This is to certify that the

thesis entitled

STRENGTH AND COMPRESSIBILITY
OF FRESH AND DECOMPOSING
PAPERMILL SLUDGE

presented by

RICHARD KEITH LOWE

has been accepted towards fulfillment
of the requirements for

M.S. degree in CIVIL ENGINEERING

O. B. Andersland
Major professor

Date May 19, 1981

STRENGTH AND COMPRESSIBILITY
OF
FRESH AND DECOMPOSING
PAPERMILL SLUDGE

By

Richard Keith Lowe

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Civil Engineering

1981

ABSTRACT

STRENGTH AND COMPRESSIBILITY
OF FRESH AND DECOMPOSING
PAPERMILL SLUDGE

By

Richard Keith Lowe

This study was prompted when a paper mill operating a sludge landfill began experiencing operational problems following the disposal of excess biological solids resulting from secondary treatment processes. Sludge instability, the generation of large amounts of leachate, and difficulty in maneuvering haul equipment on the sludge were among the problems encountered. A laboratory research program was initiated to determine the physical and engineering properties of a primary and a combined primary and secondary papermill sludge. The effect of decomposition of the organic fraction on sludge strength was also investigated.

Physical and engineering properties, including consolidation behavior and shear strength, were measured for fresh sludge samples to determine the effects of the addition of secondary sludge. Decomposition of the combined sludge was accelerated for the laboratory study by the addition of nutrients, in proportions similar to those in a bacterial cell, and seed micro-organisms followed by sample storage at $35^{o}C$ between tests. The ignition test provided information on the organic content of fresh and partially decomposed samples.

Decomposition of the sludge organic fraction reduced the amount and strength of interlocking fibers in the sludge mass. In addition to a

reduction in sludge strength, large amounts of gas were generated, the permeability of the sludge was greatly reduced, and sludge volume change increased 25 percent due to 27 percent decomposition.

ACKNOWLEDGEMENTS

The writer wishes to express his appreciation to Dr. O. B. Andersland, Professor of Civil Engineering, for the standards he set during the writer's education and for his guidance, encouragement, and patience during this research. Thanks are also due to other members of the guidance committee; Dr. C. E. Cutts, Professor of Civil Engineering and Dr. L. E. Vallejo, Assistant Professor of Civil Engineering. The writer also wishes to express his appreciation to the people at Soil Testing Services of Wisconsin, Inc. for their help in supplying information during preparation of the manuscript. Special thanks are also due my wife, Carol, for typing the manuscript and for her patience during my graduate studies.

Thanks are also due to Nekoosa Papers Inc., Port Edwards, Wisconsin, for supplying the sludges and financial support which made this research possible.

TABLE OF CONTENTS

Chapter Page

LIST OF TABLES

TABLE		Page

TABLE		Page

LIST OF FIGURES

FIGURE		Page

FIGURE Page

LIST OF SYMBOLS

A = area; or pore pressure parameter

A_f = pore pressure parameter at failure

a = primary compressibility of soil skeleton, in^2/lb

$\bar{a}$ = y intercept, effective stress basis

B = pore pressure coefficient

b = secondary compressibility of soil skeleton, in^2/lb; or slice width

C_c = compression index

C_α = coefficient of secondary compression

c_v = coefficient of consolidation

c_{vo} = original coefficient of consolidation

c_{vi} = coefficient of consolidation after ith degree of decomposition

$\bar{c}$ = cohesion

c_u = $(\sigma_1 - \sigma_3)/2$ = undrained shear strength

dz = differential thickness

e_o = initial void ratio

G_s = specific gravity

H = consolidating layer thickness

H_o = original sample height

H_d = decomposed sample height

H_{of} = original field thickness of a peat layer

H_{ol} = original laboratory thickness of a peat sample

ΔH_f = field primary compression of a peat layer

ΔH_l = laboratory primary compression of a peat sample

H_s = secondary compression

h = head of water; or slice height

k = coefficient of permeability

k_o = original coefficient of permeability

k_i = coefficient of permeability after ith degree of decomposition

k_f line = line through $\overline{p}_f$ versus $\overline{q}_f$ plots

$M_\alpha = \cos\overline{\alpha} + \sin\overline{\alpha}(\tan\overline{\phi}/\text{Factor of Safety})$

$\overline{p}$ = effective consolidation pressure

$\overline{p}_f = (\overline{\sigma}_1 + \overline{\sigma}_3)/2$

$\overline{q}_f = (\overline{\sigma}_1 - \overline{\sigma}_3)/2$

S = settlement

T = dimensionless time factor

t = time

t_p = time for primary compression

u = pore pressure

Δu = pore pressure change

V_o = sample volume

V_c = sample volume after consolidation

ΔV = volume change

W = weight

W_1 = ovendry sample weight

W_2 = weight of ash after ignition

W_w = weight of water

W_s = weight of solids

W_m = weight of mineral matter

W_{fc} = weight of cells produced by decomposition

$\overline{W}_{fi}$ = weight of undecomposed organic matter after partial decomposition

W_{fi} = total weight of organic matter

W_{fo} = weight of undecomposed organic matter

W_{fp} = weight of decomposition byproducts

w = water content

X_f = organic fraction

X_{fo} = initial organic fraction

X_{di} = degree of decomposition

X_{fi} = organic fraction after ith degree of decomposition

y = cell yield

$\bar{\alpha}$ = angle of k_f failure line; or angle between vertical and line connecting center of base of slice and center of failure circle

γ_d = dry unit weight

γ_w = wet unit weight

ε_v = vertical strain

$\bar{\sigma}_1$ = effective major principal stress

$\bar{\sigma}_3$ = effective minor principal stress

$\bar{\sigma}_c$ = consolidation pressure

$\bar{\sigma}_o$ = initial or present overburden pressure

$\Delta\bar{\sigma}$ = change in stress

$1/\lambda$ = viscosity of soil structure, lb-sec/in^2

τ = shear strength

$\bar{\phi}$ = angle of internal friction

CHAPTER I

INTRODUCTION

During the summer of 1976, Nekoosa Papers, Inc. began operating a sludge landfill for disposal of its primary papermill sludge. Prior to site development, a comprehensive geologic investigation included the installation of a groundwater monitoring system. Site operation proceeded as designed, with sludge placement on a progressive ramp and travel on roadways constructed over the sludge. Confinement dikes provided lateral restraint while a small active filling area was maintained. In the fall of 1977, secondary treatment facilities began producing excess biological solids which were dewatered in conjunction with the primary sludge and the combined sludge was disposed of in the landfill.

After introduction of the combined primary and secondary sludge, movement of the sludge pile toward perimeter dikes was noted. The active area of the sludge pile exhibited instability including sloughing of the sludge pile and drainage of large quantities of leachate from the toe and active face. Disposal in this area was curtailed, while perimeter dike heights were increased several times to confine what appeared to be a increasing volume of sloughing sludge and leachate. These problems were blamed on lower consistencies of the combined primary and secondary sludge.

The initial intent of this study was to contribute information relative to sludge stability, drainage, trafficability and probable long term landfill performance through a review of available literature, laboratory testing and analysis. In considering long term landfill performance, it was decided to include, as part of this study, the effects of possible decomposition of the organic fraction of the sludge material on its stability, settlement and drainage.

A review of pertinent literature was initiated in an effort to determine if similar problems had occurred at other sludge disposal sites and if corrective measures could be applied to this study site. A laboratory research program included determination of the physical properties of the primary and combined primary and secondary sludge. Engineering properties of the sludge materials, including consolidation characteristics and shear strength, were evaluated in one dimensional consolidation tests and triaxial strength tests, respectively.

Decomposition of the organic fraction of the combined sludge was accelerated by the addition of nutrients, in proportions similar to those found in an average bacterial cell, and seed micro-organisms. Microbial attack on fibers, including a reduction in length, diameter, and structural integrity, are associated with a reduction in shear strength. Triaxial strength tests provided information on changes in the sludge compressibility and strength due to decomposition. Significant strength reductions and higher volumes of leachate released by decomposing sludges reduce landfill stability and increase the need for internal drainage systems.

CHAPTER II

LITERATURE REVIEW

A. Physical Properties of Papermill Sludge

The physical properties of papermill sludges serve as a basis for comparison of different sludge types and give a qualitative indication of their engineering behavior. Some physical properties of interest to the engineer in designing a papermill sludge landfill include composition, water content, unit weight, organic fraction, specific gravity, pH, and permeability.

1. Composition

The physical and chemical characteristics of pulp and papermill primary sludges vary widely depending on the type of products produced, source of wood fiber, plant design and efficiencies. The major sludge constituents include: water, noncombustible solids (clay fillers, titanium oxide, aluminum hydrate, ferric chloride, and lime) and an organic portion composed of cellulose (wood fibers), starches, dextrins, and trace amounts of other organic compounds. The relative proportions of each of these constituents are influenced to a high degree by the grade of paper produced by the mill. Where the product is heavy paper or board, requiring a low filler content, the resulting sludge will have a high fiber content and will be relatively easy to dewater. Fine paper or heavily coated board requires the use of mineral fillers and coatings which, when lost in processing, lead to a high ash sludge which resists dewatering, due in part to the coating of the cellulose fibers by mineral constitutents.

With an increase in number of pulp and paper mills utilizing secondary waste activated treatment systems, the need arises for disposal of the excess biological solids. According to surveys conducted by the National Council of the Paper Industry for Air and Stream Improvement, Inc. (N.C.A.S.I.) in 1975 and 1976, more than 80 percent of the paper mills identified as practicing dewatering of biological solids were doing so in combination with primary sludges. The availability of adequate quantities of primary sludge solids and the inability to obtain landfillable or economically combustible cakes of secondary sludge at costs comparable to those incurred in dewatering the combined sludges are given as the main reasons for this practice. Secondary sludges generally require conditioning prior to dewatering in order to achieve satisfactory solids capture efficiencies. Depending on the dewatering system employed, additives such as polymers, lime, flyash, alum and ferric chloride are used as flocculants in conjunction with primary sludges to increase dewatering efficiency.

The major components in a number of pulp and paper mill residues are given in Table 2.1. As seen in Table 2.1, the percentage of each constituent may vary widely depending on the particular mill. The significance of these variations is seen in the influence which various constituents have on physical properties and behavior of the sludge residue.

2. Water Content

The water content, w, of a soil or sludge is defined as the ratio of the weight of water, W_w, to the weight of dry solids, W_s, expressed as a percentage, $w = (W_w/W_s)100\%$. In comparison with mineral soils, organic soils (including papermill sludge) generally have much higher water contents which vary markedly with different mills and also within

TABLE 2.1 MAJOR COMPONENTS OF PULP AND PAPER MILL RESIDUES

(After Perpich and Zimmerman 1978)

Item (dry weight basis unless noted)	Range (%)
Moisture (% total weight)	60 to 80
Ash	10 to 55
Wood fiber	25 to 90
Biological solids	0 to 25
Lime and ferric chloride	0 to 40
Titanium dioxide	0 to 5
Kaolin (clay)	0 to 52

TABLE 2.2 PERMEABILITY VALUES OF PULP AND PAPER MILL RESIDUES
(after Perpich and Zimmerman, 1978)

Residue type	Ash (% dry weight)	Permeability (cm/sec)
primary	52	3×10^{-6}
primary	20	5×10^{-7}
primary/secondary	16	4×10^{-7}
primary/secondary	45	3×10^{-5}
primary	40	2×10^{-5}
primary	40	1×10^{-5}
loose primary/secondary	40	2×10^{-3}
consolidated primary (at 500 psf)	--	2×10^{-7}

deposits from a single mill (Gillespie, et al., 1970; Andersland, et al., 1972). Because of the high water content of papermill sludges, some prefer to use solids content. The solids content is defined as the ratio of the weight of solids to the wet sample weight expressed as a percentage and is related to the water content by the expression:

$$w(\%) = 100 \frac{100}{(\%\ \text{dry solids} - 1)} \qquad (2.1)$$

In examining primary sludge samples taken from eight different sites representing ages up to 15 years, water contents were found to vary from 740 percent to 46 percent (Gillespie, et al., 1970). The variation in the vertical direction was greater than that in the horizontal direction, but was inconsistent with depth or overburden pressure, indicating that stratification was due to production changes at the mills during the past placement history.

The compressibility (volume change) and thus the volume of water expelled, and the shear strength (stability) are both highly dependent on the sludge solids or water content. Sludges with higher water contents will experience greater volume change under an applied load. The volume reduction of the sludge is accompanied by a nearly equal volume of leachate released. A sludge of low solids content has little shear strength while the same material at successively higher solids contents will acquire considerable shear strength (Charlie, et al., 1979).

3. Unit Weight

The wet unit weight of sludge may be defined as the weight of the sludge-water aggregate per unit volume. The unit weight is influenced by the water content, the unit weight of the solid constituents, and the degree of saturation. The dry unit weight, γ_d, is determined from the relationship:

$$\gamma_d = \gamma_{wet}/(1 + w) \tag{2.2}$$

where γ_{wet} is the total unit weight and w is the water content (dry weight basis). The total unit weight of fresh sludges before dewatering may approach that of water (62.4 PCF) while the unit weight of a dewatered sludge cannot exceed that of the solid constituents.

Values reported by Andersland, et al., (1972) and Charlie, et al., (1979) indicate that for freshly dewatered primary or combined primary and secondary sludge, the total unit weight was approximately 70 PCF. The materials' unit weight, used in calculating the overburden pressure at various depths in a sludge deposit, is required for settlement and stability calculations. Mineral soils, with much larger unit weights, used in conjunction with sludge for landfill drainage blankets and final cover have a pronounced affect on settlement and stability calculations.

4. Organic Fraction

Organic matter includes those sludge components containing carbon with the exception of methane, carbon dioxide, and hydrolysis products of carbon (Eastman, 1978). The most common method for measurement of soil organic content is ignition at high temperature to a constant weight. The weight loss expressed as a percentage of the oven dry sample weight before ignition is taken as the organic fraction. MacFarlane (1969) found that this procedure could be in error by up to 15 percent at higher temperatures, due to loss of surface hydration water from the clay minerals and thermal decomposition of carbonate. A new method proposed by Al-Khafaji and Andersland (1981) recognizes this behavior and uses an ignition temperature of $400^{\circ}C$ until a constant weight is obtained. This lower ignition temperature minimizes loss of surface hydration water and allows the organic fraction (X_f) to be calculated within $\pm$ 1 percent accuracy as:

$$X_f = 1 - 1.02 \, (W_2/W_1) \qquad (2.3)$$

where W_2 is the weight of ash after ignition and W_1 is the oven dry sample weight prior to ignition.

5. Specific Gravity

The specific gravity of a papermill sludge can be defined as the ratio of the weight in air of a given volume of sludge solids to the weight in air of an equal volume of distilled water at 4^oC. The procedure for specific gravity determination follows that outlined in ASTM Designation D854-72.

Accurate determination of the specific gravity is difficult due to large amounts of entrapped air or gas bubbles in the sludge material. Andersland, et al., (1972) reported values for the specific gravity of primary sludge ranging from 1.87 to 2.24 with the average being just slightly greater than 2.0. Specific gravity may be estimated by the proportion of mineral solids and organic material. Values for high ash sludges may approach the specific gravity of the mineral fraction and can be approximated using a weighted average for the specific gravities of the organic and mineral fractions (Al-Khafaji, 1979).

6. Hydrogen Ion Concentration (pH)

The hydrogen ion concentration (pH) is a measure of the acidity or alkalinity of a solution. The pH of a papermill sludge is usually of interest in studying the effect of the leachate on the groundwater, but it is also of interest due to its influence on the decomposition process. A neutral pH (between 6 and 8) is one of the most important factors in promoting microbiological activity needed for the decomposition process

(Al-Khafaji, 1979).

The effect of the addition of lime, used as a conditioner in the dewatering process, is that it also raises the pH of the freshly dewatered sludge. Few micro-organisms can survive if the pH is above 11. The pH, in addition to influencing decomposition, has been shown to influence vane shear strengths as shown in Figure 2.1.

7. Permeability

The coefficient of permeability, k, is a constant of proportionality related to the ease with which water passes through a porous medium. Test methods for direct determination of k are described by Bowles (1978).

Falling head permeability tests conducted on primary papermill sludge have shown the existence of a threshold gradient below which no flow occurs (Andersland and Laza, 1972). After this threshold gradient was exceeded, large variations in k with the average head of water were observed, especially at higher organic fractions (Figure 2.2). These findings lead to the conclusion that gas bubbles in the sludge substantially contribute to reduced leachate flow rates and development of a residual pore water pressure observed in an experimental landfill study (Andersland, et al., 1972).

Values of k for papermill sludges have been shown to be dependent on the water (or solids) content, the organic fraction, and additives such as lime (Andersland and Laza, 1972). Some representative values of k for various types of papermill sludge are given in Table 2.2.

B. Stress Deformation Behavior of Papermill Sludge

An efficient landfill design requires information on the volume change and stability of papermill sludge in response to stress changes.

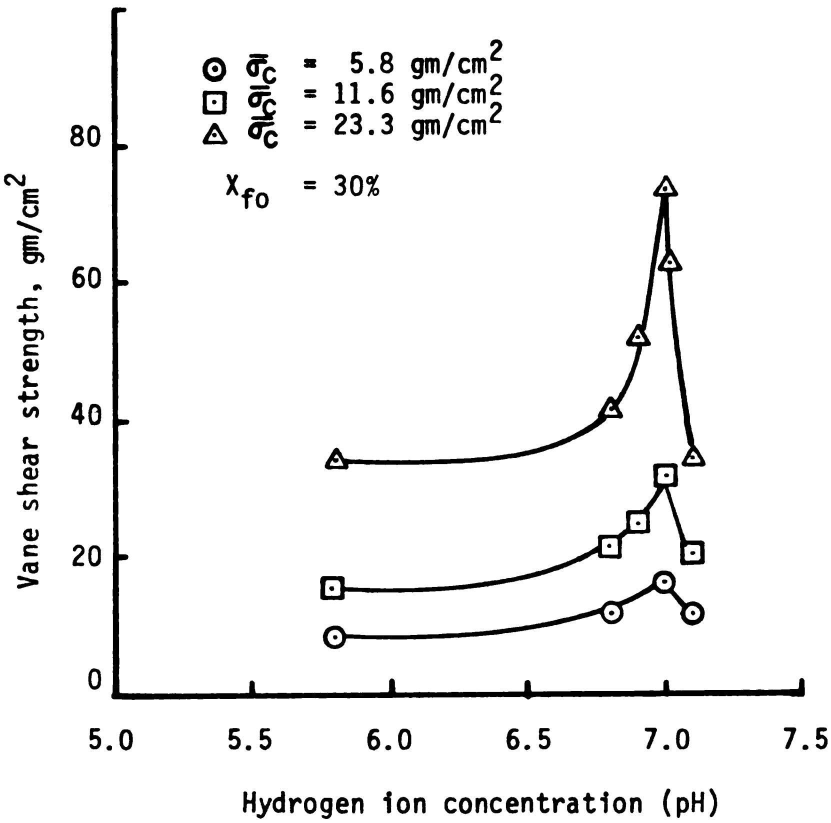


Figure 2.1 Vane shear strength versus pH, anaerobic conditions. (after Al-Khafaji, 1979).

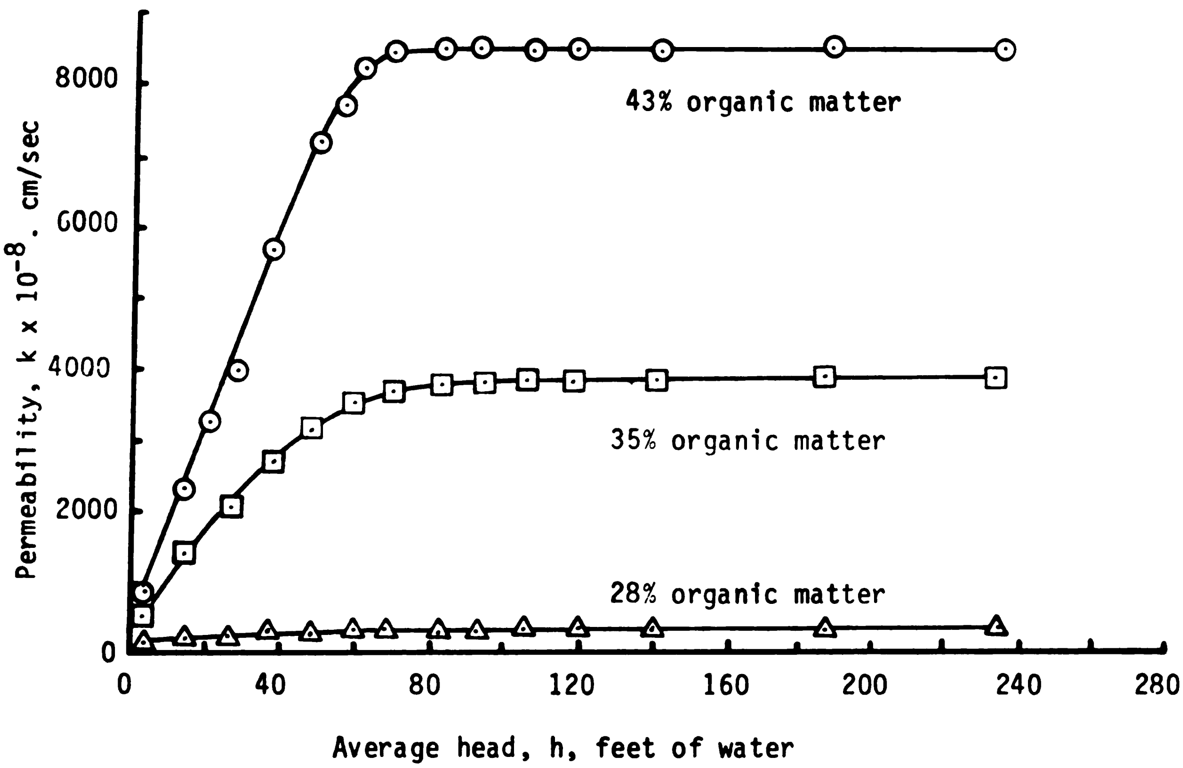


Figure 2.2 Changes in permeability with changes in organic content and head (after Laza, 1971).

Information on the compressibility and shear strength of papermill sludge are summarized.

1. Compressibility

Compression of papermill sludge, when placed in a landfill, results in a decrease in sludge volume accompanied by surface settlements. This volume reduction, involves a time dependent release of leachate and results in more space available for landfilling.

Volume change and settlement. Terzaghi's (1943) one-dimensional consolidation theory assumes that volume changes associated with a consolidating stratum occur only in the vertical direction and the resulting change in surface elevation is termed settlement. For highly compressible clays and organic soils (including papermill sludges) this settlement includes both primary and secondary compression. A common method of estimating the primary compression, S, for a soil or sludge material involves integration of the equation:

$$S = \int_0^H \varepsilon \, dz \cong \int_0^H \frac{C_c}{1 + e_0} \log_{10} \frac{\bar{\sigma}_0 + \Delta\bar{\sigma}}{\bar{\sigma}_0} \, dz \qquad (2.5)$$

where C_c is the compression index, e_0 is the initial void ratio, $\bar{\sigma}_0$ is the effective vertical overburden pressure, $\Delta\bar{\sigma}$ is the stress increment, and dz is a thin layer summed over the layer thickness H. Equation 2.5 has been found to adequately predict primary settlement in an experimental high ash papermill sludge landfill (Vallee, 1973). One-dimensional laboratory consolidation tests provide parameters required in the use of equation 2.5 (see Figure 2.3 for typical results). Another method of estimating primary compression, ΔH_f, in a peat layer of initial thickness H_{of} involved the expression:

$$\Delta H_f = \frac{H_{of}}{H_{o1}} \Delta H_1 \qquad (2.6)$$

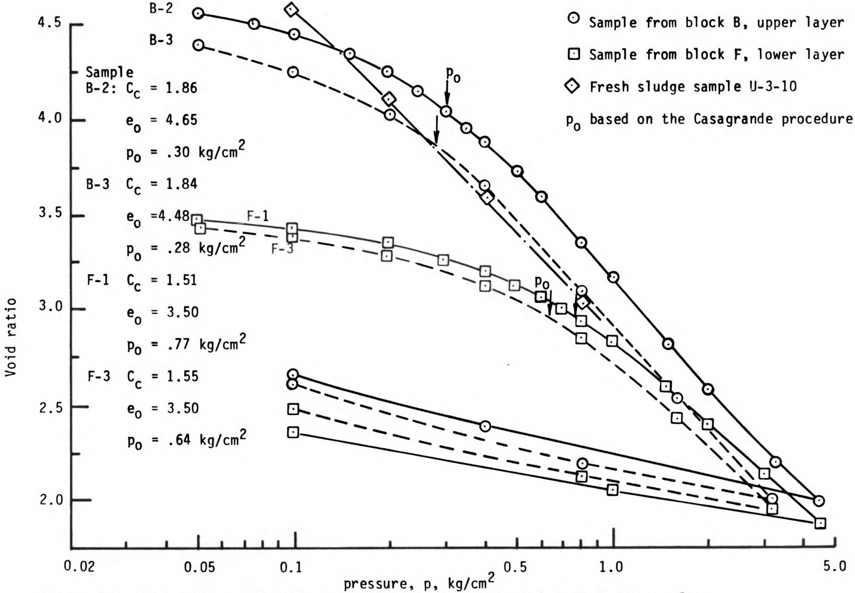


Figure 2.3 Void ratio-- effective stress relationships, undisturbed sludge samples. (after Vallee, 1973).

where ΔH_1 is the compression of a laboratory sample of original thickness H_{01} (MacFarlane, 1969). Equation 2.6 was also found to adequately predict surface settlements in an experimental landfill (Vallee, 1973).

Secondary (long term) compression is usually linearly continuous with the logarithm of time, proportional to the applied load and layer thickness, and may be estimated on the basis of the equation

$$H_s = HC_\alpha \log t/t_p \tag{2.7}$$

where H_s is the secondary compression, C_α is the coefficient of the secondary compression and equals the slope of the long term settlement versus log time plot divided by the sample thickness at the beginning of the long term stage (Figure 2.4), t is the field time considered, t_p is the estimated field time for primary compression, and H is the thickness of the peat layer at time t_p. Other methods of estimating total compression (Gibson and Lo, 1961; Wahls, 1962) have been found to yield results in general accord with field observations (Figure 2.5).

