Settlement of Sludge Landfills with Fiber Decomposition

Affaissement des Remblais par Décomposition des Fibres

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SYNOPSIS: Many of the engineering properties of saturated organic sludge landfill deposits are dependent upon the organic content of the materials. Because of this, changes in the organic fraction due to decomposition will effect the stability, compressibility and leachate drainage characteristics of the deposit. This, in turn, will significantly alter the impact of a landfill area on the adjacent environment. The purpose of this laboratory study has been to evaluate what effects fiber breakdown has on the compressibility behavior of these landfilled materials.

INTRODUCTION

With the advent of secondary treatment facilities, the combined saturated sludges produced by many industries and municipalities appear to have sufficient nutrients to support organic decomposition. The effects of this breakdown could significantly alter the economic and environmental impact of a landfill deposit on the surrounding area, since these sludges are now starting to exhibit instability problems and increased leachate generation rates due to this microbial activity. Previous papers have reported the environmental factors which control and influence fiber breakdown in an organic sludge deposit (Wardwell, et al., 1980). This paper presents the results of laboratory testing made to study the compressibility behavior and resulting leachate generation of a combined sludge composed of organic cellulose fiber and inorganic minerals. Long-term one-dimensional consolidation tests have been conducted on this organic sludge to determine the effects of fiber decomposition on the secondary compression and leachate production from these landfilled materials. A rheological model is proposed to represent the compressibility of these saturated sludges and other types of organic soils, both with and without fiber breakdown.

LABORATORY EXPERIMENTATION

To reduce the number of experimental variables and to achieve some degree of uniformity between the samples, a man-made organic sludge composed of various percentages of kaolin clay, cellulose fiber, and water, was used in the experiments. Although mixture was used to represent the basic components of papermill sludge, the results are expected to apply to the behavior of other organic soils and other wastewater treatment sludges.

To evaluate the effects of fiber decomposition on the compressibility of these materials, samples with varying organic contents representative of most sludges were mixed with sufficient nutrients to promote decomposition and were loaded vertically under a one-dimensional compressive load for a period of six months. Duplicated samples, deficient in nutrients, were also loaded in the same manner to determine the long-term compressibility of organic deposits without fiber breakdown and to provide control samples in evaluating the effects of decomposition on the compression characteristics.

Table I lists the samples studied and their physical characteristics. The set of numbers in the Sample Designation represents the general organic level. The symbol 'D' are those samples which were deficient in nutrients while the symbol 'S' indicates those samples which were seeded to promote microbial activity. These samples were prepared at organic levels similiar to most organic sludges and at water contents somewhat representative of those encountered with organic soils encountered in the field. C:N is the ratio of carbon substrate in each sample to the total Kjeldahl nitrogen. As such it is an indication of the level of nutrient levels in each sample.

TABLE I

Organic Sludge Properties

Sample Designation	Specific Gravity G_s	Organic Content OC (%)	Molding Water Content WC (%)	C:N
II-40-D	2.19	40.0	109.7	-
-S	2.19	37.7	118.7	41.9
II-55-D	2.07	59.8	219.6	-
-S	1.99	53.3	166.7	32.0
II-70-D	1.91	76.7	292.4	-
-S	1.91	71.6	234.7	53.0

To simulate a selected field stress condition, and to provide uniformity of the samples, the samples were placed in a specially constructed aluminum molding chamber and consolidated under a 24 kN/m^2 (500 pound per square foot) load at 100% humidity for a period of 48 hours. After specimens were cut from the sample prepared in the preloading chamber and placed in the oedometer rings, each sample was loaded to 17 kN/m^2 (350 psf) for a

24 hour period and then sequentially loaded, using a pressure increment ratio of one, to the desired final load of 48 kN/m^2 (1000 psf). The final stress was maintained for a period of 190 days while compressive movements were monitored. When dealing with the design of sludge landfills, this load increase is equivalent to a sludge layer of approximately 4.3 meters (15 feet) if the lifts are drained with interior granular blankets.

