X

ENGINEERING RESEARCH INSTITUTE
Iowa State University
Ames, Iowa

Effect of Portland Cement Treatment of Crushed Stone Base Materials as Observed from Triaxial Shear Tests

by

E. G. Ferguson, Instructor
Department of Civil Engineering

and

J. M. Hoover, Associate Professor
Department of Civil Engineering

December 1967

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the Iowa State Highway Commission nor the Bureau of Public Roads, U.S. Department of Commerce, sponsors of this project.

NOT RELEASED FOR PUBLICATION
SUBJECT TO CHANGE BEFORE PUBLICATION BY
HIGHWAY RESEARCH BOARD

EFFECT OF PORTLAND CEMENT TREATMENT OF CRUSHED STONE BASE MATERIALS AS OBSERVED FROM TRIAXIAL SHEAR TESTS

by

E. G. Ferguson and J. M. Hoover
Iowa State University

ABSTRACT

The objective of this study was to observe and evaluate a number of factors affecting the overall stability of three crushed limestones when treated with small amounts of type I Portland cement. Consolidated-undrained triaxial shear with pore pressure and volume change was the primary test method utilized in the study.

It was observed that use of shear strength only, or the shear parameters of cohesion and friction only, may not be fully adequate criteria for determination of stability of cement treated granular materials. Instead, it might be suggested that overall stability be evaluated in terms of shear strength, stress-strain stress-volume change and pore pressure relationships as determined at a failure condition of minimum volume change (maximum volume decrease during triaxial testing).

Up to three percent cement treatment, by dry weight produced the following observations:

1. Varying values of the shear parameters, c' and Ø', with increasing cement content with manner of variations differing for each of the materials tested.
2. Reduced pore water pressure to insignificant quantities.
3. Reduced magnitude of vertical strain required to achieve ultimate strength as compared with the untreated materials. Magnitude of vertical strain appeared relatively independent of confining pressures but decreased with increasing cement content and cure period.

4. Analysis of volume change as related to stress-strain characteristics at a failure condition of maximum volume decrease may more fully explain the behavior of untreated and treated granular materials under actual field conditions. It is suggested that stability must also be a function of the lateral restraining support that can be developed within a granular material and the amount of expansion required to achieve this support. Addition of cement to the three crushed stone materials reduced the amount of lateral strain developed up to the point of minimum volume failure criteria, resulting in a potential Poisson's ratio of near zero.

INTRODUCTION

The objective of this study was to observe and evaluate a number of factors affecting the overall stability of three crushed limestones when treated with small amounts of type I Portland cement. Consolidated-undrained triaxial shear with pore pressure and volume change was the primary test method utilized in the study.

It was observed that use of shear strength only or the shear parameters of cohesion and friction only, may not be fully adequate criteria for determination of stability of cement treated granular materials. Instead, it might be suggested that overall stability be evaluated in terms of shear strength, stress-strain, stress-volume change and pore pressure relationships as determined at a failure condition of minimum volume change (maximum volume decrease during triaxial testing).

METHOD OF INVESTIGATION

Cement contents were set at 0, 1 and 3 percent by dry weight (generally less than acceptable for freeze-thaw durability criteria). Previous laboratory investigations in this range of cement content for use with crushed limestone are quite limited. Field tests have shown that cement-modified crushed limestone performs satisfactorily, resulting in a general improvement of the frictional properties from that of the untreated material (1).

For each of the three materials, a series of six specimens were tested with 1 and 3% cement following 7 and 28 day curing. Specimens in each series were tested at lateral pressures of 10, 20, 30, 40, 60, and 80 psi. A duplicate series of tests were also performed on the untreated materials. Specimens were compacted by vibration in a four-inch diameter by eight-inch high cylindrical mold attached to a

Syntron Electric Vibrator table. The material was placed in the mold in four equal layers and rodded 25 times per layer with a 3/4 inch diameter, rounded tip rod. A constant frequency of 3600 cycles/min. and amplitude of 0.368 mm were used with a surcharge weight of 35 lb for a period of two minutes. Previous work has shown that this method of compaction is capable of achieving standard AASHO density with a minimum amount of degradation and segregation of the specimen. Specimens were sealed and cured for the required periods in an atmosphere of about 75°F and near 100% relative humidity.

The consolidated-undrained triaxial shear test used for this investigation included measurement of positive and negative pore water pressure, and volume change as well as the load conditions. A rate of axial deformation of 0.01 inch/min. was used for all tests, producing a rate of strain of approximately 0.1% per min. Readings of pore pressure, volume change, and axial load were taken at increments of 0.025 inch of axial deformation.

MATERIALS

Each of the three crushed stones selected for this study were considered as representative of Iowa State Highway Commission approved crushed stone for rolled stone bases.

1. A weathered, moderately hard limestone of the Pennsylvania System obtained from near Bedford, Taylor County, Iowa. Hereafter referred to as the Bedford sample. The system outcrops in nearly half of the state. Formations in this system are generally quite soft and contain relatively high amounts of clay. Calcite is the predominate mineral constituent with a small amount of dolomite (calcite/dolomite ratio = 25). Non-HCl acid soluble minerals constitute 10.92% of the whole material and consist almost entirely of micaceous materials with a trace of quartz.
2. A hard limestone obtained from near Gilmore City, Humboldt County, Iowa. Hereafter referred to as the Gilmore sample. This material is from the Mississippian System which outcrops in a rather discontinuous and patchy band across the center of the state. Formations are quite variable but contain ledges of concrete quality rock. Calcite is the predominate mineral with no dolomite present. Only 1.66% of the whole material is non-HCl acid soluble and consisted almost entirely of kaolinite.
3. A hard dolomite (calcite/dolomite ratio = 1.16) obtained from near Garner. Hancock County, Iowa. Hereafter referred to as the Garner sample. From the Devonian System, this material is very uniform and has shown remarkable similarity through several counties. Non-HCl acid soluble minerals constitute 5.70% of the whole material and consist almost entirely of micaceous materials with a trace of quartz.

Having been crushed to Iowa State Highway Commission gradation specifications, the three limestones were tested in the same condition that they were received from the quarry stockpile, i.e., physical and chemical properties were in no way altered upon receipt. Table 1 presents the engineering properties of each of the three materials.

The cement used for this investigation was a Type I Portland cement obtained locally. Prior to the investigation of the shear strength of the Portland cement treated crushed limestones, investigations were conducted on the freeze-thaw durability of the treated materials (5). ASTM brushing loss tests showed that the required cement contents were about 5, 3, and 5% by weight for the Bedford, Garner and Gilmore samples, respectively (Iowa Freeze-Thaw tests indicated required cement contents of 4.5, 1.5, and 3% by weight respectively).

Table 1. Representative engineering properties of crushed stone materials

	Bedford	Garner	Gilmore'
Textural composition, %			
Gravel (2.00 mm)	73.2	61.6	66.8
Sand (2.00-0.074 mm)	12.9	26.0	23.3
Silt (0.074-0.005 mm)	8.4	10.2	5.9
Clay (0.005 mm)	5.5	2.2	4.0
Colloids (0.001 mm)	1.7	1.4	0.9
Atterberg limits, %			
Liquid limit	20.0	Non-plastic	Non-plastic
Plastic limit	18.0		
Plasticity index	2.0		
Standard AASHO-ASTM density			
Optimum moisture content, % dry soil weight	10.8	7.6	9.3
Dry density, pcf.	128.0	140.5	130.8
Modified AASHO-ASTM density			
Optimum moisture content, % dry soil weight	8.0	5.4	5.7
Dry density, pcf.	133.5	147.6	140.8

Specific gravity of minus No. 10 sieve fraction	2.73	2.83	2.76
Textural classification	--Gravelly sandy loam--		
AASHO classification	A-1-b	A-1-a	A-1-a

Table 2 shows the average moisture-density relationships for the three materials at the two cement contents for vibratory compaction and the standard AASHO density of the untreated material. It is readily apparent that there is little variation in density due to the method of compaction or the addition of cement.

Table 2. Moisture-density relationships for the three materials at two cement contents.

	Standard AASHO untreated	Vibratory 1% cement	Vibratory 3% cement
BEDFORD			
Optimum moisture content % dry soil weight	10.9	10.2	9.7
Dry Density, pcf	127.4	127.6	128.3
GARNER			
Optimum moisture content, % dry soil weight	7.6	6.6	5.7
Dry Density, pcf	140.5	138.4	135.1
GILMORE			
Optimum moisture content, % dry soil weight	9.4	9.8	9.0
Dry Density, pcf	130.8	131.0	133.5

ANALYSIS OF RESULTS

Failure Criterion

Shearing strength of a soil, assuming only frictional resistance, is dependent upon the contact pressure between the soil grains. Presence of pore water pressure alters the contact between grains and thus affects the resistance to shearing.

Loading of a granular soil specimen results in an initial volume decrease, after which expansion begins, the latter resulting in a decrease in pore pressure, and a corresponding increase in effective lateral pressure. The increase in the effective lateral pressure results in a gain of axial strength even though failure may have already begun. Holtz (3) states that because of this type of failure, "the maximum principal stress ratio. $\left(\frac{\bar{\sigma}_1 - \bar{\sigma}_3}{\bar{\sigma}_3}\right.$ or $\left.\frac{\bar{\sigma}_1}{\bar{\sigma}_3}\right)$ appears to represent the most critical stress condition of the point of incipient failure under variable effective axial and lateral stresses." With regard to volume change, Holtz (3) made the following statement regarding triaxial shear test of fine sand and sandy clay materials:

> A study of the volume change conditions during the test indicates that specimens consolidate to some minimum volume, after which the volume increases as loading is continued. It is believed that the minimum volume condition or some point near this condition, indicates the condition of incipient failure. That is, the condition at which consolidation ceases and the mass begins to rupture. The maximum pore-pressure condition should occur when the specimen has been consolidated to a minimum volume, because at this point the pore fluid has been compressed to the greatest degree.

Cement treated granular material used for the investigation recorded herein did not follow the above mentioned method of failure. After attaining the point of minimum specimen volume, the effective stress ratio continued to increase and a maximum value was achieved only after expansion had occurred. This may be attributed to the fact that granular materials are capable of developing large resistances to shear through the phenomena of interlocking. Expansion occurs as the particles begin to slide over each other and as sliding just begins, the shear stress and rate of volume expansion reach a maximum value. This indicates that the difference in shear strength at minimum volume, and at maximum effective stress ratio may be an indication of the amount of interlocking within a granular material.

Analysis of results reported herein are based on both maximum effective stress ratio and minimum volume change as primary conditions of failure. Results for both methods are compared with the untreated material and further justification for the minimum volume criteria as a condition of failure is made.

Shear Strength Parameters

Analysis of stress conditions was accomplished through use of a modified Mohr-Coulomb diagram in which $\frac{1}{2}(\overline{\sigma}_1 - \overline{\sigma}_3)$ was plotted against $\frac{1}{2}(\overline{\sigma}_1 + \overline{\sigma}_3)$ at every point measured during testing[a]. The advantage of this method is that the stress conditions are represented by a series of points instead of a circle, enabling more accurate positioning of the failure envelope. The slope of the resulting failure envelope is designated as tan α , where α is the slope angle from horizontal, and the ordinate intercept as y. The modified shear parameters were converted to $\emptyset'$ and c' through use of the following relationships:

$$\sin \emptyset' = \tan\alpha . \qquad c' = \frac{y}{\cos \emptyset'}$$

Plotting the stress conditions to the point of failure represents a stress history of the material, and shows a method of stress build-up.

