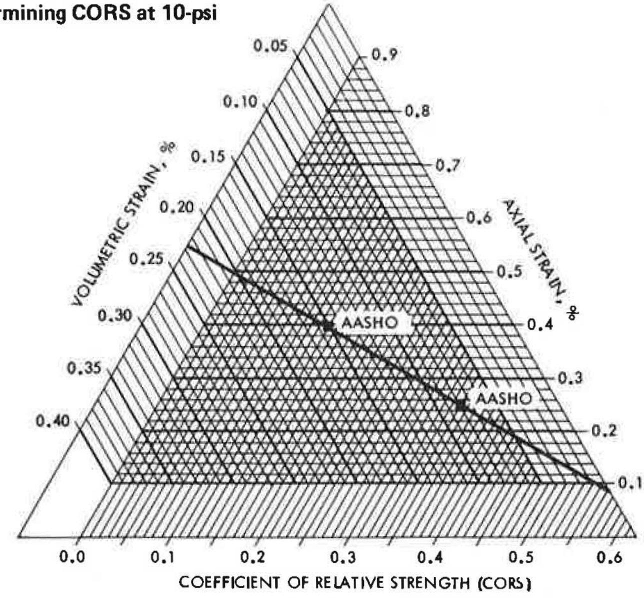


Table 2. CORS based on volumetric strain-axial strain at minimum volume and 10-psi lateral pressure.

Material		Field	Laboratory Mix		
Type	Number	Mix	4 Percent	5 Percent	Untreated
Limestone	429	0	0.22	0.20	0.19
Dolomite	479	0.26	0.33	0.25	0.06
Dolomite-chert	728	0.35	0.39	0.21	ND[b]
Gravel	1241	0	0.34	—[a]	ND
Gravel	1269	0	0.05	—[a]	ND
Gravel-sand	1485	0.21	0.34	0.38	0.16
Limestone	1676	0.32	0.25	0.27	0.16
Limestone	1677	0.07	0.21	0.54	ND
Limestone	1743	0.10	0.33	0.23	ND
Limestone	1746	0.19	0.17	0.31	ND
Limestone-dolomite	1750	0.09	0.09	—[a]	ND
	1751	0	—[a]	0.19	ND
Dolomite-chert	1788	0.45	0.45	0.36	ND
Dolomite	1822	0.34	0.17	0.45	ND
Limestone	1846	0.26	0.38	0.37	0.25
Dolomite-chert	1855	0.48	0.25	0.35	0.19
Gravel	1903	0.38	—[a]	0.28	ND
	1904	0.15	0.35	—[a]	0.27
Limestone	2318	0.22	0.47	0.34	ND
Limestone	2514	0.07	—[a]	0.24	ND
	2515	0.20	0.22	—[a]	ND

[a]Not recommended for testing by ISHC. [b]Not determined.

Table 3. CORS based on volumetric strain-axial strain at minimum volume and 20-psi lateral pressure.

Material		Field	Laboratory Mix		
Type	Number	Mix	4 Percent	5 Percent	Untreated
Limestone	429	0.04	0	0.32	0.14
Dolomite	479	0.24	0.35	0.34	0
Dolomite-chert	728	0.47	0.25	0.35	ND[b]
Gravel	1241	0.09	0.32	—[a]	ND
Gravel	1269	0	0	—[a]	ND
Gravel-sand	1485	0.46	0.36	0.21	0.18
Limestone	1676	0.24	0.35	0.38	0
Limestone	1677	0.25	0.13	0.10	ND
Limestone	1743	0.22	0.34	0.21	ND
Limestone	1746	0.33	0.16	0.14	ND
Limestone-dolomite	1750	0.23	0.12	—[a]	ND
	1751	0.08	—	0.23	ND
Dolomite-chert	1788	0.45	0.43	0.27	ND
Dolomite	1822	0.17	0.18	0.35	ND
Limestone	1846	0.27	0.28	0.31	0
Dolomite-chert	1855	0.37	0.35	0.40	0.16
Gravel	1903	0.20	—[a]	0.45	ND
	1904	0.37	0.35	—[a]	0.21
Limestone	2318	0.45	0.45	0.26	ND
Limestone	2514	0.28	—[a]	0.34	ND
	2515	0.16	0.24	—[a]	ND

