CREEP BEHAVIOR OF CEMENT-STABILIZED SOILS

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The deformation characteristics of some cement-stabilized soils subjected to sustained compressive stresses and the influence of creep on the stress-strain behavior of the test soils were studied. The test specimens having 1.32-in. diameter by 3.00-in. height were prepared by using the static compaction method. Results of the study indicate, among other things, that the Burger model predicts reasonably well the deformation-time function, that the creep strain is nonlinearly proportional to the creep stress, that molding moisture content has no significant influence on the creep strain but increasing the cement content decreases considerably the creep strain, and that the creep strain increases with increasing clay content. Among the clay minerals studied, Na-montmorillonite exhibits the greatest creep strain. The cement-stabilized soils cured under isotropic pressure have a strength significantly lower than those cured under anisotropic pressure. Creep results in an increase in the strength and deformation modulus but decreases the failure strain. The percentage of change in the strength, modulus, and failure strain due to creep varies considerably with factors such as creep duration, stress level, molding moisture content, cement content, and clay content. The more active the clay, the greater the percentage of strength gain; however, no consistent result has been obtained for modulus gain and failure strain loss.

•UNDER sustained stresses due to either load or environmental effect, or both, the cement-stabilized soil in a pavement may undergo creep. Creep results in a relief of stresses in the cement-stabilized soil layer and influences the propagation of thermal and shrinkage cracks. The consequences of creep, therefore, could affect significantly the characteristics of cement-stabilized soil and the performance of the pavement.

A consideration of creep is necessary not only in the determination of suitable and representative properties of the components of a pavement section for stress and deformation analyses but also in the establishment of appropriate failure criteria for pavement design. Both of these are among the requirements for the integrated system approach proposed by the ASCE Committee on Structural Design of Roadways (1) for the development of a rational design technique for pavements.

Although the importance of creep has been recognized, very little information on the creep behavior of cement-stabilized soils has been available. In one of the few publications on creep in soil-cement, Dunn (2) reported an increase in Poisson's ratio as the rate of loading was decreased. George (3) performed the compression creep test on a 10 percent cement-stabilized silty clay and a 6 percent cement-stabilized sandy soil under a stress level of 50 percent. He reported that the lower the relative humidity, the greater the creep and that the Burger model predicted reasonably well the creep test results. Bofinger (4) studied the creep behavior of a 6 percent cement-stabilized heavy expansive clay under a direct tensile stress and concluded that the creep characteristics of the soil-cement under direct tension could not be estimated from specimens stressed in compression. Pretorius (5) conducted the compression creep test under 90 percent and 65 percent relative humidity and reached the same conclusion as George that both the magnitude and rate of creep increased with a decrease in the relative humidity. He

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also reported that the creep curves leveled off similar to the shrinkage curves and suggested the possibility of some unique relationship between shrinkage and creep independent of the ambient humidity.

From this it is seen that there still remains much to be done in this area. This study was therefore undertaken to investigate the creep behavior of some cement-stabilized soils by using the unconfined compression creep test method. The variables considered in this study included both compositional and environmental factors. The compositional factors studied were clay and cement contents; the environmental factors included creep stress level, creep duration, and molding moisture content.

TEST MATERIALS AND PROGRAM

Materials

Soils used in this study included Providence silt, which is a natural gray silty soil in the Providence area of Rhode Island, kaolin clay (kaolinite), grundite bond clay (illite), Black Hill southern bentonite (Ca-montmorillonite), and Black Hill western bentonite (Na-montmorillonite). Grain size distribution and index properties of the test soils are shown in Figure 1 and Table 1 respectively. Type I portland cement and distilled water were used in preparing test specimens.

Compaction

Test specimens were compacted by using the static compaction method to minimize the thixotropic effect. The test specimens, 1.32-in.-diameter by 3.0-in. height, were compacted in 3 equal layers using a universal testing machine. The compaction load was increased steadily at a constant deformation rate of 0.01 in. per minute to 2,300 lb. (This compaction pressure was needed to produce a density of 101.2 pcf, approximately equal to 97 percent of maximum dry density of modified AASHO compaction.) The height of the specimen was then held constant, and due to the stress relaxation effect the sustained load gradually decreased. The sustained load was finally released as soon as it reached 700 lb. After compaction the specimens were sealed in 2 rubber membranes and cured in a moist room where the temperature was kept nearly constant at 70 F.