A least squares method of the Bureau of Reclamation was used for the determination of the shear strength parameters. This is a mathematical process of determining the tangent line in terms of $\emptyset'$ and c' and assumes a straight—line envelope of failure in that all results are on a common failure envelope. Variations in the strength of individual specimens tend to alter the strength parameters determined by this method, whereas with the modified Mohr-Coulomb method, these variations are easily noticed and the results are not as readily affected by specimen variation.

The modified Mohr-Coulomb diagram was thus used for visual analysis and determination of the validity of results, whereas the least squares method was used for the determination of the shear strength parameters only.

Cohesion and angle of internal friction

General Shear strength parameters determined for the various conditions of

---

[a] $\overline{\sigma}_1$ and $\overline{\sigma}_3$ represent the maximum and minimum effective principal stresses, respectively.

cement content, and length of cure are presented in Table 3.

Relationships between cohesion and cement content were not consistent for the three materials indicating the possibility of varying mechanisms of stabilization. The effect of the cement on the three crushed stones can be more clearly shown in Figures 1, 2, 3 and 4. The plots have no special meaning other than showing the relation between ϕ', c', per cent cement, length of cure, and the condition of failure together, instead of attemping to analyze them individually.

As mentioned previously, granular materials tend to exhibit the ability to resist shear through interlocking, and the change in shear resistance from conditions of minimum volume to maximum effective stress ratio may be an indication of the degree of interlocking. The effect of interlocking tends to decrease at higher lateral pressures (6). This can be shown by the fact that the difference between the stress conditions at minimum volume and at maximum effective stress ratio decreases as the lateral pressure increases. This variation in interlocking results in a slight decrease in the friction angle, and an increase in cohesion between conditions of minimum volume and maximum effective stress ratio.

As may be noted from the data, it is difficult to determine the actual effect of the cement on the shear parameters of the materials. Not only are the properties of the materials altered by the cementing action, but also by variations in moisture content, density and gradation, from that of the untreated materials. To determine the effect of the bonding action of the cement it would first be necessary to determine the properties of the cement treated materials at a time of zero cure. Since this was not practical, an attempt was made to determine the changes in shear strength between cure periods of 7 and 28 days for each of the cement contents. Assuming that for a given material and cement content, the specimens are identical initially, the change in shear properties between 7 and 28 days should be due primarily to the increase in strength of the cement bonds.

Table 3. Shear strength parameters determined by least squares method.

Material and treatment	Failure criteria			
	Maximum effective stress ratio		Minimum volume	
	Ø' degrees	c' , psi	Ø', degrees	c', psi
Bedford crushed stone:				
Untreated	45.7	6.7	46.2	4.2
1% cement 7-day cure	47.0	24.2	47.9	15.9
1% cement 28-day cure	44.6	42.5	45.5	29.6
3% cement 7-day cure	47.0	67.0	47.7	56.6
3% cement 28-day cure	45.3	78.7	46.0	70.5
Garner crushed stone:				
Untreated	49.2	14.2	49.5	5.6
1% cement 7-day cure	54.6	21.6	53.1	9.2
1% cement 28-day cure	49.0	41.2	46.3	30.4
3% cement 7-day cure	50.1	90.5	50.6	64.6
3% cement 28-day cure	51.0	96.2	51.2	87.9
Gilmore crushed stone:				
Untreated	45.1	17.1	45.5	8.9
1% cement 7-day cure	50.6	18.1	51.8	0.8
1% cement 28-day cure	51.2	18.2	51.5	3.2
3% cement 7-day cure	48.6	57.4	49.0	43.8
3% cement 28-day cure	50.6	64.0	51.1	52.3

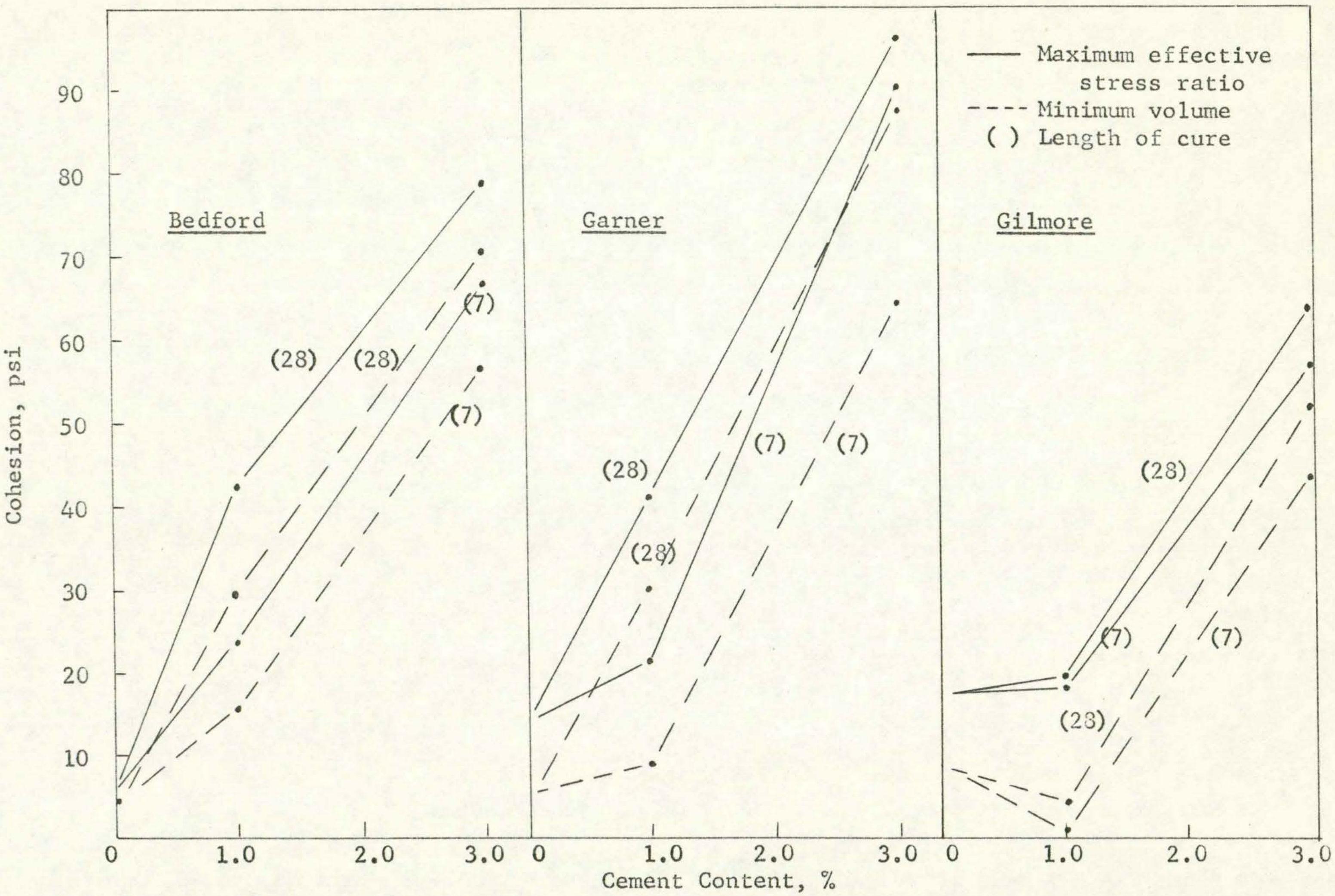

Figure 1 Cohesion-cement content relationship for the three crushed stones at maximum effective stress ratio and minimum volume criterion of failure

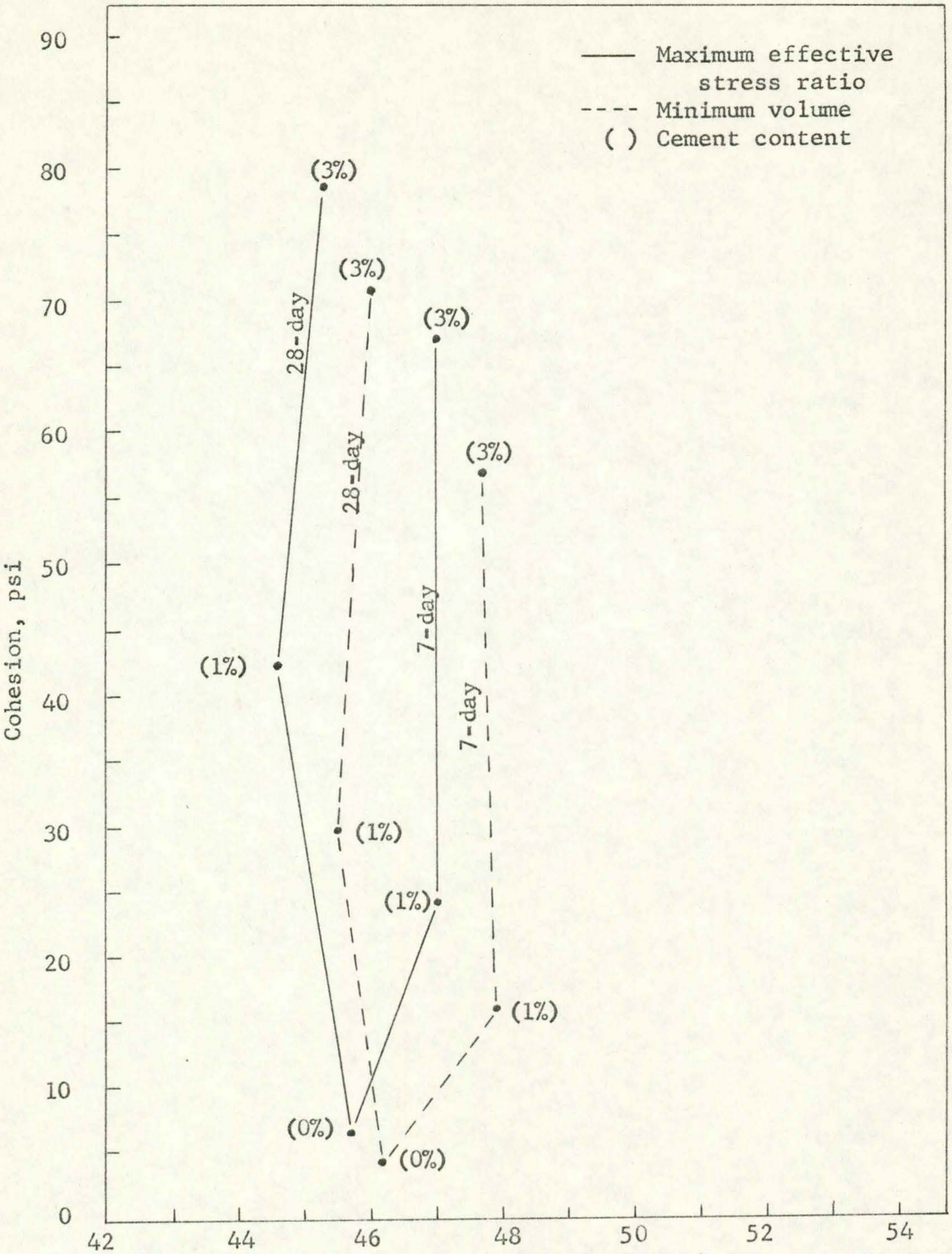

Figure 2 Effect of cement content and length of cure on shear strength parameters for Bedford crushed stone