Consolidation behavior. Time rate of settlement predictions involving primary compression are usually based on Terzaghi's (1943) one-dimensional consolidation equation given as:

$$\frac{du}{dt} = c_v \frac{d^2u}{dz^2} \tag{2.8}$$

where u is the excess pore pressure at time t at a distance z from the midpoint of a doubly drained stratum, and c_v is the coefficient of consolidation. Solution of equation 2.8 requires the use of tabulated dimensionless factors (Perloff and Baron, 1976) and knowledge of the coefficient of consolidation, c_v. These dimensionless factors are based on the results of several consolidation tests, which show that the time (t) required to reach a given degree of consolidation increases in

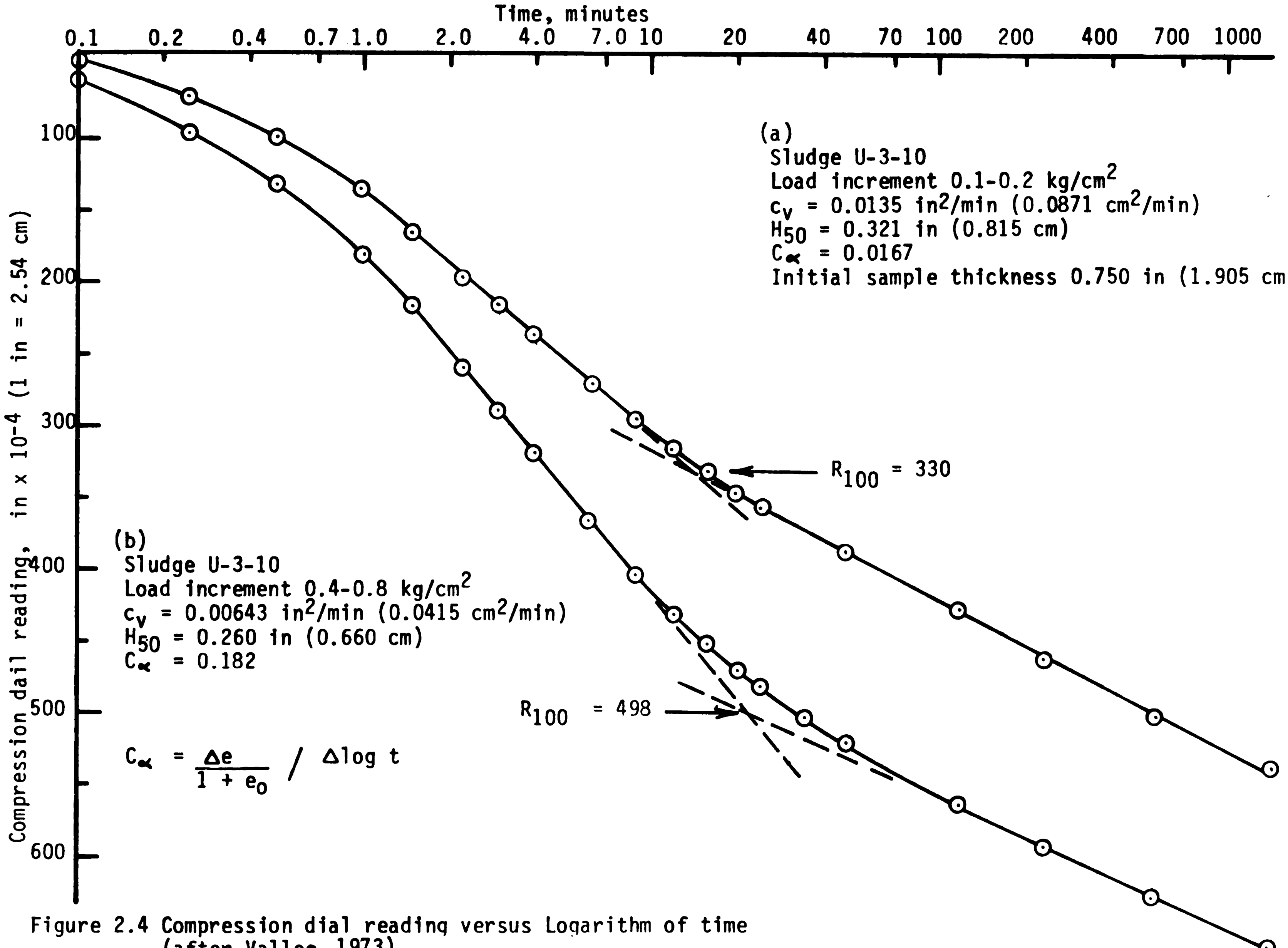


Figure 2.4 Compression dial reading versus Logarithm of time (after Vallee, 1973).

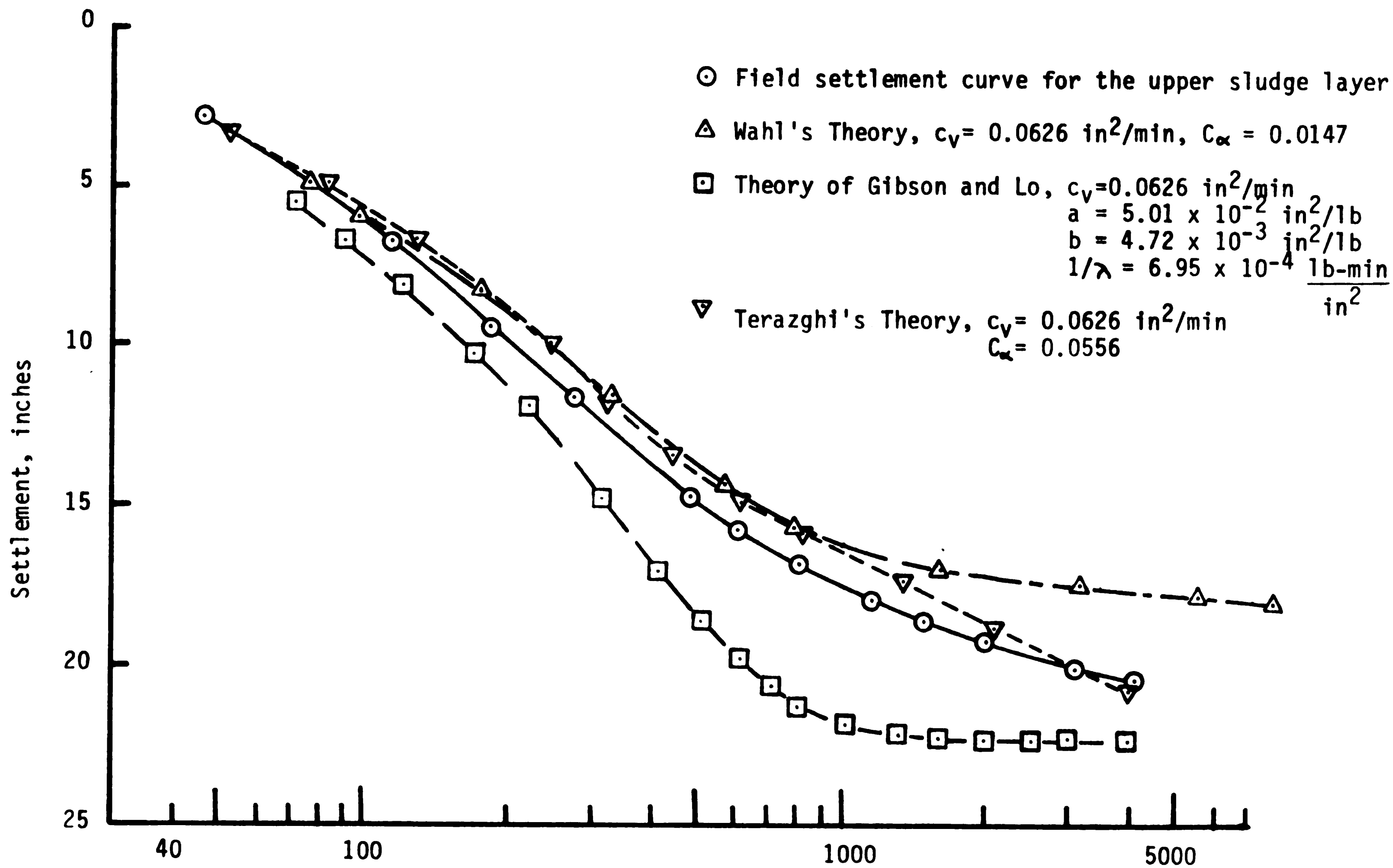


Figure 2.5 Comparison of actual and predicted time-settlement curves (after Vallee, 1973)

proportion to the square of the thickness of the layer (H) (Terzaghi and Peck, 1967), hence the relationship

$$t = \frac{TH^2}{c_v} \qquad (2.9)$$

where T is a tabulated dimensionless time factor.

The governing factor affecting the time-settlement relation appears to be the selection of a representative value of c_v. Vallee (1973) reports average laboratory values of c_v to be nearly four times smaller than backfigured field values of c_v. Similar results were observed on several peat embankments in British Columbia where it was suggested that the time required for a given degree of consolidation (t_{field}) be calculated as

$$t_{field} = \frac{H_{o\ field}^{i} \times t_{lab}}{H_{o\ lab}^{i}} \qquad (2.10)$$

where H_o is the initial layer or sample thickness and i is an exponential parameter (generally 1.5 for peat, but may be as high as 2.0) (MacFarlane, 1969; Lea and Brawner, 1963).

Leachate generation. Consolidation settlement, involves volume change as pore water is squeezed from the sludge. The amount of expelled water (leachate) will equal the volume change of the sludge less any change in gas volume (Charlie, et al., 1979).

2. Shearing Resistance

The components of shearing resistance (cohesion, dilatancy, and friction) are dependent on soil composition (Lambe, 1960) and determine in part the behavior of excavated slopes in these materials and the stability of embankments constructed on them. While freshly dewatered papermill sludges of low solids content possess little strength, the same material consolidated to a higher solids content may acquire considerable strength (Andersland, et al., 1972; Charlie, et al., 1979). Proceeding on the assumption that conventional shear strength theories, used to describe mineral soil behavior, apply to papermill sludge, the undrained and drained strength characteristics are outlined below.

Total stress basis. Due to the low permeability of saturated papermill sludges, pore pressures caused by rapid construction on, or excavation in these materials may take several days to dissipate. This may approximate an undrained condition ($\bar{\Phi} = 0$ analysis) where the strength, $c_u = 1/2\ (\sigma_1 - \sigma_3)_f$, may be determined from undrained triaxial tests, unconfined compression tests, or vane shear tests. The results are often expressed as a ratio of undrained shear strength to consolidation pressure (c_u/p). An interesting result of undrained triaxial tests conducted on a model sludge (pulp fiber and kaolinite) shows the linear dependence of c_u/p on fiber content (Figure 2.6).

Effective stress basis. Since the strength of a saturated soil is not constant but changes with effective stress, drainage (consolidation) occurring during load application increases the effective stress, and thus the soil shear strength. Measurement of pore water pressures during undrained triaxial tests allows determination of the effective stress strength envelope,

$$\tau = \bar{c} + (\sigma - u)\tan\bar{\Phi} \qquad (2.11)$$

which is normally tangent to the drained test envelope (Wu, 1976). The terms in equation 2.11 are defined in Figure 2.7. As shown in Figure 2.8, consolidated-undrained ($\overline{\text{CIU}}$) and consolidated-drained (CID) triaxial tests on fiber-clay soils have given widely differing values for the shear strength parameter $\bar{\Phi}$ when compared on an effective stress basis. The unusually high friction angles obtained from the $\overline{\text{CIU}}$ test are due to

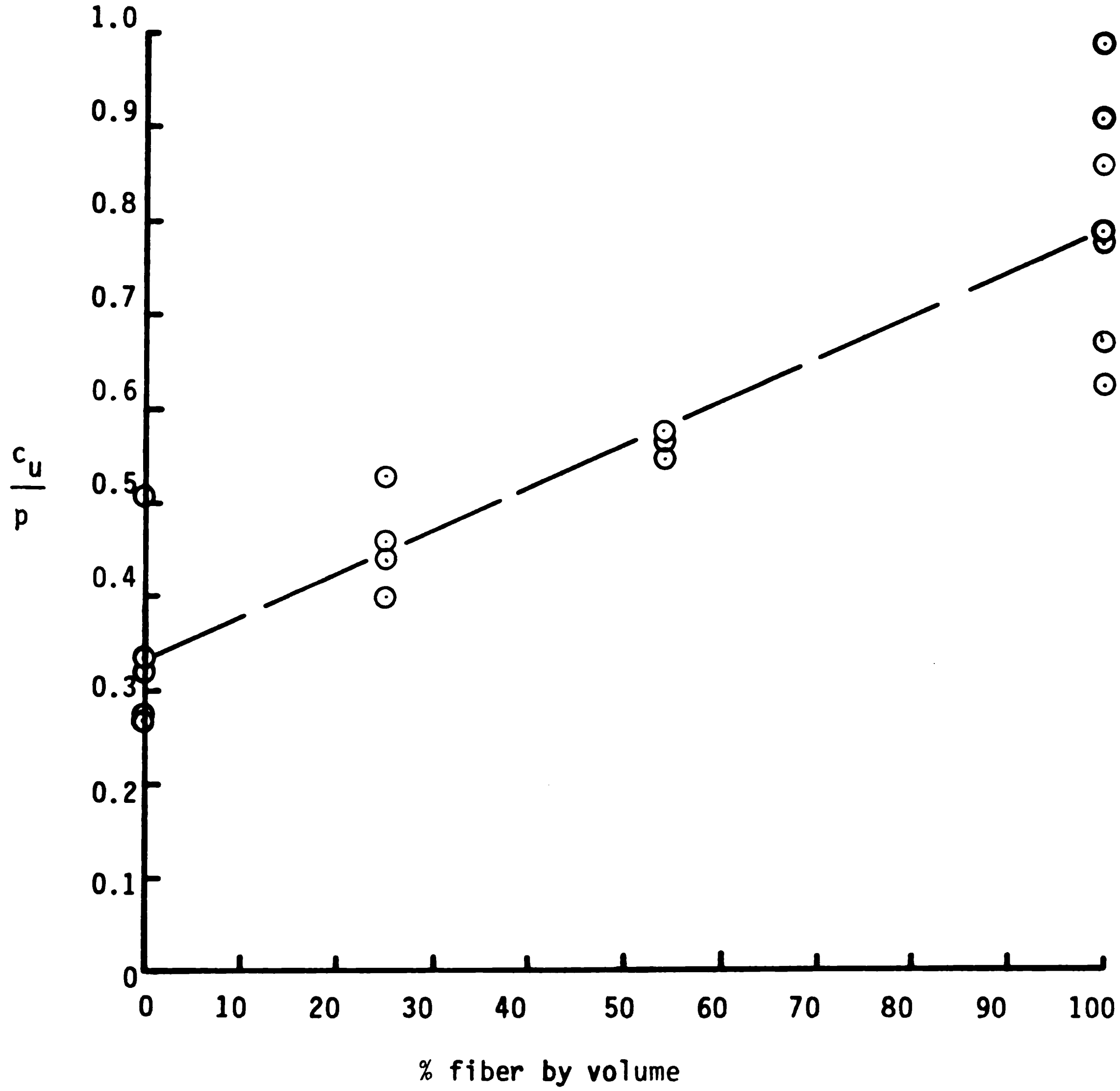
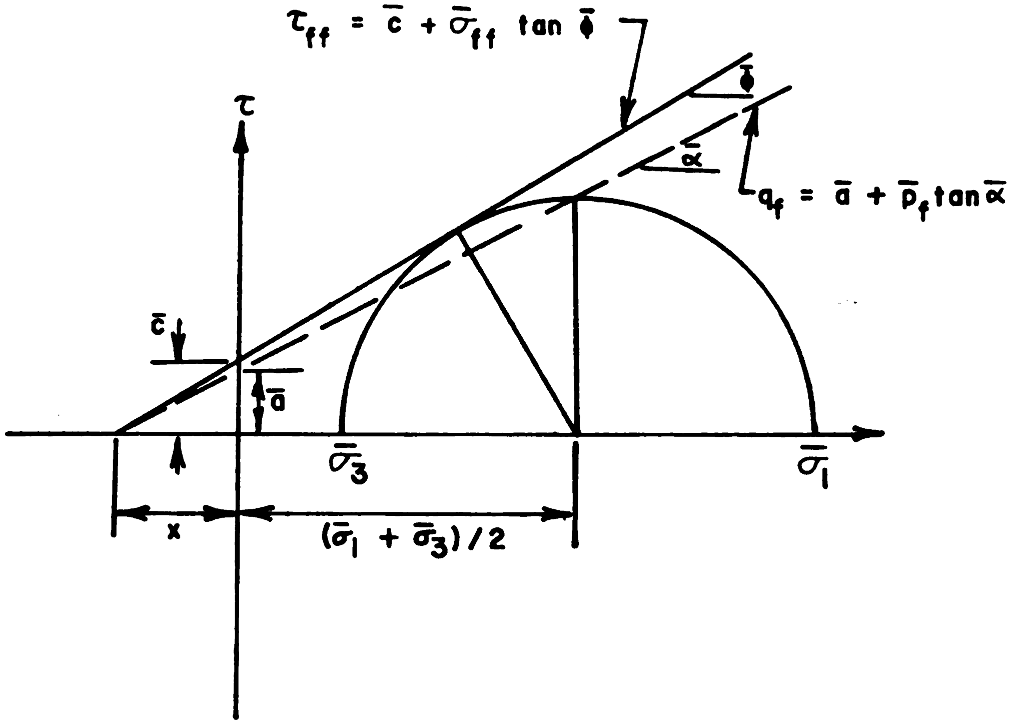


Figure 2.6 Ratio of undrained strength to consolidation pressure versus Percent fiber by volume (data from Khattak, 1978).



$$\tan \bar{\alpha} = \frac{(\bar{\sigma}_1 - \bar{\sigma}_3)/2}{(\bar{\sigma}_1 + \bar{\sigma}_3)/2 + x}$$

$$\sin \bar{\phi} = \frac{(\bar{\sigma}_1 - \bar{\sigma}_3)/2}{(\bar{\sigma}_1 + \bar{\sigma}_3)/2 + x}$$

$$\therefore \tan \bar{\alpha} = \sin \bar{\phi}$$

$$\tan \bar{\alpha} = \frac{\bar{a}}{x} \quad \text{or} \quad x = \frac{\bar{a}}{\tan \bar{\alpha}}$$

$$\tan \bar{\phi} = \frac{\bar{c}}{x} \quad \text{or} \quad x = \frac{\bar{c}}{\tan \bar{\phi}}$$

$$\therefore \frac{\bar{a}}{\tan \bar{\alpha}} = \frac{\bar{c}}{\tan \bar{\phi}}$$

$$\text{but } \tan \bar{\alpha} = \sin \bar{\phi}$$

$$\therefore \frac{\bar{c}}{\tan \bar{\phi}} = \frac{\bar{a}}{\sin \bar{\phi}}$$

$$\bar{c} = \frac{\bar{a}}{\cos \bar{\phi}}$$

Figure 2.7 Equations and definitions for shear strength theory, effective stress basis.

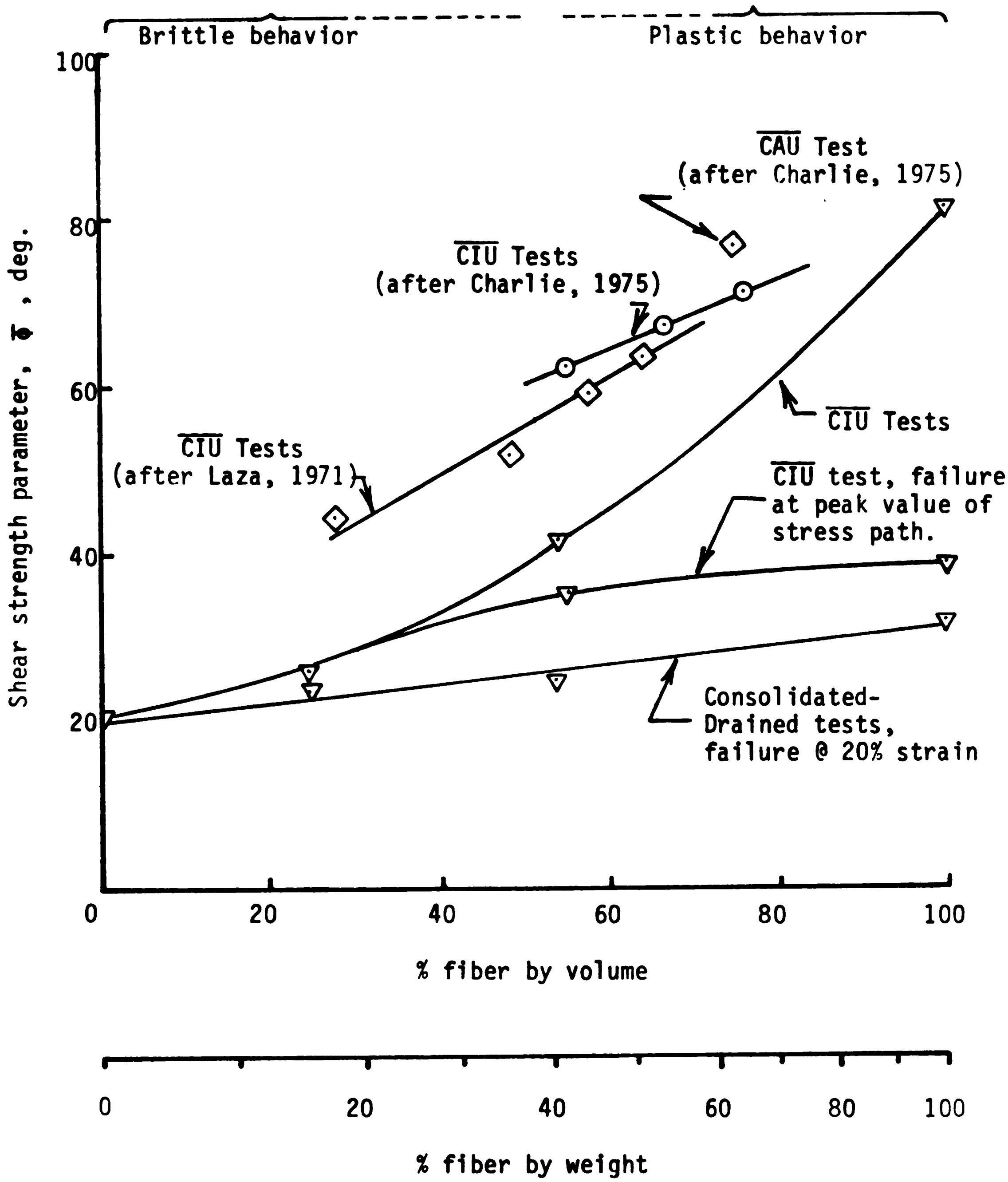


Figure 2.8 Fiber (organic) content vs. Shear strength parameter $\bar{\Phi}$, consolidated undrained and consolidated drained triaxial tests (after Khattak, 1978).

fibers being able to transfer tensile loads across potential failure surfaces. For higher organic fractions, the pore pressure will approach the cell pressure causing the effective minor principal stress ($\bar{\sigma}_3$) to approach zero. Nevertheless, the high fiber content corresponds to a friction angle ($\bar{\phi}$) approaching 90 degrees (Andersland and Charlie, 1975; Khattak, 1978). The large friction angles obtained from the undrained triaxial test and the continued increase in stress for strains approaching 30 percent have led researchers to question the validity of the test method and seek other definitions of failure.

An alternate method for defining failure involves the maximum ratio of shear stress to effective normal stress (maximum obliquity) which results in intermediate $\bar{\phi}$ values as shown in Figure 2.8 (Andersland, et al., 1981). There is no information available regarding the use of these $\bar{\phi}$ values for field stability applications.

C. Decomposition of Sludge Materials

In the past engineers have designed papermill sludge landfills assuming little or no fiber decomposition with greater attention being given to the existing engineering properties and field behavior of these materials as influenced by solids content and organic fractions (Andersland and Charlie, 1975). With the advent of secondary treatment facilities many mills are mixing waste activated sludge with primary sludge before dewatering and landfilling the combined mixture (Miner and Marshall, 1975). Nutrients added during secondary treatment processes to promote growth of BOD removing aerobic bacteria may contain sufficient amounts of nitrogen and phosphorous to support anaerobic bacterial growth and fiber decomposition (Al-Khafaji, 1979; Charlie, et al., 1979). A review of the processes involved in decomposition and their affects on settlement and stability are discussed below.

1. Decomposition Processes and Observed Field Behavior

Decomposition of organic soil components is dependent on the availability of nutrients, moisture, and suitable temperatures. In field deposits aerobic decomposition generally develops above the water table were sufficient nutrients and oxygen are available. The rate and extent of aerobic decomposition are also influenced by the nutrient and oxygen concentration and by the moisture content, temperature, and pH level.

Anaerobic decomposition involves the activity of anaerobic microorganisms where no oxygen is present; primarily below the ground water table. This process is slower than aerobic decomposition, occurs at lower temperatures, and produces foul odors. The anaerobic micro-organisms transform complex organic materials into simpler forms of organic by-products resulting in a decrease in the organic solids fraction while producing carbon dioxide, volatile acids, methane, water, and new bacterial cells (Al-Khafaji, 1979). These changes in the sludge can drastically alter its mechanical behavior over a period of time.