Method

Creep tests were conducted under unconfined compression. The test apparatus was composed of a loading system that consisted of a supporting frame, lever, and dead weights and a deformation gauge graduated to 0.0001 in. per division. All creep tests were carried out under a room temperature of approximately 70 F. Unless otherwise specified, the creep tests were conducted under a stress level of 60 percent in terms of the unconfined compressive strength at the start of creep and lasted for 7 days. This stress level was selected because Gopalakrishnan et al. (6) reported that a linear creep stress-strain relation existed up to such an intensity for concrete. After the creep tests, all specimens were tested at a deformation rate of 0.005 in. per minute for unconfined compressive strength. Finally, moisture contents of the test specimens were determined.

Program

The test program included two series—creep behavior and the effect of creep on stress-strain properties of the test soils. Both series were conducted in terms of the following factors:

1. Environmental factors such as creep duration, stress level, sample age, and molding moisture content were investigated. A 6 percent cement-stabilized Providence silt and a 60 percent stress level were used for studying the factors other than stress level. For the study of stress-level effect, soils with 3 different kaolinite contents—10, 25, and 50 percent—and various stress levels up to 60 percent of the unconfined compressive strength at the start of creep were used. For creep duration effect, the creep tests lasted for 28 days.

2. Compositional factors included clay content and cement content. For cement-content effect, Providence silt stabilized with 3, 6, 9, and 12 percent cement was studied. For clay-content effect, both amount and type of clay were considered. Note that the Providence silt contained 8 percent by weight of sand-, 87 percent of silt-, and 5 percent of clay-size particles. In preparation of the test specimens with various textural compositions, the sand- and clay-size particles in the Providence silt were extracted by using the sieve and sedimentation methods respectively. In studying the amount of the clay-size effect, the sand-size content was held constant at 8 percent and only kaolinite clay was used. Various amounts of the clay-size content studied were 10, 25, 50, 75, and 92 percent. Kaolinite, illite, Ca-montmorillonite, and Na-montmorillonite at a content of 25 percent by dry soil weight were used to investigate the effect of the clay type on the creep behavior.

RESULTS AND DISCUSSION

Creep Strain

A typical creep strain versus duration relationship for various creep stress levels in terms of the unconfined compressive strength at the start of the creep test is shown in Figure 2. Note that the actual stress level decreased with increasing time, because the strength of the test samples increased with curing time. Also shown in Figure 2 is the prediction of axial strain by using the Burger model. The viscoelastic constants of the Burger model were estimated from the creep test results by using the approach described by George (3). The comparison indicates that the Burger model describes remarkably well the deformation of the cement-stabilized soils subjected to sustained stresses, confirming George's (3) conclusion from cement-stabilized sandy soil and silty clay. Pagen and Jagannath (7) also reported the applicability of the Burger model for nonstabilized compacted soils.

Creep rates, expressed as change in axial strain per logarithmic cycle change in time, as a function of time are plotted for various stress levels in Figure 3. It is seen that a nearly linear relationship holds between log strain rate and log time and that almost the same slope holds for each stress level. A nearly linear relationship also holds between log creep rate and stress levels, Figure 4. The absolute slope of the relation seems to be decreasing with an increase in creep duration for the conditions studied. Similar relationships between log strain rate and log time and between log strain rate and stress level were observed for untreated soils by Mitchell et al. (8), Singh and Mitchell (9), and others.

Pagen and Jagannath (7) presented a linear relationship between creep stress and strain at low stress levels for compacted soils. Meanwhile, Gopalakrishnan et al. (6) concluded from multiaxial compression creep tests on concrete that creep stress-strain proportionality existed up to a stress level of 60 percent. However, Figure 5 illustrates a nonlinear creep stress-strain relationship for the cement-stabilized soils studied.

Increasing cement content increased the strength of the cement-stabilized soils. Under a constant stress level of 60 percent of the strength at the start of the creep test, however, the creep strain decreased with cement content (Fig. 6). It is probably a result of the increased stiffness of interparticle bonding due to increasing cementation, because the deformation modulus, which is defined as the slope of the stress-strain relationship at the origin, increased with increasing cement content. For a given sustained stress level, increasing modulus decreased the deformation.

For a constant dry density, increasing molding moisture content did not significantly vary the creep strain under 60 percent stress level, as shown in Figure 7. It was found that, within the range of conditions studied, the strength of the test soil decreased with increasing molding water content, but the deformation modulus was nearly independent of the variation of molding water content. This further implies that the creep strain under a sustained stress is closely related to the deformation modulus.