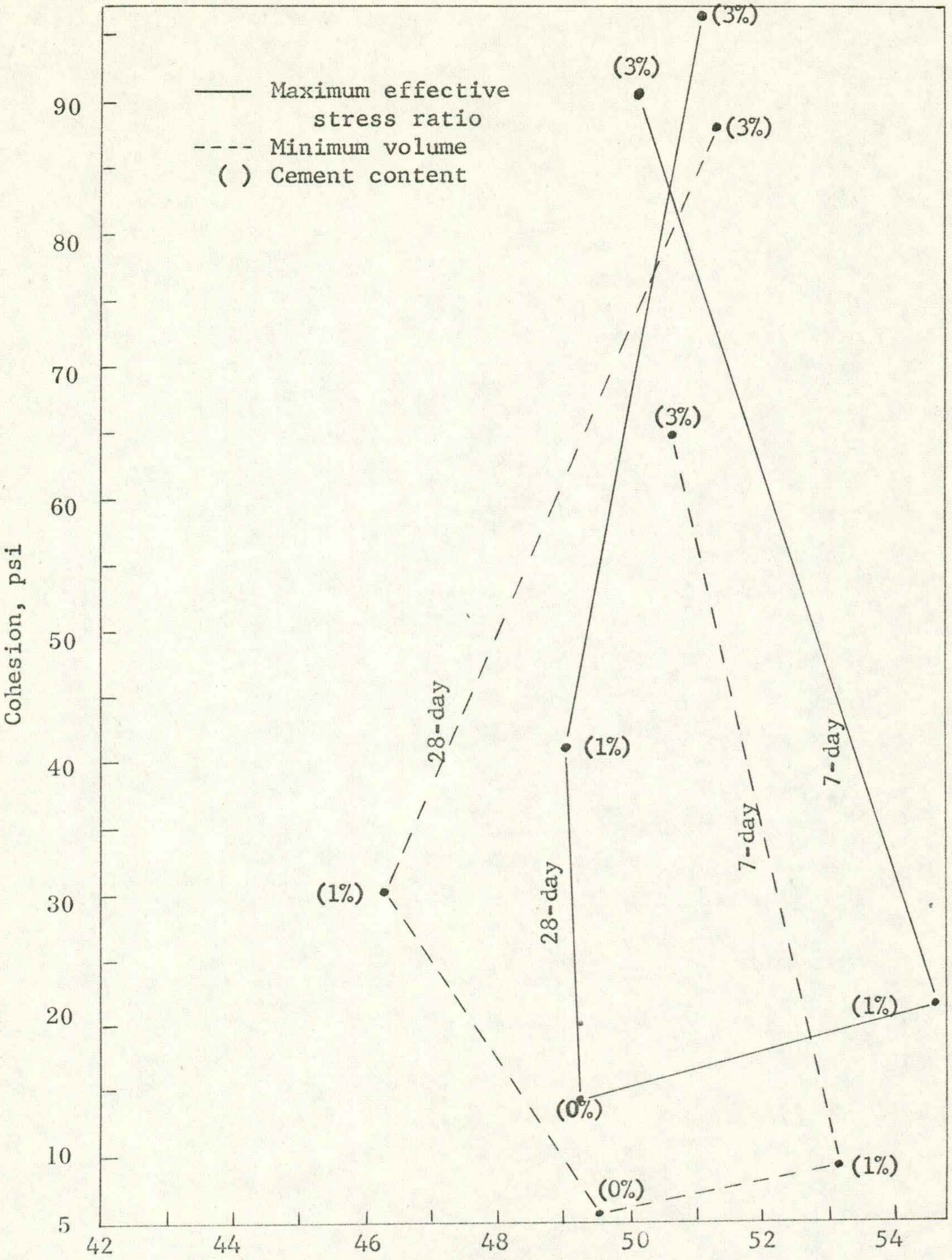

Figure 3 Effect of cement content and length of cure on shear strength parameters for Garner crushed stone

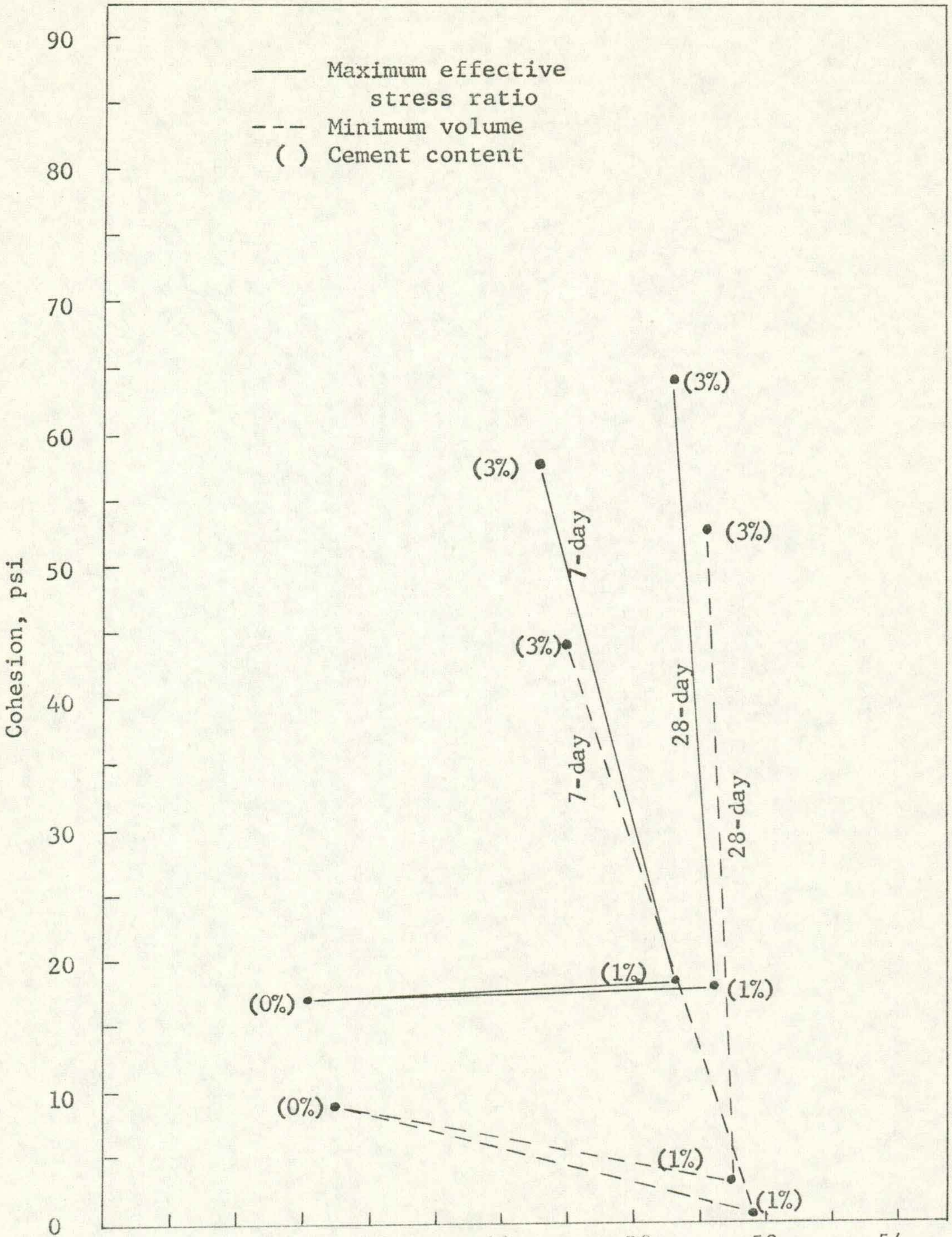

Figure 4 Effect of cement content and length of cure on shear strength parameters for Gilmore crushed stone

Bedford crushed stone The Bedford stone was quite porous, and the texture of the surface was fairly rough, enabling the formation of a strong cement bond between the aggregate and the matrix. The coarse aggregate particles were somewhat rounded in shape, and there was a higher percentage of fines than in the other two materials.

Previous investigations into the effect of cement treatment on granular materials, have shown that cohesion increases with cement content, but that the angle of internal friction undergoes little change. Only the Bedford stone appeared to follow this pattern. At seven day cure, both cement contents showed an increase in cohesion with a small increase in ϕ'. At 28 day cure, the cohesion increased further, but there was a reduction in ϕ' from that obtained with the untreated stone. The results for both conditions of failure followed the same pattern.

The change in stress conditions from minimum volume to maximum effective stress ratio, resulted in an increase in cohesion with a slight decrease in ϕ' for both the cement treated and untreated specimens, Figures 1 and 2. The magnitude of this change appeared to be constant for the varying conditions of cement content and length of cure. Cement tended to increase the interlocking action of the untreated material by bonding the fines. Increasing the strength of these bonds, through increased length of cure or additional cement did not appear to increase the degree of interlocking. As the strength of the cement bond increased from 7 to 28 days there was an increase in cohesion with a reduction in ϕ'.

Garner crushed stone The Garner crushed stone treated with 1% cement at 7 days cure had a large increase in ϕ' and a small increase in cohesion from that of the untreated material, Figures 1 and 3. After 28 days of cure, the cohesion increased and ϕ' reduced to a value lower than the untreated. At a cure period of 7 days, the 3% cement treatment showed a large increase in cohesion with a small increase in ϕ' from that of the untreated, with additional curing resulting in further increases in both cohesion and angle of internal friction.

Visually the coarse aggregate of the Garner material had much the same shape and texture of the Bedford crushed stone. However, the Garner produced much higher densities than either of the other two stones, which is partially indicative of the presence of more points of grain to grain contact as well as a higher true specific gravity. The strength properties of any cement treated material are dependent upon the number of these contact points, as this is where cement bonds may develop. Uniform sand has relatively few points of contact and requires higher cement contents for adequate stabilization. As the gradation of a material becomes more beneficially distributed, the cement content required for adequate stabilization tends to decrease.

Variation in strength between individual specimens appeared to be more pronounced with the Garner crushed stone than was observed for the other two stones. Strength variation was not directly related to variations in density but may have been related to uneven distribution of cement within the specimen or some other form of sample variation. It was evident that the addition of cement had a much greater effect on the shear strength parameters of the Garner than either of the other crushed stones and thus, the variations in individual specimens would be more pronounced.

The change in shear strength between the failure conditions of minimum volume and maximum effective stress ratio for the 1% cement treated Garner did not follow the same pattern as the Bedford and Gilmore materials. Between these points there was an increase in both $\emptyset'$ and c'. The fact that the angle of internal friction increased between these points cannot be explained by the information available.

Addition of 3% cement to the Garner crushed stone tended to increase interlocking as indicated by the high increase in cohesion and slight decrease in $\emptyset'$ from conditions at minimum volume to maximum effective stress ratio. The change in strength properties between 7 and 28 days cure, due to the increase in the strength of the cement bond, resulted in an increase in cohesion and an increase in the angle of internal friction.

Gilmore crushed stone At the point of maximum effective stress ratio there was an increase in $\emptyset'$ and c' for both cement contents at 7 day cure, Figures 1 and 4. From 7 to 28 day cure, cohesion of the 1% cement treated material reduced slightly and had a fairly large increase in Ø', while the 3% material had an increase in both Ø' and c'.

The Gilmore stone is a very hard, angular material having the smallest amount of fines of the three stones, Table 1. Untreated Gilmore specimens had a much greater tendency to collapse, when handled, than specimens of the other two stones, though produced a higher amount of cohesion, Table 3. The larger value of cohesion may be due to the higher degree of interlocking that the material can develop, as is indicated by the increase between the two conditions of failure at 0 and 1% cement contents, Figure 1.

It appears that cement may not function as just a bonding agent at points of contact between the larger Gilmore aggregate and the matrix as it does with the Bedford stone. Instead the cement tended to bond the fines together resulting in a matched or interlocked coarse material that developed strength from the interlocking rather than the bonds between the aggregate. To better illustrate this point, shear strength of a material composed of uniform spheres can be increased through the addition of smaller spheres which tend to fill the voids between the larger spheres and increase the effect of interlocking. The more rigid the material in the voids can be made, the higher the degree of interlocking. The same is true for angular material, however, it is capable of developing a higher degree of interlocking due to particle shape. The Gilmore stone was very angular resulting in very irregular shaped voids. The cement may tend to strengthen the fines present in the voids between the coarse aggregate and create rigid, coarser particles, matching the shape of the voids.