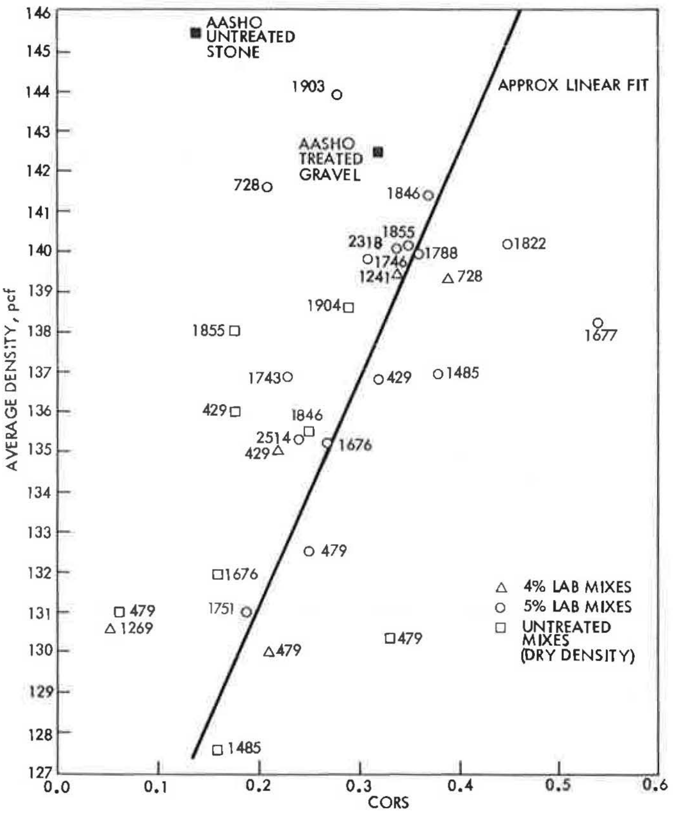
[a]Not recommended for testing by ISHC. [b]Not determined.

Table 4. CORS based on volumetric strain-axial strain at minimum volume and 30-psi lateral pressure.

Material		Field	Laboratory Mix		
Type	Number	Mix	4 Percent	5 Percent	Untreated
Limestone	429	0.15	0.22	0.28	0.15
Dolomite	479	0.34	0.29	0.37	0.12
Dolomite-chert	728	0.31	0.34	0.47	ND[b]
Gravel	1241	0.30	0.29	—[a]	ND
Gravel	1269	0	0	—[a]	ND
Gravel-sand	1485	0.36	0.33	0.36	0.28
Limestone	1676	0.26	0.31	0.37	0.12
Limestone	1677	0.18	0.06	ND	ND
Limestone	1743	0.29	0.32	0.07	ND
Limestone	1746	0.28	0.26	0.29	ND
Limestone-dolomite	1750	0.22	0	—[a]	ND
	1751	0.22	—[a]	0.06	ND
Dolomite-chert	1788	0.25	0.34	0.31	ND
Dolomite	1822	0.32	0.25	0.31	ND
Limestone	1846	0.29	0.37	0.32	0.22
Dolomite-chert	1855	0.36	0.37	0.37	0.31
Gravel	1903	0.25	—[a]	0.29	ND
	1904	0.33	0.33	—[a]	0.30
Limestone	2318	0.35	0.33	0.34	ND
Limestone	2514	0.29	—[a]	0.29	ND
	2515	0.25	0.28	—[a]	ND

[a]Not recommended for testing by ISHC. [b]Not determined.

