One-Dimensional Compression Characteristics of Artificial Soils Composed of Multioriented Geosynthetic Elements

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Results and conclusions are presented from laboratory one-dimensional primary and secondary compression tests on specimens of artificial soils composed of multioriented geosynthetic elements. The purpose of the tests was to determine the influence of the parameters on the one-dimensional compression characteristics of artificial soils composed of the following elements: properties of the polymeric constituent material and size and geometric shape of the elements. Values of one-dimensional primary and secondary compression parameters for these artificial soils are also compared with those for natural soils.

In previous work, the use of multioriented geosynthetic inclusions for reinforcing granular soils was investigated (*1,2*). In addition, the potential use of multioriented geosynthetic elements as lightweight, highly porous artificial soil was noted, and laboratory California bearing ratio (CBR) and permeability tests on specimens composed entirely of these elements were conducted. In the present study, the one-dimensional compression characteristics of artificial geosynthetic soils are examined, and typical results and conclusions from 40 constant-stress primary and secondary compression tests are presented. Each specimen tested was composed of discrete, multioriented, geosynthetic elements of a single prototype; overall, 20 prototypes manufactured in three different shapes from six polymeric materials were tested. The goals of this study were to determine the influence of the following parameters on the one-dimensional primary and secondary compression characteristics of artificial geosynthetic soils: properties of the polymeric constituent material and size and geometric shape of the elements.

BACKGROUND

Previous laboratory tests on artificial soil specimens composed of multioriented geosynthetic elements have indicated the following properties (*2*): dry densities of the specimens ranged from 2.39 to 3.53 kN/m^3 (15.2 to 22.5 pcf), which represent a reduction of about 80 to 90 percent compared with typical compacted soils; coefficients of permeability varied from 0.14 to 0.17 cm/sec (0.28 to 0.34 ft/min), which are comparable to those for clean sands and clean sand-gravel mixtures; and CBR values ranged from 0.7 to 3.7. It was concluded from this limited laboratory testing program that lightweight, highly porous artificial soils could be produced from multioriented geosynthetic elements but that additional research was needed to establish the stress-strain-strength and degradation characteristics of these artificial soils.

CURRENT STUDY

Multioriented Elements

Twenty artificial soil prototypes were manufactured using six polymeric materials, six basic shapes, two sizes, and two stem shapes (Figure 1, Tables 1–3). All the prototypes consist of six stems extending radially from a central hub; 16 prototypes had enlarged heads on four stems, and four prototypes had no heads on any stems. All prototypes were cast in specially designed, two- or three-cavity injection molds. Where heads were cast on the end of the stems, manufacturing limitations permitted heads to be included on only four of the six stems. The multioriented elements are generally similar in shape and size to toy jacks and are therefore referred to as "jacks" for brevity.

The size of the headless prototypes is defined as the distance from the outer tips of either two corresponding heads (for prototypes with heads) or two corresponding stems (headless prototypes) measured along a longitudinal axis passing through the center of two stems in parallel (including the hub). The size of all prototypes with heads was 25.4 mm (1 in.). Headless prototypes were manufactured in both 19.1 and 25.4 mm (¾ and 1 in.) sizes.

The first shape (called "Original" herein) was used in previous studies (*1,2*) and is the most complex shape used in this investigation. The stems of the Original shape are square prisms, with the cross-sectional area of the four stems that support the heads being less than the headless stems; the heads are cubes and their cross-sectional area is greater than the cross-sectional area of the stems to which they are attached (Figure 1).

The stems of the other five basic shapes have the same nominal cross-sectional area (10.1 mm^2) and vary according to the size of the elements (19.1 or 25.4 mm as previously defined). The shape of the stems and heads (square prism or cylinder) and the absence of stems or orientation of the heads relative to the two headless stems are described as follows (see Figure 1): (a) headless, (b) all four heads parallel to the headless stems (rocket shape), (c) all four heads perpendicular to the headless stems (pinwheel shape), and (d) two heads parallel and two heads perpendicular to the headless stems (up-down shape).

Selected properties of the six polymers from which the prototypes were made are given in Table 2. The materials are appropriate for injection molding manufacturing processes and were selected to

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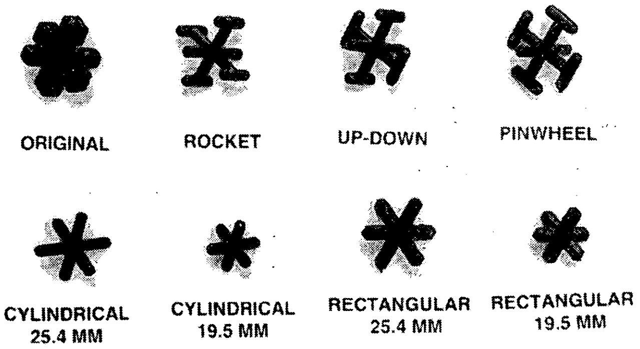

FIGURE 1 Geometric shapes of multioriented geosynthetic prototypes.

provide a wide range of strength and deformation characteristics. The strongest and stiffest material is the 20 percent glass-filled polypropylene (PPG) with a flexural modulus (E) of 4,479 MPa (650 ksi) and a tensile strength (F_t) of 55.1 MPa (8.0 ksi); the weakest and most flexible material is the low-density polyethylene (LDPE) with E = 282 MPa (41 ksi) and F_t = 8.3 MPa (1.2 ksi). Values of specific gravity range from a high of 1.24 for 40 percent mineral-reinforced polypropylene (PPM) to a low of 0.88 for copolymer polypropylene (PPPE).