The method of strength increase mentioned above can also be shown by the strength properties of the 1% cement treated Gilmore material at the point of minimum volume, Figure 4. Cohesion was reduced from 8.9 psi for the untreated material, to 0.8 psi and 3.2 psi for the 7 and 28 day cure periods respectively.

The angle of internal friction was increased from 45.5° for the untreated material to 51.8° for the 7-day cure and 51.5° for the 28-day cure.

The degree of interlocking as indicated by the increase in cohesion between minimum volume and maximum effective stress ratio was quite large as shown by the cohesion increase with a small decrease in ϕ', Figure 4.

Addition of 1% cement apparently did not result in bonding of the aggregate but resulted in bonding of the fines, increasing the angle of friction. Additional cement caused no further increase in ϕ' but resulted in higher cohesion.

Pore Pressure

Figure 5 shows the relationship of pore pressure to lateral pressure at both conditions of failure for the untreated materials. Figure 6 illustrates the same relationship for the treated Bedford stone. Similar patterns of pore pressure versus lateral pressure were observed for the treated Garner and Gilmore samples. Irregularities could be attributed to variations in the degree of saturation. The difference between each pair of curves was relatively indicative of the amount of expansion required to develop the stress conditions at maximum effective stress ratio. At the lower lateral pressures, the difference was quite large, but tended to decrease with increasing lateral pressure and could be attributed to the greater amount of initial (consolidating) volume decrease at the higher lateral pressures.

Increase in cement content generally resulted in lowering of pore pressures at minimum volume, and less relative expansion was required to reach the maximum effective stress ratio state. Reduction in pore pressure was much greater for the Bedford than for either the Garner or Gilmore materials. Cement probably reduced the plasticity of the fines in the Bedford and in turn reduced the tendency for pore pressure associated volume decrease.

Strain

Addition of cement to a soil forms a brittle material; that is, the point of ultimate strength occurs within smaller increments of strain than for the untreated material. Increases in cement content normally result in a corresponding decrease in the amount of strain required to reach ultimate strength.

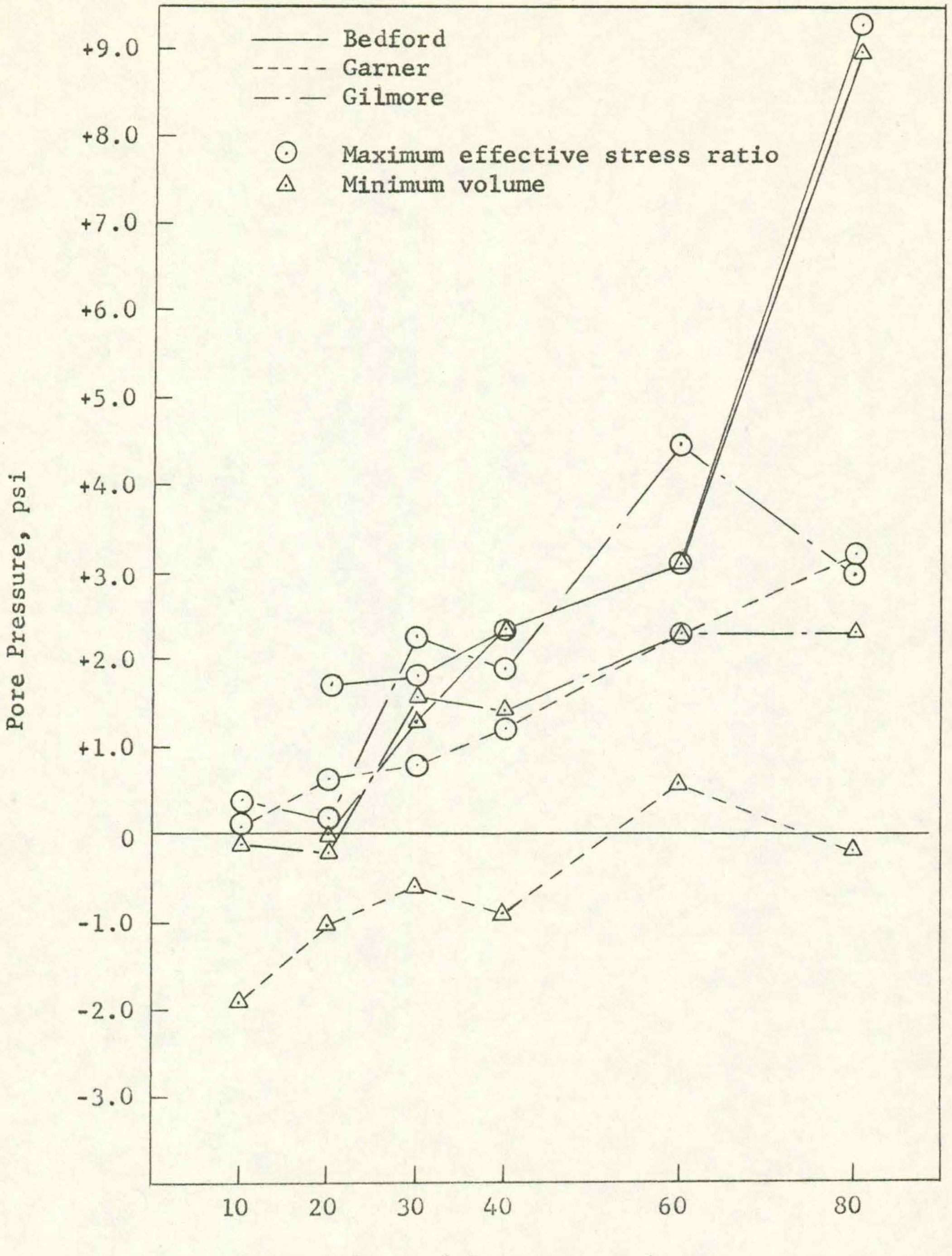

Figure 5 Pore Pressure-lateral pressure relationship for the three untreated crushed stones

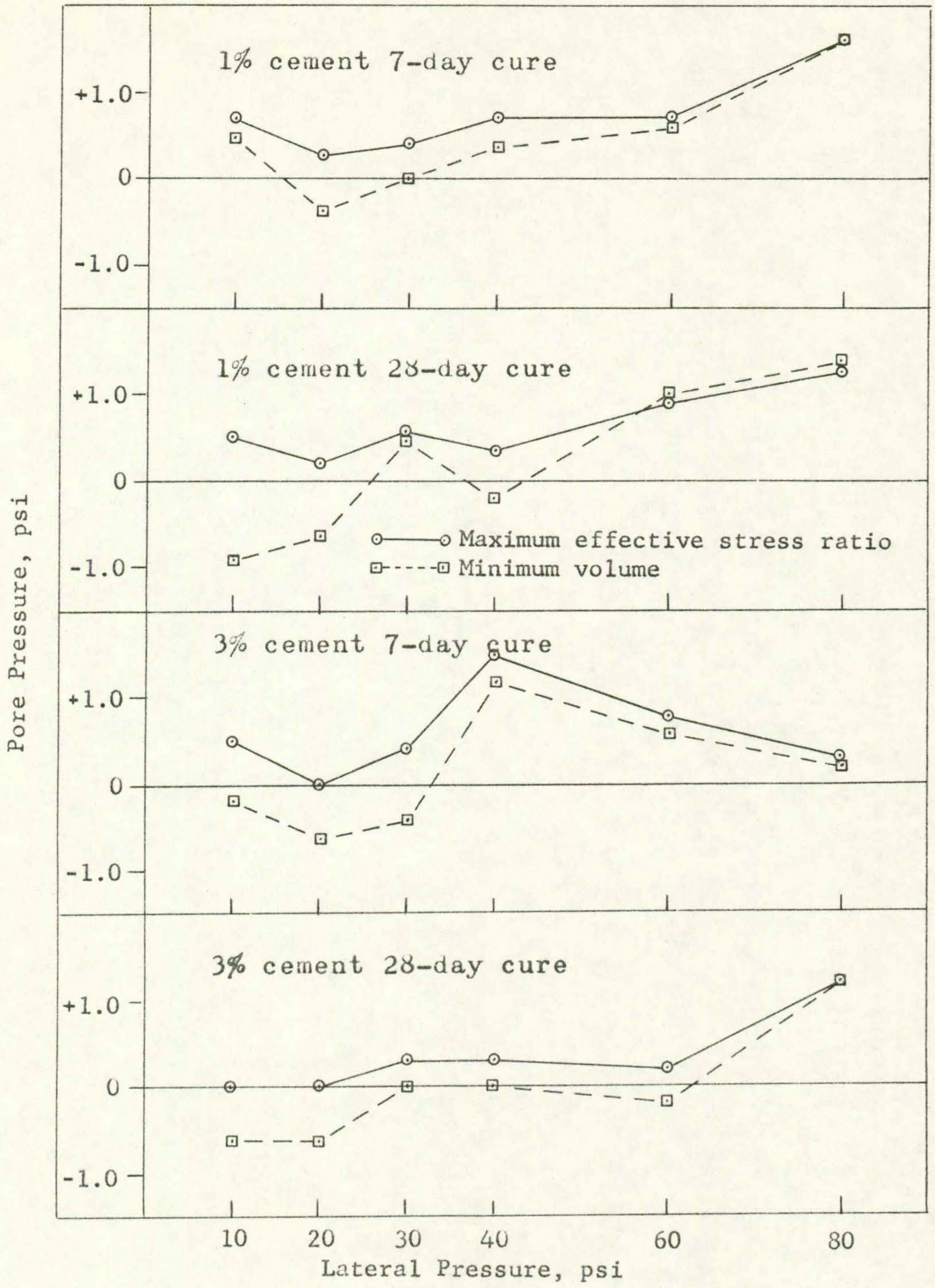

Figure 6 Pore pressure-lateral pressure relationship for the cement treated Bedford crushed stone