Figure 11. Density versus CORS based on volumetric strain-axial strain at minimum volume and 10-psi lateral pressure.



properties will have much less effect than at low lateral pressures. Such reasoning substantiates the use of volumetric strain-axial strain as a means of flexible pavement materials evaluation. However, the variation of CORS with lateral pressure indicates that a knowledge of the lateral pressures that would exist in the field under design loads must be known for the CORS to be valid. Currently there are very few data available that indicate what lateral pressures are developed in flexible pavement structures. A very rough approximation using a Boussinesq solution, assuming Poisson's ratio as 0.5, a 100-psi point load, a 6-in. depth, and offset distance of 1 ft, yielded about 13 psi. It must be recognized that none of the assumptions underlying the Boussinesq solution is met in flexible pavement structures and that Poisson's ratio is not 0.5 for soils. A decrease of Poisson's ratio, however, decreases calculated lateral stresses. Fish and Hoover (2) indicated that Poisson's ratio for the treated materials at minimum volume was about ±0.40. The untreated materials in this study had a Poisson's ratio of about ±0.30. It is, therefore, likely that the lateral stress developed would be less than the very approximate figure of 13 psi calculated above. From the previous discussion it appears that the most applicable values of CORS would be those obtained at 10-psi lateral pressure.

Variations in CORS within a particular material may occur because of individual test variations and the recording of test data at set increments of strain and may lead to some minor inconsistencies in the CORS determined for a material. Readings in the minimum volume portion of the triaxial test were taken at intervals of 0.010-in. deflection. For an 8-in. specimen height, 0.010 in. between readings is about 1 percent axial strain. Volume change readings were recordable to 0.01 in. of variation in water level in a 1-in. diameter tube. For a sample volume of 100 in.^{3}, a movement of 0.01 in. in the volume change tube is about 0.01 percent volumetric strain. Volumetric strain, therefore, changed more slowly than axial strain in this portion of the test, increasing the importance for precise determination of axial strain at which minimum volume occurs. It would be desirable in future studies to obtain continuous monitoring of volume change and axial deflection in order to firmly fix the point of minimum volume more accurately.

The concept presented in the preceding paragraph can be noted in the volumetric strain-axial strain data shown in Figures 5 through 8. Many points on the plots appear to be grouped vertically. This results from the test data being taken at set intervals of axial deflection during the shear phase of the test. Continuous and even more precise recording of test data would tend to separate the vertical nature of the plot and result in greater precision of pinpointing a CORS value in the laboratory when the techniques described in this report are used.

It should be reemphasized that the values of CORS obtained in this study are based on a very limited number of tests of the AASHO control materials. The quantity of material available was extremely limited. Four tests were run on each AASHO material at 10-, 20-, 30-, and 40-psi lateral pressure. This resulted in the CORS at each lateral pressure being determined on the basis of 2 points (Fig. 10), one for the AASHO untreated and one for the AASHO treated materials.

CORS Based on Other Variables

As previously indicated, the highest degree of correlation of data was obtained between volumetric strain and axial strain at minimum volume. For comparative purposes only, CORS were developed for other variables at minimum volume conditions by using data showing lesser degrees of correlation than volumetric strain-axial strain. Development and use procedures were somewhat different from those noted with the triangular chart (Fig. 10) because a single variable was plotted against the 2 AASHO-CORS, and the CORS for each material and mix type were thus determined on the basis of that single variable. CORS were determined for the individual variables of volumetric strain, axial strain, modulus of deformation, effective stress ratio, and average modulus of deformation, each at 10-psi lateral pressure and minimum volume.

Reasonably good comparisons of single variable CORS based on the volumetric strain ($\Delta V/V$) and axial strain ϵ at minimum volume were noted with those given in Table 2. Such comparisons indicate the potential of a simplified triaxial technique for determination of CORS using 10-psi lateral pressure and calculating only the precise axial strain at the precise, but continuously monitored, point of minimum volume.

CORS determined by using the modulus of deformation (2) at 10-psi lateral pressure varied widely within each mix type and material as well as among the various materials. The average modulus of deformation (2) CORS were not consistent with those determined by using the modulus at 10 psi and still varied widely within a material for the different mix types although the variability among materials was considerably less.