Although the same mold was used to manufacture jacks of the same shape, the dimensions of the jacks made from different polymers varied somewhat from the nominal values. For example, the total volume per jack for the Original shape varied from 1,650 mm^3 (0.101 in.^{3}) for high-density polyethylene (HDPE) to 1,830 mm^3 (0.112 in.^{3}) for PPM.

Experimental Procedures

One-dimensional, constant-stress primary and secondary compression tests were performed on dry specimens of artificial jack soils confined within 152-mm (6-in.)-diameter steel molds. In the primary compression tests, loads were applied in increments to the maximum applied stress (σ_v) possible with the available equipment (300 kPa = 6.3 ksf). After the primary compression tests were complete, the maximum stress was maintained for 7 days to measure secondary compression.

Pilot tests conducted on specimens of the same prototype but varying heights showed that the height of the specimen affected the results somewhat owing to friction between the jacks along the exterior of the specimens and the interior surfaces of the molds. However, the general stress-strain characteristics and relative relationships for different prototypes were essentially independent of specimen height. As a compromise between manufacturing cost and ratio of specimen height to element size, a specimen height of 102 mm (4 in.) was selected for the main testing program. Thus, for specimens composed of 25.4 mm (1 in.) jacks, the ratio of specimen diameter to jack size was about 6:1 and the ratio of specimen height to jack size was about 4:1. For the 19.1 mm (¾ in.) jacks, the ratios were about 8:1 and 5.3:1.

To avoid undesirable gaps around the edges of the specimens, the specimens were made by placing jacks one by one into the mold until the final height was achieved. Thus, the relative densities of

TABLE 1 Shapes and Nominal Dimensions of Multioriented Inclusions

				Nominal Geometric Dimensions				
				Stems		Heads		
Shape	Size[a] (mm)	Stem Shape	Head Shape	Length (mm)	Width or Diameter (mm)	Length (mm)	Width or Diameter (mm)	Nominal Total Volume (mm^3)
Original	25.4	Square Prism	Cubic	3.97	3.18	6.35	6.35	1,760
		Square Prism	None	11.11	4.76	None	None	
Headless Rectangular	25.4	Square	None	11.11	3.18	None	None	704
Headless Rectangular	19.1	Square	None	7.94	3.18	None	None	512
Headless Cylindrical	25.4	Cylinder	None	11.11	3.58	None	None	704
Headless Cylindrical	19.1	Cylinder	None	7.94	3.58	None	None	512
Rocket[b]	25.4	Cylinder	Cylinder	7.94	3.58	12.70	3.58	1,080
		Cylinder	None	11.11	3.58	None	None	
Pinwheel[c]	25.4	Cylinder	Cylinder	7.94	3.58	12.70	3.58	1,080
		Cylinder	None	11.11	3.58	None	None	
Up-Down[d]	25.4	Cylinder	Cylinder	7.94	3.58	12.70	3.58	1,080
		Cylinder	None	11.11	3.58	None	None	

[a] Distance from the outer tip of either two corresponding heads (for jacks with heads) or two corresponding stems (for headless jacks) along a longitudinal axis passing through the center of two stems in parallel (including the hub).

[b] All four heads are parallel to the headless stems.

[c] All four heads are perpendicular to the headless stems.

[d] Two heads are parallel and two heads are perpendicular to the headless stems.

TABLE 2 Selected Properties of Polymeric Materials

	Polymeric Material					
Property	Polypropylene 20% Glass Filled (PPG)	Polypropylene Mineral Filled (PPM)	Polypropylene Homopolymer (PP)	Polypropylene Copolymer (PPPE)	High Density Polyethylene (HDPE)	Low Density Polyethylene (LDPE)
Tensile strength (MPa)	55.1	31.7	34.8	21.0	22.0	8.3
Elongation at yield (%)	2	10	11	10	10	850
Flexural Modulus (MPa)	4,480	2,340	1,720	1,070	1,070	282
Notched Izod Impact (J/cm)	0.53	0.27	0.37	1.07	1.05	0.75
Deflection Temperature (°C) @ 455 kPa	138	132	140	145	130	88
Specific Gravity	1.04	1.24	0.89	0.88	0.95	0.92