Figure 8 demonstrates the influence of clay-size content on the creep strain for soils containing kaolinite as the predominant clay mineral. Note that while the silt-size content was varied simultaneously with the clay-size content, the sand-size content was kept constant at 8 percent by weight. The results show that increasing the clay-size

Figure 1. Grain size distribution curves of test soils.

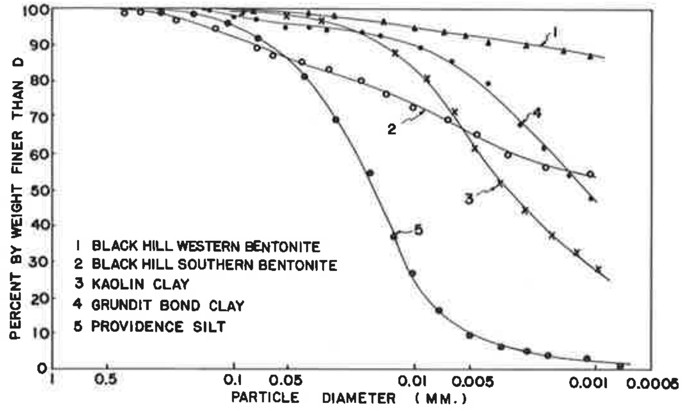


Table 1. Index properties of test soils.

Property	Providence Silt	Kaolinite	Illite	Ca-Montmorillonite	Na-Montmorillonite
Specific gravity	2.75	2.71	2.70	2.72	2.74
Atterberg limits (percent)					
Liquid limit	28	52	108	170	587
Plastic limit	24	30	46	64	103
Plasticity index	4	22	62	106	484
Grain size (percent)					
Sand size	8	1	4	12	1
Silt size	87	58	36	32	10
Clay size	5	41	60	56	89
Classification					
Unified Soil System	ML	CH	CH	CH	CH
AASHO system	A-4(8)	A-7(15)	A-7(20)	A-7(20)	A-7(20)
Activity	0.8	0.5	1.0	1.9	5.4

Figure 2. Typical strain versus creep duration relationship for 8 percent sand + 82 percent silt + 10 percent kaolinite.

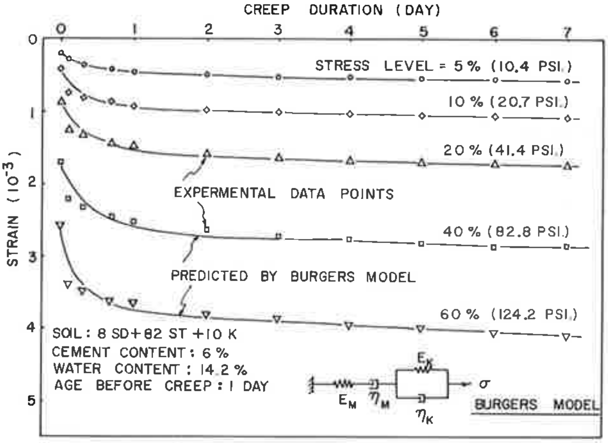


Figure 3. Creep strain rate versus duration for various stress levels for 8 percent sand + 82 percent silt + 10 percent kaolinite.

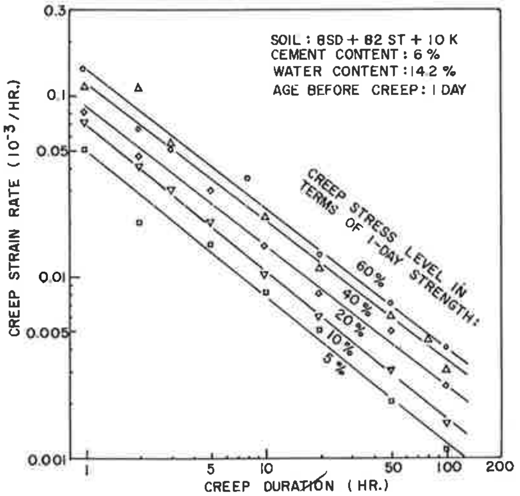


Figure 4. Creep strain rate versus stress level for 8 percent sand + 82 percent silt + 10 percent kaolinite.