CORS determined for 10-psi lateral pressure by using the value of effective stress ratio at minimum volume indicated relatively high variability within a material for different mix types as well as among materials. A number of the field mix CORS were high, which may be a reflection of the brittleness of the reheated and recooled mixes when analyzed on a strength basis. It was generally concluded that CORS developed on the basis of a strength parameter alone did not appear valid.

Maximum Effective Stress Ratio Criteria

Specimen conditions at maximum effective stress ratio may not be as indicative of actual field conditions as those at minimum volume. Ferguson and Hoover (3) concluded that stresses at the condition of minimum volume in a triaxial shear test may be more closely related to actual field conditions than the stresses at maximum effective stress ratio. This conclusion appears especially valid in view of the relatively high value of Poisson's ratio (±0.4) for the bituminous-treated materials (2). Loading past the point of minimum volume results in a volume increase and consequently increased lateral strain. Under field conditions this increase of lateral strain would result in increased lateral pressure from adjacent material. In the triaxial test, lateral pressure remains constant, and therefore specimen conditions past the point of minimum volume might not be indicative of actual field response (4).

CORS Based on Effective Stress Ratio-Cohesion

A study of the correlation matrices developed for each mix type indicated that the only variables that had reasonably consistent correlations (between mix types) were effective stress ratio and cohesion (ESR-C). Correlations were consistent among mix types for the 10-psi tests but dropped considerably within a mix type with increasing lateral pressure. Any CORS that were to be developed on the basis of the effective stress ratio-cohesion variables would thus be highly dependent on existing lateral pressures.

Although the AASHO materials fit into the correlations at minimum volume criteria, they do not fit into the maximum effective stress ratio criteria. Instead of falling on the ESR-C regression lines, the AASHO materials lay well above the same. The densities of the AASHO treated and untreated specimens were higher than those of the Iowa materials. This is probably due, in part, to the very tight gradation control on the AASHO materials. It is believed that this density difference is the cause of the AASHO control points lying above the ESR-C regression. It was previously shown that the CORS determined on the basis of volumetric strain-axial strain were partially a function of density, i.e., in general as density increased CORS increased. The AASHO materials volumetric strain-axial strain values of minimum volume, however, compared favorably with their respective laboratory and field mixes. This indicates that, although volumetric strain-axial strain data are somewhat dependent on density, these data are nearly as sensitive to density changes as the strength criteria of ESR-C.

CORS were determined on ESR-C basis by using a triangular chart similar to that used for volumetric strain-axial strain at minimum volume. Table 5 gives the CORS thus determined at 10-psi lateral pressure (CORS shown as 0 were actually negative values). Field mixes are not included because of the high variability of the cohesion term. The extreme range of cohesion in the field mixes is probably the result of hardening of the asphalt and length of time prior to reheating for production of test specimens.

In general, there is only limited variation in CORS between materials and mix types (Table 5). Materials 1485 and 1846 indicate no basic change of CORS from untreated to either 4 or 5 percent asphalt treated. Material 1676 indicates a higher value of CORS for the untreated than either treated mix, a rather unrealistic situation. CORS

Figure 12. Modulus of deformation versus CORS based on volumetric strain-axial strain at minimum volume and 10-psi lateral pressure.