All values supplied by manufacturers or distributors

TABLE 3 Basic Characteristics of Multioriented Inclusions

Prototype					
Shape	Polymer	Size (mm)	Mass per Jack (g)	Volume per Jack (mm^3)	Specific Gravity
Original	PPG	25.4	1.74	1,770	0.98
	PPM	25.4	2.13	1,830	1.16
	PP	25.4	1.58	1,780	0.89
	PPPE	25.4	1.53	1,740	0.88
	HDPE	25.4	1.54	1,650	0.93
	LDPE	25.4	1.57	1,750	0.90
Headless Rectangular	PPG	19.1	0.50	500	1.00
	PPG	25.4	0.68	700	0.97
	LDPE	19.1	0.44	490	0.90
	LDPE	25.4	0.61	690	0.88
Headless Cylindrical	PPG	19.1	0.44	460	0.95
	PPG	25.4	0.62	660	0.95
	LDPE	19.1	0.39	430	0.92
	LDPE	25.4	0.56	620	0.91
Rocket	PPG	25.4	1.01	1,050	0.96
Pinwheel	PPG	25.4	1.00	1,020	0.98
Up-Down	PPG	25.4	1.00	1,000	0.98
Rocket	LDPE	25.4	0.91	1,000	0.91
Pinwheel	LDPE	25.4	0.90	1,000	0.91
Up-Down	LDPE	25.4	0.91	1,000	0.91

the specimens were intermediate between a loose state representing a situation where the jacks would be dumped in place and a dense condition produced by vibratory compaction after being placed. Because there were differences in the dimensions and volume for jacks of the same shape but different material, there were inevitable differences in initial void ratio for nominally identical specimens. For example, for the Original shape jacks, the initial void ratios for the specimens made from the six different polymers varied from 2 to 2.8 (see Figure 2a).

Because the specimens were dry and the pore spaces were large, the pore air pressures generated during each loading increment were dissipated almost instantaneously. Therefore, the first reading (15 sec) for each loading increment was assumed to represent the end of primary compression and the beginning of secondary compression. The specimen deformations were very large in some instances, so all deformation results are presented in terms of true strain instead of engineering strain, where true strain is given by the following equation:

$$\epsilon_v = \int_{H0}^{H} \frac{dH}{H} = \ln \frac{H}{H_0} \qquad (1)$$

where H_0 is the original height of the specimen, and H is the height of the specimen at any time after loading.

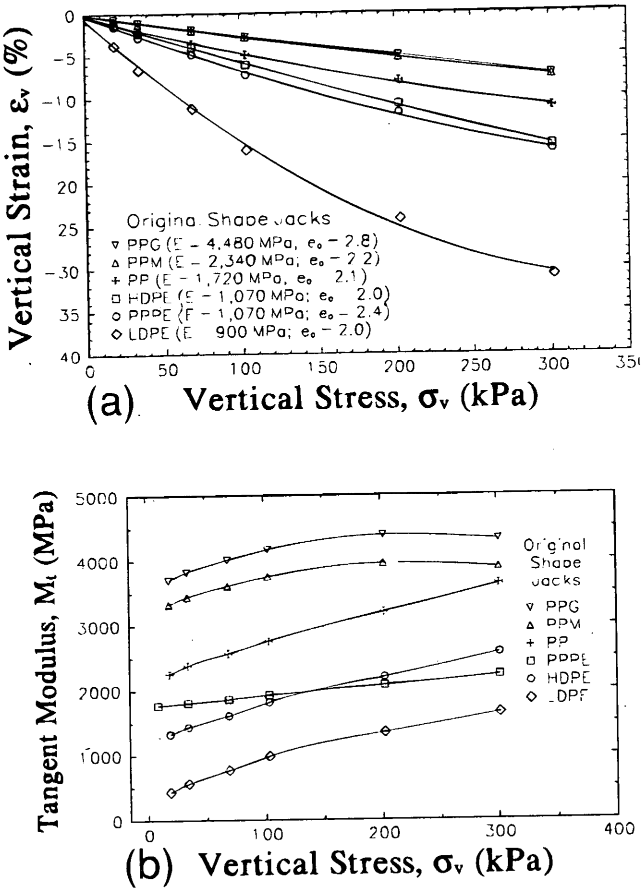

FIGURE 2 Effect of polymeric material type on one-dimensional primary compression of artificial jack soil: (*a*) strain versus stress, (*b*) tangent modulus versus stress.

Results From Primary Compression Tests

Effect of Polymer Type

The type of polymer used to manufacture the jacks has a significant effect on the relationship between applied vertical stress and primary compressive strain, as shown in Figure 2a for specimens of Original shape jacks. The flexural modulus of the plastic appears to be the most important factor; as flexural modulus increases, the compressibility of the artificial soil decreases. In one-dimensional compression, the decrease in volume results primary from two phenomena: (a) rearrangement of jacks from sliding along the stems and heads and (b) distortion of the jacks occurring primarily from bending of stems. Therefore, less bending of stems and less compression occur for stiffer plastics. As the applied load is increased, additional bending of stems occurs. At some point the bending of stems produces additional contact points between jacks, and the stiffness of the material increases. This is illustrated in Figure 2a by the flattening of the strain-stress curves with increasing stress. Note that the flattening of the curves is less for the stiffer plastics because less additional contacts are produced at lower values of strain. This stiffening effect is more clearly demonstrated in Figure 2b, where the results from Figure 2a are plotted in terms of one-dimensional tangent modulus (M_t) versus σ_v. For each specimen, M_t increases with increasing σ_v. Values for M_t for each specimen were obtained by performing a polynomial least-squares regression on the strain-stress data with ϵ_v as the dependent variable and σ_v as the independent variable, differentiating the regression equation to obtain the slope of the strain-stress curve ($d\epsilon_v/d\sigma_v$), calculating the slope at the same levels of stress applied in the test, and inverting the slope to obtain the tangent modulus ($d\sigma_v/d\epsilon_v$).