2. Effects on Compressibility

Decomposition reduces the organic solids volume of an organic soil. The effect of decomposition on settlement characteristics of fiber-clay soils under a constant effective consolidation pressure of 3.42 kPa (34.9 gm/cm^2) is shown in Figure 2.9. A decrease in sample height of about 57 percent due to 50 percent decomposition of the organic fraction was observed for a pressure of 3.42 kPa (34.9 gm/cm^2). Settlement versus time data collected during load application permitted the evaluation of c_v using the Taylor square root of time method. Figure 2.10 shows the

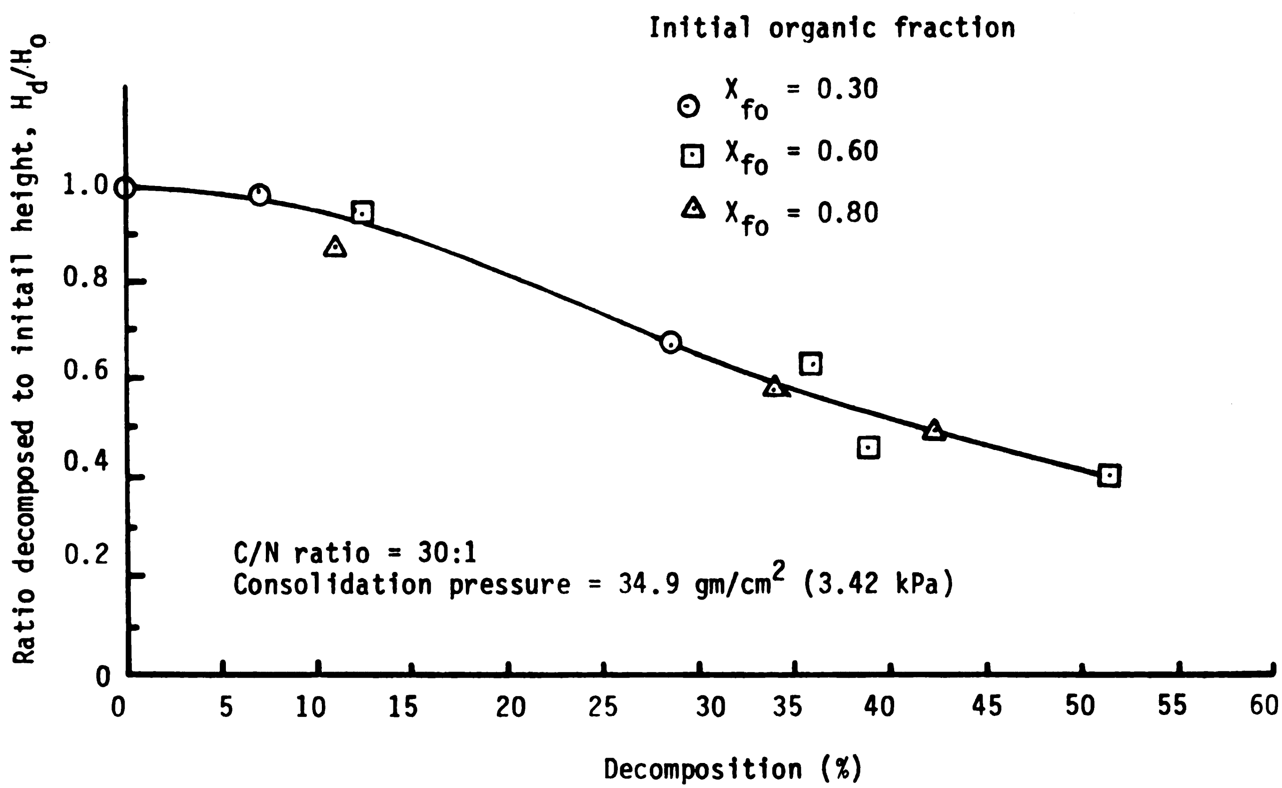


Figure 2.9 Ratio of decomposed to initial sample height versus Percent decomposition (after Al-Khafaji, 1979).

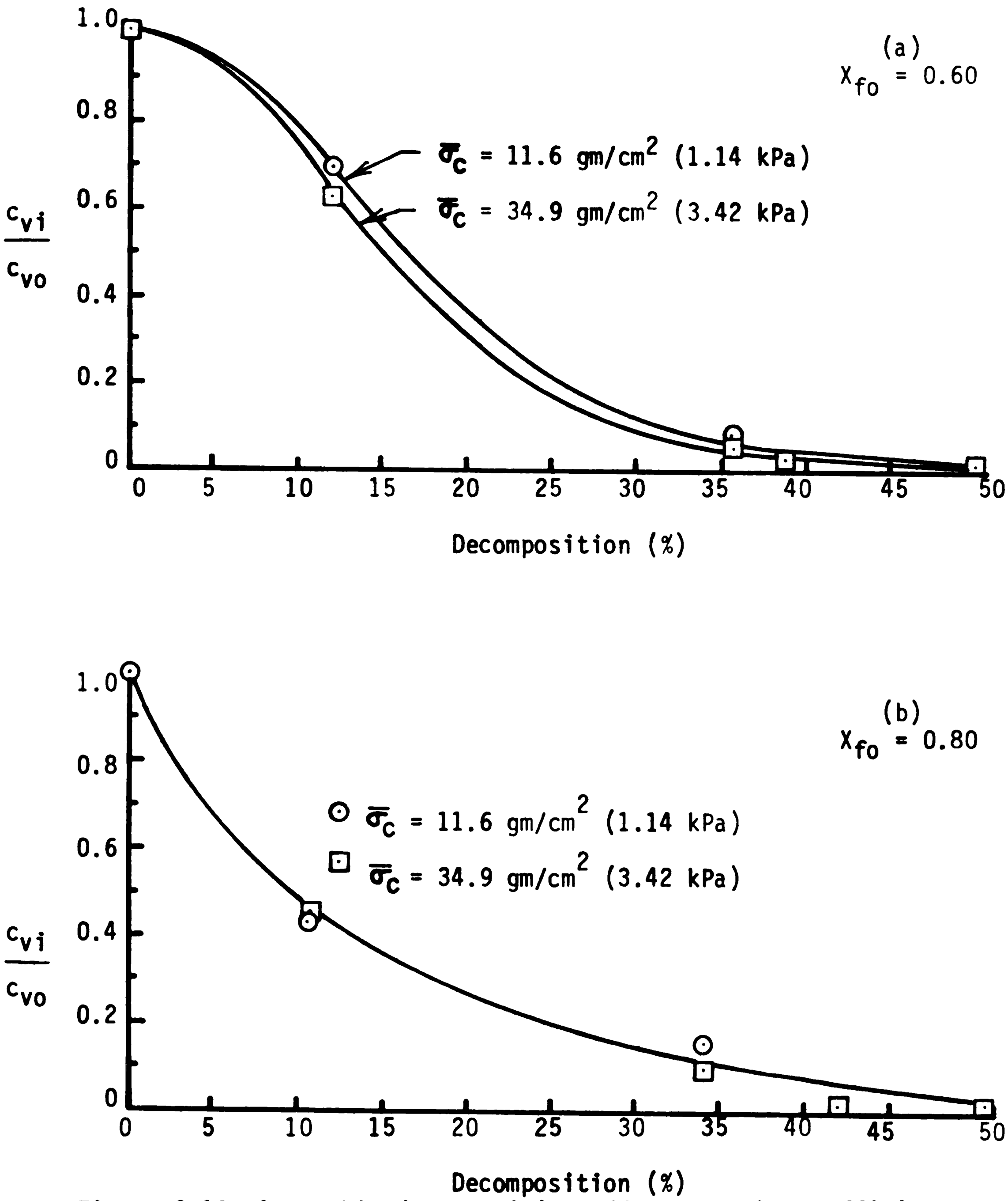


Figure 2.10 Anaerobic decomposition effects on the coefficient of consolidation. (a) Initial organic fraction X_{fo}=0.60. (b) Initial organic fraction X_{fo}= 0.80. (after Al-Khafaji, 1979).

decrease in c_v with increasing decomposition. Indirect determination of the coefficient of permeability k, through use of c_v in conjunction with other consolidation test data, at various stages of decomposition gave the results shown in Figure 2.11.

Based on these results, one would expect decomposition in a papermill sludge landfill deposit to result in large surface settlements accompanied by a large volume of leachate draining from the sludge for long periods of time and the production of foul odors due to gas generation. Conditions must be suitable for decomposition if these changes are to occur.

3. Decrease in Strength

The short term (no decomposition) stability of papermill sludge as determined from the undrained shear strength appears to be highly dependent on the solids content or consolidation pressure (Charlie, et al., 1979) and fiber size and content. Disintegration of fibers in papermill sludge, as a result of decomposition, decreases the reinforcement due to interlocking fibers leading to a reduction in undrained shear strength. The increased compression resulting from decomposition of organic solids would tend to counteract this decrease in strength (Charlie, et al., 1979).

Miniature vane shear tests performed on fiber-clay soils at various stages of decomposition under a common consolidation pressure yielded results shown in Figure 2.12. Significant decreases in vane shear strength would have serious implications relative to the stability of papermill sludge landfill deposits experiencing small amounts of decomposition.

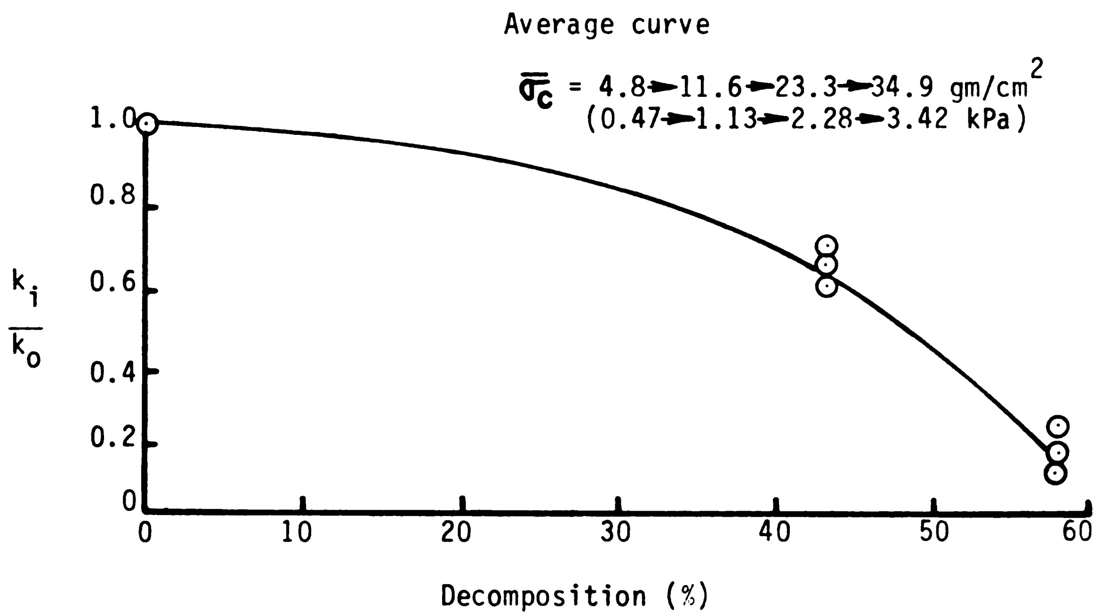


Figure 2.11 Anaerobic decomposition effects on the coefficient of permeability, initial organic fraction X_{fo}=0.80. (after Al-Khafaji, 1979).

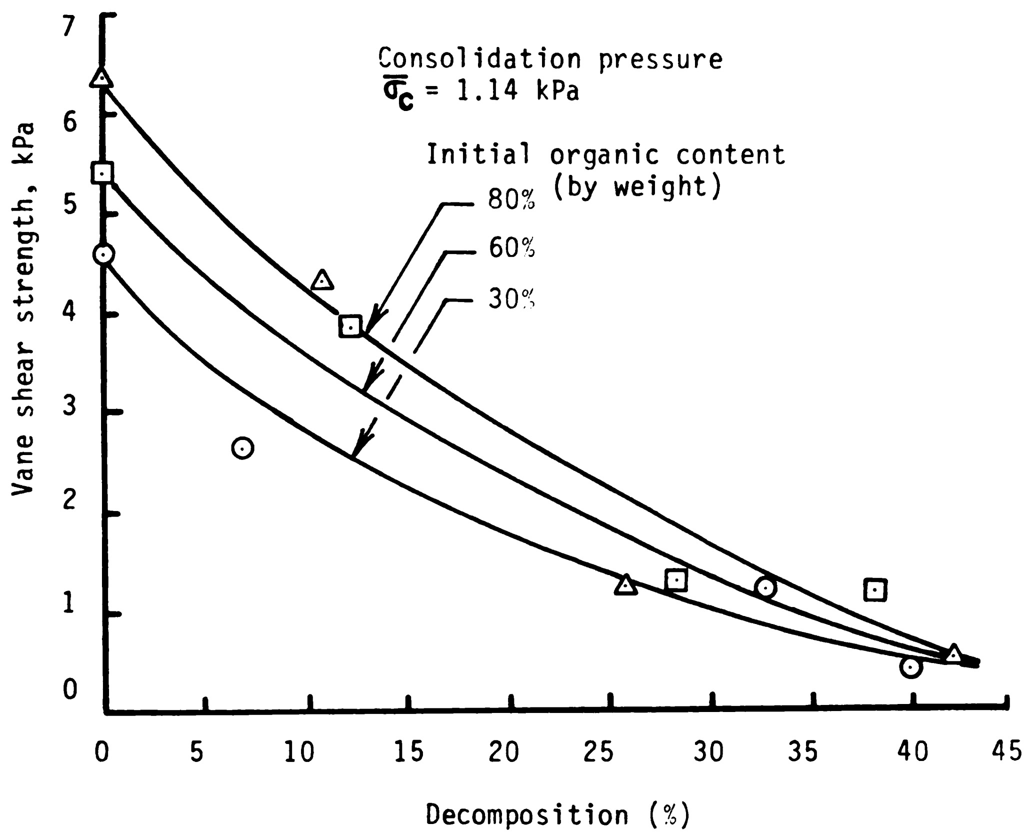


Figure 2.12 Vane shear strength versus Decomposition for three model organic soils (kaolinite and pulp fiber) at a consolidation pressure of 1.14 kPa (after Al-Khafaji,1979).

D. Current Landfill Practices

The pulp and paper industry generates large quantities of waste effluent, of which a portion is recovered as settled solids requiring an economical and environmentally sound method of disposal. After primary settling, many mills further treat their effluent by chemical and biological means resulting in the generation of excess biological solids which also require disposal. At the present time the most widely practiced method of disposal is a solid waste landfill site designed and licensed to accept papermill waste.

Since dewatering processes are normally continuous operations which generate up to 400 cubic yards of residue per day, transportation costs require the landfill site be located near the dewatering plant. Considerations for the proper geologic setting, determined from studies of the soil profile, bedrock geology, hydrogeology, and surface drainage characteristics, have been outlined by Perpich (1976).

Two methods of landfill operation, which have received favorable response from licensing agencies, are forming the landfilled sludge into a large progressive ramp utilizing small containment dikes for leachate control or a cellular type construction with dikes used for lateral confinement of the residue. The latter method, in many cases, uses vertical lifts of 10 to 20 feet separated by horizontal sand layers to promote drainage. Specific methods of landfill operation and their performance are outlined below.

1. Trafficability and Placement

Freshly dewatered pulp and papermill residues are usually of such a soft consistency that they will not support vehicles other than lightweight, wide-tracked bulldozers. Performance studies at a landfill operated by Nekoosa Papers, Inc. indicated that a small dozer with standard tracks encountered considerable difficulty when maneuvering on the sludge outside the progressive ramp roadway area. Experience at a landfill in Rumford, Maine, operated by the Boise Cascade Paper Group, which disposes of sludge very similar to the combined sludge generated by Nekoosa Papers, Inc., has indicated that a wide-track muskeg dozer was very successful in spreading the landfilled sludge (Charlie, et al., 1979).

In the progressive ramp type construction a minimum amount of dike construction is required, but transporting the sludge to the small active area of the pile necessitates construction of haul roads on the sludge material in many cases. One method of road construction which has been found successful at a number of sites, shown in Figure 2.13, uses materials readily available at most papermills. In a cellular type construction, sand dikes constructed in some convenient geometric from usually serve as haul roads with the sludge being dumped into the cell and spread by a dozer or muskeg tractor.

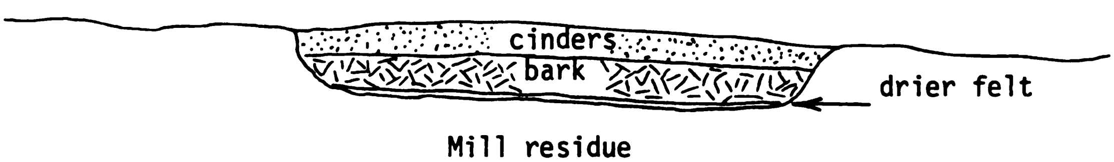


Figure 2.13 Road construction on mill residue (after Perpich and Zimmerman, 1978).

Sludges of lower consistency (low solids content) will tend to flow at flat angles and may require lateral confinement provided by a cellular type of construction, whereas for higher consistency sludges, disposal in a large ramped pile may be more economical.

In a landfill operated by the Boise Cascade Paper Group in Rumford, Maine, a large active area was maintained with the sludge being spread by a muskeg dozer in horizontal layers. This method of operation was conveniently used with horizontal sand drainage blankets between lifts of sludge. Effectiveness of this mode of operation is dependent to a large degree on the type of equipment used in spreading the sludge and its maneuverability. If equipment spreading the sludge can effectively move the sludge away from haul roads or sand dikes, the distance between dikes can be increased requiring a much smaller volume of sand for berm construction, thus maximizing the space available for filling per acre of land.

2. Rate and Extent of Landfill Volume Change

As sludge accumulates in a landfill disposal site, the material near the bottom of the landfill consolidates under the pressure of the overlying material. This densification results in additional volume available for landfilling. The engineer must estimate this volume change when predicting the life of a landfill. The long term deformation must be considered when shaping final contours so that surface drainage will be maintained for the life of the landfill (Perpich, 1976).

Consolidation tests performed on representative fresh sludge samples are useful in predicting the volume change expected under landfill conditions. The pore water drainage during consolidation (roughly equal to the sample volume change) is useful in estimating the amount of leachate expelled from the landfill. This pore water drainage will occur gradually over the life of the landfill and also for several years after filling to completion. Methods for estimating the volume of leachate expelled from a landfill, as a function of time, have been given by Charlie, et al., (1979). Leachate generation rates will be useful in waste treatment volume estimates and in evaluating the environmental impact of the site. Data on leachate generation rates, rainfall, runoff, and evapotranspiration may be used in conjunction with infilitration rates of the natural subsoils to estimate leachate dilution and contamination potential.

3. Landfill Stability

Consolidation, in addition to decreasing the sludge volume also enhances the material stability. Assuming that papermill sludges behave in accordance with the Mohr-Coulomb failure theory,increased overburden pressure and consolidation will increase the sludge shear strength, provided pore water pressures are allowed to dissipate. The undrained (short term) strength of primary and combined sludges appears to be related to the solids and organic content (Charlie, et al., 1979). Many existing papermill sludge landfills, without drainage systems, retain low solid contents and very low shear strength and stability of both primary and combined primary and secondary sludge deposites.

A case study at the Boise Cascade Papermill in Rumford, Maine, describes problems identical to those experienced at the Nekoosa Papers, Inc. landfill in Saratoga, Wisconsin. Large quantities of leachate draining from the sludge pile was followed by sloughing of the sludge deposit toward the low containment dikes. Low slope angles were observed. The instability was attributed to the low sludge solids content, low shear strength, and additional factors including steep subgrade and possible fiber decomposition. Modification of the operational plan included placement of a 12 inch thick blanket drain over the existing subgrade with underdrain pipes for collection of leachate. Sludge lifts 10 feet thick were separated by drainage blankets including underdrain and collector pipes. This construction method proved successful for approximately 16 months, after which, sludge lift thicknesses were increased to 20 feet without difficulty. It was estimated that after the sludge consolidated, the deposit would be stable at slopes steeper than 45 degrees (Charlie, et al., 1979).

The large volume of sand required to construct the granular drainage layers, the cost of the collection pipe, and the need for construction of haul roads over the sludge increased the operating costs. However, the additional consolidation resulted in nearly tripling the site capacity, increased stability, and provided a positive method for leachate collection. Where site preparation costs are high (i.e., in the case of clay liners or extensive networks of leachate collector pipes) the benefit from the additional consolidation is an increase in stability, which in turn allows increased sludge volumes to be stored per acre of land.

CHAPTER III

MATERIALS STUDIED, SAMPLE PREPARATION, AND TEST PROCEDURES

A. Materials Studied

The sludge materials used in this study were obtained from Nekoosa Papers, Inc. Water Quality Center in Saratoga, Wisconsin. Samples were obtained immediately after being dewatered by a vacuum filtration system. Small amounts of sludge were obtained over a period of time (approximately 60 minutes) and combined to form a larger more representative sample. The samples were stored in air tight bags at about 40^{o}F (4^{o}C) prior to laboratory testing.

Two samples types were collected; an untreated primary sludge and the typical sludge produced at the plant, a combined primary and secondary sludge conditioned with polymer and lime. Neither of these sludges fit the definition of a high ash sludge as given by Gillespie, et al., (1970). As indicated by their respective organic contents and visual appearance, both of these sludges would be considered highly fibrous. An attempt was made to obtain samples of combined sludge representative of the material deposited in the landfill, while primary sludge samples were obtained for comparison purposes.

Both the primary and combined primary and secondary sludge materials were similar in color to wet brown cardboard. Visual examination of both sludges revealed pieces of bark up to an inch in length, numerous wood chips, and measurable fibers averaging 6 millimeters in length. Both sludges contained fine filler materials too small to be visually identified. The primary sludge had a higher proportion of fiber and wood chips than did the combined sludge. The primary sludge averaged 27.0 percent solids (270 percent water content) of which approximately 49 percent was organic compared to the combined sludge which was of a softer consistency, averaging 23.9 percent solids (318 percent water content) with an organic fraction equal to 58 percent. The organic fraction of the primary sludge was composed primarily of bark, wood chips, and cellulose fiber. The organic fraction of the combined sludge contains the organic material contributed by the primary sludge and nearly all the biological solids from the secondary sludge. A summary of the sludge physical properties is given in Table 4.1.

B. Test Procedures and Sample Preparation

Equipment and test procedures used in evaluating the physical properties and stress deformation characteristics of the papermill sludges are given in this section. Standard test procedures are referenced where applicable, with deviations from procedure and special methods of sample preparation described in greater detail.

1. Physical Properties

Information on the physical properties of papermill sludges are useful in providing a qualitative evaluation of their field behavior. Water content, unit weight, organic fraction, specific gravity, and pH are considered in the following sections.

Water content. The water content of a soil or sludge, which is the ratio of the weight of water to the weight of dry soil or sludge in the sample, was determined by drying at a temperature of 105^{o}C. Details outlining the test procedure are given in ASTM D2216-71. Since the water content of a papermill sludge is usually very high, some prefer to use solids content as a basis for comparison. A simple conversion from water content to solids content was given by equation 2.1.

Unit weight. The unit weight or density of a sludge material is defined as the weight of the sludge material per unit volume. The test procedure involved careful packing of the sludge into a container of known volume (1/10 ft^3) and weighing to determine the quantity of sludge contained in the bucket. The sludge was placed in five equal lifts and kneaded by hand to eliminate air pockets. Care was taken to avoid any water loss from the sample during placement of the top layer. The measured unit weights of the sludge materials are given in Table 4.1.

Organic content. The procedure for determining the organic fraction of a soil, or papermill sludge has been given by ASTM D2974-71. This method involves firing an oven dried sample at 550^oC, which results in dehydration of the clay minerals and can lead to errors of up to 15 percent (MacFarlane, 1969; Al-Khafaji, 1979). Al-Khafaji (1979) tested kaolinite and fiber samples at various temperatures for different burning durations and found that ignition at 400^oC would eliminate much of the error due to loss of surface hydration water. The organic fraction may be calculated by use of equation 2.3. The correction coefficient, 1.02, accounts for dehydration of the mineral fraction at a temperature of 400^oC. Al-Khafaji (1979) has shown that this method is accurate to within ±1 percent for fiber-clay mixtures. This method was used for determination of the organic fraction of the sludge materials used in this study.

Specific gravity. The procedure given by Bowles (1978) was used for determination of the sludge specific gravity. The oven dry sample weight was determined after the test. Boiled distilled water was used as the displacement medium. To help de-air the sample a vacuum was applied. Use of the vacuum for more than a few hours had little affect on the results obtained. Three trials were performed on each sludge type with variations between tests being 0.01 or less.

Hydrogen ion concentration. The pH of the sludge material was determined with a Beckman pH meter on samples of leachate squeezed from the fresh sludge.

2. Consolidation Tests

The consolidation test provides information concerning the amount and rate of volume change of a soil or sludge sample under load. An explanation and recommended test procedure for conventional consolidation tests is given by Bowles (1978). This section describes the method of sample preparation, equipment, and test procedures utilized for the various types of consolidation tests performed.

Sample preparation. Consolidation test specimens were prepared by placing the sludge material into the consolidometer ring by hand in 4 layers approximately one half centimeter in thickness. The sludge was kneaded into the ring to minimize void space with care being taken to avoid water loss from the sample. The sample top and bottom were leveled so as to conform to the inner dimensions of the ring (2.5 inch diameter by 0.75 inch high). The specimen and ring were then weighed, permitting calculation of the initial sample weight and density. The sample and ring were then placed on a saturated porous stone in the cell container shown in Figure 3.1. Drainage was allowed through the sample top and bottom by porous stones attached to the loading pad and base. The assembly was then placed in the Wykeham Farrance consolidometer (Figure 3.2) used for earlier studies on soft sludge materials (Vallee, 1973).

Consolidation test methods. The procedure followed for

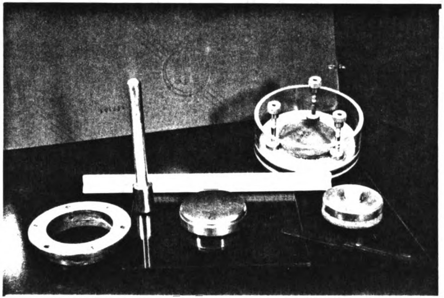


Figure 3.1 Fixed ring consolidation unit and sludge sample.

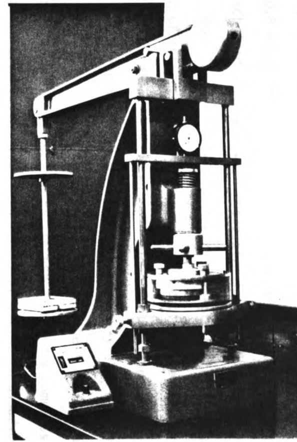


Figure 3.2 Consolidation machine with sludge sample in place.

consolidation tests is the same as that given by Bowles (1978) with minor changes. Except for the final load increment, a load increment ratio ($\Delta P/P$) of one was used with loads of 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, and 10.0 kg/cm^2 being applied. Settlement versus time data was recorded for each load increment with successive loads applied at 24 hour intervals. When loads were left on for this length of time an appreciable amount of secondary compression was included (Figure 2.4). MacFarlane (1969) lists an alternate method of load application which largely eliminates the effects of secondary compression and yields a more well defined e-log p curve. In this method, successive load increments (same as listed above) were applied at the end of primary compression as determined from Taylor square root of time plots. A disadvantage of this method is that no straight line (long term compression) segment is obtained on log time versus settlement plots, which makes evaluation of c_v and C_α difficult.

Another test procedure proposed by MacFarlane (1969), called single increment tests, involves application of the anticipated field load in one increment. Several loads, similar to those expected in the landfill, were applied to duplicate samples for a period of 24 hours or until a straight line portion was easily identified on a settlement versus log time plot. Results of this test method were used in conjunction with equation 2.6 and 2.10 to estimate the magnitude and rate of compression. At the end of each of these tests samples were weighed prior to and after ovendrying to determine the final water content and sludge dry weight.

3. Triaxial Testing

The triaxial test provides information on the shear strength and deformation characteristics of soil or papermill sludge. The consolidated-undrained ($\overline{CIU}$) test was used to evaluate the undrained shearing resistance of the sludge material. Measurement of pore water pressures generated during application of the axial stress allowed evaluation of the shear strength parameters on an effective stress basis. The consolidated-drained (CID) test was performed at a slow rate allowing pore pressures to dissipate so that the applied total stresses were equal to effective stresses and the shear strength parameters obtained were also on an effective stress basis.