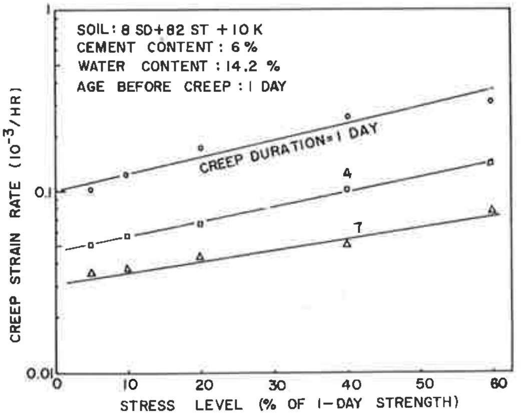


Figure 5. Relationship between creep stress and strain.

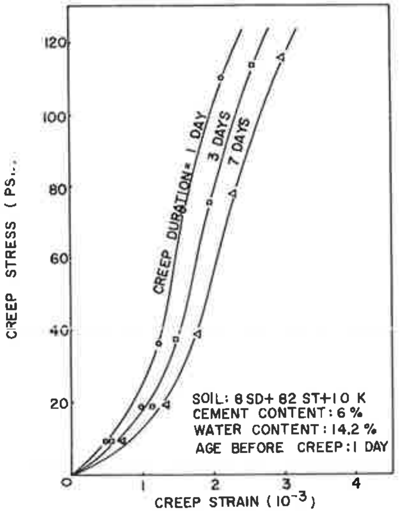


Figure 6. Effect of cement content on creep strain under 60 percent stress level.

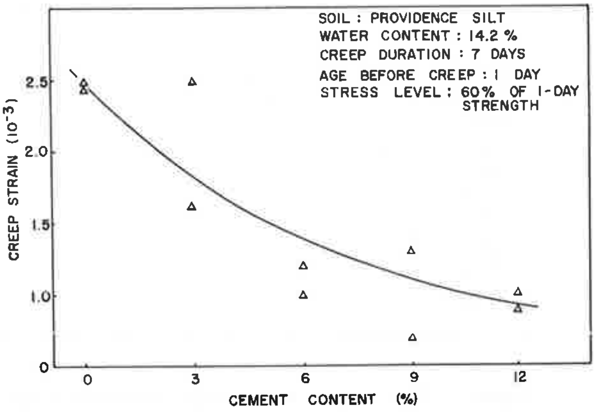
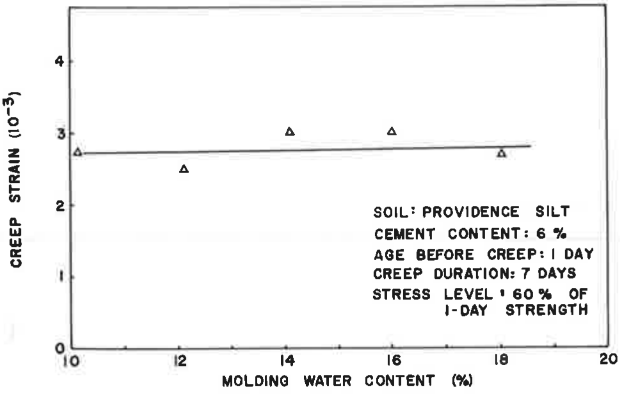


Figure 7. Creep strain as a function of molding water content for Providence silt.



content increased the rate and magnitude of creep. The magnitude of creep strain increased with increasing clay content at a rate, shown in Figure 9, that first increased to approximately 50 percent clay content, then gradually decreased, and finally approached a constant.

For a constant clay-size content of 25 percent by weight, creep under 60 percent stress level varied with a variation of clay mineral. Figure 10 shows that, among kaolinite, illite, and montmorillonite, montmorillonite clay exhibited the largest creep. This is probably attributable mainly to the particle size of the montmorillonite clay. The montmorillonite clay possesses the smallest particles of the 3 clays. For a given clay content by weight of dry soil, the test specimen containing montmorillonite clay thus has the largest amount of particles. The more particles in the test specimens, the more interparticle contact; and the more intergranular contact, the greater the deformation. The largest creep deformation was therefore observed in the montmorillonite clay specimens. Meanwhile, the montmorillonite clay particles contain intercrystalline water. The viscous nature of the intercrystalline water could also possibly contribute measurable time-dependent deformation; this effect, however, would be significant only under high stress levels.

