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A Concept of Time–Density Reducibility for Soil

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ABSTRACT

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A concept of time-density reducibility for soil samples, analogous to time-temperature and time-moisture simplicity is presented. Stress relaxation tests were conducted to determine the time-dependent relaxation modulus and the time-density shift function of one soil sample. The hypothesis that the concept of time-density reducibility is valid was verified for one soil sample.

INTRODUCTION

The concept of time–temperature equivalence for polymers is that, in addition to time effects, the viscoelastic functions of polymers are sensitive to temperature variations and are affected to the same extent for each unit of temperature change (Ferry, 1961). This concept was developed empirically in advance of the theories which now support it.

The concept of a moisture shift factor for samples of clay soils was developed on the basis of the argument that increasing the moisture content of clay is analogous to increasing the temperature of polymers (Krizek, 1968). Rao and Hammerle (1973) applied the concepts of time–moisture and time–temperature shift functions to the relaxation modulus of soil samples and found that the samples were hydro-rheologically as well as thermo-rheologically simple. In this paper a concept of time–density reducibility is proposed and its applicability to one soil sample is verified.

THEORETICAL CONSIDERATIONS

Krizek (1968) discussed several phenomenological soil–polymer parallels, stating that the variations in temperature affect the mobility of molecular segments of polymers and hence influence their viscoelastic functions. A change in the density of a soil sample changes the orientation and spacing of particles.

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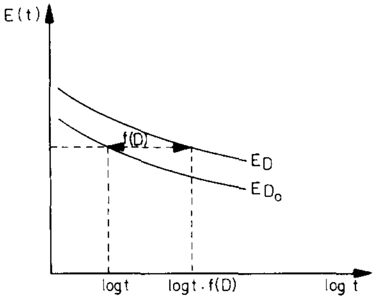

Fig. 1. Illustration of the shift principle.

This alters interlocking and attractive forces between particles, leading to changes in soil strength and viscoelastic functions. Thus, changes in density of a soil and changes in the temperature of a polymer should affect the respective viscoelastic functions in a qualitatively similar manner. This leads to the concept of time–density reducibility (shift function) for soil and to postulation of the hypothesis that for soils, in addition to time–temperature and time–moisture shift functions, there also exists a time–density shift function and like thermo- and hydro-rheological simplicity, the time–density reducibility is also an inherent property of soils.

The time–density reducibility, analogous to a time–temperature shift function, implies that the effect of density on viscoelastic properties of soil can be offset by shifting the curve horizontally along the time axis. Considering the plot of relaxation modulus of soil as a function of log t for densities D_o and D (Fig. 1), the following relationship can be derived (Seed et al., 1960; Hammerle and Mohsenin, 1970):

$$E_D\ (\log t) = E_{D_o}\ [\log t + f(D)] \tag{1}$$

where t is time, E_D and E_{D_o} are relaxation modulus functions at densities D and D_o, respectively, and $f(D)$ is measured horizontally relative to D_o as shown in Fig. 1. Let:

$$\log A_D(t) = f(D) \tag{2}$$

where A_D is a density shift factor and a function of density. Substituting eq. 2 in eq. 1 and defining reduced time, Z, as:

$$Z = tA_D \tag{3}$$

it can be written as:

$$E_D(t) = E_{D_o}\ (Z) \tag{4}$$

Hence, t units of time at density D are equivalent to tA_D units of time at density D_o. Mathematically it can be expressed as:

$$A = \frac{t_D}{t_o} \qquad (5)$$

where t_D is the time required to observe some phenomenon at density D, and t_o is the time required to observe the same phenomenon at reference density D_o. This expression is similar to the time–temperature shift function for polymers (Ferry, 1961). If the time–density reducibility is applicable to soil, then shifting a series of its property curves, measured at different densities but at one temperature and one moisture content, should produce a single master curve.

MATERIALS AND METHOD

Tests were conducted on a sample of silt loam to verify applicability of time-density reducibility to its time-dependent deformation modulus. The soil was classified according to USDA Soil Texonomy as a fine-loamy, mixed, hyperthermic Aeric Fluvaquent. The soil sample was taken of a surface layer of 20 cm thickness. It was oven-dried and passed through a 2 mm sieve. The sieved sample contained 34.3% sand, 52.5% silt and 13.2% clay as per the international classification. Its maximum void ratio ($e_{\max}$) and minimum void ratio ($e_{\min}$) were 1.93 and 0.51, respectively. The soil sample was mixed with adequate water in a mixer to obtain a moisture content of 8% on a dry weight basis. The mixture was then placed in cylindrical plastic moulds (15 cm in diameter and 10 cm deep) and was compacted with a rammer to obtain specimens of predetermined density. The specimens were prepared within a half hour of testing. The samples were sealed in containers and kept in an environment chamber at 90% relative humidity to prevent drying. The densities of the soil specimens used in this study were 1.28, 1.39, 1.45 and 1.52 Mg/m^3. The corresponding relative densities of the samples were 62.36, 73.75, 79.22 and 85.22 percent, respectively. The relative density (D_r) is defined as:

$$D_r = \frac{(e_{\max} - e)}{(e_{\max} - e_{\min})} \qquad (6)$$

where e is the void ratio of the specimen and $e_{\max}$ and $e_{\min}$ are the maximum and minimum attainable void ratios, respectively. Die loading tests were conducted on the soil samples using the Instron Universal Testing Machine (Model TM-M) to determine their force deformation and relaxation responses. A cross head speed of 10 cm/min was used for die loading and a constant deformation of 1.6 mm was maintained while the stresses relaxed. The tests were repeated three times on each sample. A computer programme, developed on the basis of an analytical method for determining viscoelastic constants presented by Chen and Fridley (1971), was used for calculation of the time-dependent deformation modulus function from the test data. Determination of the time–density shift function was done on the basis of the method for determination of time–temperature shift functions outlined by Ferry (1961).