RESULTS

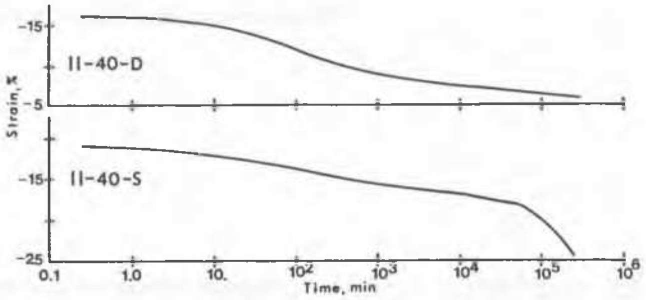
Table II lists the changes in sample characteristics which occurred during the simultaneous microbial breakdown of the fibers and compression of the sample height. The relationship between the logarithm of time and strain for the last loading sequence is presented in Figure 1. As may be seen, the time rate of settlement for organic soils is complicated by the effects of decomposition on the compressibility behavior.

TABLE II

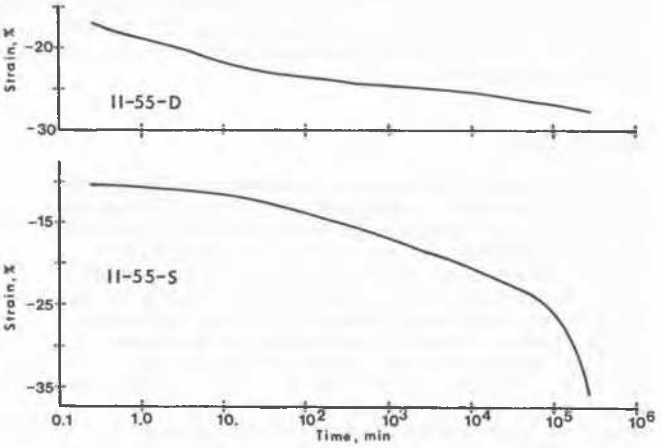
Changes in Sample Characteristics

Sample	Δ OC %	Δ WC %	Dry Density pcf initial	Dry Density pcf final	Wet Density pcf initial	Wet Density pcf final
II-40-D	---	20.8	37.1	48.2	77.7	90.9
-S	4.9	33.3	36.1	44.7	78.9	82.6
II-55-D	---	42.8	21.0	28.7	66.4	78.7
-S	6.8	53.1	26.5	36.6	70.5	77.0
II-70-D	---	53.3	16.3	21.3	65.1	71.4
-S	8.7	100.7	19.2	31.3	64.9	74.3

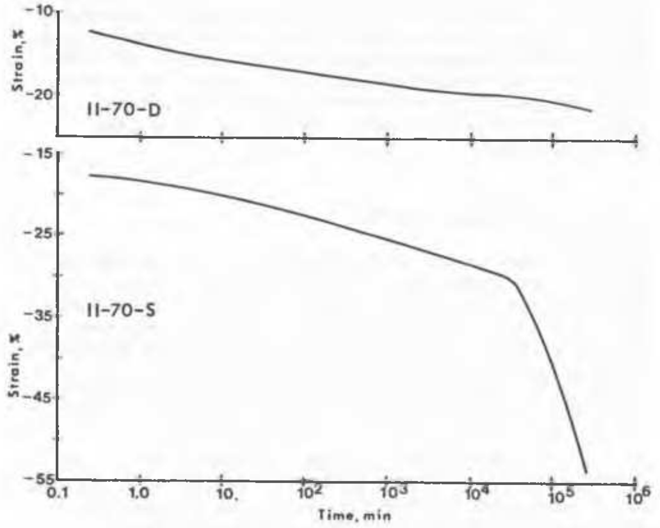
The decomposition of the cellulose fibers is a time dependent process. With a balanced, stabilized population of microbes, the decomposition of organic substrate would be expected to be constant, as evident by the constant gas production rates reported by Wardwell, et al. (1980). As a result, the secondary compressions are also influenced by this linear activity and will not always be exponentially decreasing as normally associated with secondary compression relationships without fiber decomposition. The results as shown on Fig. 1 provide evidence to support the concept that linear microbial activity influences the linear compressibility of the soil matrix. On a logarithm of time versus strain plot, the secondary compressions with fiber decomposition appear to be accelerating with time. However part of this behavior is associated with the compressed time scale at the larger log cycles of time, similar to the abrupt changes in the compression curves noticed by Lo (1961) with his Type III curve for highly compressible clays. As observed during this experiment, rapid increase in secondary compressions as plotted on logarithm of time basis is related somewhat to the linear rate of organic decomposition associated with a constant microbial activity and may not necessarily be related to entirely to an instantaneous "structural breakdown".



a) Organic Content = 40%



b) Organic Content = 55%



c) Organic Content = 70%

Fig. 1 Logarithm of Time versus Compressive Strain

EVALUATION

The compression of organic sludges and resulting leachate production is a result of a two stage process consisting of primary consolidation and long term secondary compression. Even though the magnitude of primary consolidation is relatively large with organic sludges, the high rate of secondary compression often times creates the most problems with organic deposits due to the long term nature of these movements.