Figure 10 also indicates that Na-montmorillonite crept considerably more than Ca-montmorillonite. A variation in the nature of exchangeable cation would cause a change in the interparticle electrical potential accompanied by a change in the thickness of the adsorbed water layer surrounding the clay particles. The higher the valence of the cation, the less the total attraction of the clay for water. The montmorillonite clay saturated with monovalent Na-ion would therefore adsorb thicker water layers than divalent Ca-ion. Although the thicker adsorbed water layer could be partly responsible for the greater creep, the real cause is not yet fully understood.

Comparisons of the observed creep deformations with the predicted results by means of the Burger model are also shown in both Figures 8 and 10. An excellent agreement between the predicted values and the data points is seen, especially in the range of steady-state creep. Thus it may be concluded that the Burger model applies for the cement-stabilized soils in the range of conditions studied.

Creep Effect on Strength

Creep caused an increase in the unconfined compressive strength of all test soils within the conditions under investigation. The percentage of strength increase due to creep, however, was nearly independent of the creep duration, as shown in Figure 11. Also shown in Figure 11 is the effect of creep on the failure strain and modulus, which are discussed individually later. For a constant creep duration of 7 days, the percentage of increase in strength increased with increasing creep stress level, as illustrated in Figure 12. To gain an insight into the mechanism of the strength increase, a study of the influence of the curing pressure on the strength was made. In this study the test specimens were cured under various types of pressure, i.e., isotropic pressures of 15, 30, and 50 psi and a K_o-stress condition with an axial pressure of 30 psi. The curing pressures were applied by using a pressure membrane apparatus. For K_o-pressure curing, the test specimens were retained in the compaction mold and wrapped in a rubber membrane.

Results of the strength tests are summarized in Figure 13. Whereas both creep and K_o-stresses caused an increase in strength, isotropic curing pressures had no significant influence on the strength. A possible explanation is as follows: Under the isotropic curing pressures, the test specimens would largely undergo elastic compression with little volume reduction because the test specimens were compacted under a pressure of 170 psi, which was much greater than the highest isotropic curing pressure, 50 psi. The elastic compression could cause an increase in the interparticle contact, thereby increasing intergranular cementation. Upon release of the isotropic curing pressures, however, some of the cementation would be ruptured due to elastic rebound of soil grains, since no discernible volume decrease was detected after isotropic pressure curing. Consequently, no significant strength increase due to isotropic curing pressure was observed. The specimens cured under creep- and K_o-stress conditions,

Figure 8. Creep strain versus duration for various contents of kaolinite.

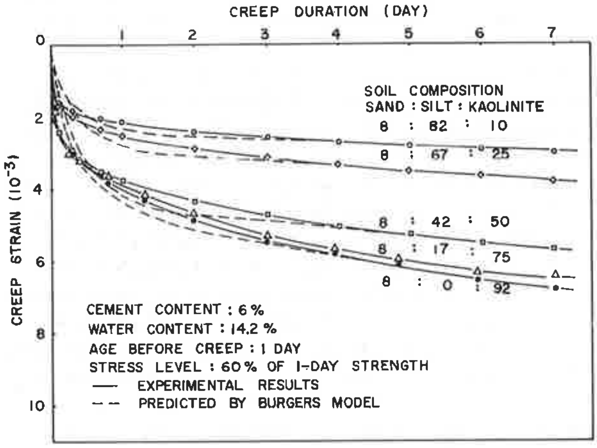


Figure 9. Influence of kaolinite content on creep strain.

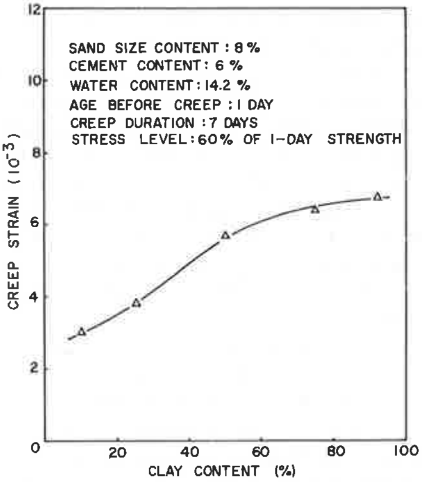


Figure 10. Creep strain versus duration for various types of clay mineral.