RESULTS AND DISCUSSION

The time-dependent deformation modulus decreases with decrease in density of the soil sample (Fig. 2). To relate time to density the dimensionless values of time–density shift factors, A_D, (Table I) were estimated using eq. 2. The regression equations for the shift factor with both density difference $(D_o - D_i)$ and the relative density difference $(D_{r,o} - D_{r,i})$ were obtained. These relationships are:

$$A_D = \exp\{-29.285\,(D_o - D_i)\} \tag{7}$$

and

$$A_{D_r} = \exp\{-0.3166\,(D_{r,o} - D_{r,i})\} \tag{8}$$

where D_o and $D_{r,o}$ are the reference density (1.52 Mg/m^3) and reference relative density (85.23%), respectively. The parameters D_i and $D_{r,i}$ are the intermediate densities $(1.28 < D_i < 1.52)$ and intermediate relative densities $(62.30 < D_{r,i} < 85.23)$, respectively.

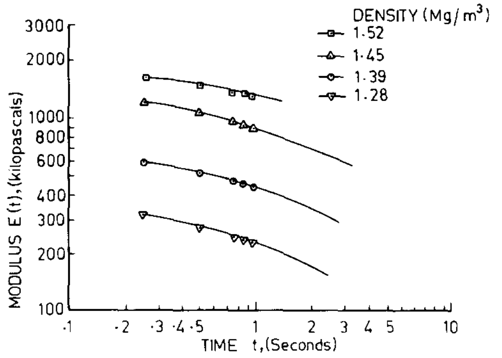

Fig. 2. Deformation modulus as a function of time for specimens of silt loam.

TABLE I

Time-density shift factor of the silt loam samples

Soil sample No.	Density (Mg/m^3)	Relative density (%)	t (s)	t_o (s)	$\Delta\log A = \log t - \log t_o$	$\Sigma\Delta\log A = \log A_D$	A_D
1	1.52	85.22	0.25	0.25	0.00	0.00	1.0000
2	1.45	79.22	0.25	1.5	−0.7781	−0.7781	0.1666
3	1.39	73.75	0.25	3.4	−1.1335	−1.9116	0.0122
4	1.28	62.36	0.25	2.55	−1.0008	−2.9202	0.0012

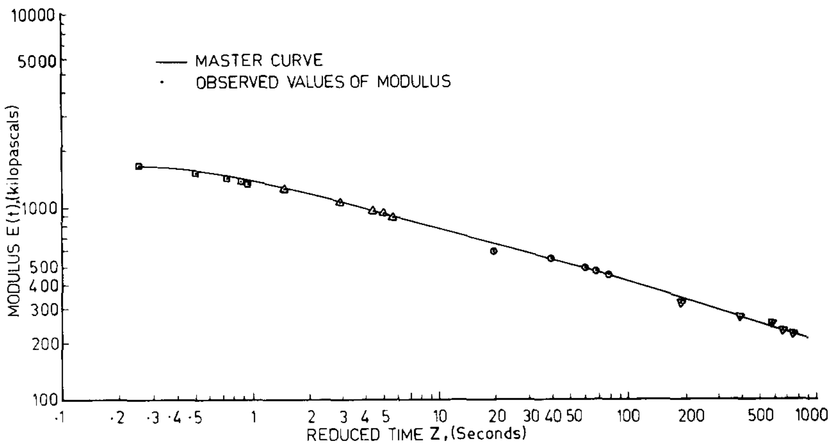

Fig. 3. Master curve for deformation modulus of the subsamples of silt loam.

The time-dependent deformation modulus $E(t)$, expressed in kilopascals (kPa), was plotted against test time t, expressed in seconds (s), for all the soil specimens at different densities. The modulus curves at different densities were shifted horizontally to higher times until coincidence with the upper curve was obtained and a single master curve at the reference density D_0 of 1.52 Mg/m^3 was achieved. The method for obtaining a master curve by graphical shifting is explained by Hammerle and Mohsenin (1970). The reduced time Z was calculated using eq. 3. The observed values of deformation modulus, when plotted as a function of reduced time, almost coincided with the master curve (Fig. 3). The paired t test applied to observed values of the deformation modulus and the corresponding values obtained from the master curve shows that the differences are not significant at 5% level of probability. This indicates that the concept of time-density reducibility is valid and applicable to the soil sample.

CONCLUSION

An expression for a time-density shift factor analogous to the time-temperature shift factor has been derived. Experimental evidence indicates that the concept of time-density reducibility is applicable to samples of a silt loam representing a fine-loamy, mixed, hyperthermic Aeric Fluvaquent.

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