Owing to the substantial amount of time required to manufacture the number of jacks required for a test—which ranged from about 350 to 1,600 jacks—the remaining prototypes were made from only the stiffest and strongest material, PPG, and the most flexible and weakest material, LDPE.

Influence of Stem Shape and Size

To determine the influence of the size and shape of the stems on the compressibility of artificial jack soils, headless jacks were manufactured using PPG and LDPE with two stem configurations (square prism and cylinder) and in two sizes (25.4 mm = 1 in. and 19.1 mm = ¾ in.). The nominal cross-sectional area of the stems for all four prototypes was the same (10.1 mm^2 = 0.0156 in.^{2}). The lengths of the stems measured from the outer edge of the hub to the tip of the stems were 7.9 and 11.1 mm (5⁄16 and 7⁄16 in.) for the 19.1 mm (¾ in.) and 25.4 mm (1 in.) sizes, respectively. The results from primary compression tests conducted on artificial soil specimens made from these jacks (Figure 3) indicate that the length of the stem (for a given cross-sectional area) significantly affects the compressibility, but the cross-sectional shape of the stem does not. Both these trends are consistent with the assumption that one-dimensional compression of artificial jack soils occurs primarily from bending of the stems.

It can be shown that a solid square and a solid circle with the same area have the following ratio for their moments of inertia:

$$\frac{I_{\text{sqr}}}{I_{\text{cir}}} = \frac{\pi}{3} \qquad (2)$$

For stems made from the same polymer (therefore same E) and with the same cross-sectional area, those with a square cross-sectional shape have a flexural rigidity (EI) about 5 percent greater than those with a circular cross-sectional shape. Thus, for specimens contain-

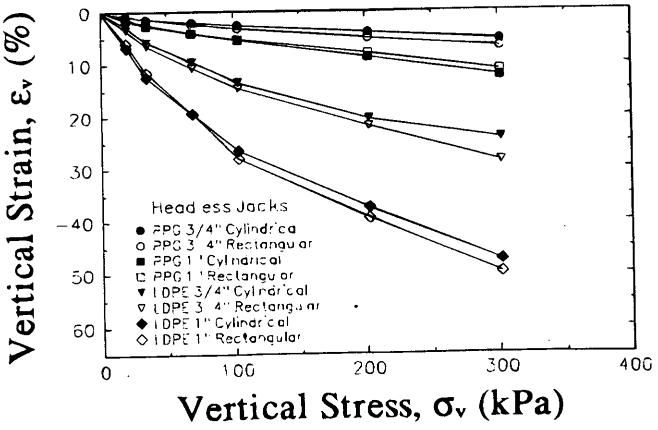

FIGURE 3 Influence of stem shape on strain-stress curves for headless jacks.

ing the same number of jacks, the load per jack, and therefore the load per stem, would be the same, and the specimens containing jacks with square prismatic stems should compress about 5 percent less than those with cylindrical stems. To compare the compression characteristics for the same size and same polymer but different cross-sectional shapes, the ratios of change in height for the comparable samples ($\Delta H_{sqr}/\Delta H_{cir}$) were calculated at each level of stress. For the 24 combinations of polymer, size, and stress level, $\Delta H_{sqr}/\Delta H_{cir}$ varies from 0.84 to 1.25, averaging 1.06, suggesting that the jacks with square stems are slightly more compressible than those with circular stems, which is opposite of the expected result. To account for the differences in number of jacks per specimen (N_J) caused by the slight differences in volume between the jacks with square stems and those with circular stems, and for random differences in placement, the deflections for each specimen were normalized by multiplying them by N_J. The calculated values of $(\Delta H \cdot N_J)_{sqr}/(\Delta H \cdot N_J)_{cir}$ range from 0.64 to 1.09, averaging 0.94. This average value suggests that the jacks with square stems are about 6 percent less compressible than those with circular stems, very close to the 5 percent predicted from Equation 3. Therefore, moment of inertia of the stems appears to affect the compression characteristics. Cross-sectional shape does not.

Substantial differences in stress-strain behavior are evident for the 25.4 mm (1 in.) and 19.1 mm (¾ in.) jacks made of the same polymer, as indicated in Figure 3. For the same polymer, the 25.4-mm (1-in.) jack specimens compressed an average of 82 percent more than the 19.1-mm (¾-in.) jack specimens. Two factors support this relationship: (a) the specimens containing larger jacks have fewer jacks per specimen (average $N_J = 1{,}409$) than those made of smaller jacks (average $N_J = 776$), and thus the load per jack is higher for the larger jacks; and (b) the stems of the larger jacks are longer and therefore more flexible. To provide additional insight into the effect of size on the one-dimensional compressibility of artificial jack soils, the following simplified theoretical relationship is developed.