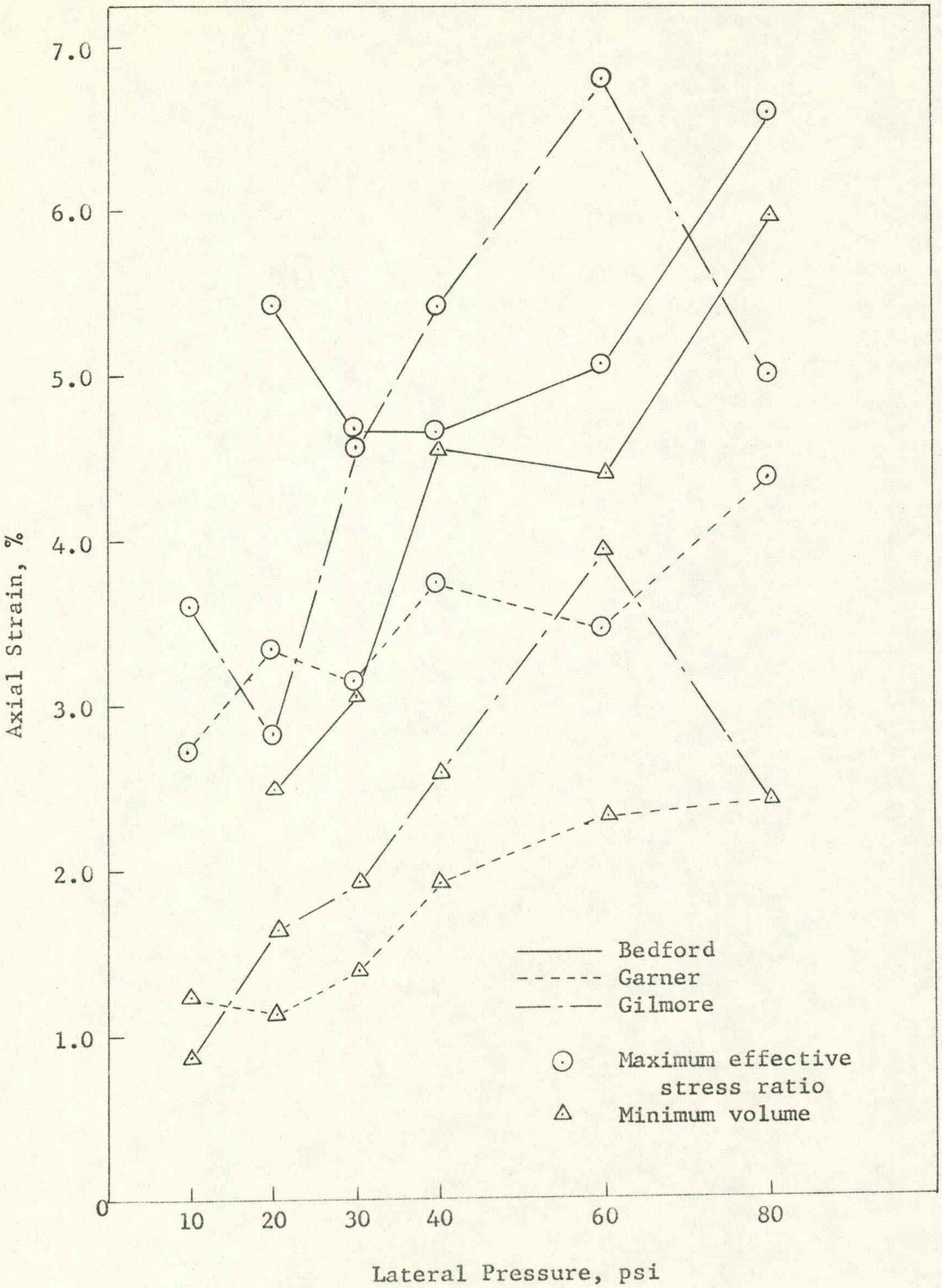

Figure 7 Axial strain-lateral pressure relationship for the three untreated crushed stones

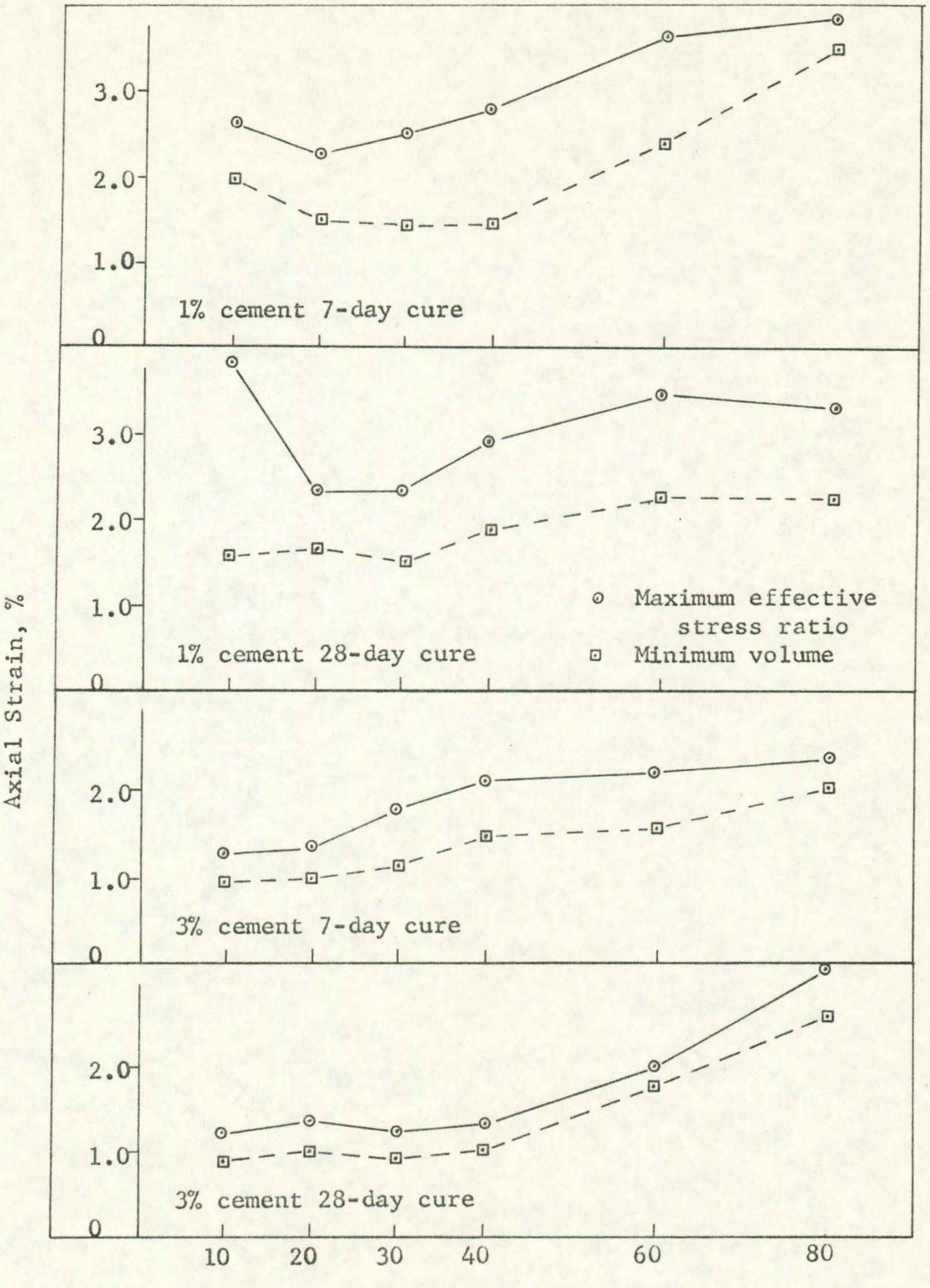

Figure 8 . Axial strain-lateral pressure relationship for the cement treated Bedford crushed stone

Variance of strain between the failure conditions of minimum volume and maximum effective stress ratio was quite pronounced for the untreated materials, Figure 7. Also the amount of strain required to achieve these conditions generally tended to increase with increasing lateral pressure.

Addition of cement to the three stones reduced the amount of strain required to achieve conditions of minimum volume and maximum effective stress ratio as illustrated in Figure 8 for the treated Bedford stone. Similar patterns of strain were observed for the treated Garner and Gilmore stones. Increases in strength through increases in the amount of cement, or length of cure, resulted in a corresponding decrease in strain. The effect of lateral pressure on the strain was not as pronounced for the cement treatments and was more evident for the Garner crushed stone than for the other two materials.

As mentioned previously, between the conditions of minimum volume and maximum effect stress ratio, a specimen begins to expand, which may result in disruption of the cement bond. Thus, as the portion of the strength due to the cementing action within a specimen is increased, because of increased cement content, or curing, there is a corresponding decrease in the amount of strain that can be tolerated between the conditions of minimum volume and maximum effective stress ratio.

Volume Change

Use of two concepts of failure in the preceeding analysis of results, indicates that the commonly acceptable shear strength parameters of c' and Ø', plus pore pressure and strain characteristics, may not be fully suitable as a means of evaluation of the overall stability of granular material. Such criteria of shear strength may result in values that are unique only to the method of testing, and which do not actually occur under field conditions.

Evidence for the above belief is suggested by the relationship between the major principal stress and volume change during axial loading. With application of axial load for a given lateral pressure, the volume of a specimen tends to decrease, occurring almost entirely in the vertical direction. After the specimen reaches a point of minimum volume, and the volume begins to increase with additional increments of strain, the volume increase appears to be entirely in the horizontal direction. During the initial portion of the expansion phase, the major principal stress ratio continues to increase until a point of maximum effective stress ratio is reached. As many investigators have indicated, this expansion is required to overcome interlocking and allow for the formation of a failure plane.

It may be hypothesized that the above mode of failure develops only under conditions of constant lateral pressure such as in a conventional triaxial shear test. Such conditions may not occur in the field since lateral pressures will increase as a result of resistance to expansion of the loaded material until a condition of maximum lateral support is achieved after which the material fails by shearing, as in the triaxial test. Under field conditions the limiting value of lateral pressure may be dependent upon the amount of restraint given by the shoulders and the surcharge adjacent to the point of loading, as well as the materials being utilized.

The preceeding form of stability may be illustrated by the relationship between major principal effective stress and percent volume change, Figure 9. Assume that a low lateral pressure exists in a base course material prior to the application of an axial load. As the load is applied, the base course material will deflect vertically downward, until a point of minimum volume is achieved. After achieving this point, horizontal expansion increases rapidly resulting in increased lateral support and increased bearing capacity. This progressive increase in lateral support will continue until a limiting value of lateral support is achieved. This tends to indicate that the stability of a granular material is not entirely a function of the shear strength, but must also be a function of the lateral support that can be developed, and of the expansion required to develop that lateral support.

Another procedure for the reader to visualize the above illustration is to assume an imaginary line tangential to the curves of Figure 9, beginning at zero volume change and moving up to the left towards about 700 psi effective stress. The points of minimum volume for each lateral pressure condition are close to this line. As the axial load is applied, at a low lateral pressure, the stress increases to the point of minimum volume, lateral expansion starts, confining pressure increases and the process is repeated until a limiting value of confinement (dependent on restraint of shoulder, surcharge, and type of material) is achieved.

It is thus felt that the mode of failure in a base course is by progressive build-up of lateral support by lateral expansion of the loaded material. Prior to lateral expansion, the strength properties may be that of the laboratory tested material, but after lateral expansion occurs, the strength properties of a given core of material are dependent upon the surrounding material.

Initial compression under a small increment of strain has been referred to as elastic compression because the elastic Poisson's ratio is less than one-half (7). As strain increases, expansion predominates, because the plastic Poisson's ratio may be greater than one-half (7). Reaction of the various specimens under load, with respect to volume change and axial strain, is shown in Figures 10 through 15. Initial slope of the curves shown, may be assumed to represent a degree of magnitude of Poisson's ratio. Since Poisson's ratio is defined as the ratio of lateral to vertical strain under axial loads, it can be shown that when lateral strain equals zero, volume change is equal to the axial strain and the material is in a compressed state. Likewise, for a non-compressible material, for which Poisson's ratio is about 0.5, both the lateral and vertical strains are finite quantities and the rate of volume change is near zero.