Procedures used in preparing triaxial test specimens, a description of the equipment and its use are considered in the following sections. Procedures used were similar to those outlined by Bishop and Henkel (1962) and Bowles (1978).

Sample preparation. Conventional triaxial test specimens, described by Bishop and Henkel (1962), were 3 inches long by 1½ inches in diameter. Preliminary tests indicated the volume reduction of this sample size to be nearly 50 percent under a consolidation pressure of 2.5 kg/cm^2. Due to these large volume changes, it was decided to use larger samples (4 inches long by 2 inches in diameter) for the testing program. Samples were prepared by kneading the sludge, by hand, into a cylindrical mold while taking care to fill all voids and maintain the original water content of the sample (Figure 3.3). The top of the sample was then leveled off perpendicular to the sample axis and the mold disassembled by pulling its sides directly away from the sample to avoid smearing of the sides. The sample was weighed and dimensions noted after which saturated porous stones were placed on the sample ends. Next moist filter paper side drains (Bishop and Henkel, 1962) were wrapped around the sample and porous stones. The sample was then mounted in the triaxial cell, and with the loading cap in place, the entire assembly was enclosed in two

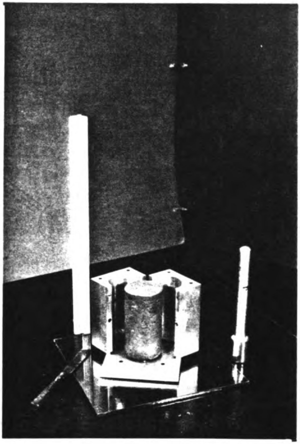
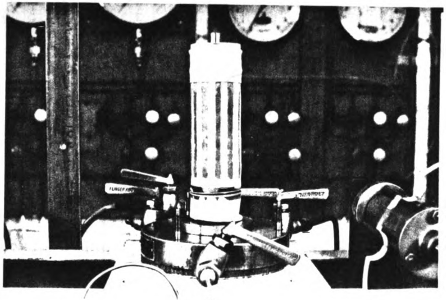


Figure 3.3 Triaxial sample and mold.

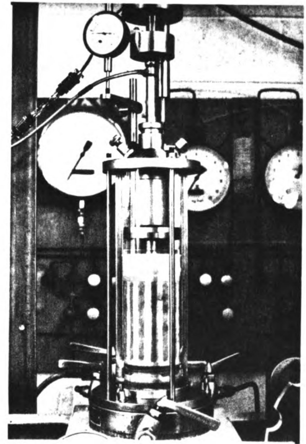
watertight membranes (Figure 3.4).

Triaxial equipment. The triaxial apparatus shown schematically in Figure 3.5 includes the following equipment: 1) a self-compensating mercury pressure system, 2) a triaxial cell, and 3) a pore pressure measuring system. The self compensating mercury pressure system allows cell pressures to be maintained accurately over long periods of time. The conventional triaxial cell (Bishop and Henkel, 1962) was modified to allow 4 inch long by 2 inch diameter samples to be tested and to permit electronic measurement of the load from within the cell (Figure 3.4). The pore pressure measuring unit connects the bottom of the sample to a pressure gauge through a mercury U-tube. Adjusting the level of the mercury with the pressure control cylinder permitted measurement of the pore pressures developed during load application under undrained test conditions.

Consolidated-undrained triaxial test. After the test specimens were mounted in the cell, the cell pressure was slowly brought to the desired consolidation pressure. After a short period of time the drainage line connecting the sample to a calibrated burette was opened to begin the consolidation process and sample drainage was recorded at given times. Time for the consolidation phase of the test varied depending on the sample composition, but was continued until the straight line (long term) portion of the volume change versus square root of time curve became well defined, after which, the drainage line was closed. To increase the degree of saturation, a back-pressure was next applied to the sample by increasing the pore water pressure simultaneously with the cell pressure in order to maintain a constant effective consolidation pressure. The magnitude of the back pressure varied, but 2.5 kg/cm^2

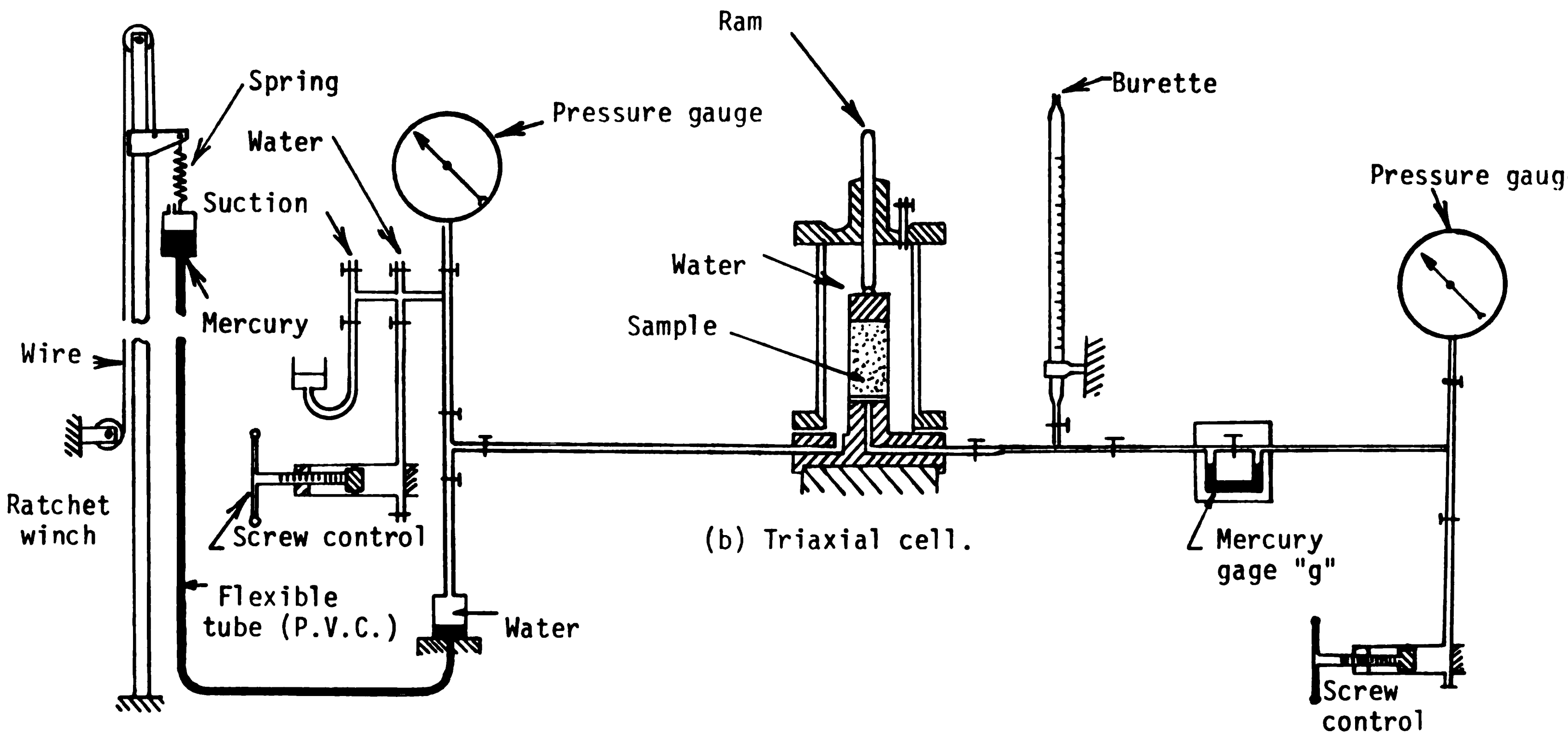


(a)



(b)

Figure 3.4 Triaxial test (a) Mounting the cylindrical sample (b) Sample in cell prepared for testing.



(a) Self-compensating mercury pressure control.

(b) Triaxial cell.

(c) Null method for pore pressure measurement.

Figure 3.5 Triaxial test equipment.

was usually found adequate to give full saturation in the primary sludge samples and 3.5 kg/cm^2 was required for the combined sludge samples. This back-pressure was maintained overnight (approximately 16 hours). The pore pressure parameter, B, was next determined by increasing the cell pressure by a small increment (0.2 kg/cm^2) and measuring the pore pressure response, with B calculated as follows:

$$B = \Delta u / \Delta \sigma_3 \tag{3.1}$$

The back-pressure and cell pressure were then returned to their initial values and after the sample returned to equilibrium, application of the deviator stress was begun. A deformation rate of 2.5 x 10^{-3} inches per minute (6.5 x 10^{-3} cm/min) was utilized in the research program based on experimental work performed by Laza (1971). This strain rate was found to allow excess pore pressures developed during load application to become reasonably equally distributed throughout the sample. During the test, data on axial pressure, axial deformation, and pore pressures were recorded. All tests were carried to at least 20 percent axial strain after which samples were removed from the cell and weighed prior to and after oven drying to determine the final water content.

Consolidated-drained triaxial test. The procedure for sample preparation and consolidation of drained test specimens was the same as that in the undrained test. After consolidation was completed, application of the axial stress began. The rate of deformation was determined from volume change versus time data recorded during the consolidation phase of the test (Bishop and Henkel, 1962). The rate of deformation calculated by this method depends on the anticipated failure strain. For this study the time to failure was calculated with a deformation of 20 percent axial strain taken as failure. The rate of deformation varied with sludge type and consolidation pressure, from 8.6x10^{-5} inches per minute to 2.05×10^{-4} inches per minute (2.03×10^{-4} cm/min to 5.21×10^{-4} cm/min, respectively). The corresponding time to failure varied from 121 hours to 50 hours. During testing the drainage line connecting the sample and burette was left open and the sample drainage, axial deformation, and load were recorded up to 20 percent axial deformation. The sample was then removed from the cell and the final water content determined.

4. Anaerobic Decomposition of Papermill Sludge

In order to investigate the effect of fiber breakdown on the undrained shear strength of the combined primary and secondary sludge used in this research program, samples were allowed to decompose anaerobically. Nutrients added to the samples, environmental control, and preparation of decomposed samples for use in the triaxial test are described in the following sections.

Sample preparation, nutrient proportions and seeding material. Although the combined primary and secondary papermill sludge used in the research program may have contained sufficient nutrients to promote decomposition by itself, time restraints made it desirable to aid the decomposition process by providing a favorable environment and supplying nutrients known to enhance microbial activity. A municipal sludge obtained from an anaerobic digester served as the micro-organism seed source used to initiate the anaerobic decomposition process. The amount of seeding material used was approximately 0.3 percent of the total dry sample weight. To continue to reproduce and thus bring about decomposition, the micro-organisms must have a minimum supply of the elements of which they are composed (Table 3.1). The approximate empirical fomulation of a bacterial cell (McKinney, 1962) given as $C_5H_7O_2N$ served as a guide in selection of nutrient quantities. Pulp fiber contributed by the primary sludge and bacteria from the secondary sludge supplied the carbon. Ammonium chloride (NH_4Cl) was used to supply the nitrogen. Other nutrients found in bacterial cells and their source compounds included K_2HPO_4 for phosphorous and potassium, $MgSO_4$ for magnesium, $CaCl_2$ for calcium, and $FeCl_3$ for iron. A summary of the calculations used to determine the exact quantities of the compounds to give the desired amounts of nutrients are given Appendix B. The compounds were introduced into the sample by first dissolving in distilled water and thoroughly mixing with 4500 grams (wet weight) of the combined papermill sludge. The material was then transferred into plastic lined containers with small amounts of the seeding material stirred in during filling in an effort to minimize the exposure of the anaerobic micro-organisms to the atmosphere. Enough distilled water was added to allow thorough mixing of the materials. The containers were then covered and transferred to a constant temperature environment.

Environmental control. To allow the micro-organisms to metabolize at a near optimum rate, samples were stored in an incubator at a temperature of 35^{o}C. The decomposition process is known to produce volatile acids, and if allowed to go unchecked, may depress the pH below 6, thus eliminating the methane producing bacteria. Hence, based on previous research (Al-Khafaji, 1979), 5.6 percent by weight of sodium bicarbonate was added to the sample in an effort to maintain a neutral pH.

Decomposition measurement. Decomposition in organic soils involves the breakdown of complex organic materials into more stable humus products and conversion into simpler organic materials used to build bacterial cells. The ignition test used for measurement of soil organic content does not distinguish between undecomposed organic matter and micro-organisms formed during decomposition, hence it under estimates the degree of decomposition.

A schematic diagram illustrating the makeup of the typical organic soil before and after partial decomposition is shown in Figure 3.6. Attempts to separate the micro-organism cell content from the decomposed organic content have proven difficult.

The degree of decomposition is given by Al-Khafaji (1979) as

$$X_{di} = \frac{1}{1 - y} \left[\frac{1 - X_{fi} / X_{fo}}{1 - X_{fi}} \right] \qquad (3.2)$$

where y is the cell yield, X_{fo} and X_{fi} are the initial and final organic fractions determined from equation 2.1 and X_{di} is the degree of decomposition. The cell yield, y, is a biomass error term which has been very difficult to determine accurately, but is thought to range from 0.05 to 0.2 for soils undergoing anaerobic decomposition (Al-Khafaji, 1979). Due to the uncertainty involved in the determination of the cell yield, it was assumed equal to zero. This same assumption was made in obtaining the percent decomposition shown in Figures 2.9 - 2.12.

Triaxial test samples. The magnitude of decomposition in the decomposing samples was monitored by ignition of small samples as described earlier. When 26.6 percent decomposition was reached, a portion of the samples were transferred from the incubator to a refrigerator in an effort to retard further decomposition. The sample was then spread in pans and air dried to a consistency which would allow molding of triaxial test specimens. A portion of the dried material was then used for preparation of the triaxial test specimens described in section 3.

In order to measure any possible affect of the nutrients and seeding material on the strength of the undecomposed sludge, a portion of

TABLE 3.1 CONCENTRATION OF MAJOR ELEMENTS IN A BACTERIAL CELL (after McKinney, 1962)

Element	Concentration Percent
Carbon	49.0
Hydrogen	6.0
Oxygen	27.0
Nitrogen	11.0
Phosphorous	2.5
Sulfur	0.7
Sodium	0.7
Potassium	0.5
Calcium	0.7
Magnesium	0.5
Iron	0.1

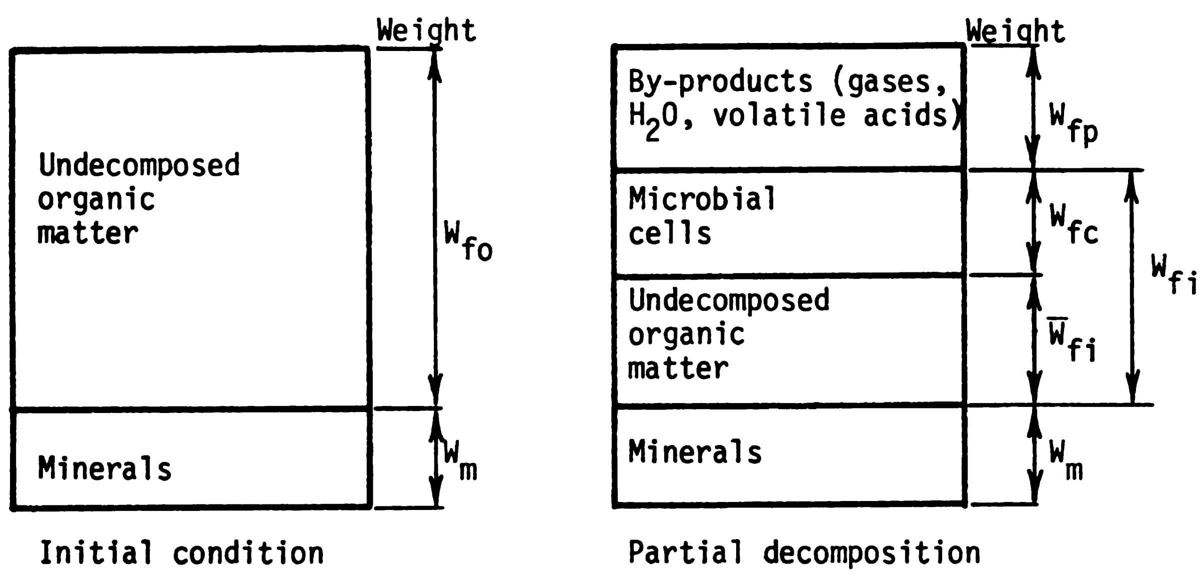


Figure 3.6 Schematic diagram showing sludge solids, before and after partial decomposition (after Al-Khafaji, 1979).

the prepared sample was placed in a refrigerator so as to inhibit decomposition. Three ($\overline{\text{CIU}}$) triaxial tests were then performed on this material and the results compared to those of the fresh material in order to isolate possible effects of the nutrients and seeding material on the undrained shear strength from the effects of decomposition. Due to the expected decrease in sample permeability with decomposition (Figure 2.11) a deformation rate of $1.4\text{x}10^{-3}$ in/min was used for ($\overline{\text{CIU}}$) tests on partially decomposed samples.

CHAPTER IV

EXPERIMENTAL RESULTS

The experimental results presented in this section provide information regarding the physical properties and the stress deformation behavior of the papermill sludge.

A. Physical Properties of the Papermill Sludge

Table 4.1 summarizes the physical properties of the primary and combined papermill sludge samples. Information on the water content, solids content, organic fraction, unit weight, specific gravity, and pH is provided. The average water content for the two sludge types are converted to solids contents through use of equation 2.1. Based on measured values of organic fraction and solids content, the combined sludge sample appears representative of the sludge generated during 1979 (Table 4.1). The pH of both sludges was measured to be 11.9 at the time of sample procurement. Subsequent measurements showed a gradual decrease in the pH with time. The observed decrease was more pronounced for the combined sludge than for the primary sludge.

B. Stress Deformation Behavior of the Sludge

Stress deformation characteristics of the two sludge materials were evaluated in laboratory consolidation tests and triaxial shear tests. Duplicate consolidation tests provided comparative information on the compressibility of the two sludge materials. The shear strength was evaluated for fresh samples of primary and combined sludge and partially decomposed samples of the combined sludge.

1. Compressibility

The consolidation test results are summarized in Table 4.2. The results of three consolidation tests for primary sludge samples on a strain versus logarithm of effective pressure plot are shown in Figure 4.1. Curves Q-P1 and Q-P2 represent rapid load increment (quick) tests in which the effects of secondary compression are minimized. Curve C-P1 represents conventional consolidation test (Bowles, 1978) results utilizing 24 hour load increments. This test method includes varying amounts of secondary compression during each load increment which may account for the higher C_c value. Figure 4.2 summarizes the consolidation test results for the combined sludge samples. Curves Q-C1 and Q-C2 represent quick tests, while curve C-C1 is for a conventional test on the combined sludge. Here the value of C_c for the conventional test is between the quick test values. It is seen that the combined sludge is more compressible than the primary sludge based on values of C_c. Single load increment tests (MacFarlane, 1969) using anticipated field loads were performed to better simulate possible field conditions and to distinguish between primary and secondary compression more clearly. Figure 4.3 compares typical settlement versus logarithm of time data for primary and combined sludge samples under a load increment of 0.1 to 0.8 kg/cm^2. The higher compressibility of the combined sludge shown in Figure 4.3 was typical of all single load increment test results. The coefficient of secondary compression, C_α, shown in Figure 4.4a increased over the range of consolidation pressures from 0.2 to 6.4 kg/cm^2 with the combined sludge exhibiting higher C_α values. Values of the coefficient of consolidation shown in Figure 4.4b were determined by the square root of time fitting method. The effects of secondary compression in conventional test made use of the logarithm of time method for determining c_v difficult. Data for c_v obtained from logarithm of time curves for single load increment and 24 hour load increment tests are listed in Table 4.2 for comparison. The coefficient of permeability, k, was also determined indirectly from consolidation test results. Average values of k for a range of consolidation pressures for the primary and combined sludge are shown in Figure 4.5.

Previous research has found the permeability of partially decomposed sludge to decrease with increasing decomposition (Al-Khafaji, 1979). Figure 4.6 summarizes the results of tests on model sludges and the combined sludge used for this study. The values of c_v for fresh samples of combined sludge were found to decrease nearly 80 percent as a result of 26.6 percent decomposition. Isotropic consolidation of triaxial test specimens provided the data for the papermill sludge. More complete test data is given in Appendix D.

2. Shear Strength of Fresh Sludge

The results of triaxial tests on fresh samples of primary and combined sludge are summarized in Table 4.3. Data from consolidated-undrained ($\overline{CIU}$) and consolidated-drained (CID) triaxial tests are provided. Typical stress-strain curves for $\overline{CIU}$ tests on combined sludge, given in Figure 4.7, show increasing stress at strains over 20 percent. This behavior was observed for all tests on fresh sludge samples; thus failure was taken at 20 percent axial strain. Typical results of a $\overline{CIU}$ test on primary sludge are presented in Figure 4.8. The obliquity ratio $\bar{\sigma}_1/\bar{\sigma}_3$, deviator stress $(\bar{\sigma}_1 - \bar{\sigma}_3)$, pore pressure change Δu, and pore pressure parameter A are all plotted against axial strain. The obliquity ratio becomes very large at higher axial strains due to the small effective minor principal stress $\bar{\sigma}_3$. A gradual increase in the deviator stress with increasing strain is observed and A approaches a constant value of approximately 0.6. Results of four $\overline{\text{CIU}}$ tests on the primary sludge are summarized in Figure 4.9. The $\bar{p}_f$ - $\bar{q}_f$ plot shown in Figure 4.9a yields values of $\bar{\Phi}$ = 63.4 degrees and $\bar{c}$ = 0 through use of the transformations shown in Figure 2.7. Figure 4.9b shows the change in final water content with consolidation pressure, and Figure 4.9c compares the undrained strength with consolidation pressure. Figure 4.10 shows typical results of a $\overline{\text{CIU}}$ test for the combined sludge. The effective angle of internal friction $\bar{\Phi}$, final water content, and undrained shear strength (c_u) are summarized in Figure 4.11. A friction angle of $\bar{\Phi}$ = 49 degrees and cohesion intercept of $\bar{c}$ = 0.21 kg/cm^2 give the combined sludge a lower shear strength than the primary sludge at pressures greater than 0.25 kg/cm^2. Figure 4.11b shows the final water content versus effective consolidation pressure for the combined sludge. Figure 4.11c gives the undrained shear strength of the combined sludge for various consolidation pressures.

Typical results of CID triaxial tests on primary sludge are shown in Figure 4.12. Results of two of these tests, shown in Figure 4.13 on a $\bar{p}_f$ - $\bar{q}_f$ plot, give $\bar{\Phi}$ = 33.2 degrees and $\bar{c}$ = 0.116 kg/cm^2. Typical stress-strain and volume change data for a combined sludge sample in the CID test are given in Figure 4.14. The results of three of these tests are summarized in the $\bar{p}_f$ - $\bar{q}_f$ plot shown in Figure 4.15. A $\bar{c}$ = 0.113 kg/cm^2 and $\bar{\Phi}$ = 23.0 degrees for the combined sludge give it a lower shear strength than the primary sludge.

3. <u>Decomposition Effects on Shear Strength</u>

To evaluate the effect on shear strength of nutrients and seeding material added to aid decomposition, a series of three $\overline{CIU}$ tests were run on the freshly mixed material prior to decomposition. Typical results of one of these tests are shown in Figure 4.16. Note the addition of nutrients to the combined sludge causes the obliquity ratio to be smaller and the pore pressure parameter (A) to be larger than values observed for the fresh combined sludge. A summary of the results of three $\overline{CIU}$ tests on the combined sludge with nutrients and seeding material added is given in Figure 4.17. Comparison of Figures 4.17 and 4.11 show the addition of nutrients to have decreased $\bar{\phi}$ from 49 degrees to 39.6 degrees. No measurable change in $\bar{c}$ or the final water content were observed, but the undrained strength c_u decreased with addition of nutrients and the seeding material.

The effect of decomposition of the organic fraction on the shear strength of the combined papermill sludge was measured in a series of five $\overline{CIU}$ triaxial tests with pore pressure measurements.

Changes in the organic fraction during 25 days of decomposition were measured by ignition of small samples at various stages of decomposition. Partially decomposed samples were partially air dried and stored at $4^{o}C$ until testing. Storage at this low temperature slowed decomposition to a level which allowed a series of five $\overline{CIU}$ triaxial tests to be performed at the same level of decomposition. At the time of testing, the average degree of decomposition using equation 3.2 was 26.6 percent.

Typical results of one of these triaxial tests are shown in Figure 4.18. Due to a decrease in the influence of fibers on the material shear strength, a peak value on the deviator stress versus strain plot is observed at about 16.6 percent strain. This peak deviator stress was observed in 4 of the 5 $\overline{CIU}$ triaxial tests performed on the decomposed sludge. Results of the 5 tests performed on partially decomposed sludge are summarized in Figure 4.19. The $\overline{p}_f$ - $\overline{q}_f$ plot in Figure 4.19a gives $\overline{\Phi}$ = 28.7 degrees and $\overline{c}$ = 0.11 kg/cm^2. Figure 4.19b shows the final water content versus consolidation pressure and Figure 4.19c compares the undrained strength (c_u) with consolidation pressure. The scatter of data results from inconsistencies in the degree of consolidation due to decomposition and the associated gas generation which occurred during the $\overline{\text{CIU}}$ test. Further effects of decomposition are discussed in the next chapter.

TABLE 4.1 PHYSICAL PROPERTIES OF THE PAPERMILL SLUDGE

Property	Combined Sludge	Primary Sludge
water content (% of dry weight)	318	270
solids content (1) (% of total weight)	23.9 (24.6)*	27.0
organic fraction (2)	0.58 (0.54)*	0.49
unit weight (lb/ft^3)	69.2	70.9
specific gravity (3)	1.89	1.91
pH (4) (range of values)	8.3-7.6	10.3-8.6

(1) Solids content of fresh sludge. Related to water content by the equation:

$$w\% = 100\left[\frac{100}{\%\text{ solids by wt.} - 1}\right]$$

(2) Organic fraction. $X_f = 1 - 1.02(W_2/W_1)$ where W_1 = oven dry sample weight prior to ignition and W_2 = weight of ash after ignition at 400^oC.

(3) ASTM D854-72 test method.

(4) Measured values at treatment plant were 11.9 for both sludge types.

* Average of values collected daily by Nekoosa Papers, Inc. for 1979.