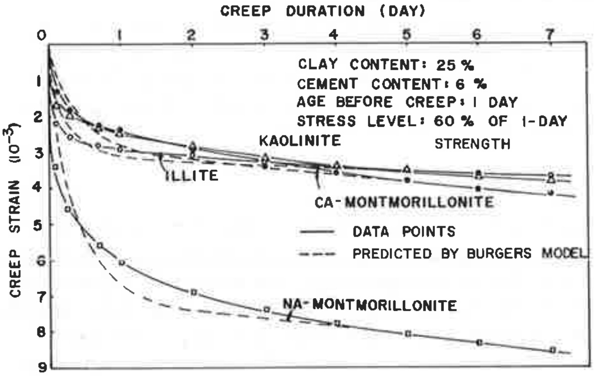
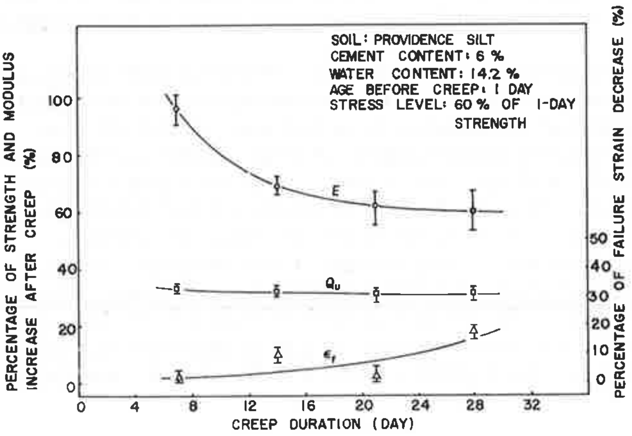


Figure 11. Effect of creep on strength, modulus, and failure strain as a function of creep duration.



on the other hand, would undergo little elastic compression but would experience particle reorientation along the potential rupture planes as a consequence of the shear strain effect induced by the deviator stress. Results of the particle reorientation would be a densification and an increase in intergranular cementation. Therefore, a significant strength increase after creep- and K_o-stress curing was obtained.

The strength increase after curing under a sustained anisotropic stress would suggest that the strength determined from the laboratory-compacted specimens, which are generally cured under an isotropic pressure, would underestimate the actual field strength, because in the field the soil is normally confined by anisotropic pressures. The engineering significance of the underestimation, however, depends on the intensity of the anisotropic pressure to which the soil specimen in the field is subjected.

The effect of molding moisture content on the percentage of strength increase after creep is shown in Figure 14. The percentage of strength increase due to creep increased with an increase in molding moisture content to a maximum, then decreased with a further increase in water content. The maximum percentage of strength increase occurred at a water content fairly close to the optimum water content for the compaction effort used.

Under a constant creep stress level of 60 percent, the strength gain after creep increased with increasing cement content; the percentage of increase, however, was nearly a constant at 25 percent, as shown in Figure 15. When the cement content was kept constant at 6 percent, increasing the clay-size content increased the strength gain at a rate following almost the same trend as creep strain (Fig. 9). The percentage of strength gain, however, increased with an increase in clay content to a maximum around 60 percent clay content, then decreased with further increase in the clay-size content. The similarity between the trend of strength gain and creep strain indicates a close interrelation between the strength and the sample density; the more the sample densified under the sustained stresses, the greater the strength gain.

Table 2 summarizes the effect of creep on strength, modulus, and failure strain for various clay minerals studied. The test results indicate that, for a constant clay content, the percentage of strength gain increased in the order kaolinite, illite, Ca-montmorillonite, and Na-montmorillonite; the more active the clay, the greater the percentage of strength increase after creep.

Creep Effect on Deformation Modulus

For all test conditions, the deformation modulus increased after creep. The percentage of increase in deformation modulus due to creep decreased with increasing creep duration at an ever-decreasing rate and eventually approached a constant, as shown in Figure 11. For a constant creep duration, however, the percentage of modulus gain increased with increasing stress level (Fig. 12). The effect of molding moisture content on the percentage of modulus increase followed almost the same trend as that for strength gain; namely, the percentage of modulus gain first increased with increasing molding moisture content, then decreased with further increase in moisture content, as shown in Figure 14.

Although increasing cement content did not affect significantly the percentage of strength gain, Figure 15 shows that an increase in cement content increased considerably the percentage of modulus gain. For a constant sand-size content, increasing the clay-size content of a 6 percent cement-stabilized soil seemed to decrease the percentage of modulus gain (Fig. 16). While the clay-size content was kept constant, varying the clay mineral caused a variation in the percentage of modulus increase (Table 2). Unfortunately, no definite trend regarding the variation of modulus increase with the activity of the clay mineral studied was observed.