Assumptions

- All deformations occur as a result of bending of stems.
- Each specimen contains an equivalent number of layers of jacks (N_L), with the same number of jacks in each layer. N_L is inversely proportional to the size of the jacks (S_J) and is not necessarily an integer.
- The vertical deflection of a specimen under an applied load is equal to the vertical deflection per jack times the number of layers ($\Delta H = \Delta H_J \cdot N_L$).
- Each jack in a specimen carries the same vertical force, $F_J = F_v/N_J$, where F_v is the total applied vertical force. Each jack compresses by the same amount (ΔH_J).
- N_J is inversely proportional to S_J.
- ΔH_J is inversely proportional to the flexural rigidity (EI) of the stems.
- ΔH_J is proportional to F_J.
- The vertical force carried by each stem in a jack is the same, and this force is applied at the tip of the stem. The deflection of each stem can be approximated by small deflection theory for a cantilever beam with a point load at the end of the beam. Therefore, ΔH_J is proportional to $L^3 \cos^2\theta$, where L is the length of the stem and θ is the angle of the longitudinal axis of the stem referenced to horizontal. The average value of θ is assumed to be the same for each specimen.
- The constant of proportionality for any specific relationship is independent of the other factors.
- The compression and extension of the stems caused by the longitudinal components of the applied forces is negligible compared with the deflections caused by bending of the stems. With these assumptions, the following ratio for deflections of two specimens supporting the same total vertical load (F_v) can be derived:

$$\frac{\Delta H_a}{\Delta H_b} = \frac{\left(\frac{L^3}{EI}\right)_a}{\left(\frac{L^3}{EI}\right)_b} \qquad (3)$$

In Equation 3, the influence of size of jacks is evident only in terms of length of the stems; the effect of size on the number of jacks is offset by a proportional change in the number of layers.

For the situation where the size is varied but the polymer is the same $[(EI)_a = (EI)_b]$, Equation 3 reduces to

$$\frac{\Delta H_a}{\Delta H_b} = \left(\frac{L_a}{L_b}\right)^3 \qquad (4)$$

For the 25.4- and 19.1-mm jacks, the theoretical ratio of deflections based on Equation 4 becomes $\Delta H_{25.4}/\Delta H_{19.2} = 2.74$, compared with the actual average value of 1.82. The simplifications in this theory are numerous and a deviation from the theoretical ratio is expected. That the actual ratio is less than the theoretical ratio can be explained qualitatively in terms of major deviations from two of the assumptions. First, the deflections are quite large; hence large deflection theory is more appropriate. The deviation from small deflection theory increases as the factor PL^2/EI increases (*3*), where P is the bending force (perpendicular to the stems) and the other terms are as previously identified. Hence, the deviation from small deflection theory is greater for higher stresses, longer stems, and more flexible polymers, with the deflection perpendicular to the stem less than for small deflection theory and the deflection parallel to the stem greater than for small deflection theory. The deviation is greater for the perpendicular deflection than for the parallel deflection, so the net result for a stem oriented at 45 degrees to the horizontal is that the actual vertical deflection is less that predicted by small deflection theory, and the difference is greater for higher values of PL^2/EI. Using the average values for number of jacks and the lengths of stems, the ratio of PL^2/EI for the 25.4-mm (1-in.) jacks compared with the 19.1-mm (¾-in.) jacks is 3.6. Thus, the actual ratio of deflections should be smaller than the ratio predicted from small deflection theory (Equation 4), as is the case.

A second factor that tends to reduce $\Delta H_{25.4}/\Delta H_{19.2}$ is sliding of jacks relative to each other during loading owing to the smooth surfaces of the jacks. Because most of the sliding likely occurs along the stems of adjacent jacks, it would be reasonable to expect that the amount of sliding would be proportional to the length of the stems. Thus, the overall value of $\Delta H_{25.4}/\Delta H_{19.2}$ would be somewhere between $L_{25.4}/L_{19.1}$ for sliding and $(L_a/L_b)^3$ for bending.

Effect of Heads and Orientation of Heads

The effect of adding heads to the jacks and the effect of the orientation of those heads on the one-dimensional primary compression characteristics are illustrated in Figure 4 for jacks made from PPG

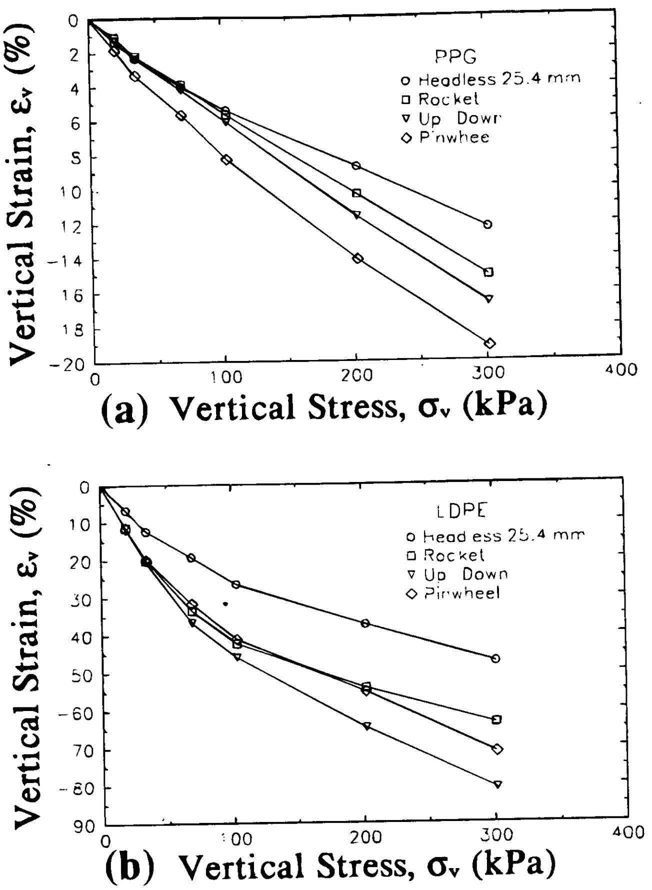

FIGURE 4 Comparison of strain-stress curves for jacks with and without heads: (*a*) PPG, (*b*) LDPE.