TABLE 4.2 SUMMARY OF CONSOLIDATION TEST RESULTS

sludge test	sludge sample	load increment (kg/cm^2)	c_v (cm^2/min) $\sqrt{time}$	c_v (cm^2/min) log time	strain (%)	C_c	initial void ratio e_o	C_α
Q	P1	0.0 - 0.1	0.246	not computed	8.78	2.14	6.415	not computed
		0.1 - 0.2	0.215		11.98			
		0.2 - 0.4	0.255		18.84			
		0.4 - 0.8	0.164		26.99			
		0.8 - 1.6	0.116		35.65			
		1.6 - 3.2	0.065		44.83			
		3.2 - 1.6	--		43.96			
		1.6 - 0.8	--		42.68			
		0.8 - 1.6	0.071		43.44			
		1.6 - 3.2	0.057		45.59			
		3.2 - 6.4	0.029		53.11			
		6.4 -10.0	0.016		58.72			
		10.0 - 3.2	--		57.07			
		3.2 - 0.4	--		52.65			
Q	P2	0.0 - 0.1	0.192	not computed	11.49	2.05	6.843	not computed
		0.1 - 0.2	0.173		18.34			
		0.2 - 0.4	0.128		25.29			
		0.4 - 0.8	0.087		33.21			
		0.8 - 1.6	0.064		41.46			
		1.6 - 3.2	0.035		49.05			
		3.2 - 1.6	--		48.40			
		1.6 - 0.8	--		47.32			
		0.8 - 1.6	0.076		48.01			
		1.6 - 3.2	0.012		50.83			
		3.2 - 6.4	0.015		57.20			
		6.4 -10.0	0.008		61.87			
		10.0 - 3.2	--		60.53			
		3.2 - 0.4	--		57.22			

TABLE 4.2 cont.

sludge test	sludge sample	load increment (kg/cm^2)	c_v (cm^2/min) $\sqrt{time}$	c_v (cm^2/min) log time	strain (%)	C_c	initial void ratio e_o	C_α
C	P1	0.0 - 0.1	0.936	--	6.25	2.48	7.366	--
		0.1 - 0.2	0.518	--	9.14			--
		0.2 - 0.4	0.353	0.300	17.18			0.0113
		0.4 - 0.8	0.634	--	23.50			--
		0.8 - 1.6	0.107	0.119	30.91			--
		1.6 - 3.2	0.091	0.095	42.85			0.0240
		3.2 - 1.6	--	--	42.37			--
		1.6 - 0.8	--	--	40.76			--
		0.8 - 1.6	--	--	41.79			--
		1.6 - 3.2	--	--	43.80			--
		3.2 - 6.4	0.044	0.042	53.13			0.014
		6.4 -10.0	0.022	0.011	57.27			0.022
		10.0 - 3.2	--	--	56.19			--
		3.2 - 0.4	--	--	--			--
SI	P1	0.1 - 0.4	0.139	0.068	24.47	--	5.951	0.0187
SI	P2	0.1 - 0.8	0.130	0.092	35.40	--	6.208	0.0250
SI	P3	0.1 - 1.6	0.133	0.095	44.85	--	7.480	0.0294
SI	P4	0.1 - 3.2	0.0725	0.055	49.32	--	6.625	0.0323
Q	C1	0.0 - 0.1	1.102	not computed	6.01	2.62	7.790	not computed
		0.1 - 0.2	0.416		7.81			
		0.2 - 0.4	0.086		22.85			
		0.4 - 0.8	0.055		30.99			
		0.8 - 1.6	0.039		40.66			
		1.6 - 0.8	0.025		49.23			
		3.2 - 1.6	--		48.31			
		1.6 - 0.8	--		47.36			
		0.8 - 1.6	0.236		47.91			
		1.6 - 3.2	0.007		51.31			

TABLE 4.2 cont.

test	sludge sample	load increment (kg/cm^2)	c_v (cm^2/min) $\sqrt{time}$	c_v (cm^2/min) log time	strain (%)	C_c	initial void ratio e_o	C_α
Q	- C1 cont.	3.2 - 6.4	0.0063		59.00			
		6.4 -10.0	0.0035		63.61			
		10.0 - 3.2	--		62.10			
		3.2 - 0.4	--		57.60			
Q	- C2	0.0 - 0.1	0.227	not computed	8.51	2.63	7.627	not computed
		0.1 - 0.2	0.102		15.60			
		0.2 - 0.4	0.077		23.28			
		0.4 - 0.8	0.052		31.98			
		0.8 - 1.6	0.024		41.43			
		1.6 - 3.2	0.010		50.85			
		3.2 - 1.6	--		50.18			
		1.6 - 0.8	--		48.89			
		0.8 - 1.6	0.032		49.59			
		1.6 - 3.2	0.004		52.80			
		3.2 - 6.4	0.003		60.26			
		6.4 -10.0	0.0017		64.74			
		10.0 - 3.2	--		63.26			
		3.2 - 0.4	--		60.01			
SI	- C1	0.1 - 0.4	0.107	0.0826	28.79	--	6.765	0.0283
SI	- C2	0.1 - 0.8	0.082	0.0617	37.66	--	7.482	0.0290
SI	- C3	0.1 - 1.6	0.081	0.0420	47.96	--	7.834	0.0350
SI	- C4	0.1 - 3.2	0.124	0.0347	55.39	--	8.215	0.0440
C	- C1	0.0 - 0.1	0.203	0.1460	11.60	2.52	7.475	--
		0.1 - 0.2	0.118	0.1150	18.37			0.0170
		0.2 - 0.4	0.083	--	26.01			--
		0.4 - 0.8	0.047	0.0380	35.12			0.0310
		0.8 - 1.6	0.025	0.0150	44.79			0.0376
		1.6 - 3.2	0.015	0.0060	53.90			0.0419

TABLE 4.2 cont.

sludge test	sample	load increment (kg/cm^2)	c_v $\sqrt{time}$ (cm^2/min)	c_v log time (cm^2/min)	strain (%)	C_c	initial void ratio e_o	C_α
C -	C1 cont.	3.2 - 1.6	--	--	53.06			--
		1.6 - 0.8	--	--	51.93			--
		0.8 - 1.6	0.043	--	52.64			--
		1.6 - 3.2	0.030	--	54.36			--
		3.2 - 6.4	0.006	0.0026	61.44			0.0439
		6.4 -10.0	0.002	0.0007	65.55			--
		10.0 - 3.2	--	--	63.86			--
		3.2 - 0.4	--	--	59.50			--

Q-P1 and 2 --quick tests, primary sludge
C-P1 --conventional test, primary sludge
Q-C1 and 2 --quick tests, combined sludge
C-C1 --conventional test, combined sludge
SI-P1,2,3,and 4 -- single load increment tests, primary sludge
SI-C1,2,3,and 4 -- single load increment tests, combined sludge
c_v -- coefficient of consolidation
C_α -- coefficient of secondary compression
C_c -- compression index
* -- strain = $\Delta l/l_o = \Delta V/V_o$

TABLE 4.3 SUMMARY OF TRIAXIAL TEST RESULTS

test sample	consolidation pressure $\overline{\sigma_c}$ (kg/cm^2)	water content initial (%)	water content final (%)	initial dry density (PCF)	undrained strength c_u (kg/cm^2)	$\overline{\sigma_{1f}}$ (kg/cm^2)	$\overline{\sigma_{3f}}$ (kg/cm^2)	A_f
CU-P1	1.00	252	144	20.21	0.833	1.715	0.050	0.57
CU-P2	1.00	274	148	18.89	0.749	1.598	0.100	0.60
CU-P3	2.50	267	116	19.38	2.110	4.259	0.040	0.58
CU-P4	2.50	269	118	19.21	1.976	3.968	0.035	0.62
CU-C1	0.92	316	165	16.89	0.661	1.351	0.030	0.67
CU-C2	1.75	337	142	16.19	1.000	2.140	0.140	0.81
CU-C3	2.50	318	126	16.59	1.414	3.103	0.275	0.79
CD-P1	1.00	257	149	19.98	--	3.850	1.000	--
CD-P2	2.50	247	120	20.64	--	3.984	2.500	--
CD-C1	1.00	314	183	16.72	--	2.452	1.000	--
CD-C2	1.75	295	166	17.76	--	4.760	1.750	--
CD-C3	2.50	308	141	17.24	--	5.889	2.500	--
CU-CN1	1.00	326	163	16.46	0.577	1.224	0.070	0.81
CU-CN2	1.75	337	139	16.18	0.867	1.968	0.235	0.87
CU-CN3	2.50	332	126	16.25	1.108	2.566	0.350	0.97
CU-CD1	1.00	170	115	27.47	0.428	1.106	0.250	0.88
CU-CD2	1.75	173	100	28.11	0.725	1.950	0.500	0.86
CU-CD3	2.50	133	101	32.29	0.828	2.046	0.390	1.27
CU-CD4	3.00	171	110	27.68	0.452	1.483	0.580	2.68
CU-CD5	3.00	175	100	26.76	0.763	2.295	0.770	1.46

TABLE 4.3 cont.

CU - consolidated undrained
CD - consolidated drained
P - primary sludge
C - combined sludge
CN - combined sludge, nutrients added, no decomposition
CD - combined sludge, decomposed

Failure taken at $(\sigma_1 - \sigma_3)_{max}$ or 20% axial strain.

TABLE 4.4 SUMMARY OF SHEAR STRENGTH PARAMETERS

test specimen	assumed failure criteria	effective stress CIU test		strength parameters CID test		total stress strength parameters CIU test	
		$\bar{c}$ (kg/cm^2)	$\bar{\Phi}$(deg)	$\bar{c}$ (kg/cm^2)	$\bar{\Phi}$(deg)	c (kg/cm^2)	Φ(deg)
primary sludge	20% strain	0.000	63.4	0.116	33.2	0.00	27.0
combined sludge	20% strain	0.215	49.0	0.130	23.0	0.15	18.8
combined sludge with nutrients	20% strain	0.200	40.8	--	--	0.18	15.2
decomposed sludge	peak strength	0.113	28.7	--	--	0.15	12.3

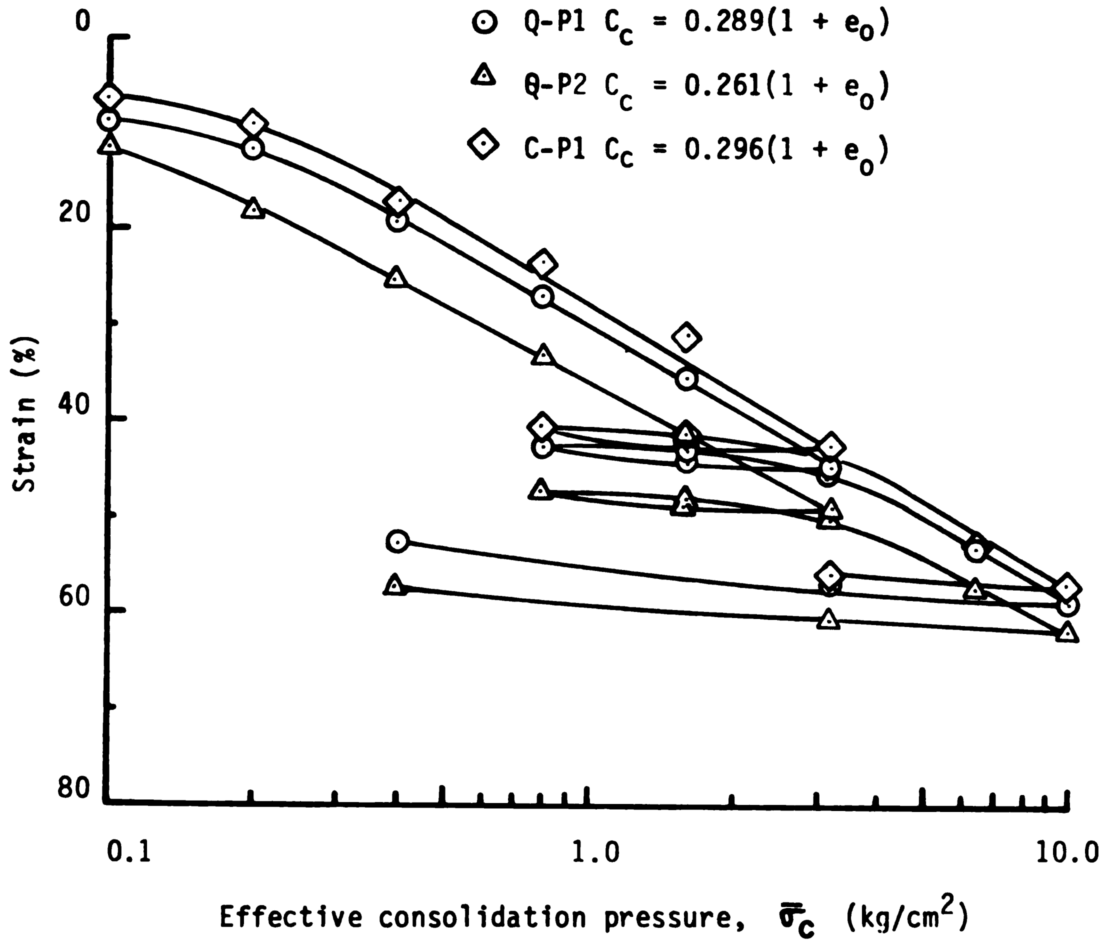


Figure 4.1 Strain-effective stress relationships, primary sludge.

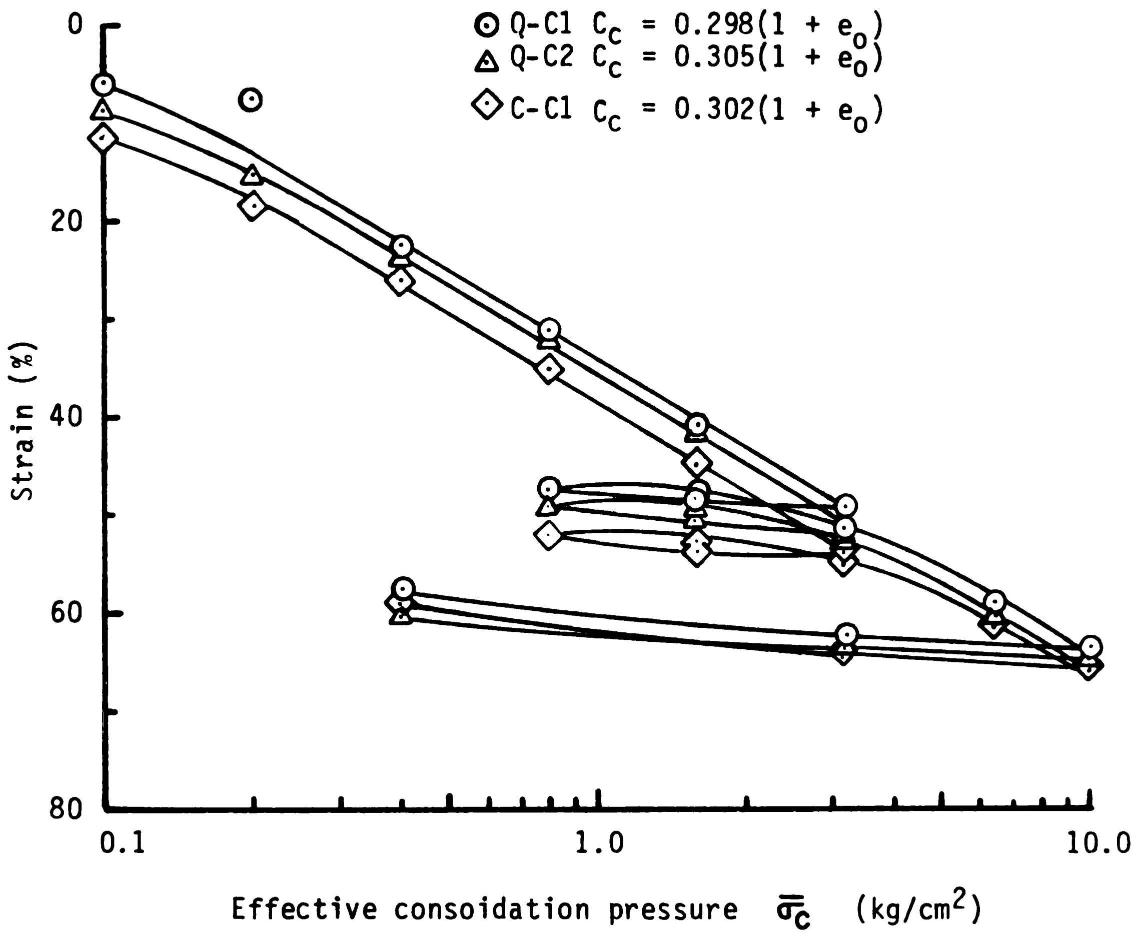


Figure 4.2 Strain-effective stress relationships, combined sludge

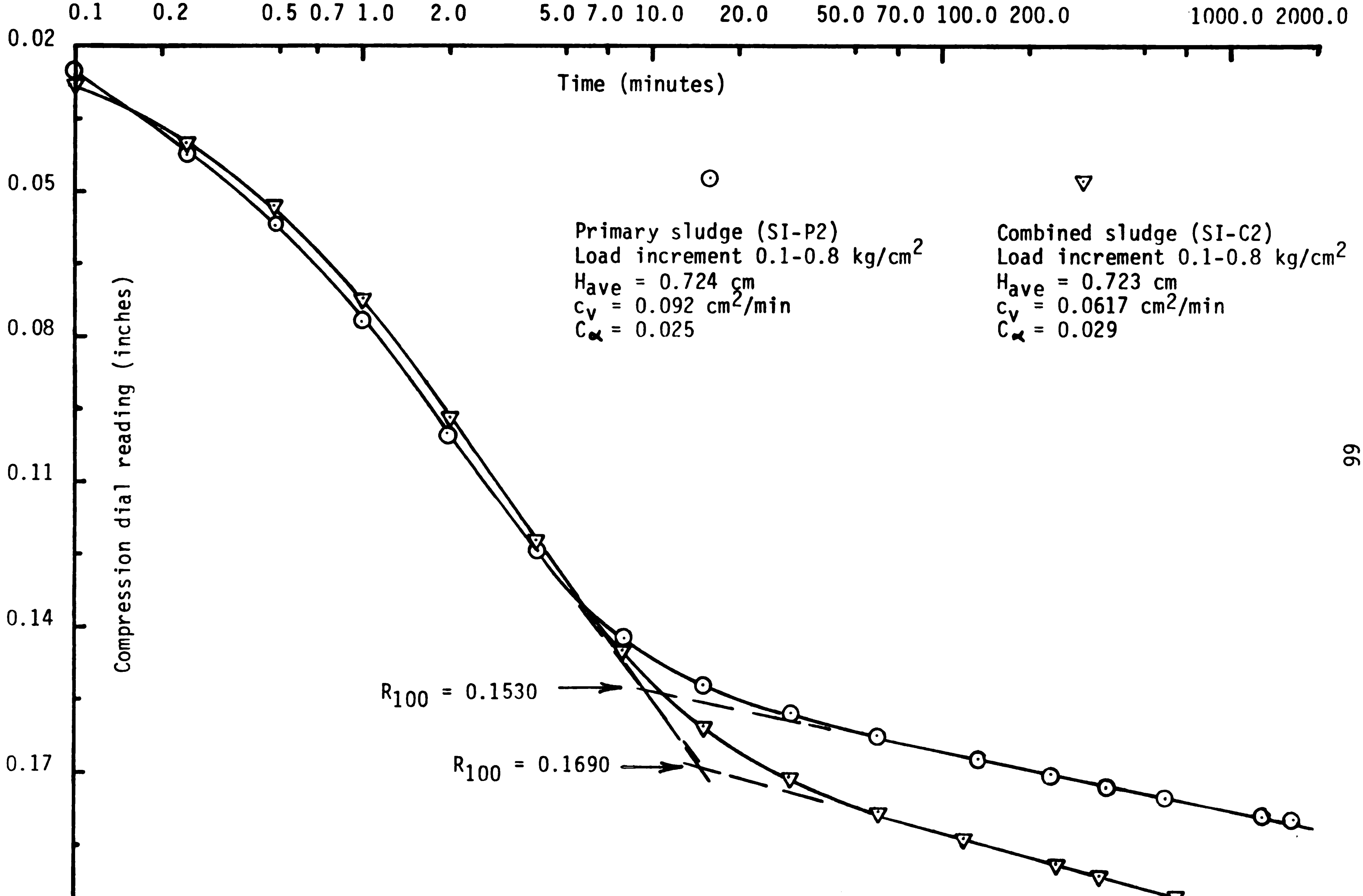


Figure 4.3 Compression dial reading versus Logarithm of time for primary and combined sludges

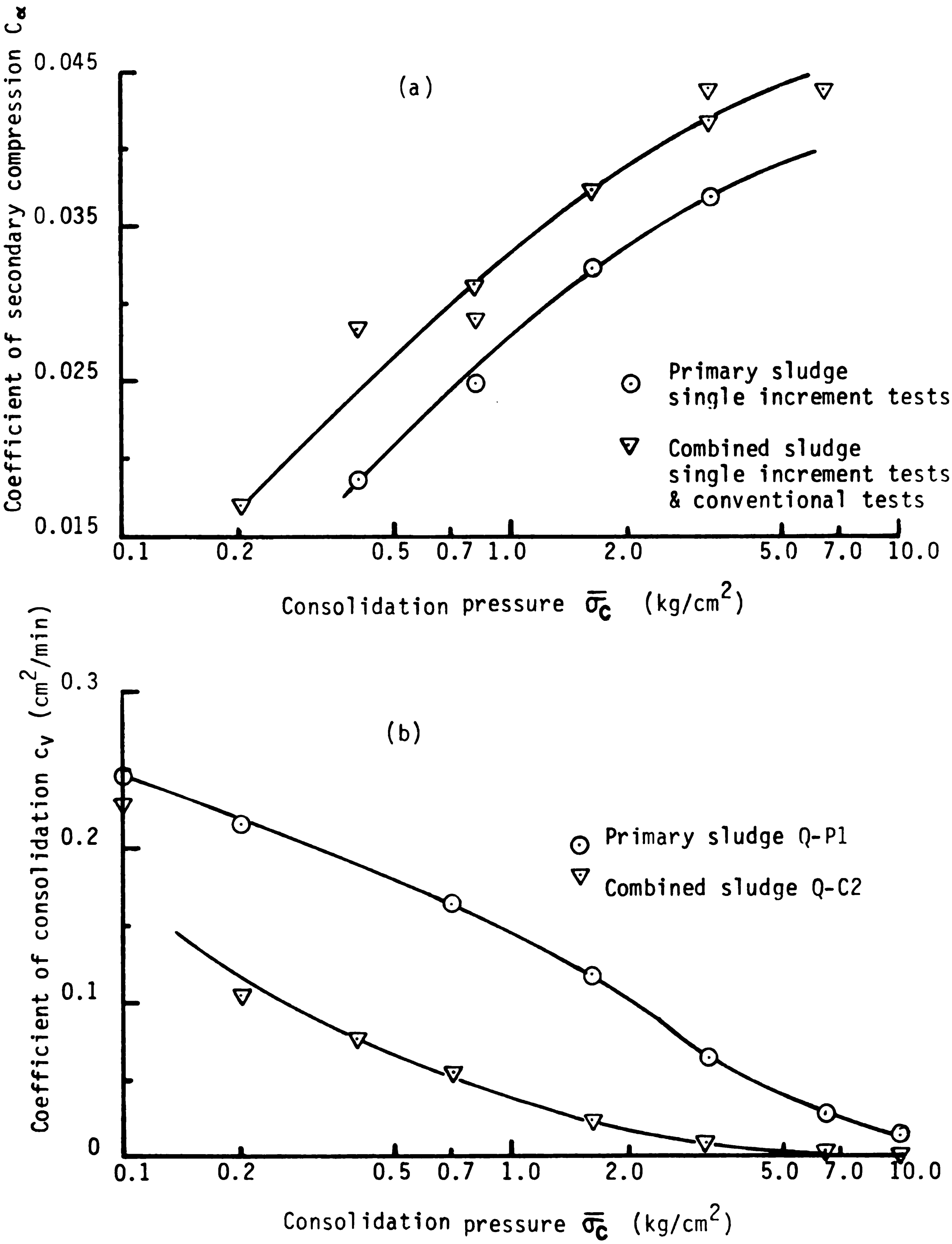


Figure 4.4 Consolidation characteristics of primary and combined sludges (a) coefficient of secondary compression, C_α (b) coefficient of consolidation, c_v.