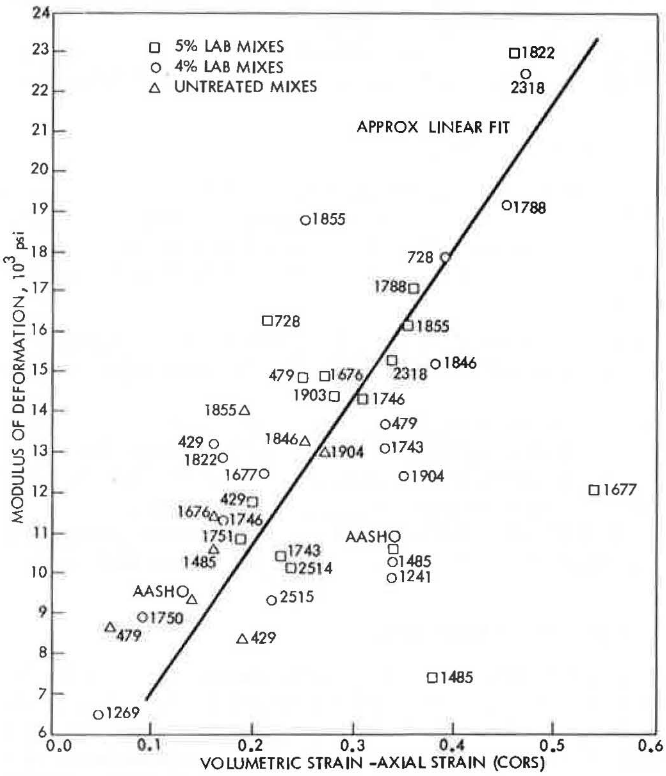


Table 5. CORS based on effective stress ratio-cohesion at maximum effective stress ratio criteria and 10-psi lateral pressure.

Material		Laboratory Mix		
Type	Number	4 Percent	5 Percent	Untreated
Limestone	429	0.29	0.23	0.18
Dolomite	479	0.25	0.16	9.24
Dolomite-chert	728	0.17	0	ND[b]
Gravel	1241	0.26	—[a]	ND
Gravel	1269	0.30	—[a]	ND
Gravel-sand	1485	0.37	0.39	0.32
Limestone	1676	0.05	0	0.16
Limestone	1677	0.22	0.20	ND[b]
Limestone	1743	0.26	0.31	ND
Limestone	1746	0.27	0.03	ND
Limestone-dolomite	1750	0.29	—[a]	ND
	1751	—[a]	0.23	ND
Dolomite-chert	1788	0.24	0.13	ND
Dolomite	1822	ND[b]	0	ND
Limestone	1846	0.25	0.23	0.24
Dolomite-chert	1855	0	0.14	0.07
Gravel	1903	—[a]	0.25	ND[b]
	1904	0.20	—[a]	0.14
Limestone	2318	0.13	0.17	ND[b]
Limestone	2514	—[a]	0.25	ND
	2515	0.29	—[a]	ND

[a]Not recommended for testing by ISHC. [b]Not determined.

for material 1855 ranged from 0.07 to a negative value to 0.14 for the untreated 4 and 5 percent laboratory mixes respectively. The 3 pairs of laboratory mixes, each using the same aggregate source—i. e., mixes 1750-1751, 1903-1904, and 2514-2515—show little variation between asphalt content or aggregate source.

As a consequence of the observations given above, CORS determined on the effective stress ratio-cohesion basis at MESR criteria do not appear valid for use in thickness design.

CONCLUSIONS

Coefficients of relative strength determined in this laboratory study are based on a very limited number of control values established from the AASHO materials and should be viewed with this in mind. The validity of the CORS determined can be fully ascertained only after extensive analysis of the pavement field performance where each material and mix type have been used.

1. Volumetric strain-axial strain relations appear to be appropriate evaluation parameters for determining coefficients of relative strength at minimum volume failure criteria.
2. Coefficients of relative strength determined on the basis of volumetric strain-axial strain tend to vary slightly with lateral pressure, all treated materials tending toward similar values of CORS as lateral pressure is increased. CORS determined at 10-psi lateral pressure are probably more indicative of actual field conditions.
3. Coefficients of relative strength determined on the basis of effective stress ratio-cohesion, at maximum effective stress ratio criteria, do not appear valid for use in thickness design.

ACKNOWLEDGMENTS

Sincere appreciation is extended to the sponsoring organizations—Iowa Highway Research Board, Iowa State Highway Commission, and Federal Highway Administration—and to S. E. Roberts and Bernard Ortgies, Iowa State Highway Commission, for their assistance and counseling. In addition, a special thanks is extended to personnel of the Engineering Research Institute, Iowa State University, for their untiring and valuable contributions to the research involved in this paper and the total project (10).

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