and LDPE. The jacks with heads in these tests essentially consisted of 25.4-mm (1-in.) cylindrical headless jacks with 3.2-mm (⅛-in.) heads on four stems oriented perpendicularly to the stems and extending 4.8 mm (3/16 in.) beyond the stems on each side; thus, the heads were 12.7 mm (½ in.) long from tip to tip. The volume of the cylindrical jacks with heads was about 50 percent more than the 25.4-mm (1-in.) cylindrical jacks without heads. The heads were oriented in three ways, as described previously, to obtain the three shapes (Pinwheel, Rocket, and Up-Down).

A comparison of the results in Figure 4 shows that for jacks made from PPG and LDPE, the specimens containing jacks with heads were more compressible than comparable specimens made of jacks without heads. Since the jacks with heads are essentially the same size as those without heads, N_L should be about the same for both. However, the jacks with heads require more space horizontally, so the number of jacks per specimen is much less for jacks with heads than those without heads; the average value of $N_{J-\text{headless}}/N_{J-\text{heads}}$ is 1.86 for PPG and 1.72 for LDPE. For jacks made from the same polymer (PPG or LDPE), the ratio of deflections for specimens of jacks with and without heads according to the theory described previously is as follows:

$$\frac{\Delta H_{\text{heads}}}{\Delta H_{\text{headless}}} = \frac{N_{J-\text{headless}}}{N_{J-\text{heads}}} \qquad (5)$$

The average actual value of $\Delta H_{\text{heads}}/\Delta H_{\text{headless}}$ for the three types of jacks with heads compared with the headless jacks for all six stress levels is 1.21 for PPG and 1.56 for LDPE. These values are less than those predicted from Equation 5, probably as a result of sliding among jacks during loading, as discussed previously. From the curves in Figure 4, it appears that the orientation of the head has some influence on the primary compression characteristics, with the Rocket shape seeming to be the least compressible, but with no discernible pattern as to which shape is most compressible. When the deflection results are corrected for the small variations in N_J, the average ratios of $\Delta H \cdot N_J$ for the other two orientations arbitrarily referenced to the Rocket shape are 1.04, 0.98, 1.02, and 1.42, suggesting that the differences in deflections probably result mainly from random variations in specimen preparation. Thus, the orientation of the heads seems to have little effect on the primary compression characteristics.

Artificial Jack Soils Versus Natural Soils

To assess the geotechnical characteristics of the artificial soils the load-deformation characteristics of the jacks were compared with a range of natural soils on the basis of Janbu's tangent modulus equation (*4*):

$$M_t = m \cdot \sigma_a \cdot \left(\frac{\sigma'}{\sigma_a}\right)^{1-a} \qquad (6)$$

where

m = modulus number,
a = stress exponent (number between 0 and 1), and
σ_a = reference stress = 1 atmosphere.

Values for m and a were determined for all artificial jack specimens tested in primary compression and are summarized in Table 4. Values of m give a general indication of the compressibility of the material; for the same value of a, lower values of m indicate greater compressibility. Values of a indicate the influence of stress level on M_t. For $a = 1$, M_t is independent of stress level, which is typical for many types of intact rock. A value of $a = 0$ indicates that M_t is linearly proportional to σ', which is characteristic of normally consolidated saturated clays. For many granular soils, a is about 0.5 (*5*).

Values of a and m for the artificial jack specimens as a function of porosity are compared with typical values for natural soils in Figure 5. The porosities of the artificial jack specimens are within the same range as for clays and peats. Both the type of polymer and geometric shape significantly affect the values of the tangent modulus parameters. The values of a for the artificial soils vary from 0.22 to 1. The lower values are for the LDPE jacks and are within the same range as for silts; the higher values are for the PPG jacks and are in the same range as for sands and moraines. The Original shape jacks—except for those made from LDPE—have a $\geq$ 0.76. Values of m for the artificial jack soils range from 4 to 65. The values for the LDPE jacks vary from 4 to 11 and are comparable to those for peats and soft clays. Values of m for PPG jacks and Original shape jacks (except LDPE) vary from 16 to 65, which compares with natural soils ranging from stiff clays to moderately dense silts. Note that the modulus number for all PPG specimens falls above the upper limit normally found for natural soils of the same porosity, indicating that for the same porosity the artificial jack soils are stiffer than natural soils.