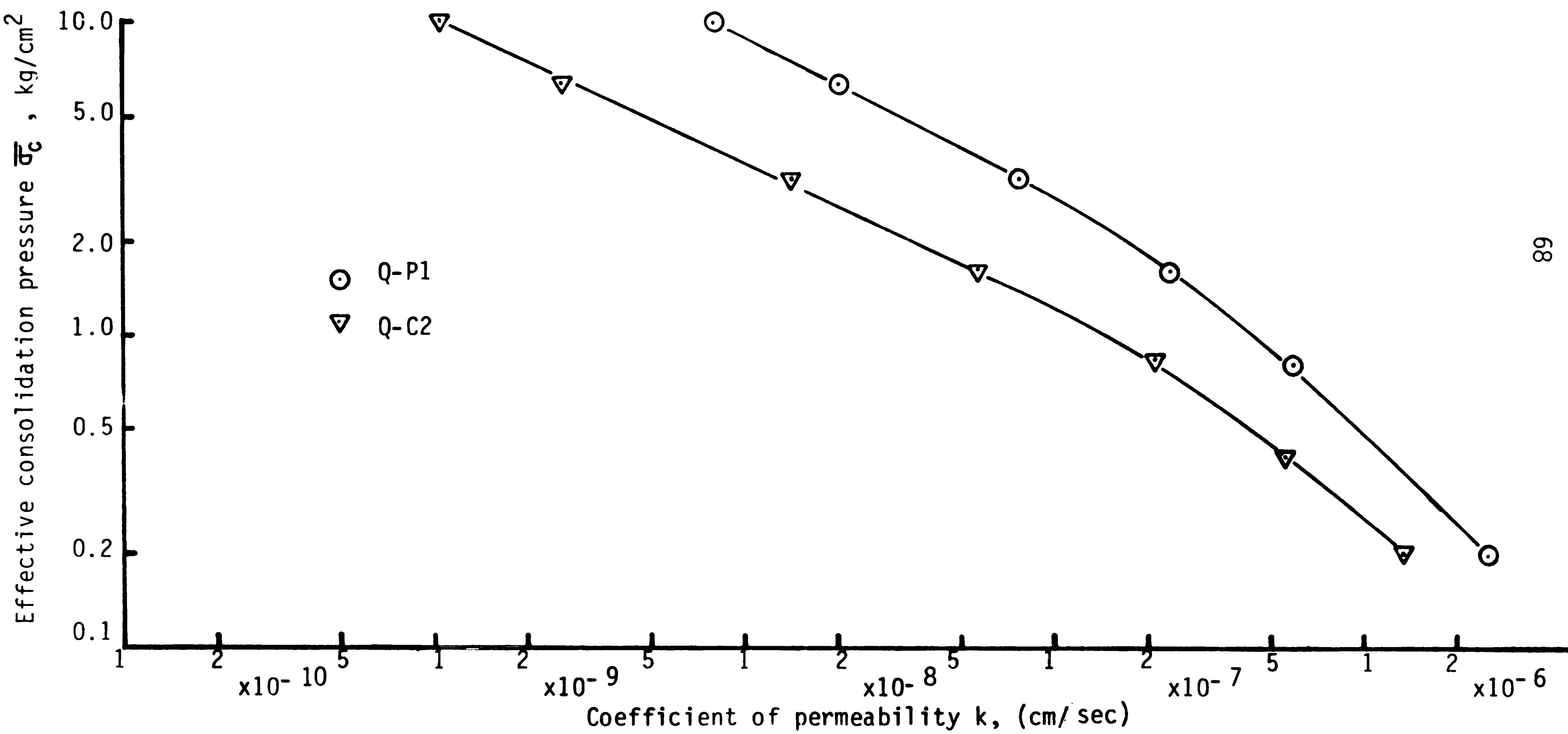


Figure 4.5 **Coefficient of permeability, k, versus Effective consolidation pressure for primary and combined sludges.**

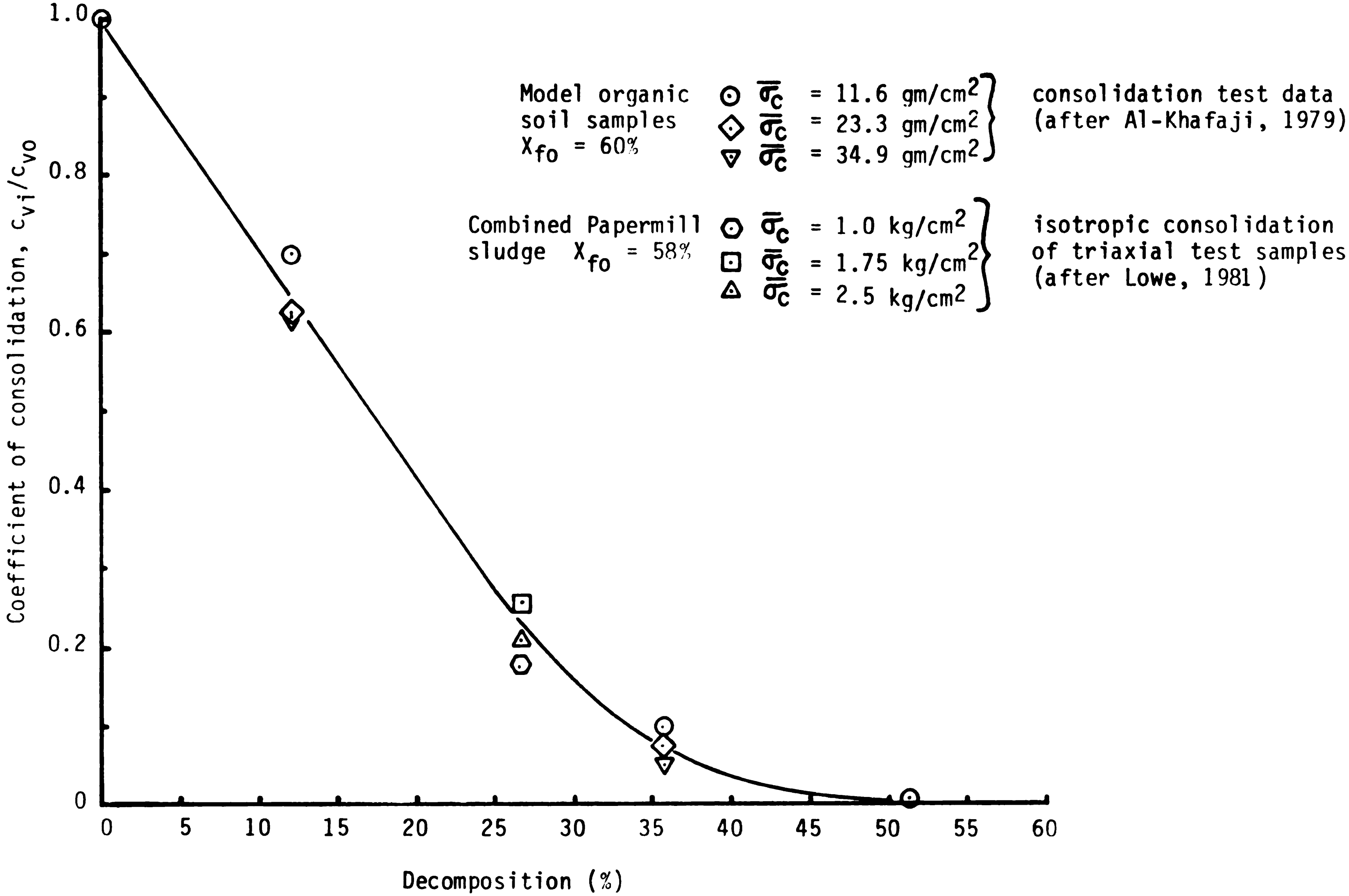


Figure 4.6 Decomposition effects on the coefficient of consolidation for model sludge samples (after Al-Khafaji, 1979) and combined papermill sludges.

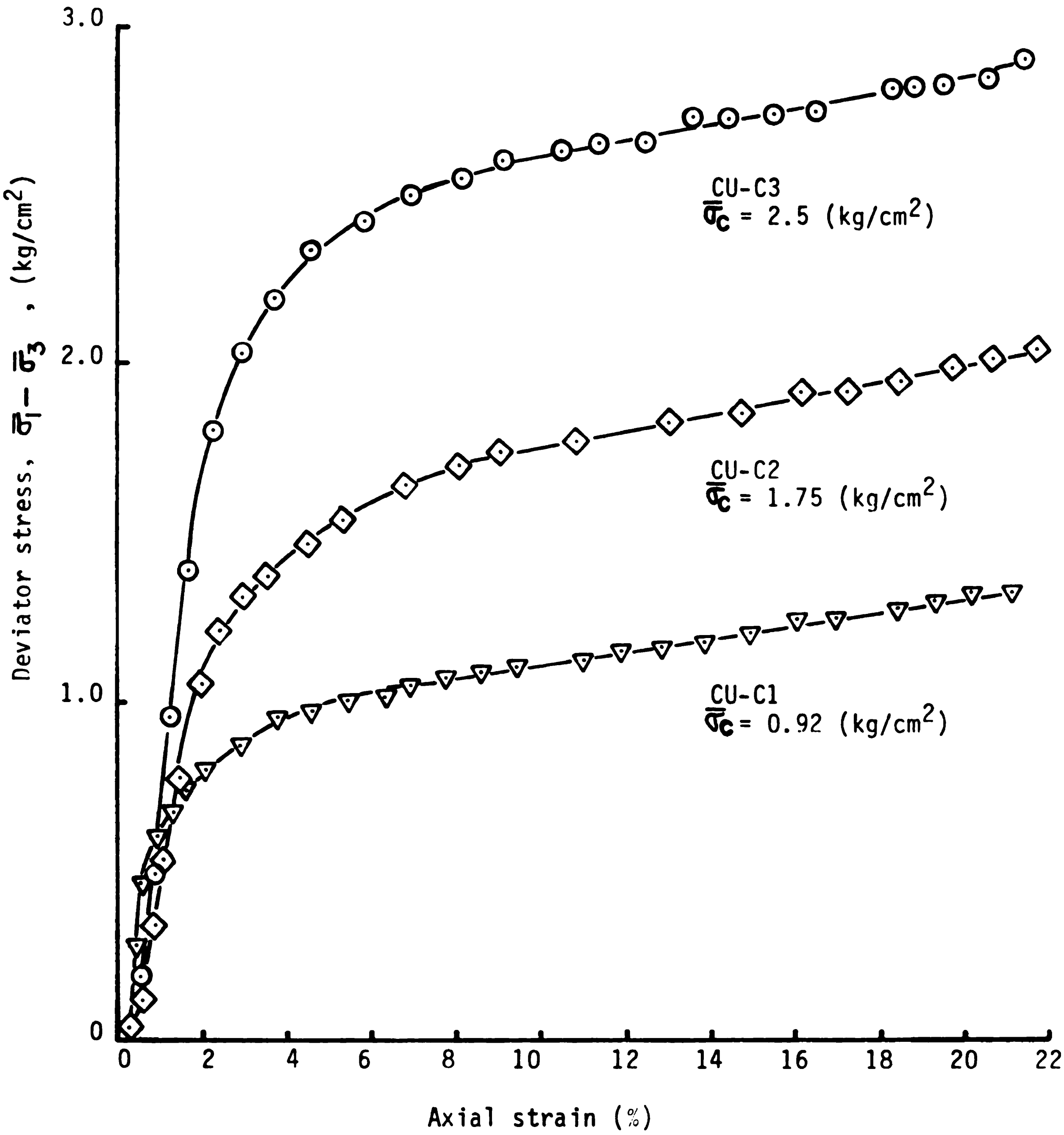


Figure 4.7 Deviator stress versus Axial strain for combined sludge samples at various consolidation pressures

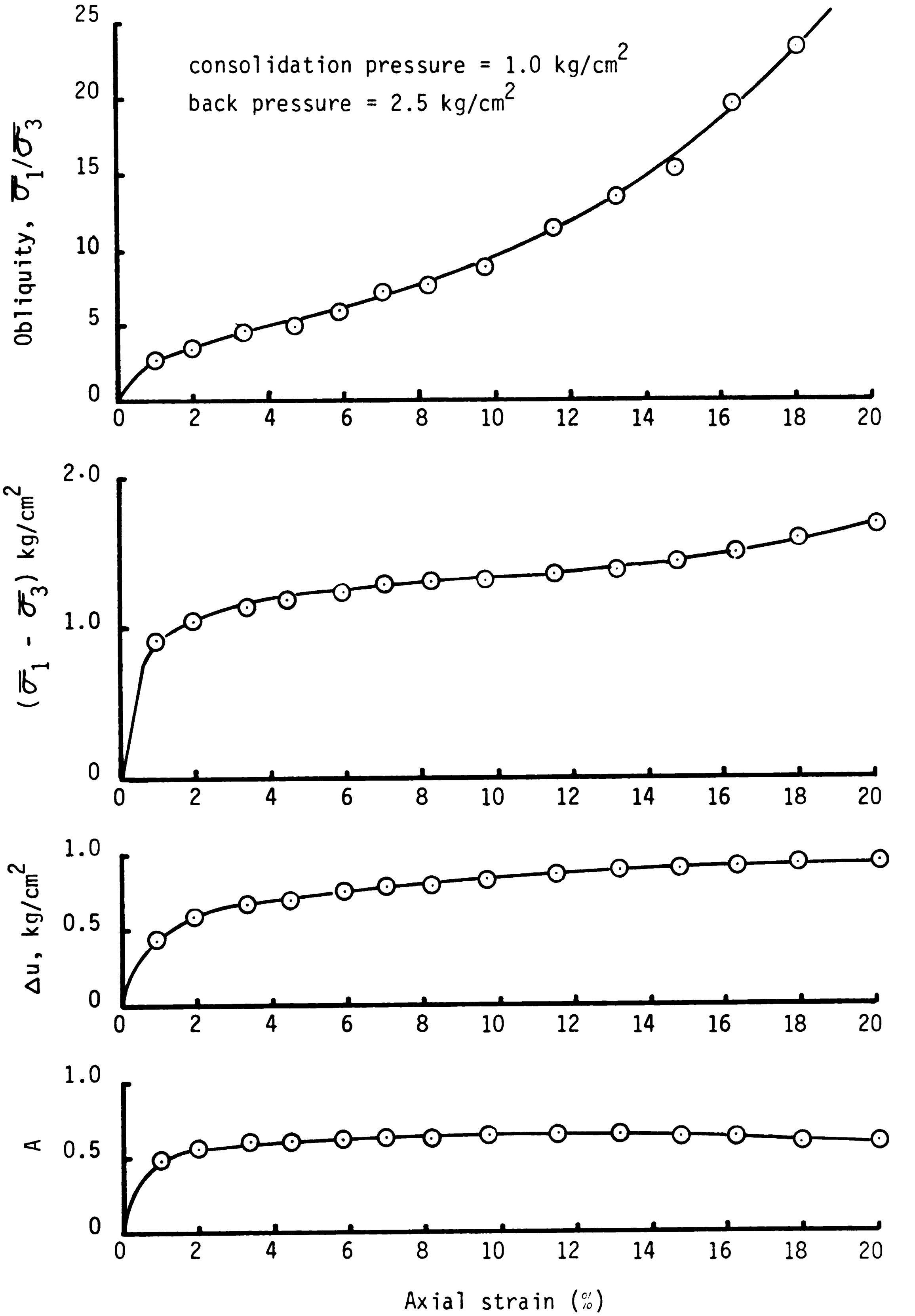


Figure 4.8 Axial strain versus Obliquity ratio, Effective deviator stress, Pore pressure, and Pore pressure coefficient, A, curves for primary sludge sample CU-P1.

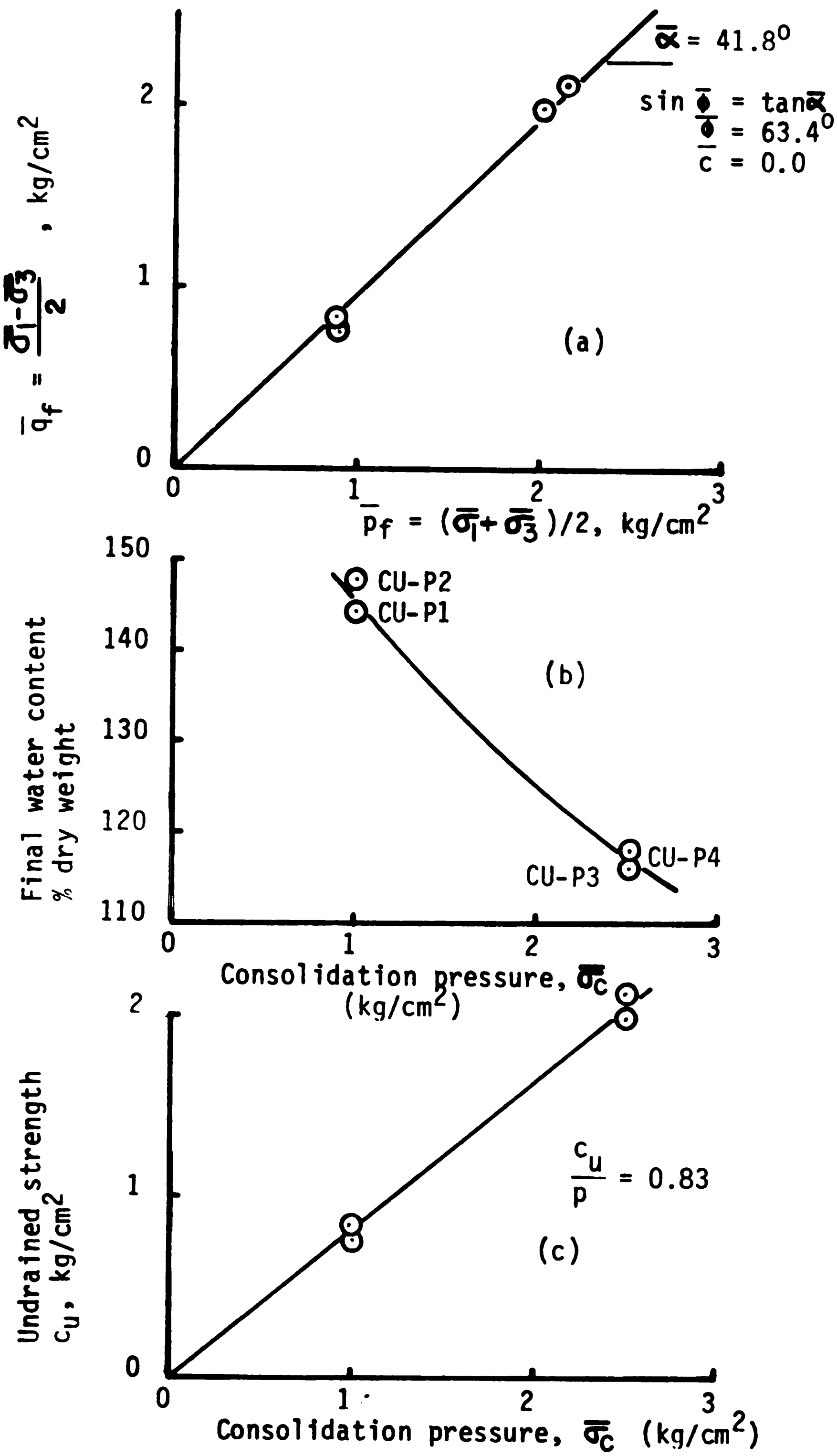


Figure 4.9 Consolidated-undrained triaxial test results for primary sludge samples. (a) k_f failure line (b) final water content (c) undrained strength.

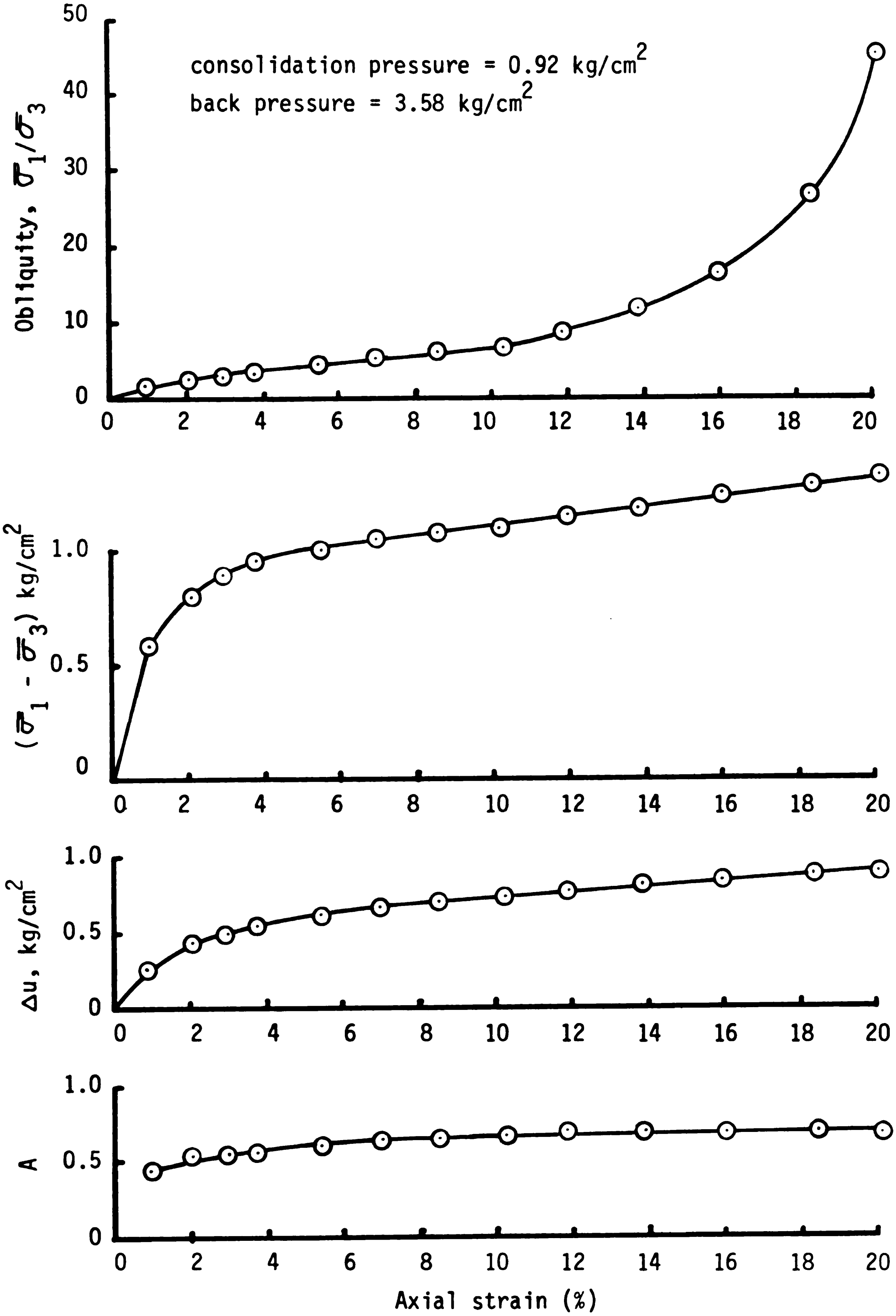


Figure 4.10 Axial strain versus Obliquity ratio, Effective deviator stress, Pore pressure and Pore pressure coefficient, A, curves for combined primary and secondary sludge sample CU-C1.

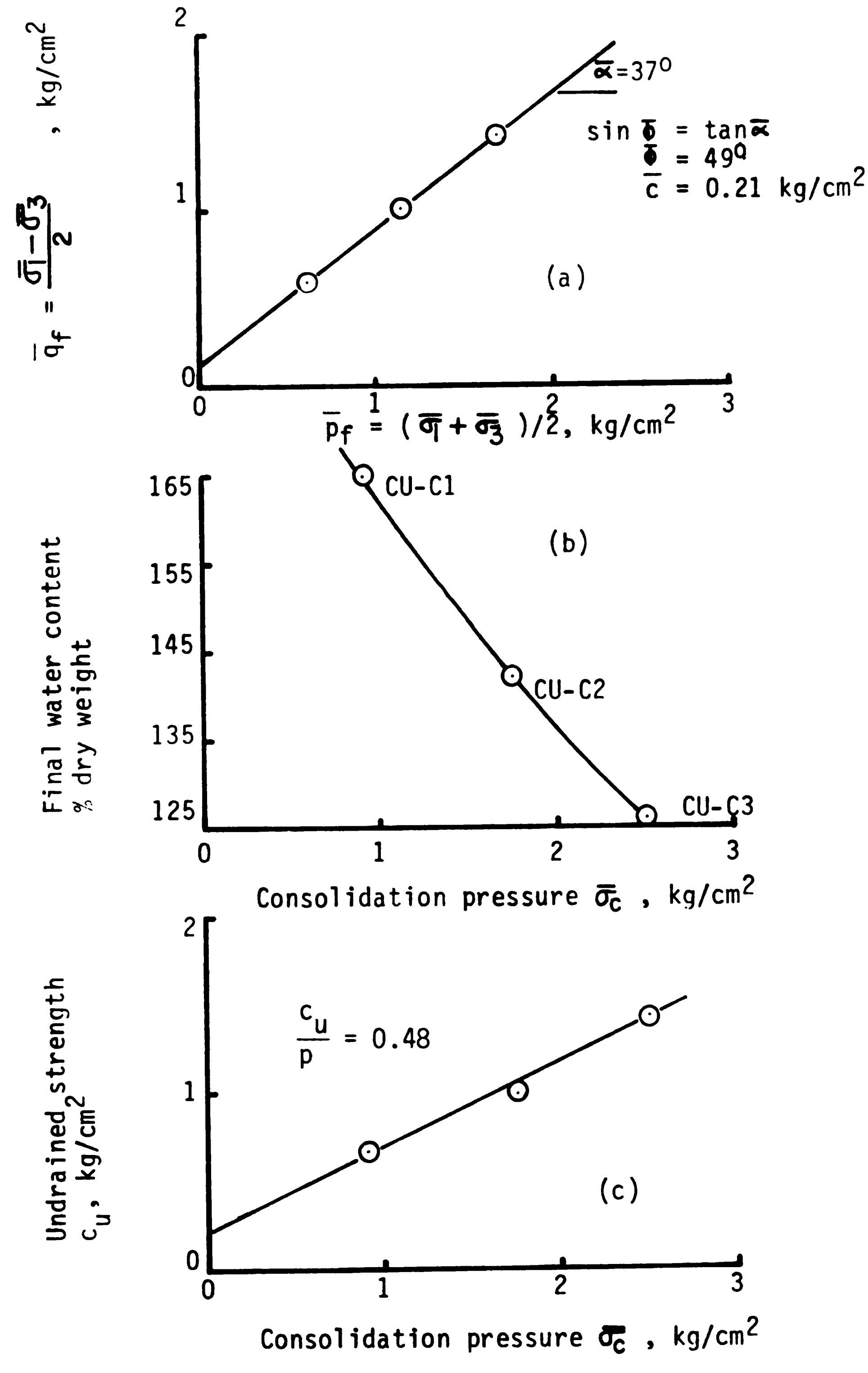


Figure 4.11 Consolidated-undrained triaxial test results for combined primary and secondary sludge samples (a) k_f failure line (b) final water content (c) undrained strength.