Mechanisms of Secondary Compression

The secondary compression of organic sludges is caused by many mechanisms, all of which are complicated by the potential for decomposition of fiber. In a sense, each fiber strand itself is symbolic of a soil matrix containing both solid and pore volume. The compressibility of an individual fiber could be represented by a "primary" phase associated with the squeezing of the water from the micro-voids followed by the individual compression and viscous movements of the solid material itself. This compressibility however won't occur until the excess pore water pressures start to dissipate from the macropores and the fibers experience a change in effective stress. In addition to the creep properties associated with many fine grained soils, the long term settlement behavior of organic soils may therefore be attributed to the elastic properties of the organic fiber and the compression of the fiber strands associated with the squeezing of the water from the internal micropores.

The secondary behavior of organic soils is influenced by fiber decomposition in two ways: 1) in the volume loss associated with the microbial metabolism and 2) in the increase in fiber compressibility as the organic structure losses its intregrity. As shown by Fig. 1, the loss of fiber will promote significant additional compression compared to those samples where the environmental conditions are detrimental to bacterial growth. Since this decomposition process is time dependent, the increase in compressibility is also related to time as illustrated by the logarithm of time versus strain curves.

Evaluation of Secondary Strains

Table III summarizes the amount of total strain after seating with the 17 kN/m^2 (350 psf) load and the amount secondary strain which has occurred for each specimen after the last loading increment, based upon the strain results presented in Fig. 1. As a rough approximation, the amount of secondary settlement which may occur at a given site would equal the thickness of deposit times the amount of secondary strain.

For those samples in which fiber decomposition was prevalent, the coefficient of secondary compression, C_α, was not a constant value but varied with time. A more useful parameter than this non-linear coefficient in evaluation the behavior of a soil deposit is the total amount of secondary strain which has occurred with decomposition in comparison to the samples without fiber breakdown. Table 3 also presents the total strain, the secondary strain and additional secondary strain associated with fiber decomposition over comparable values for the same organic content samples without decomposition. These curves provide a means of evaluating the secondary compression when the coefficient of secondary compression is variable. As may be seen on this table, the amount of compression is significantly higher with those samples which have experienced fiber decomposition.

TABLE III

Effects of Fiber Decomposition on Compressive Strains

Sample	Total Strain after seating, ε_{total}, %	Secondary Strain ε_{sec}, %	Additional Secondary Strain with Decomposition $\Delta\varepsilon_{sec}$, %
II-40-D	16.16	5.01	-
-S	18.78	11.89	6.88
II-55-D	19.33	5.74	-
-S	31.26	22.42	16.88
II-70-D	13.96	6.34	-
-S	43.28	33.63	27.29

Using this data, Fig. 2 shows the relationship between organic content and the amount of additional secondary strain which will occur with the seeded samples over the nutrient deficient specimens. As may be seen, up to 27% more compression occurred with those samples which experience fiber decomposition. This appears to confirm the theory that changes in organic levels through fiber decomposition will have a significant affect on the compressibility characteristics of an organic deposit. In addition, the amount of additional strain increases with increasing organic contents due to the higher percentages of decomposition at the higher organic levels.

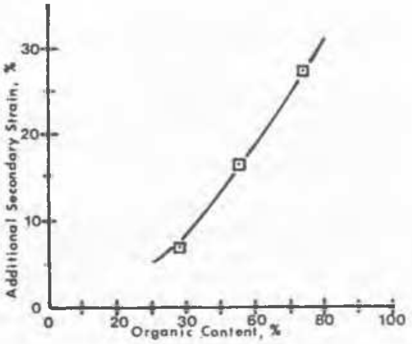


Fig. 2 Effects of Organic Content on Additional Secondary Strain

PROPOSED RHEOLOGIC MODELS

To apply the results of this testing program, a one-dimensional theory of consolidation is developed which takes into account secondary compression and the effects of fiber decomposition on the resulting strain.