TABLE 4 Values of Modulus Number and Stress Exponent for Multioriented Inclusions

Prototype				
Shape	Polymer	Size (mm)	Modulus Number m	Stress Exponent a
Original	PPG	25.4	41.9	0.94
	PPM	25.4	39.5	0.94
	PP	25.4	29.0	0.83
	PPPE	25.4	18.5	0.76
	HDPE	25.4	20.0	0.84
	LDPE	25.4	9.6	0.51
Headless Rectangular	PPG	19.1	43.7	0.65
	PPG	25.4	33.5	0.75
	LDPE	19.1	10.0	0.48
	LDPE	25.4	5.9	0.38
Headless Cylindrical	PPG	19.1	64.6	0.68
	PPG	25.4	22.9	0.73
	LDPE	19.1	11.0	0.22
	LDPE	25.4	6.2	0.35
Rocket	PPG	25.4	20.9	1.00
Pinwheel	PPG	25.4	15.9	0.78
Up-Down	PPG	25.4	18.8	1.00
Rocket	LDPE	25.4	5.2	0.49
Pinwheel	LDPE	25.4	3.9	0.44
Up-Down	LDPE	25.4	3.8	0.40

Results From Secondary Compression Tests

A series of secondary compression tests was conducted on specimens of jacks made after the conclusion of the primary compression tests. Typical results are shown in Figure 6 for the Original shape jacks. Approximate values for modified secondary compression index ($C_{\alpha\epsilon}$) were calculated for each test by determining a least-squares best-fit linear equation for $\epsilon_v = f[\log(t)]$ for each plot and calculating $C_{\alpha\epsilon}$ as the first derivative of the equation:

$$C_{\alpha\epsilon} = \frac{d\epsilon_v}{d[\log(t)]} \qquad (7)$$

where t is the time after loading. The calculated values of $C_{\alpha\epsilon}$ are listed in Table 5 and vary from about 0.3 to about 2.8 percent. From these data, it is clear that the same relationships established for primary compression are also valid for secondary compression. In general, $C_{\alpha\epsilon}$ decreases (a) as M_t decreases, (b) as the size of the jacks increase, and (c) if heads are added to the jacks. No definite trends can be established for either the cross-sectional shape of the stems or the orientation of the heads. For saturated fine-grained natural soils, typical values of $C_{\alpha\epsilon}$ range from about 0.15 to 15 percent (*6*); hence, values of $C_{\alpha\epsilon}$ for artificial jacks soils are within the lower end of the saturated fine-grained soil range.

It was also desired to establish secondary to primary compression index ratios for the artificial soil specimens. To determine values for $C_{c\epsilon}$ at $\sigma'_v = 300$ kPa, the results from the primary compression tests were plotted in $\log(\sigma'_v) - \epsilon_v$ space, as illustrated in Figure 6 for the Original shape jacks. Because the curves are not linear, a least-squares polynomial regression was performed on the data for each test, and tangent values for $C_{c\epsilon}$ were calculated by differentiating the polynomial and inserting $\sigma'_v = 300$ kPa into the equation for the first derivative:

$$C_{c\epsilon} = \frac{d\epsilon_v}{d[\log(\sigma'_v)]} \qquad (8)$$

The calculated values of $C_{c\epsilon}$ varied from 0.062 to 0.84 (Table 5). Also shown in Table 5 are values of $C_{\alpha\epsilon}/C_{c\epsilon}$ for the artificial jack specimens, which varied from 0.027 to 0.11. Values $C_{\alpha\epsilon}/C_{c\epsilon}$ for the PPG specimens varied from 0.050 to 0.093 with an average of 0.071. For the LDPE specimens, $C_{\alpha\epsilon}/C_{c\epsilon}$ ranged from 0.027 to 0.089 with an average of 0.051, suggesting that $C_{\alpha\epsilon}/C_{c\epsilon}$ may be greater for jacks made from stiffer polymers than for those made from more compressible polymers. Note that the range in values of $C_{\alpha\epsilon}/C_{c\epsilon}$ for artificial jack soils is nearly the same as the range for natural soils (0.03 to 0.1) (*7*).

SUMMARY AND CONCLUSIONS

A laboratory experimental study consisting of one-dimensional primary and secondary compression tests was conducted to determine the one-dimensional compression characteristics of artificial soils consisting of multioriented geosynthetic elements (jacks). From the results of these tests, the influence of the following parameters on the one-dimensional compression characteristics of the artificial soils was assessed: geometric shape and size of the jacks and the