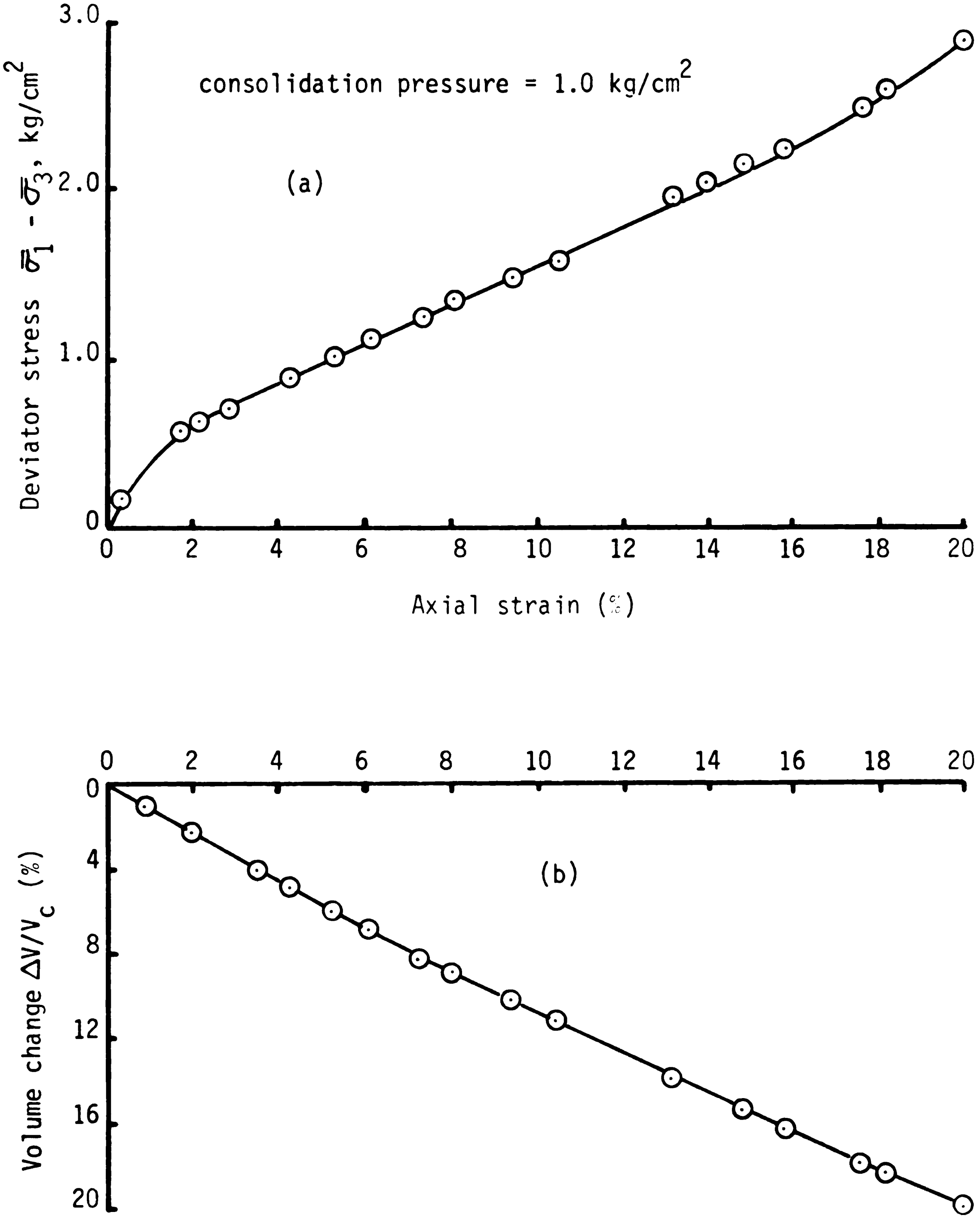


Figure 4.12 Typical results from a consolidated drained triaxial test on primary sludge sample CD-P1 (a) deviator stress (b) volume change.

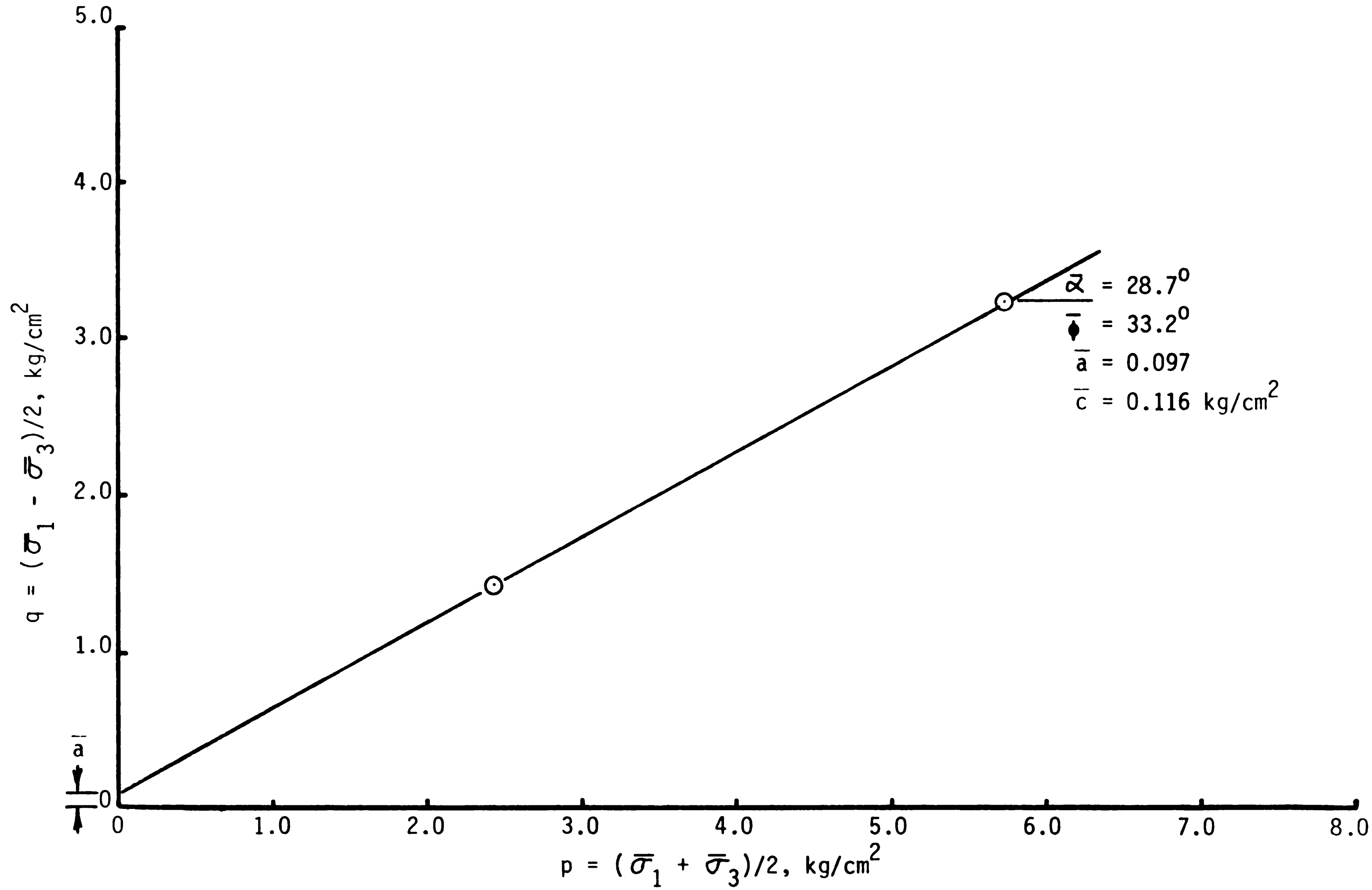
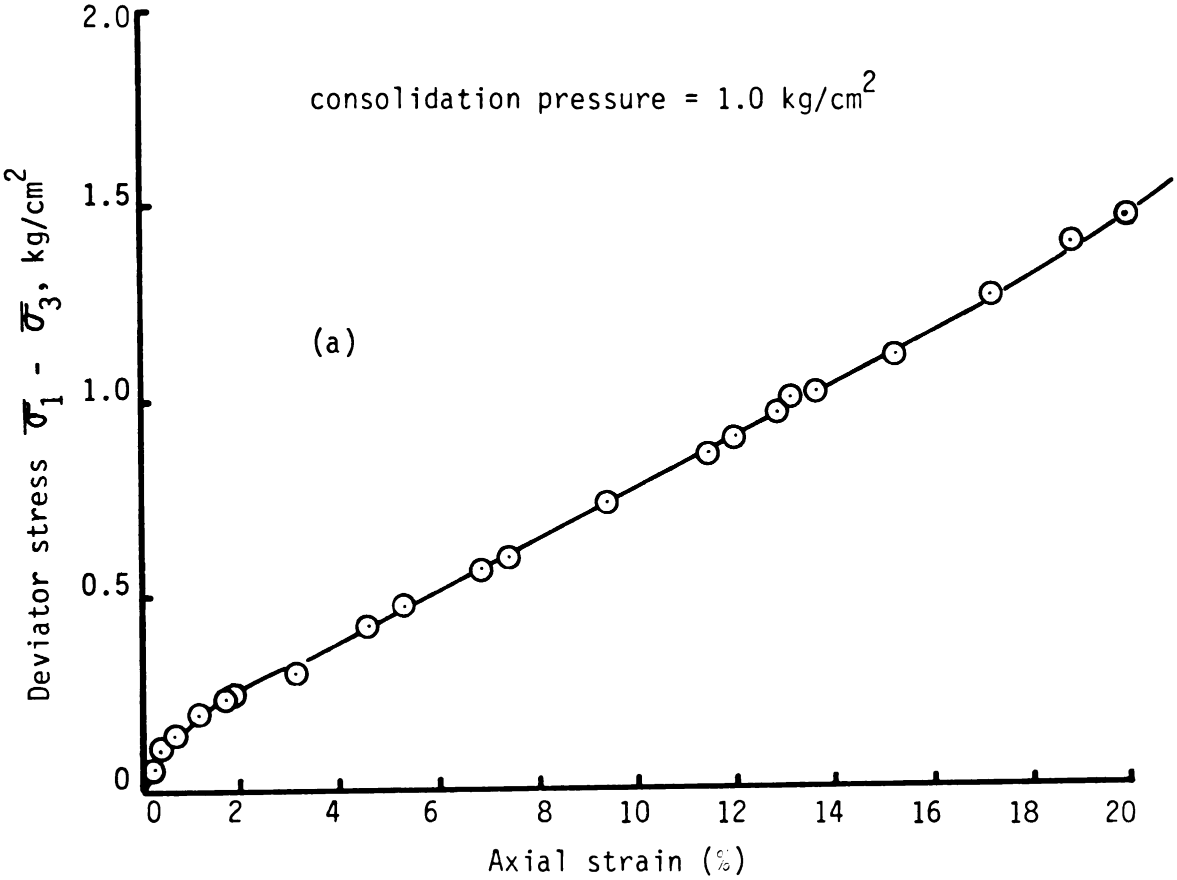


Figure 4.13 Consolidated-drained triaxial test results for primary sludge samples.



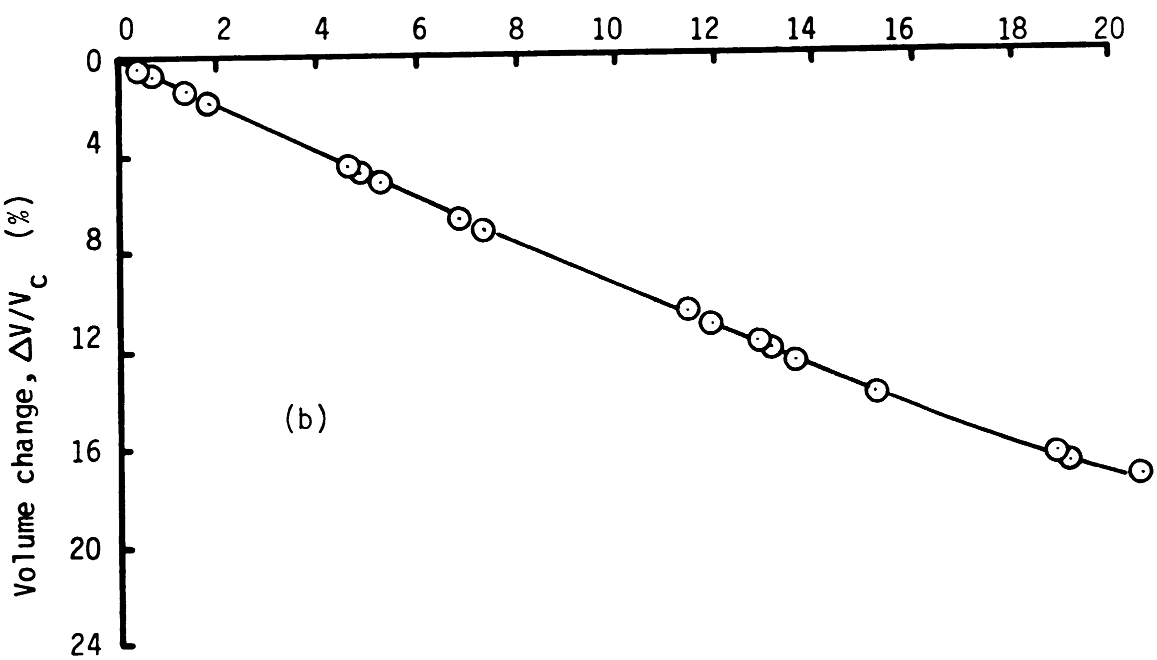


Figure 4.14 Typical results from a consolidated-drained triaxial test on combined sludge sample CD-C1 (a) deviator stress (b) volume change.

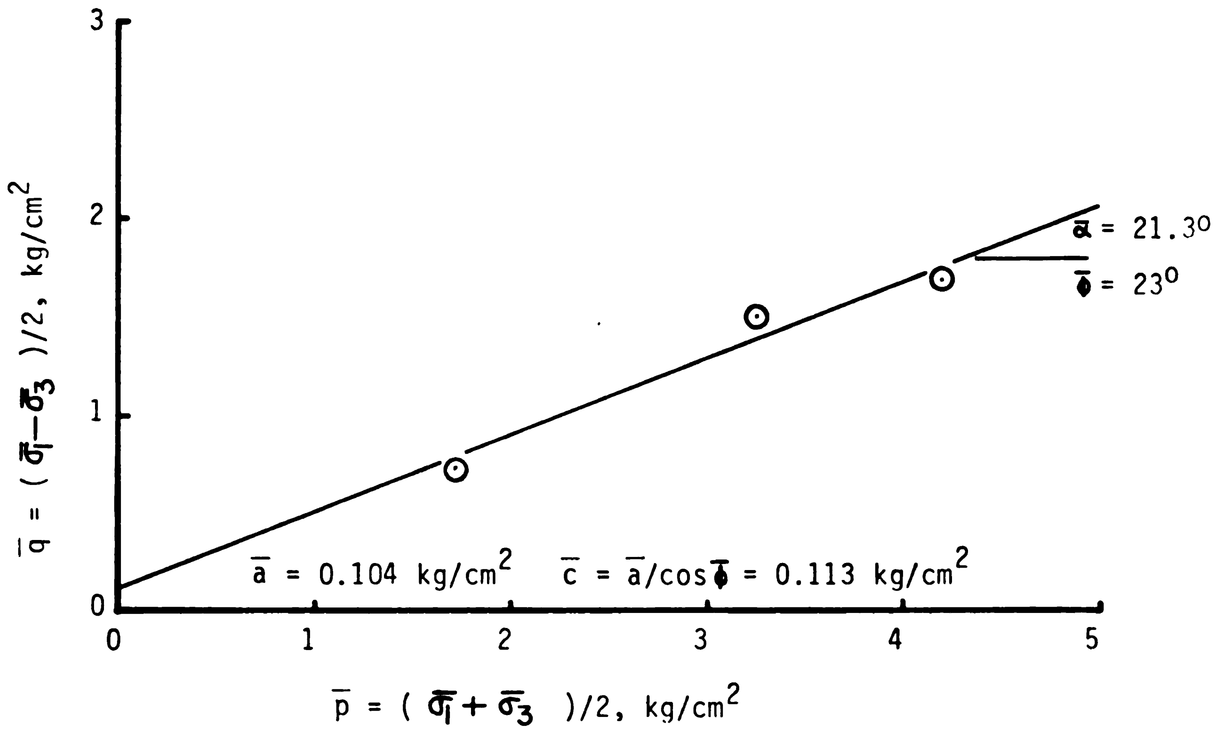


Figure 4.15 Consolidated-drained triaxial test results for combined sludge samples.

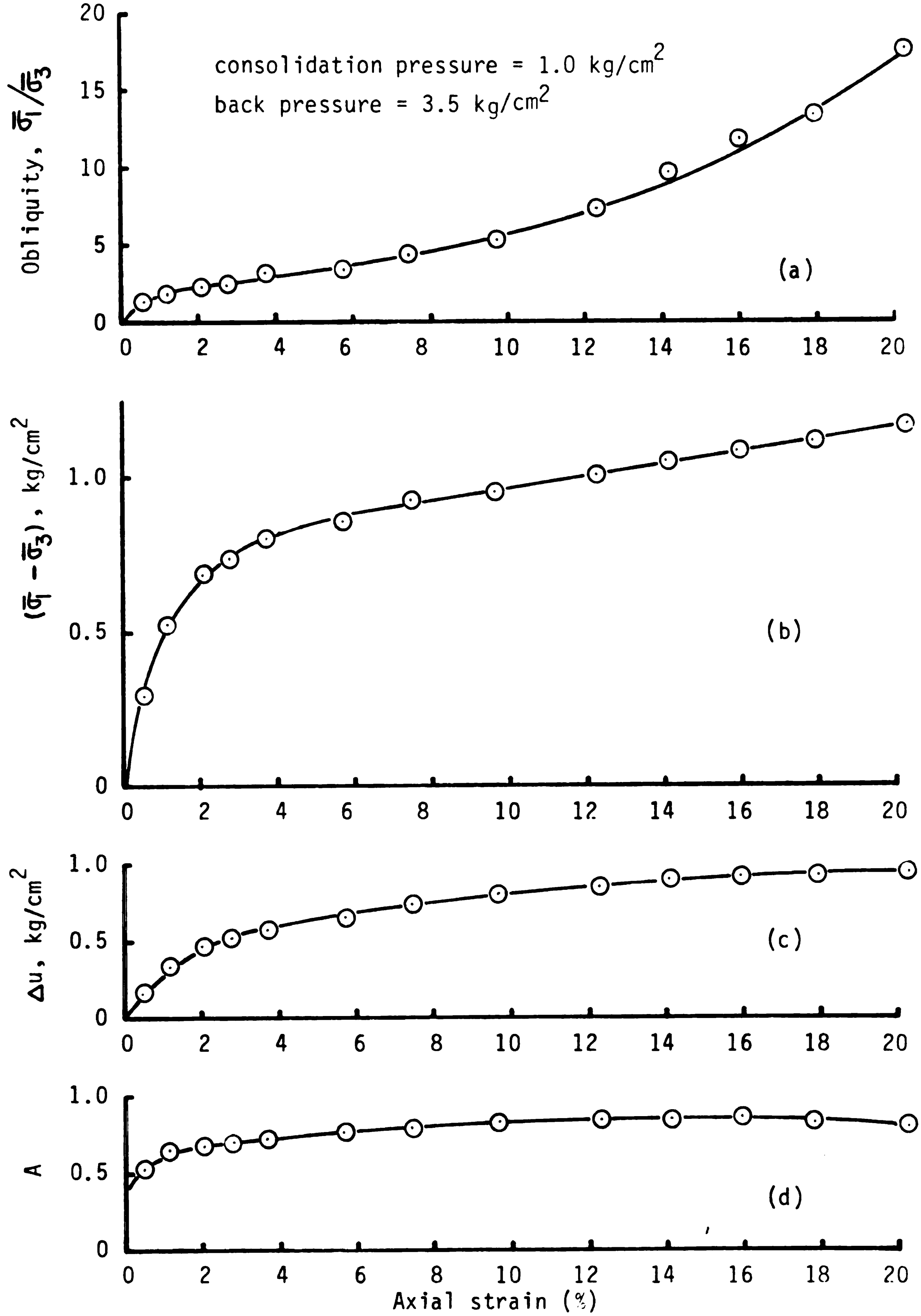


Figure 4.16 Axial strain versus Obliquity ratio, Effective deviator stress, Pore pressure and Pore pressure coefficient, A, for combined sludge with nutrients added, sample CU-CN1.

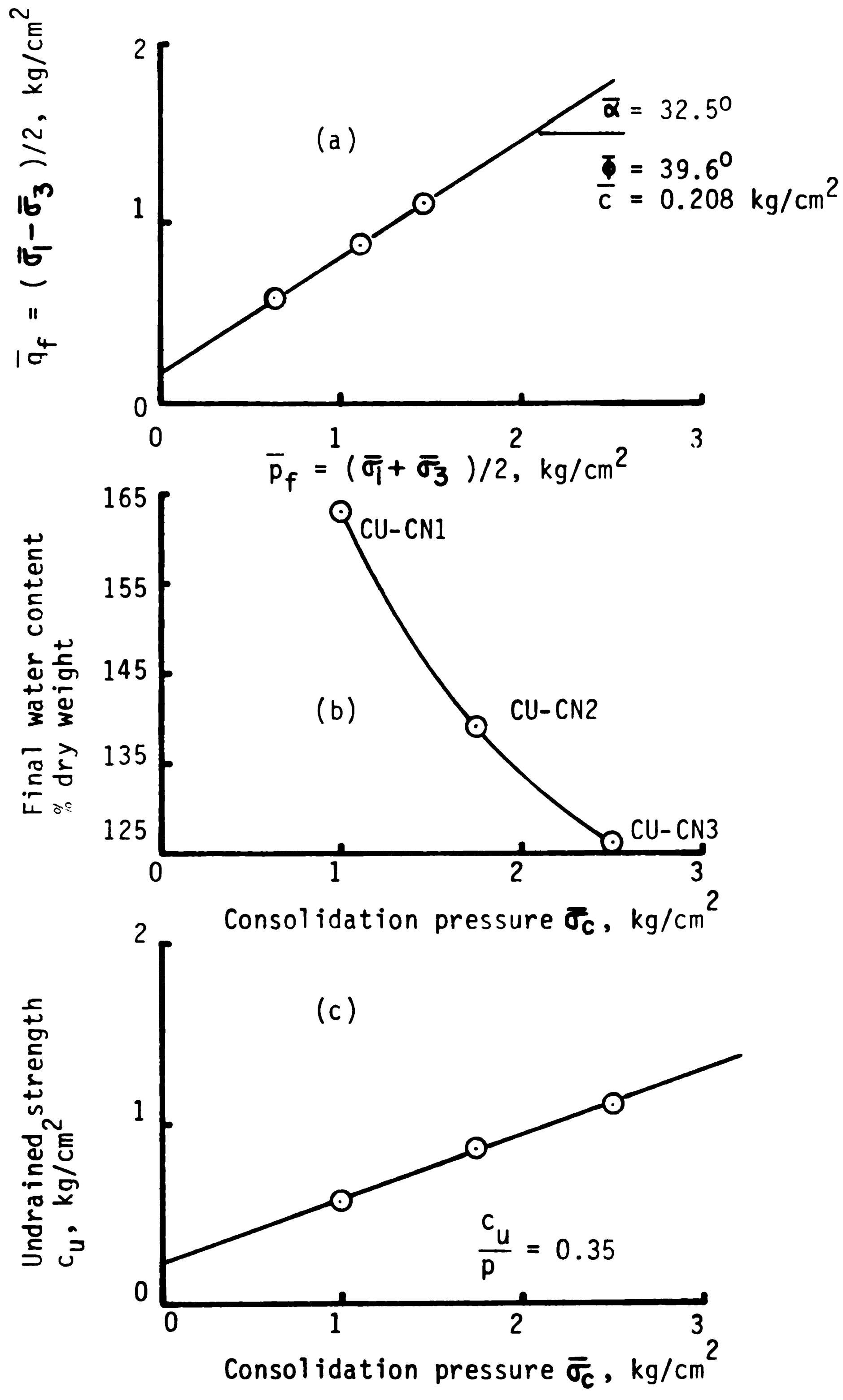


Figure 4.17 Consolidated-undrained triaxial test results for combined sludge samples with nutrients (a) k_f failure line (b) final water content (c) undrained strength.

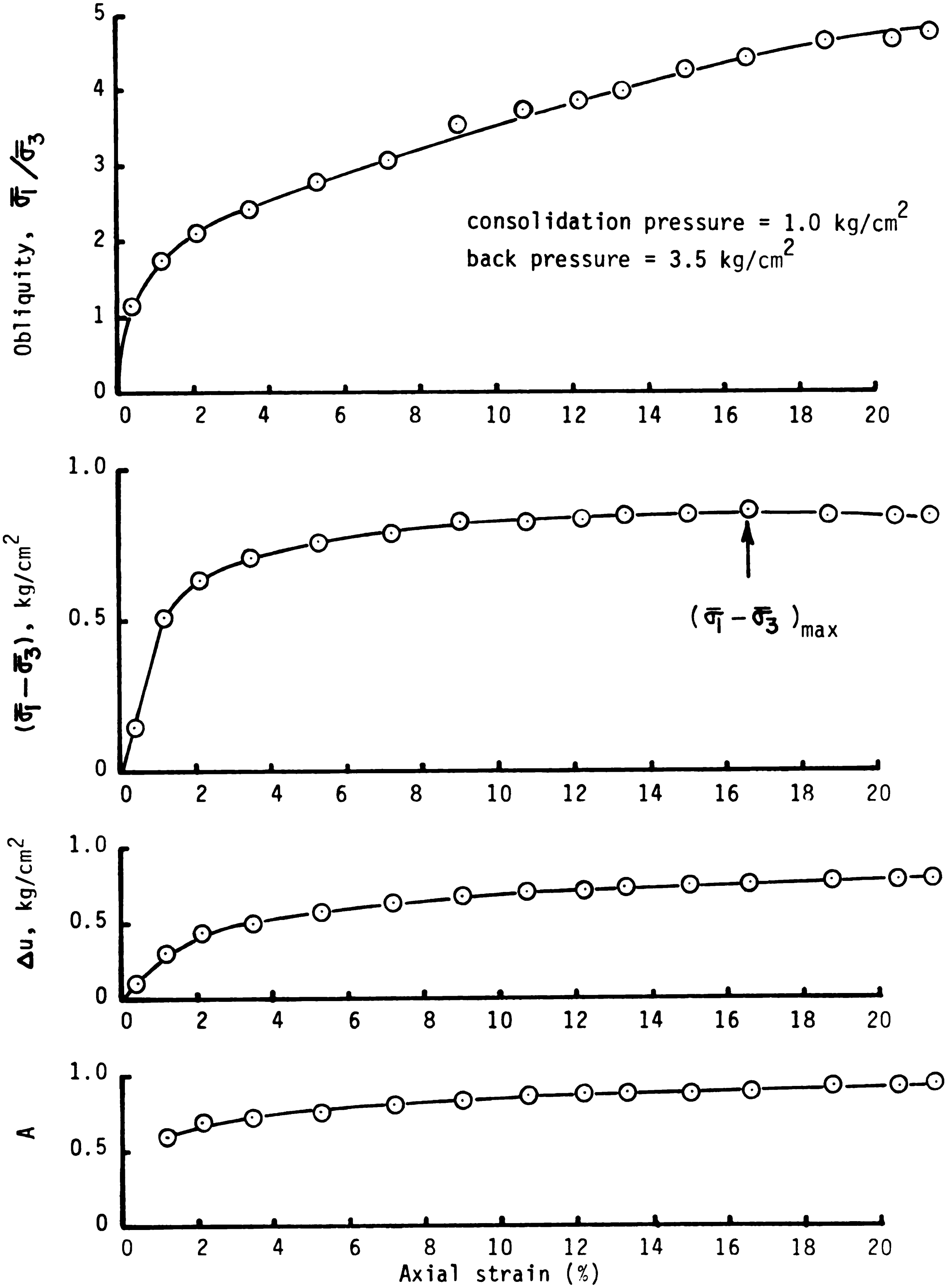


Figure 4.18 Axial strain versus Obliquity ratio, Effective deviator stress, Pore pressure and Pore pressure coefficient, A, for partially decomposed combined sludge sample CU-CD1.