Proposed Model Without Fiber Decomposition

The behavior of organic soil without fiber breakdown generally follows the basic concepts underlying Terzaghi's primary consolidation theory. However, the soil skeleton also exhibits a time dependent creep under a constant effective stress. Based on the results from the nutrient deficient samples, a model, similar to that developed by Gibson and Lo (1961) for highly compressible clays, may be used to represent the behavior of organic soils with a stable fiber content. The proposed model of the soil matrix, as presented in Fig. 3, consists of a second Kelvin-Voigt element (b_1-λ_1) placed in combination with the first element (a-λ_0) used to model the basic Terzaghi theory. These elements are composed of linear springs and linear dashpots.

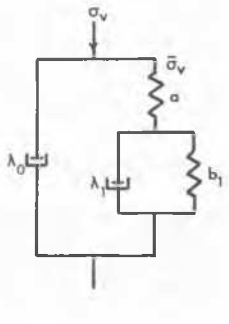


Fig. 3 Proposed Rheologic Compression Model: Organic Sludge, Without Fiber Decomposition

The behavior of the second Kelvin-Voight element, b_1-λ_1, corresponds to the process of secondary compression which occurs under sustained effective stress. For large values of time, the formula representing the secondary behavior of organic soils for step loading is:

$$\varepsilon(t) = \Delta\sigma\ [a+b_1\ \{1-\exp\ (-\frac{\lambda_1}{b_1}t)\}],\ t \geq t_a \qquad (1)$$

where $\Delta\sigma$ is the pressure increment. Eq. (1) is valid after an elapsed time, t_a, after which the excess pore pressures are completely dissipated and the applied stress has become fully effective.

The Gibson/Lo Model which is being used to represent organic soils without fiber breakdown involves four parameters: the coefficient of consolidation c_v, the viscosity of the soil structure $1/\lambda_1$, the primary compressibility 'a', and the secondary compressibility b_1. The coefficient of consolidation may be determined by using Taylor's square root plotting method (Lambe and Whitman, 1969). As described in Gibson and Lo (1961), the other parameters are estimated by looking at the behavior of these soils at long time durations, and plotting the resulting equation on logarithmic scales to evaluate the exponent as a linear relationship. Table IV presents a summary of the parameters associated with this theory.

Proposed Model with Fiber Decomposition

The observed behavior of organic soils with fiber breakdown is influenced to some degree by the linear time relationship associated with a microbial activity from a balanced population. The net result of this process is a significant break in the logarithm of time versus strain plot which appears to be an accelerated rate of secondary compression. The break in the slope occurs at a time, t_k, after a critical strain is reached. At that point, secondary compressibility of the soil matrix is increased due to the combined affects of viscous resistance and increased fiber decomposition caused by the microbial activity.

TABLE IV

Model Parameters
Without Fiber Decomposition

Sample	Compressibility		Viscosity
	Primary a (in^2/lb) $x10^{-3}$	Secondary b_1 (in^2/lb) $x10^{-3}$	$1/\lambda_1$ (lb-min/in^2) $x10^6$
II-40-D	30.1	9.1	2.5
II-55-D	38.0	11.7	3.5
II-70-D	26.1	12.4	3.5

To model the soil behavior prior to the increased secondary compressibility, the same model used for the organic soil without fiber decomposition as depicted in Fig. 3 is used to determine the viscous resistance and matrix compressibility. After the time for critical strain, t_k, a third Kelvin-Voight element, b_2-λ_2, is placed in series with the secondary compression element, b_1-λ_1, to model the increased secondary compressibility associated with the viscous resistance and increased fiber decomposition caused by the microbial activity. This model is illustrated on Fig. 4 and is similar to a model presented by Lo (1961) for loosely deposited clays.

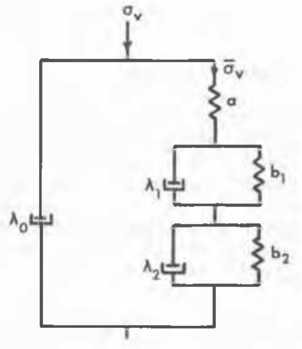


Fig. 4: Rheologic Compression Model: Organic Sludge, with Fiber Decomposition

For the time range between 100% primary consolidation, t_a, and the time that the critical value of strain occurs, t_k, Eq. (1) applies. For determination of the additional parameters b_2 and λ_2, the strain, $\varepsilon(t)$, may be shown to be:

$$\varepsilon(t) = \Delta\sigma\ [a+b_1\ \{1-\exp\ (-\frac{\lambda_1}{b_1}t)\} + b_2\ \{1-\exp\ \{-\frac{\lambda_2}{b_2}(t-t_k)\}\}],\ t \geq t_k \qquad (2)$$

in which t_k is the time at which an abrupt change in the observed settlement occurs.