It may be seen in Figures 10 through 15, that cement treatement of the three granular materials shifts the axial strain-volume change curves closer to the condition of zero lateral strain than with the untreated materials. The failure point of minimum volume is also much closer to this line for the cement treated materials. Thus, the amounts of both lateral and vertical strains developed in a treated

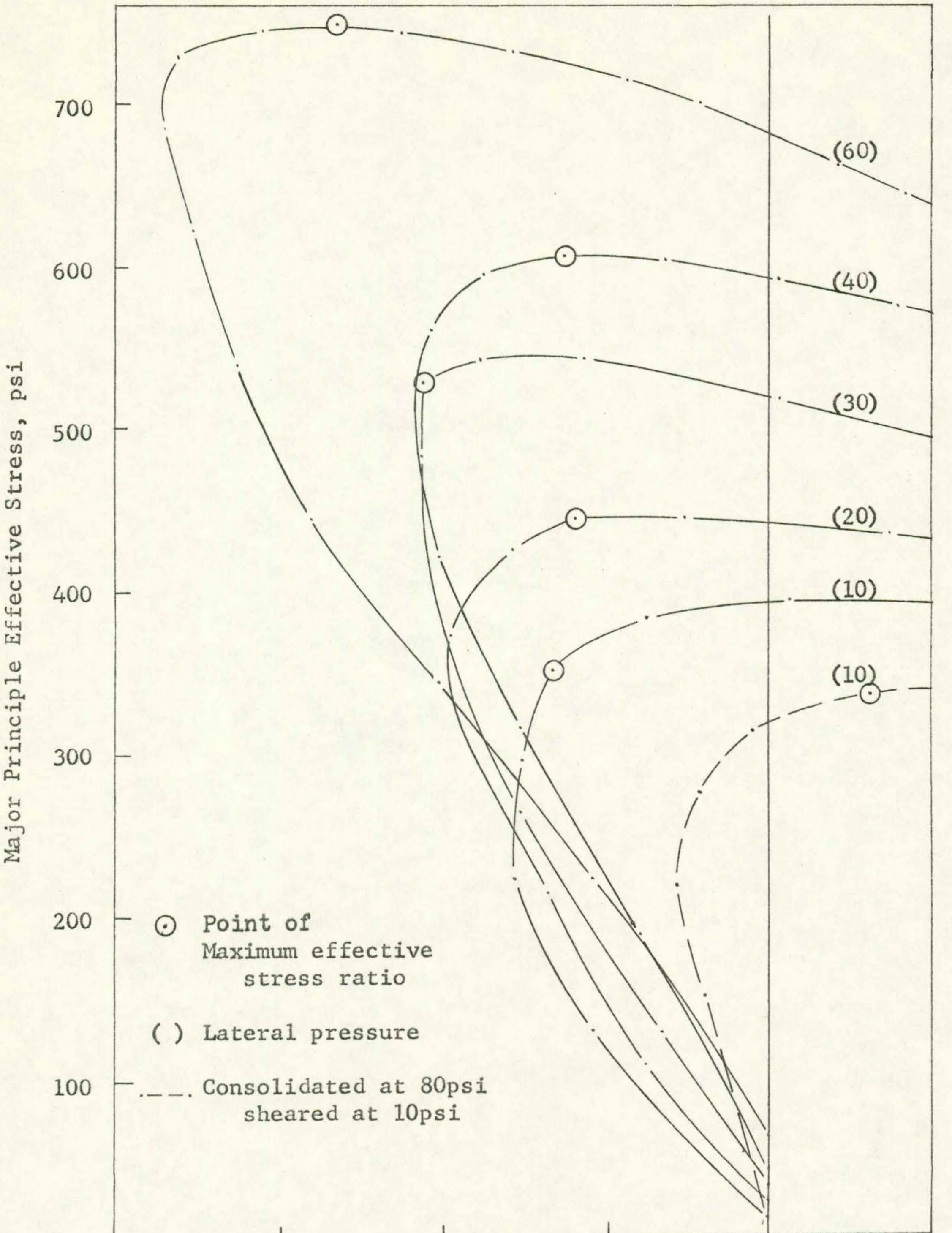

Figure. 9 Major principle effective stress versus volume change for Bedford, 3% cement treatment, 7-day cure

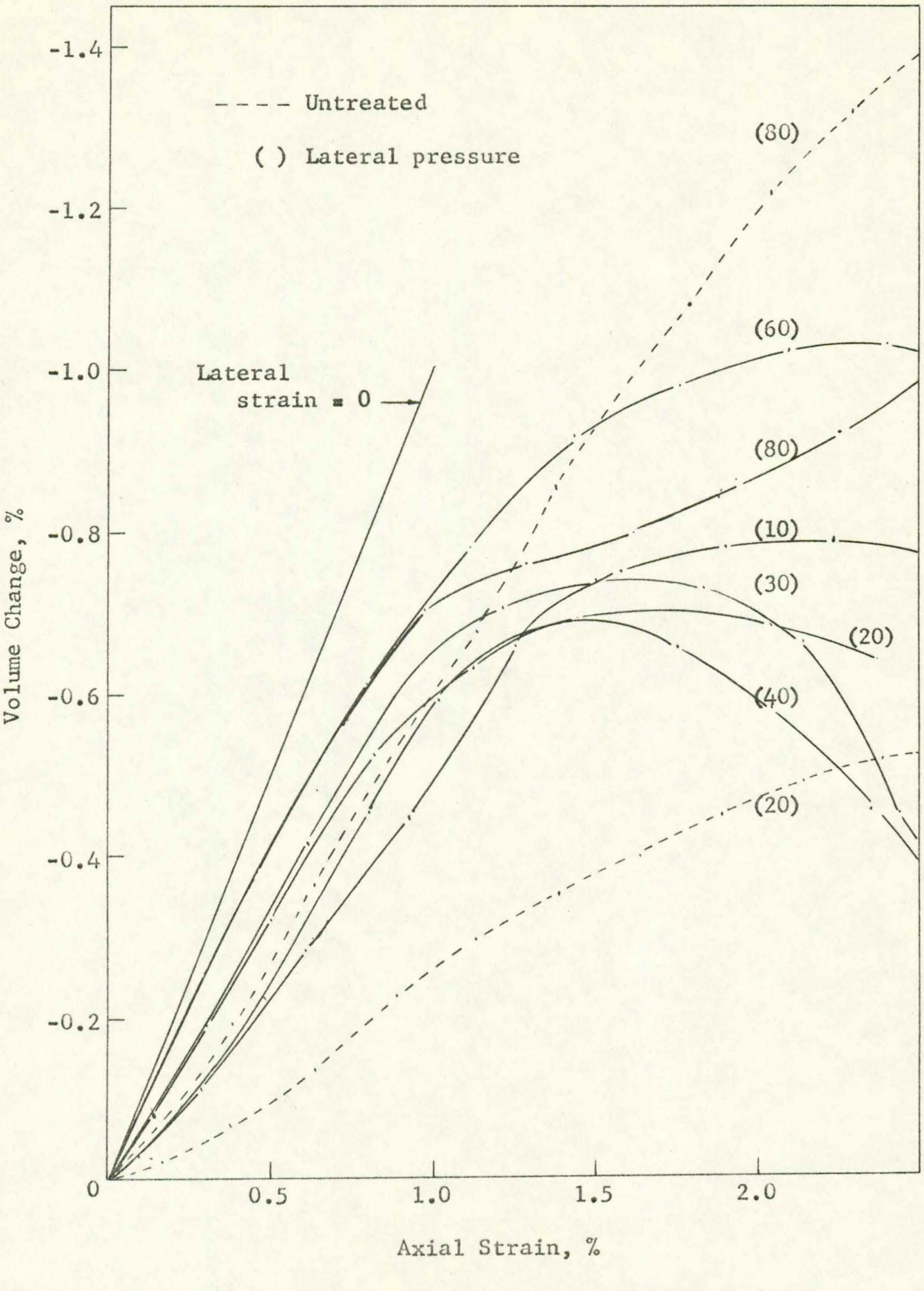

Figure 10 Volume change-axial strain relationship for Bedford, 1% cement treatment, 7-day cure

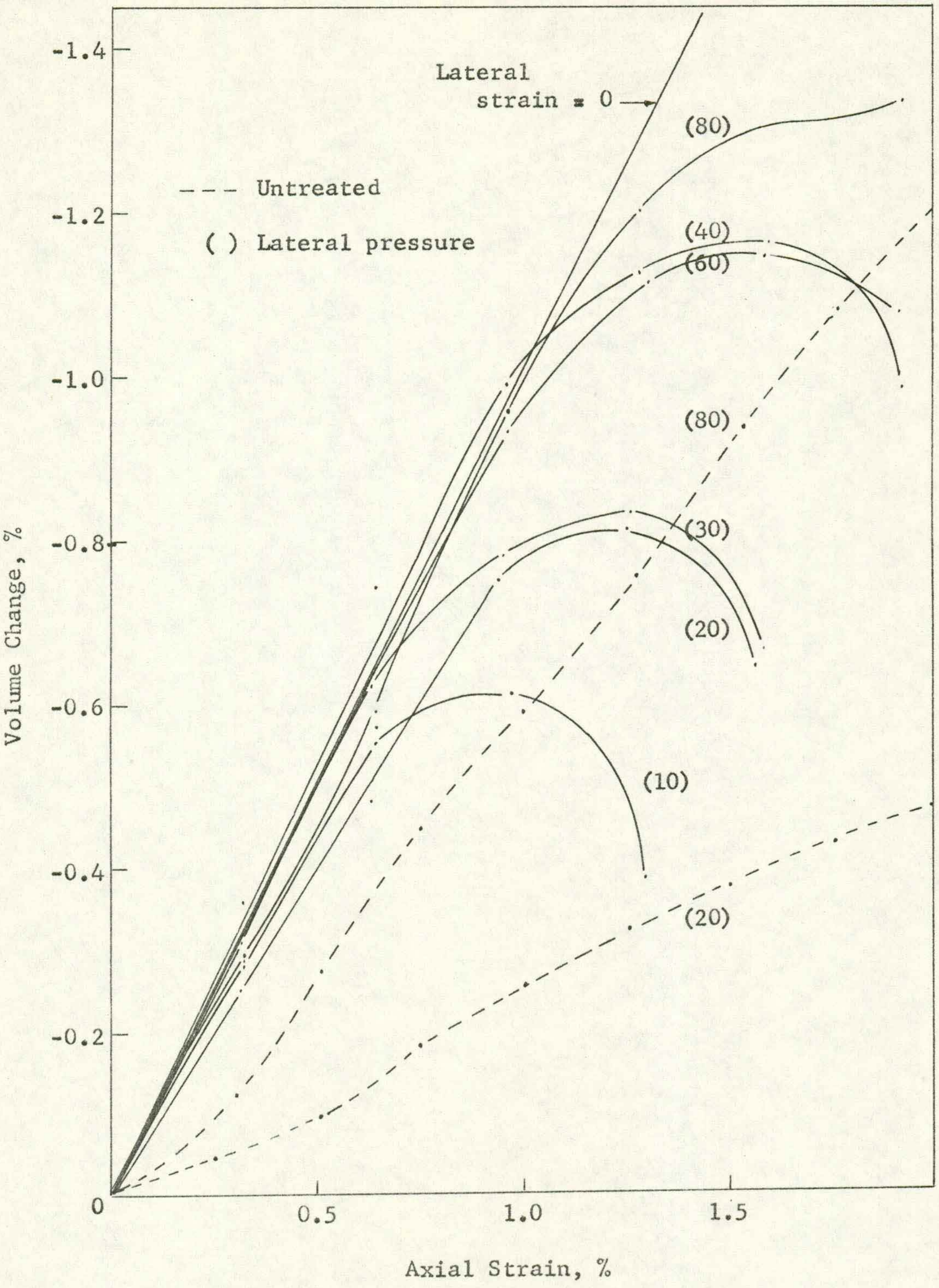

Figure 11 Volume change-axial strain relationship for Bedford, 3% cement treatment, 7-day cure