Creep Effect on Failure Strain

Within the conditions investigated, creep resulted in a decrease in the failure strain. Figure 11 shows that the longer the creep duration is, the greater the percentage of failure strain decrease is. For a constant creep duration, increasing creep stress level increased the percentage of failure strain loss (Fig. 12). The influence of molding

Figure 12. Influence of creep on strength, modulus, and failure strain as a function of stress level.

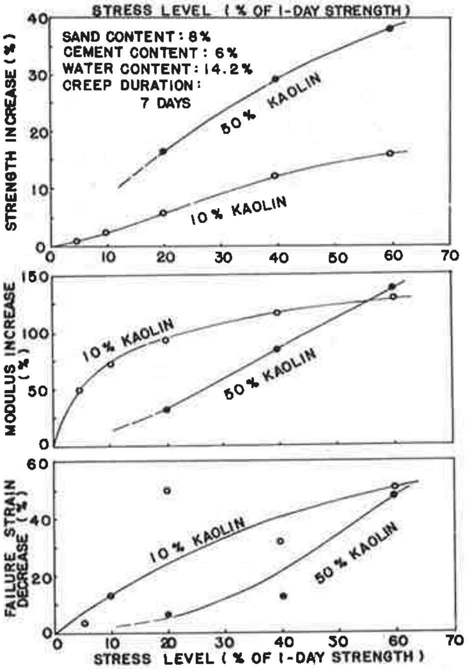


Figure 13. Effect of curing pressure on unconfined compressive strength of Providence silt.

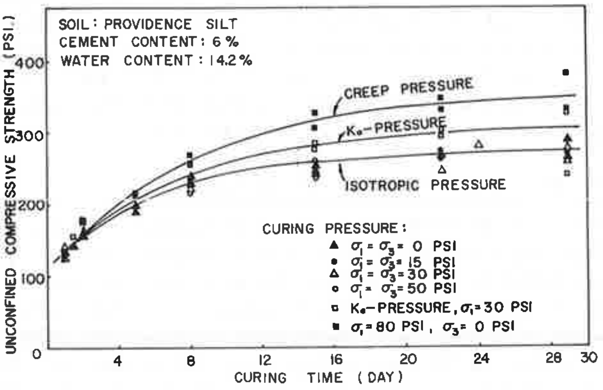


Figure 14. Effect of creep on strength, modulus, and failure strain as a function of molding moisture content.

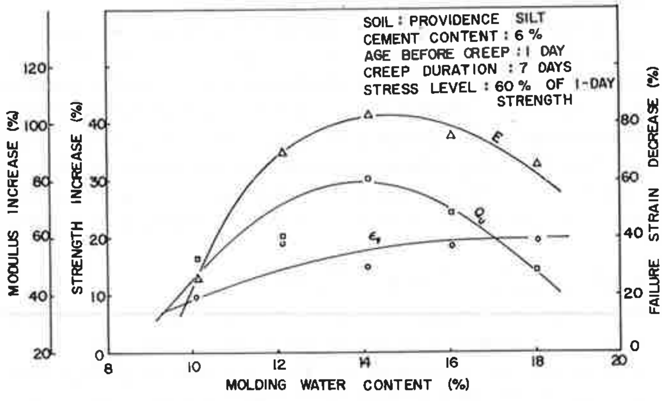


Figure 15. Effect of creep on strength, modulus, and failure strain as a function of cement content.

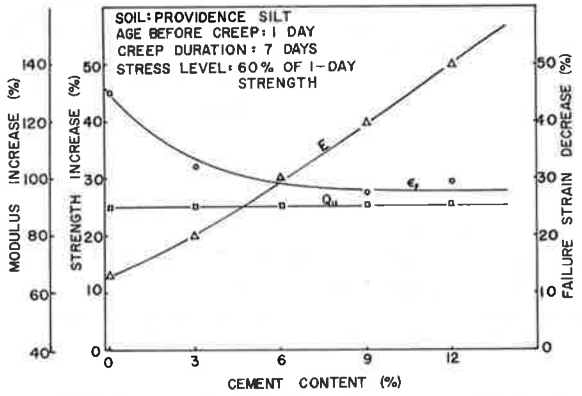


Table 2. Influence of creep on strength, modulus, and failure strain for various clay minerals.