The additional parameters, b_2 and λ_2, associated with the decomposition model may be found by noting that, as time approaches infinity, Eq. 2 becomes:

$$\frac{\varepsilon(\infty)}{\Delta\sigma} = a + b_1 + b_2 \tag{3}$$

Rewriting Eq. (2) in the form of:

$$\frac{\varepsilon(t)}{\Delta\sigma} - [(a+b_1)-b_1 \exp (- \frac{\lambda_1}{b_1} t)] = [b_2 - b_2 \exp \{- \frac{\lambda_2}{b_2} (t-t_k)\}] \tag{4}$$

and subtracting it from Eq. (3) results in:

$$\frac{\varepsilon(\infty) - \varepsilon(t)}{\Delta\sigma} - b_1 \exp (- \frac{\lambda_1}{b_1} t) = b_2 \exp \{- \frac{\lambda_2}{b_2} (t-t_k)\} \tag{5}$$

Taking the logarithm of Eq. (5) results in:

$$\log_{10} \{\frac{\varepsilon(\infty) - \varepsilon(t)}{\Delta\sigma} - b_1 \exp (- \frac{\lambda_1}{b_1} t)\} = \log b_2 - 0.434 \frac{\lambda_2}{b_2} (t-t_k) \tag{6}$$

A plot of $\log_{10} [\{(\varepsilon(\infty) - \varepsilon(t)/\Delta\sigma\} - b_1 \exp \{(-\lambda_1/b_1)(t)\}]$ against time, t, yields the intercept b_2 and the slope of 0.434 λ_2/b_2. Table V lists the parameters associated with this model

TABLE V

Model Parameters With Fiber Decomposition

Sample	Initial Compressibility			Critical Point		Additional Compressibility	
	Primary a (in^2/lb) x10^{-3}	Secondary b_1 (in^2/lb) x10^{-3}	Viscosity $1/\lambda_1$ (lb-min/in^2) x10^{6}	Time t_k (min) x10^{3}	Strain ε_k (%)	Secondary b_2 (in^2/lb) x10^{-3}	Viscosity $1/\lambda_2$ (lb-min/in^2) x10^{6}
II-40-S	21.2	10.6	5.0	60.5	9.70	29.4	10.0
II-55-S	33.1	30.0	1.8	82.0	17.88	70.4	3.0
II-70-S	38.4	26.1	2.1	31.6	17.16	86.9	2.1

As presented on Table IV and V the primary compressibility factors are similar between the deficient and seeded samples at the same organic level and do not appear to be influenced by fiber breakdown. However, for those samples with fiber decomposition, the initial secondary compressibility factor, b_1, was consistently larger than the same value determined for those samples without fiber breakdown. For a given sample, the additional compressibility factor, b_2, associated with fiber breakdown is two to three times larger than the initial compressibility factor, b_1, and in fact is larger than primary compressibility, 'a'. The critical time at which this accelerated compression occurred corresponded with the break in the arithmetic relationship between time and deflection and appears to be related to that microbial activity. These results emphasize the influence of fiber decomposition on the settlement characteristics of organic sludges.

CLOSURE

This study analyzed the effects of fiber decomposition on the long-term laboratory compression of organic sludge deposits. Since many of the engineering properties of saturated sludge landfill deposits are dependent upon its organic content, changes in the organic fraction due to fiber breakdown affects the field settlements of these deposits and, in turn, the associated leachate generation from these materials.

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REFERENCES

Gibson, R.E., Lo, K.Y. (1961) A Theory of Consolidation for Soils Exhibiting Secondary Compression, NGI Pub. No. 41, Oslo.

Lambe, T.W., Whitman, R.V. (1969) Soil Mechanics, 553 pp., Wiley, New York.

Lo. K.Y. (1961) Secondary Compression of Clays, JSMFE, ASCE (87), SM4, 61-87, New York.

Wardwell, R.E., Doxtader, K.G., Charlie, W.A. (1980) Behavior of Combined Papermill Sludges with Fiber Decomposition, Proc. 1980 TAPPI Envir. Conf., Atlanta.