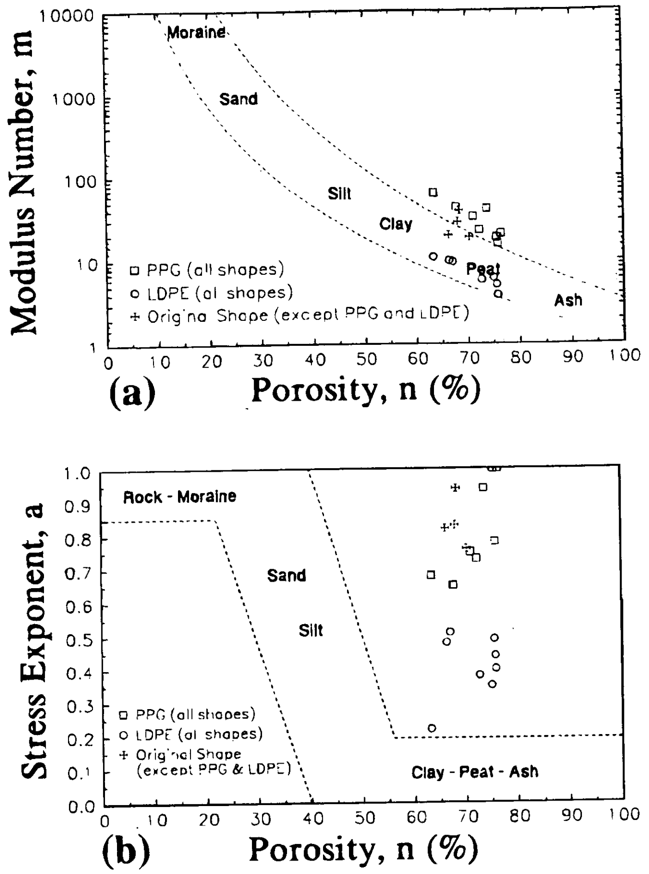

FIGURE 5 Values of Janbu's tangent modulus parameters for artificial jack soils as function of porosity: (*a*) modulus number, (*b*) stress exponent.

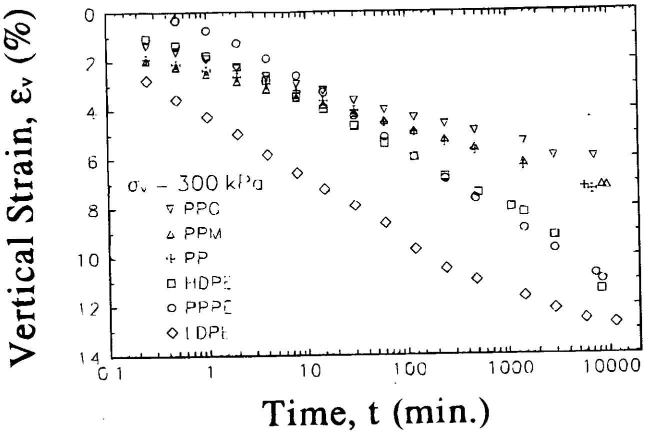

FIGURE 6 Secondary compression curves for original shape jacks.

flexural properties of the polymer from which the jacks were made. The general results and conclusions determined from this experimental study are summarized as follows.

1. A substantial portion of the one-dimensional compression of artificial jack soils occurs from bending of the stems of the jacks about the central hub.
2. For a given geometric shape and size of the jacks, the flexural modulus of the polymer used in manufacturing the jacks has the greatest influence on the one-dimensional primary and secondary compression behavior of artificial jack soils. Primary and secondary compression are reduced for increased flexural modulus of the polymer.

TABLE 5 Values of $C_{\alpha\varepsilon}$, $C_{c\varepsilon}$, and $C_{\alpha\varepsilon}/C_{c\varepsilon}$ for Artificial Jack Soils

Prototype					
Shape	Polymer	Size (mm)	$C_{\alpha\varepsilon}$	$C_{c\varepsilon}$	$C_{\alpha\varepsilon}/C_{c\varepsilon}$
Original	PPG	25.4	0.011	0.12	0.092
	PPM	25.4	0.012	0.12	0.10
	PP	25.4	0.013	0.16	0.081
	PPPE	25.4	0.026	0.23	0.11
	HDPE	25.4	0.022	0.24	0.092
	LDPE	25.4	0.023	0.38	0.061
Headless Rectangular	PPG	19.1	0.0062	0.091	0.068
	PPG	25.4	0.013	0.14	0.093
	LDPE	19.1	0.019	0.35	0.054
	LDPE	25.4	0.027	0.57	0.047
Headless Cylindrical	PPG	19.1	0.0034	0.062	0.055
	PPG	25.4	0.0087	0.17	0.051
	LDPE	19.1	0.025	0.28	0.089
	LDPE	25.4	0.024	0.52	0.046
Rocket	PPG	25.4	0.016	0.24	0.067
Pinwheel	PPG	25.4	0.014	0.28	0.050
Up-Down	PPG	25.4	0.024	0.27	0.089
Rocket	LDPE	25.4	0.028	0.50	0.056
Pinwheel	LDPE	25.4	0.020	0.73	0.027
Up-Down	LDPE	25.4	0.026	0.84	0.031

3. For the same configuration and size of jacks, flexural rigidity of the stems significantly affects the primary compression behavior, whereas cross-sectional shape has little or no influence.
4. For the same basic geometric shape of jacks, artificial soil specimens made of larger jacks are more compressible than those composed of smaller jacks.
5. Specimens containing jacks with heads are more compressible than specimens made from similar jacks without heads.
6. A simplified theory based on small bending deflection theory was developed for comparisons of primary compression of artificial soils containing jacks with different characteristics. Using this theory, the qualitative trends described in Items 2 through 4 were predicted by the theory, but quantitative values differed somewhat from the actual values.
7. Owing to the high porosities of artificial jack soils, their one-dimensional compression behavior is comparable to natural soils ranging from peat through moderately dense silt.

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