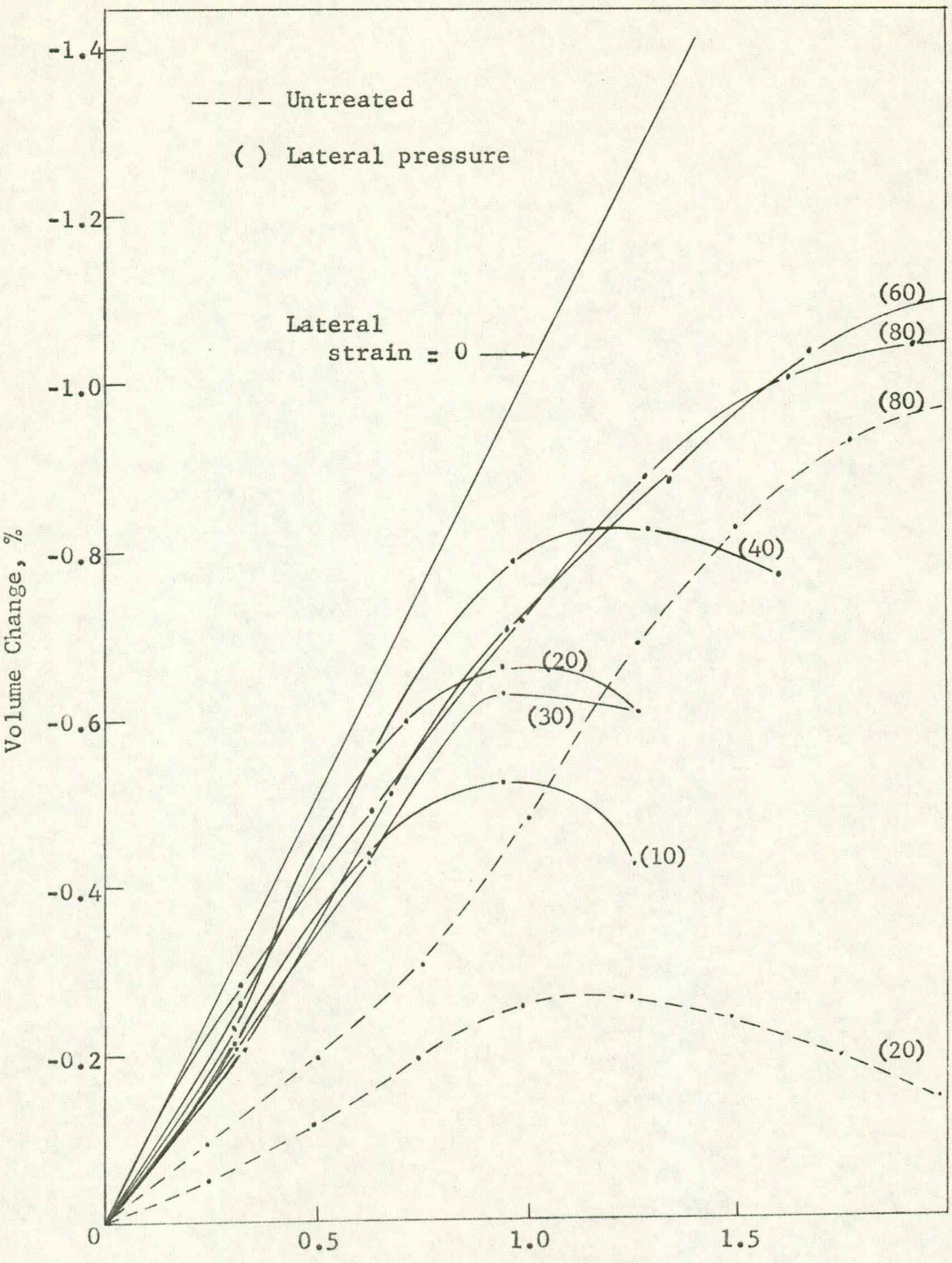

Figure 12 Volume change-axial strain relationship for Garner, 1% cement treatment, 7-day cure

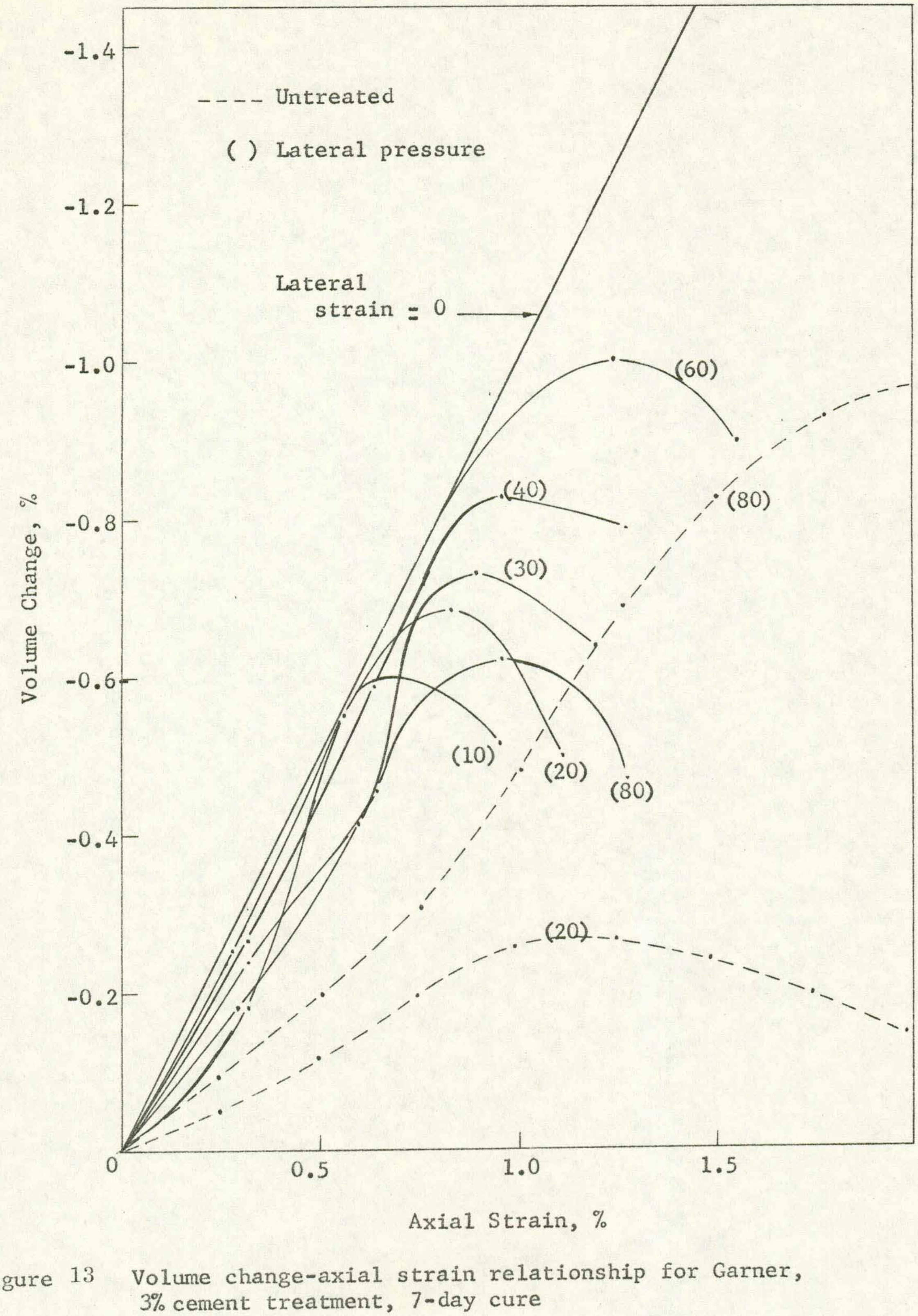

Figure 13 Volume change-axial strain relationship for Garner, 3% cement treatment, 7-day cure

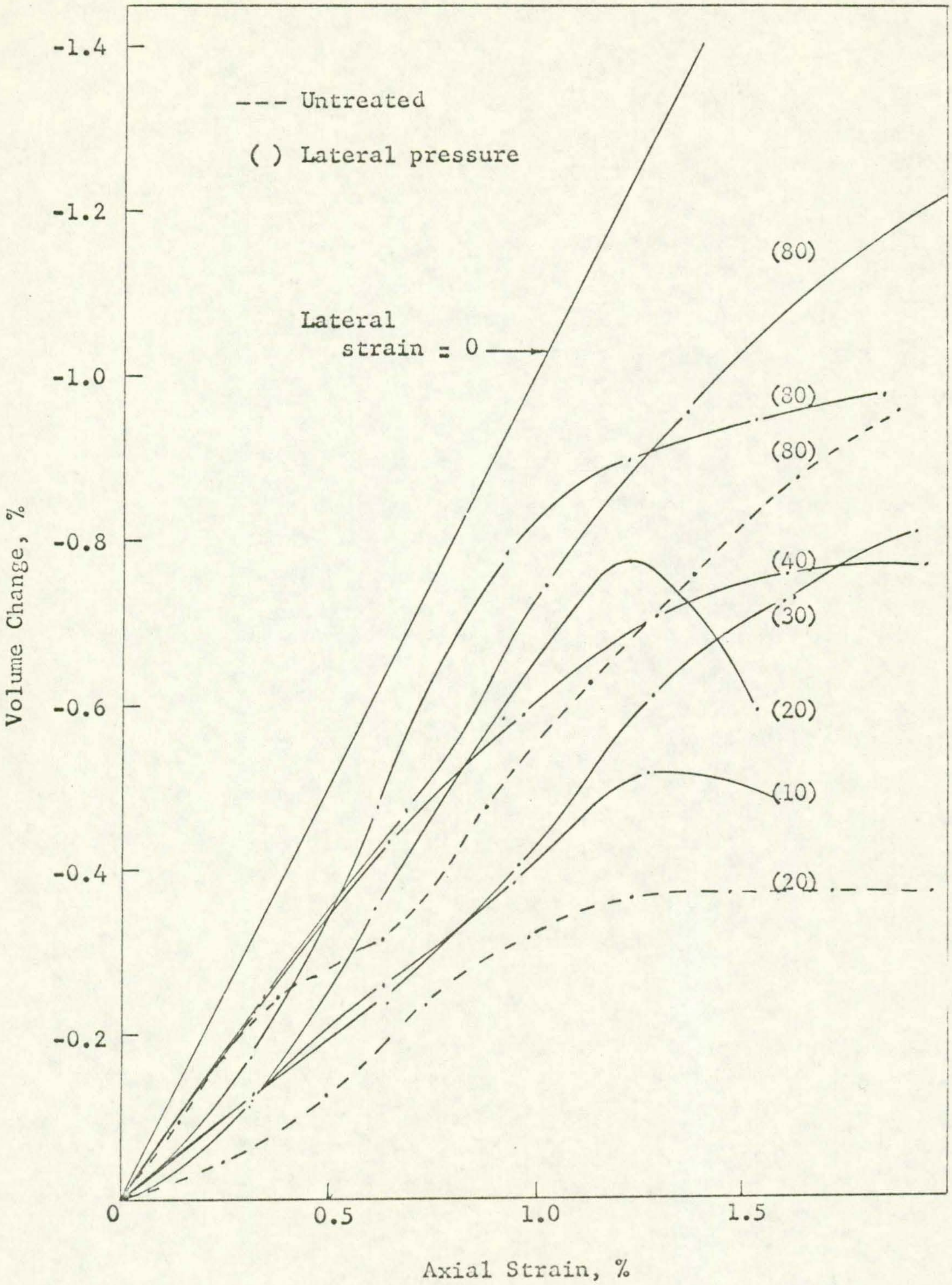

Figure 14 Volume change-axial strain relationship for Gilmore, 1% cement treatment, 7-day cure.