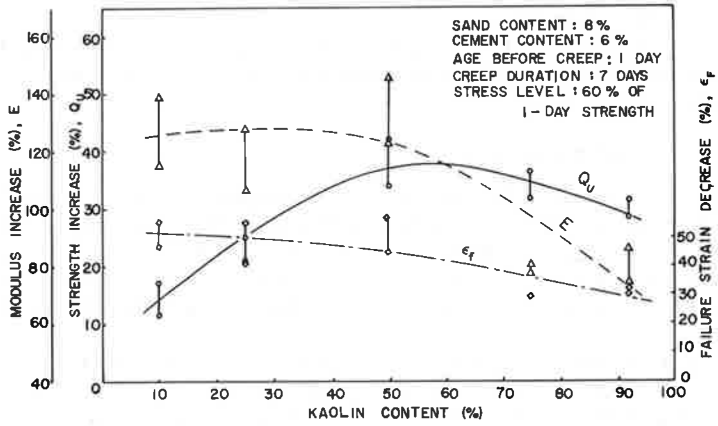
	Unconfined Compressive Strength (psi)			Deformation Modulus (10^3 psi)			Failure Strain (percent)		
Clay Mineral	8-Day Strength	After Creep	Percent Increase	No Creep	After Creep	Percent Increase	No Creep	After Creep	Percent Decrease
Kaolinite	365	446	22	66	143	117	1.26	0.66	48
Illite	394	494	25	52	126	143	1.54	0.53	66
Ca-Montmorillonite	445	594	33.5	58	183	216	1.55	0.71	54
Na-Montmorillonite	425	670	58	46	110	139	1.85	1.00	46

Note: Water content = 14.2 percent
Cement content = 6 percent
Textural composition = 8 percent sand + 67 percent silt + 25 percent clay

Creep duration = 7 days
Stress level = 60 percent of 1-day strength
Sample age prior to creep = 1 day

Each number is the average of 2 tests.

Figure 16. Effect of creep on strength, modulus, and failure strain as a function of kaolin content.



moisture content on the failure strain loss is shown in Figure 14; the percentage of decrease in failure strain increased with increasing molding moisture content.

Increasing the cement content caused a decrease in the percentage of failure strain loss (Fig. 15). For a constant cement content, an increase in clay content also resulted in a decrease in the percentage of failure strain loss (Fig. 16). The effect of clay mineral on the percentage of failure strain loss was varied, as seen from Table 2; no apparent relation between the activity of the clay mineral and the percentage of failure strain loss was obtained.

SUMMARY AND CONCLUSIONS

The creep behavior of cement-stabilized Providence silt and mixtures of Providence silt with various amounts of commercial clays was studied by using the unconfined compression creep test. The test specimens had a 1.32-in. diameter by 3.00-in. height and were compacted by means of the static compaction method. Variables investigated included creep duration, stress level, molding moisture content, cement content, and amount and type of clay content.

The following are the major conclusions reached for the soils and the test conditions investigated:

1. The steady-state deformation-time function of cement-stabilized soils subjected to sustained stresses can be predicted remarkably well by using the Burger model.
2. A nearly linear relationship holds between $d\epsilon/d \log t$ and log time, and almost the same slope holds for each stress level; a nearly linear relationship also holds between log creep strain rate and stress level; the slope of the relationship, however, varies with the creep duration.
3. For the mixture of Providence silt with 10 percent kaolinite stabilized with 6 percent cement, the creep strain is nonlinearly proportional to the creep stress within the range of creep duration and stress level studied.
4. Creep strain decreases with increasing cement content but is nearly independent of a variation in molding moisture content.
5. Increasing clay content increases creep strain; among the clay minerals studied, Na-montmorillonite exhibits the greatest creep strain.
6. Anisotropic pressure curing results in a strength greater than isotropic pressure curing; therefore the strength determined from isotropic pressure curing in the laboratory may underestimate the field strength.
7. Creep causes an increase in the strength and deformation modulus but decreases the failure strain. The percentage of strength and modulus gain and failure strain loss due to creep vary considerably with such factors as creep duration, stress level, molding moisture content, cement content, and clay content.
8. The more active the clay, the greater the percentage of strength gain; no consistent trend regarding the soil activity with the modulus increase and failure strain decrease, respectively, was observed.

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