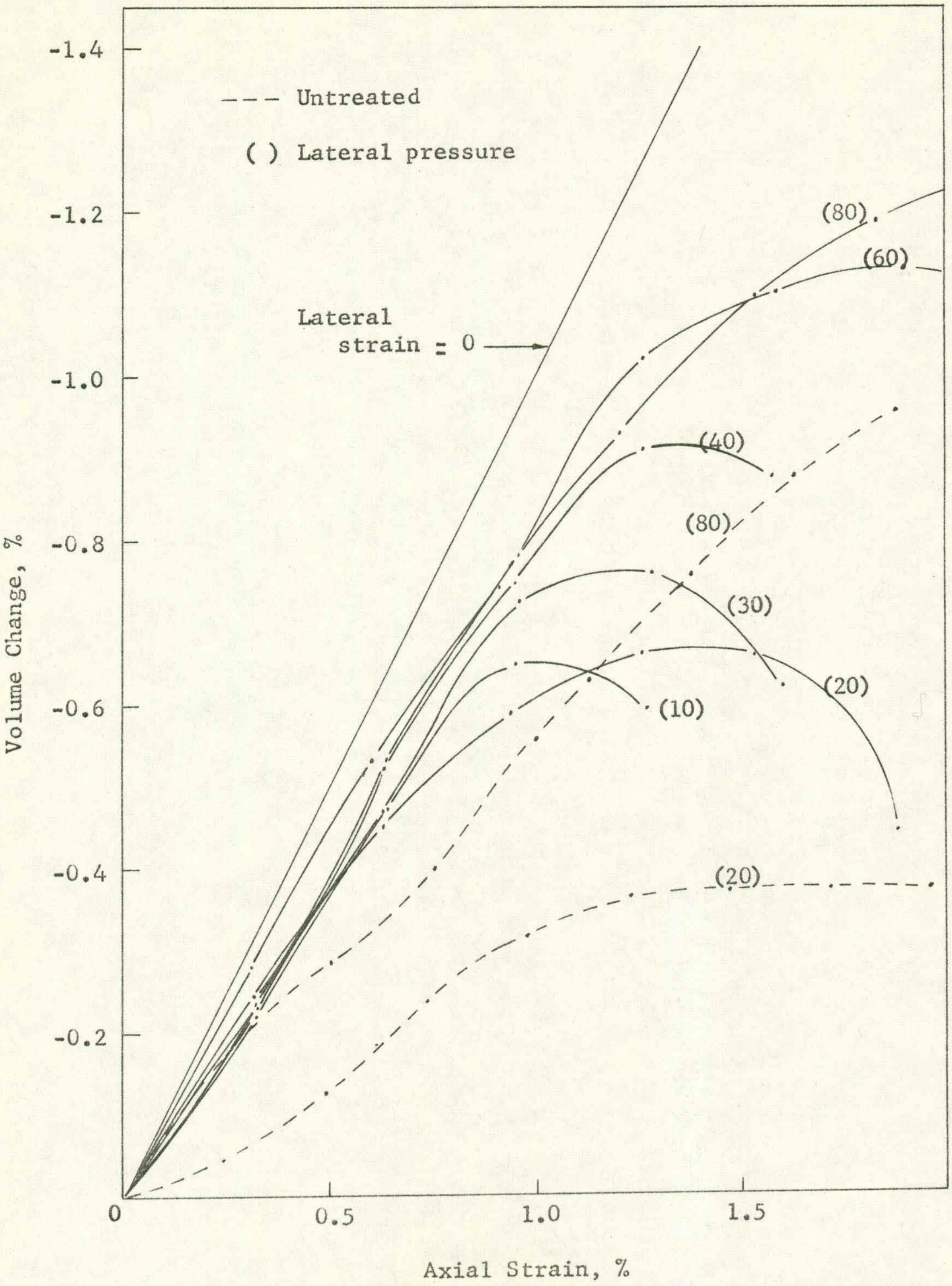

Figure 15 Volume change-axial strain relationship for Gilmore, 3% cement treatment, 7-day cure

specimen during axial loading may generally be reduced as compared to the untreated materials, up to the point of failure.

For the untreated materials, the slope of the volume change-strain curves is much closer to the condition of Poisson's ratio equal to 0.5, indicating that the material is undergoing a limited amount of lateral strain even though the volume is decreasing. The slope of the volume change-strain curves for the cement treated materials is much closer to the condition of Poisson's ratio equal to zero, which can occur only when lateral strain is very small. Using the previous assumption that lateral strain tends to increase lateral support, the cement treated materials have very little tendency to increase lateral support prior to the point of minimum volume due to the small amount of lateral strain developed. The effective stresses at the point of minimum volume, as determined in a laboratory test, should therefore be closely related to shear strength occurring under field conditions.

The untreated materials may tend to develop lateral strain even during light loadings, resulting is come increase in lateral support before the condition of minimum volume is reached. Thus the effective stresses at the point of minimum volume change, as determined under conditions of constant lateral pressure, may not be achieved under field conditions, but at least may be closer indications of potential field strength than lab strengths at maximum effective stress ratio.

Strength of cement treated crushed stone prior to minimum volume is primarily a function of the mixture. Strength of the untreated material under field conditions appears to be more closely related to the ability to develop lateral support than the "strength" characteristics of the material itself.

Shrinkage cracking could be detrimental to the strength of the base due to a reduction of lateral support in the region of any cracking. If the amount of shrinkage is excessive, a large amount of lateral deflection would be required to build up lateral support which can only occur after the ultimate strength of the material is exceeded and the bonds begin to rupture. This process could occur adjacent to cracks in the base course and though it might increase the amount of lateral support, the shear strength might actually be reduced. The smaller the quantity of cement added, however, the less the magnitude of cracking of cement treated crushed stone bases. While shrinkage studies were not conducted as a part of this research, it is generally thought that up to 3% cement by dry weight would not result in an excessive cracking,[1] though maintaining a much higher degree of total stability than the untreated stone.

---

[1] Further studies are needed to substantiate this hypothesis, although axial expansion measurements of freeze-thaw test specimens of the cement treated stones by Merrill and Hoover (5) tend to support the generality.

SUMMARY AND CONCLUSIONS

The objective of this investigation was to observe and analyze the effects of small amounts of type I Portland cement on the stability of three crushed stone base course mixes. Specimens of the crushed stones containing 0, 1, and 3% by dry weight of portland cement, cured for periods of 7 and 28 days, were tested by consolidated-undrained triaxial shear methods including measurement of pore water pressures and change of volume.

Shear strength parameters of cohesion, c', and angle of internal friction, ϕ', were determined on the basis of two failure criterion, i.e., maximum effective stress ratio and minimum volume. As previously indicated (3), the magnitude of the difference in values of shear strength at the two criteria of failure may be an indication of the amount of interlocking within a granular material. Shear strength based on the failure criteria of maximum effective stress ratio is normally the greater due to the interlocking of particles and generally results in increased cohesion coupled with slight decrease in friction angle. All untreated materials in this investigation analyzed by the two criteria of failure followed the above pattern. The addition of cement in the Bedford and Gilmore stones resulted in similar shifting of shear parameters when analyzed by the two failure criteria but were of greater magnitude than those of the untreated. The Garner stone treated with 3% cement followed a similar pattern, whereas the 1% cement treatment increased both angle of friction and cohesion. Thus, in general, the addition of cement in the three crushed stones resulted in an increase in the shear strength parameter cohesion, and was possibly due to an increased condition of interlocking.

Previous investigations have shown that cement treatment of granular materials results in a relatively constant angle of friction, whereas cohesion increases rapidly with increased cement content. However, addition of cement to the three crushed stones in this investigation produced varying values of shear strength parameters with increasing cement contents. Cohesion of the treated Bedford stone increased by as much as 72 psi, while the angle of friction remained relatively constant, as compared with the untreated specimens. Cohesion of the treated Garner stone increased nearly linearly with increase in cement content after 28 days cure. However, $\emptyset'$ reduced slightly at 1% cement then increased at 3% cement content. Addition of 1% cement to the Gilmore stone produced relatively no changes in cohesion but increased $\emptyset'$ by about six degrees above that of the untreated. At 28 days cure, the addition of 3% cement in the Gilmore produced no additional change in $\emptyset'$ but significantly increased cohesion. It is felt that addition of 1% cement in the Gilmore may not result in a complete cementation, or bonding of the large aggregate, but rather in a bonding of the fines, increasing the interlocking frictional effects between the stabilized fines and the larger aggregates.

Addition of cement to the three crushed stones reduced pore pressures to insignificant quantities. Change of pore pressure from failure conditions of minimum volume to maximum effective stress ratio may indicate the magnitude of expansion occurring during this phase of shear. Treatment of the crushed stones with cement significantly reduced the magnitude of the above change and was most pronounced with the Bedford stone, possibly due to reduction of plasticity of the fines.

Cement treatment reduced the quantity of strain required to achieve ultimate strength by either criteria of failure as compared with the untreated materials. Magnitude of strain at failure for all three treated stones was relatively independent of lateral, or confining, pressures but appeared to vary with cement content and length of cure, i. e., decreased with increasing cement content and cure period. Magnitude of strain at failure of the untreated stones generally increased with increasing lateral pressures.

Analysis of volume change characteristics of the cement treated materials led to the premise that shear strength analysis alone does not fully explain the behavior of a granular material under actual field conditions. As the untreated materials were axially loaded, there may have occurred a reduction in volume as well as a small quantity of lateral strain. In a base course, tendency for lateral expansion may be resisted by the adjacent material resulting in increased lateral support. This suggests that stability of a granular material is not entirely a function of the shear strength but must also be a function of the lateral restraining support that can be developed and the amount of expansion required to achieve this support.

The addition of cement to the three granular materials reduced the amount of lateral strain developed up to the point of minimum volume failure criteria, resulting in a potential Poisson's ratio of new zero. Thus, strength properties of cement treated materials at the point of minimum volume may more adequately represent field strength and stability conditions, than use of the strength properties at maximum effective stress ratio.

ACKNOWLEDGEMENTS

This research is part of a study of the factors influencing stability of granular base course mixes conducted at the Engineering Research Institute, Iowa State University, under sponsorship of the Iowa Highway Research Board, Iowa State Highway Commission, and the Bureau of Public Roads, U. S. Department of Commerce.

The authors wish to express their indebtedness to Dr. Richard L. Handy, Professor of Civil Engineering for his council and guidance during this investigation. Special thanks are due all members of the staff of the Soil Research Laboratory, Engineering Research Institute, for their unselfish assistance during the study.

LITERATURE CITED

1. Abrams, Melvin S. Laboratory and field tests of granular soil-cement mixtures for base courses. American Society for Testing and Materials Special Technical Publication 254:229-244. 1960

2. Balmer, Glenn G. Shear strength and elastic properties of soil-cement mixtures under triaxial loading. American Society for Testing and Materials Proceedings 58:1187-1204. 1958

3. Holtz, N. G. The use of the maximum principal stress ratio as the failure criterion in evaluating triaxial shear tests on earth materials. American Society for Testing and Materials Proceedings 47:1067-1087. 1947.

4. Hoover, J. M. Factors influencing stability of granular base course mixes: final report. Ames, Iowa, Engineering Experiment Station, Iowa State University of Science and Technology. 1965.

5. Merrill, D. C. and Hoover, J. M. Laboratory Freeze-Thaw Tests of Portland Cement Treated Granular Bases. Special Report. Ames, Iowa, Engineering Research Institute, Iowa State University of Science and Technology. 1967.

6. National Crushed Stone Association. Characteristics of graded base course aggregate determined by triaxial test. National Crushed Stone Association Bulletin 12. 1962.

7. Yamaguchi, Hakuju. Strain increments and volume change in plastic flow of a granular material. International Conference of Soil Mechanics and Foundation Engineering, 5th Proceedings 1, Div. 1-3A: 413-418. 1961