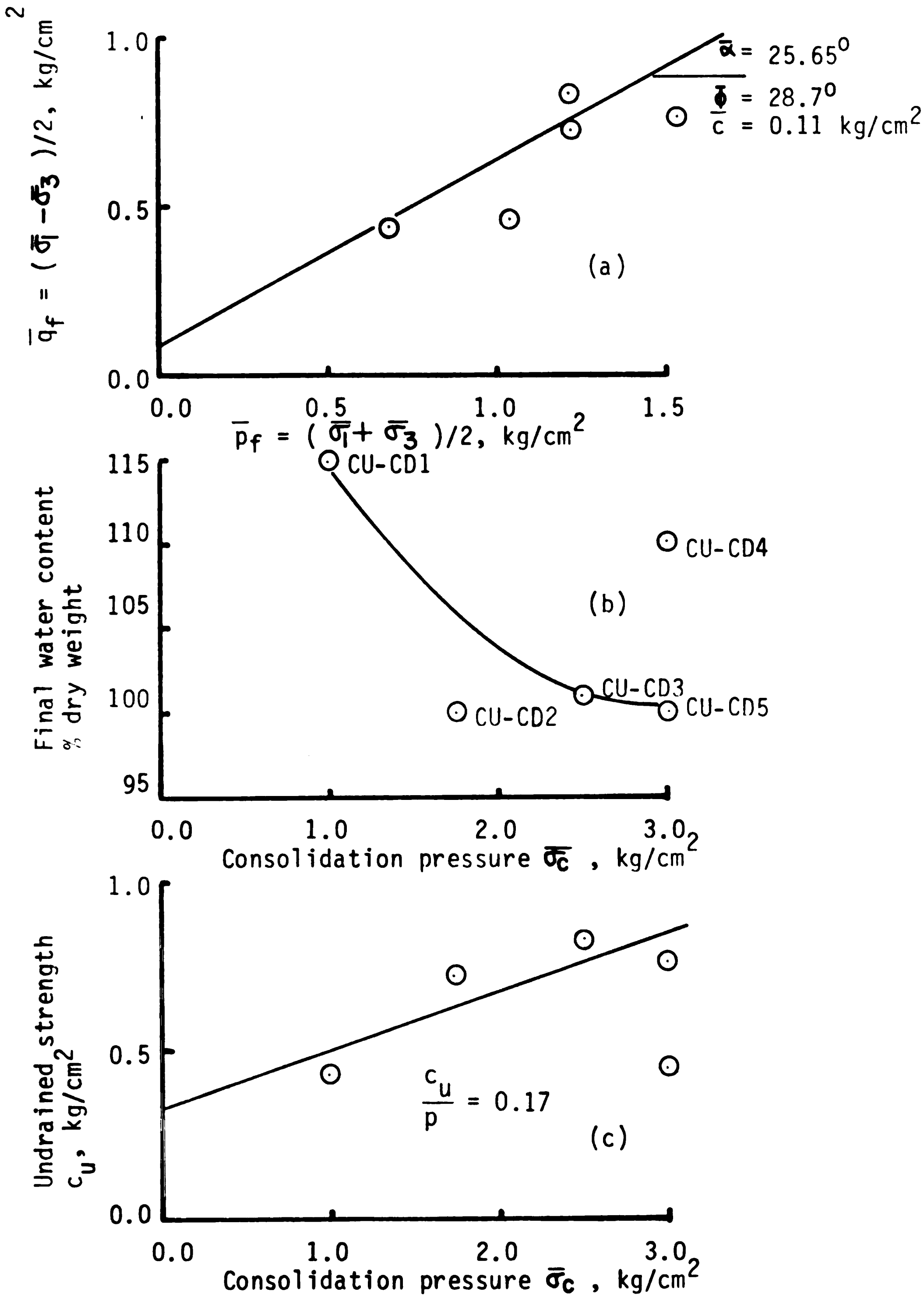


Figure 4.19 Consolidated-undrained triaxial test results for partially decomposed combined sludge samples (a) k_f failure line (b) final water content (c) undrained strength.

CHAPTER V

ANALYSIS AND DISCUSSION OF RESULTS

In addition to providing information necessary for a qualitative assessment of the engineering behavior of a papermill sludge, the physical properties, including water content, unit weight, specific gravity and organic fraction are useful in evaluating the compressibility and strength of a sludge landfill deposit.

A. Physical Properties

From data gathered daily at the mill during 1979, the observed solids content (dry weight basis) of the freshly dewatered sludge ranged from 18 to 43 percent (Appendix A). Equivalent water contents on a dry solids basis ranged from 456 to 133 percent, respectively. Variation of the organic fraction appears to be responsible for much of this variation. Measured ash contents varied from 28 to 81 percent giving an organic content between 72 and 19 percent (Appendix A). The higher organic fractions generally lead to higher water retention in the sludge. During dewatering operations the rate of application of the secondary sludge varied depending on solids capture efficiencies and visual appearance of the dewatered sludge cake. This factor accounts, in part, for the daily variation in the organic fraction of the dewatered sludge. Pulp fiber is probably the main source of the 49 percent organic content measured for the primary sludge. Addition of secondary sludge increased the organic content to 58 percent and the average water content from 270 to 318 percent. The increase in organic content, from addition of biological solids (secondary sludge) represents little increase in the amount of pulp fiber. Implications of the higher water content are considered later.

Specific gravities of the two sludge types given in Table 4.1 are similar, with the lower value for the combined sludge resulting from the lower specific gravity of the biological solids. The average measured specific gravity for the primary sludge, equal to 1.91, was slightly higher than the value for the combined sludge, equal to 1.89. This small difference, together with the difference in water contents indicates that the total unit weight of the primary sludge should be higher than the combined sludge. The unit weight values measured by packing the sludge into 1/10 cubic foot buckets, listed in Table 4.1, were 69.2 lb/cu.ft. and 70.9 lb/cu.ft. for the combined and primary sludge, respectively. Incorporating the average water contents yields dry densities of 16.6 lb/cu.ft. and 19.2 lb/cu.ft. for the combined and primary sludges, respectively.

The hydrogen ion concentration (pH) is a measure of the acidity or alkalinity of sludge. Perhaps the most significant factor regarding the pH is its' change with time. Anaerobic decomposition, when carried to its full extent, produces synthesized cellular material, the metabolic waste products methane and carbon dioxide, and a residue of nondegradable material. Anaerobic conversion of organic materials to methane can be separated into three steps: 1) Hydrolysis, in which large complex organic molecules are enzymatically broken down into smaller molecules capable of being transported into the cell; 2) Acid fermentation, which is the intracellular conversion of smaller molecules into a variety of organic materials of which the most important are short chain volatile acids; and 3) Methane production, or the conversion of short and long chain organic acids to methane. The acid fermentation phase involves the production of volatile acids which will lower the pH. If unchecked the pH may be depressed below 6.0, a range which is toxic to methane producing bacteria. During sample procurement, the sludge pH was measured at 11.9 by personnel of Nekoosa Papers. This value was said to be typical. Subsequent measurement showed a decrease in pH for both sludges. Figure 5.1 shows the pH of the combined sludge to have decreased more than the primary sludge. This pH change occurred while the samples were stored at $4^{o}C$ in sealed containers. The pH of the combined sludge decreased from a value near 12, where few micro-organisms can exist, to a value of about 8 which is favorable to most micro-organisms. Although no measurable change in the organic fraction was observed during this time, various odors were produced and both sludges became blacker in color. The foul odors and color change occurred sooner and became more distinct in the combined sludge samples. Based on these observations it would appear that both sludge samples were slowly entering the initial stages of decomposition.

B. Decomposition Observations

Accompanying the decomposition process was a decrease in the sludge organic content as measured by equation 2.3. Use of the initial organic fraction (X_{fo}) and the organic fraction after partial decomposition (X_{fi}) in equation 3.2 permitted evaluation of the degree of decomposition.

A pulp fiber with no decomposition is shown, magnified 1600 times, in Figure 5.2a. The 10 micron scale bar shows the fiber to be approximately 44 microns in diameter with holes having dimensions ranging up to 8 microns. After 25 days the average degree of decomposition, based on

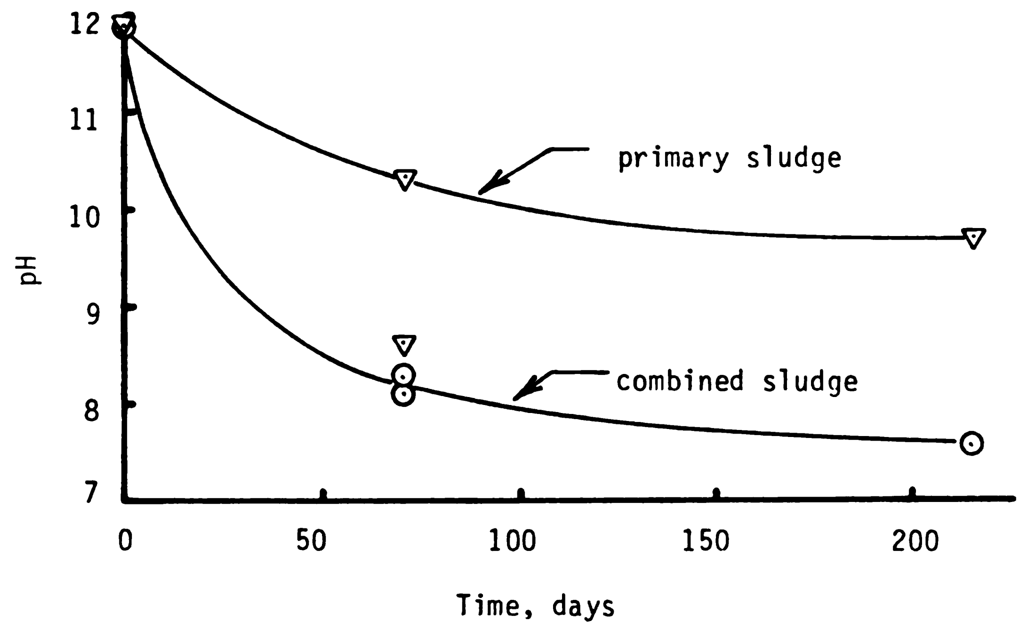


Figure 5.1 pH versus Time of sample storage at 4°C in sealed containers

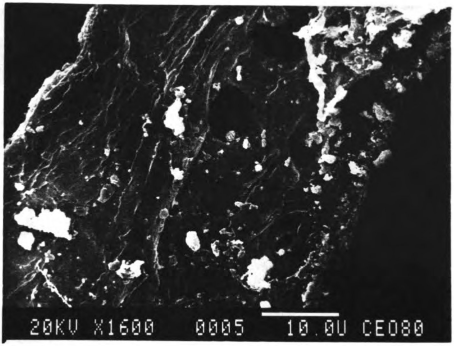
the ignition test, was 26.6 percent. Figure 5.2b shows a fiber at this stage of decomposition and indicates a general breakdown of the fiber's structural integrity. Another fiber shown in Figure 5.3a, under higher magnification, shows rod shaped bacteria on the fiber surface. At 20,000 magnification, these individual bacteria, slightly longer than 1 micron, appear as in Figure 5.3b.

Periodic observation of the sludge mass as it decomposed revealed an apparent increase in sludge volume in each of the sample containers. Upon stirring, large amounts of gas bubbles were released and the sludge volume decreased. Gas production rates of 14.5 percent per volume of sludge per day have been observed for decomposing sludge samples with a carbon to nitrogen ratio of 36:1 (Alexander, et al., 1978). Due to the lower permeability of the partially decomposed sludge, gas migration may be very slow, effectively trapping gases produced by decomposition. This trapped gas may significantly alter the stability of a landfill deposit due to a decrease in effective stresses in the sludge mass.

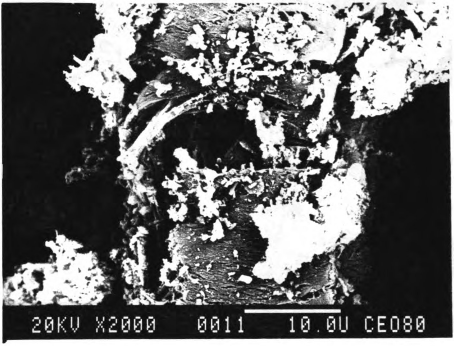
C. Consolidation Characteristics

The highly compressible nature of papermill sludge is due mainly to the organic material it contains. Pulp fibers have a high water holding capacity which gives the sludge a high water content and void ratio in comparison with inorganic soils. These factors result in large changes in sludge volume due to applied stress.

Figure 5.4 compares typical results of consolidation tests on the primary and combined sludges. Based on the compression index (C_c) the combined sludge appears to be more compressible than the primary sludge. This would be expected from the higher water contents and higher initial void ratios observed for the combined sludge. Example settlement

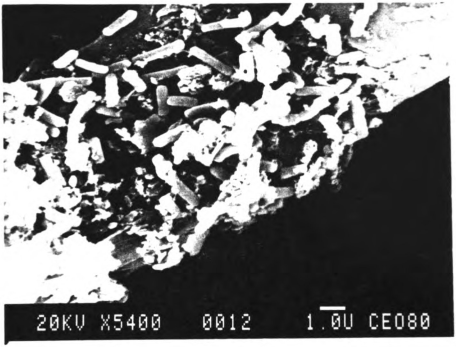


(a)

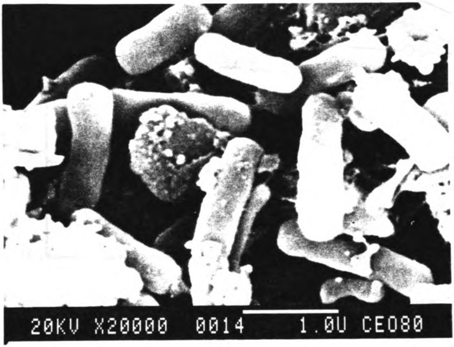


(b)

Figure 5.2 (a) 1600 magnification of a single fresh pulp fiber (b) 2000 magnification of a single pulp fiber after about 27 percent decomposition.



(a)



(b)

Figure 5.3 (a) 5400 magnification of decomposing pulp fiber with bacterial cells (b) 20,000 magnification of bacterial cells attacking pulp fiber.

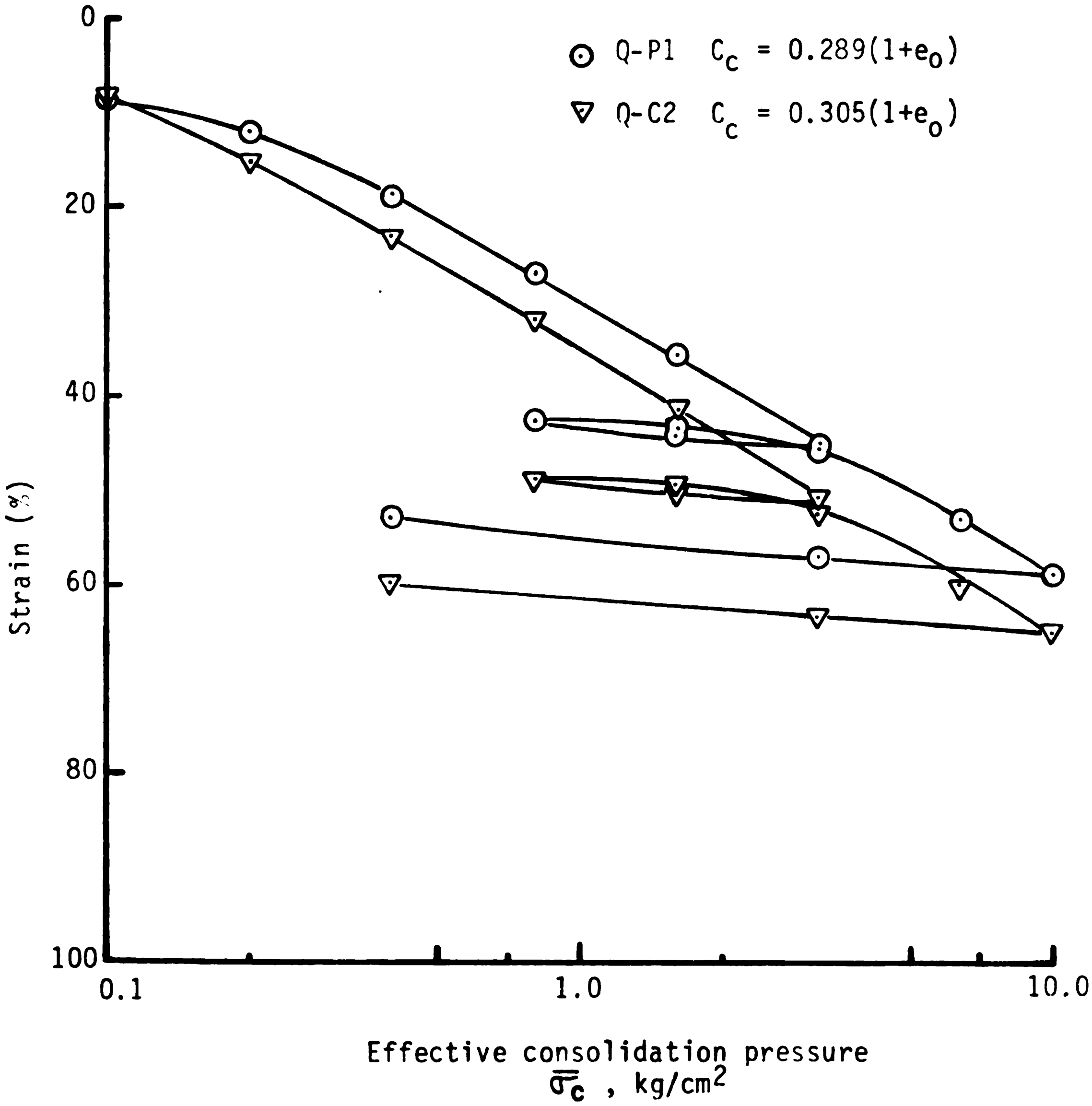
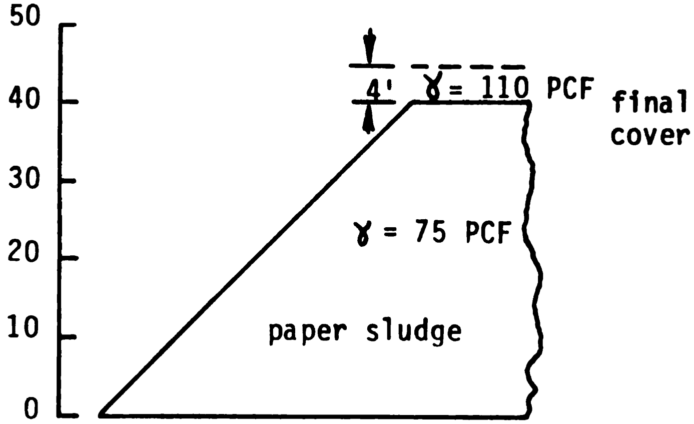


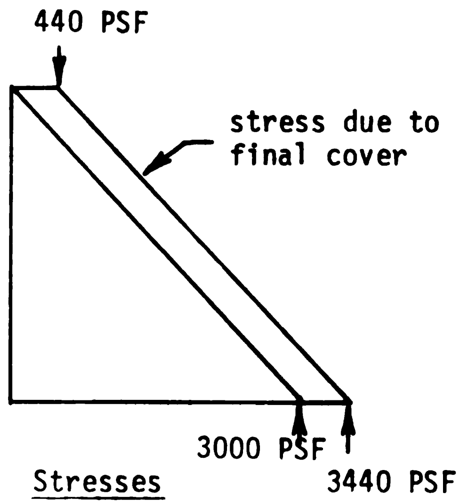
Figure 5.4 Comparison of strain-effective stress relationships for primary and combined sludge.

calculations for fresh primary and combined sludge are shown in Figure 5.5a and 5.5b, respectively. These figures show primary settlement estimates based on no initial or residual pore pressures using equation 2.5. Settlement estimates are for a 40 foot thick sludge layer subjected to a 440 psf surcharge. This pressure was estimated to be representative of a cross section consisting of a 1 foot sand drainage layer, a 2 foot layer of compacted clay covered by 1 foot of vegetated topsoil. The example calculations give primary settlement estimates of 22 and 24 inches for primary and combined sludge, respectively. Also shown in Figure 5.5 are primary settlement estimates based on equation 2.6. Resulting primary settlement estimates of 7.1 and 13.1 inches were calculated for primary and combined sludge, respectively. These estimates are much less than predicted from equation 2.5.

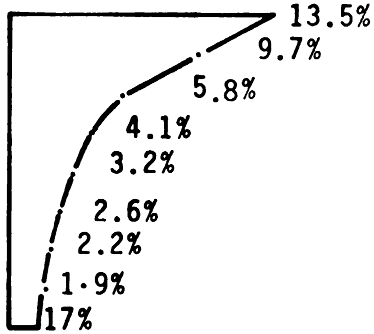
Secondary compression estimates using equation 2.7 are also included. These estimates are based on a 10 year period where secondary compression theoretically begins after primary compression is complete. Secondary compression estimates of 2.4 and 1.5 inches were calculated for the primary and combined sludge, respectively. A major reason for the higher secondary compression of the primary sludge is the longer time period over which secondary compression occurs in the primary sludge. Figure 5.5 shows estimates for the time required to complete primary compression for the two sludge types. It is seen that the time required for completion of primary compression of the primary sludge (3.3 years) is about half that required for the combined sludge (6.5 years) due to the lower permeability of the combined sludge.

Figure 5.5 also shows estimates of the volume of leachate expelled from a 1 foot square column of sludge 40 feet thick. These calculations show that one acre of primary sludge, 40 feet thick, will release





Stresses



Strains

$$\varepsilon = \frac{C_c}{1+e_o} \log \sigma_f/\sigma_o$$

Primary settlement

$$S = \int_0^H \varepsilon \, dz \cong \varepsilon_{ave} H = \underline{22 \text{ inches}}$$

$$\Delta H_f = H_{of}/H_{o1} \times \Delta H_1 = \frac{40\text{ft}(12\text{in/ft})}{0.754\text{in}} \times (0.1877-0.1765) = \underline{7.1 \text{ inches}}$$

Time for primary compression

$$t_p = \frac{T(H_o/2)^2}{c_v} = \frac{(1)(480/2)^2}{0.33\text{in}^2/\text{min}} = \underline{3.3 \text{ years to complete primary compression}}$$

Secondary settlement in 10 years

$$H_s = C_\alpha H \log t/t_p = 0.11(480-22)\log 10/33 = \underline{2.4 \text{ inches}}$$

Leachate released during primary compression

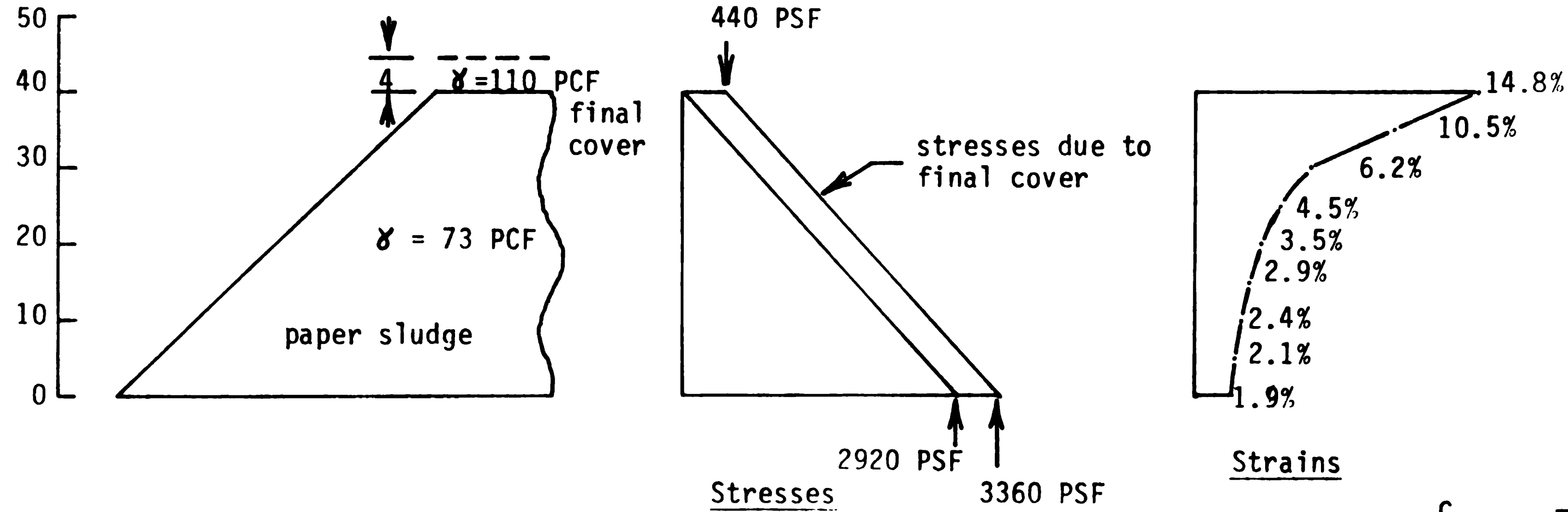
1 ft^2 column

$$22\text{in}(1\text{ft}/12\text{in}) = 1.83\text{ft}^3/\text{ft}^2$$

$$= \underline{597{,}350 \text{ gal/acre}}$$

(a)

Figure 5.5 Settlement predictions for sludge placed in a 40 foot deep pile due to placement of final cover (a) primary sludge (b) combined sludge.



$$\varepsilon = \frac{C_c}{1+e_o} \log \bar{\sigma}_f / \bar{\sigma}_o$$

<u>Primary settlement</u>

$$S = \int_0^H \varepsilon \, dz \cong \varepsilon_{ave} H = \underline{24 \text{ inches}}$$

$$\Delta H_f = H_{of}/H_{o1} \times \Delta H_1 = \frac{40ft(12in/ft)}{0.754 \ in} (0.218-0.1975) = \underline{13.1 \text{ inches}}$$

<u>Time for primary settlement</u>

$$t_p = \frac{T(H_o/2)^2}{c_v} = \frac{(1)(480/2)^2}{0.017 in^2/min} = 6.5 \text{ years to complete primary compression}$$

<u>If 26.6% decomposition occurs</u>

$$t_p = \frac{(1)(400/2)^2}{0.0039 in^2/min} = 19.5 \text{ years to complete primary compression}$$

<u>Secondary settlement in 10 years</u>

$$H_s = C_\alpha H \log t/t_p = 0.017(480-24)\log \frac{10}{6.5}$$

$$= \underline{1.5 \text{ inches}}$$

<u>Leachate released during primary compression</u>

1 ft^2 column

$24in(1ft/12in) = 2ft^3/ft^2$

= 651,658 gal/acre

(b)

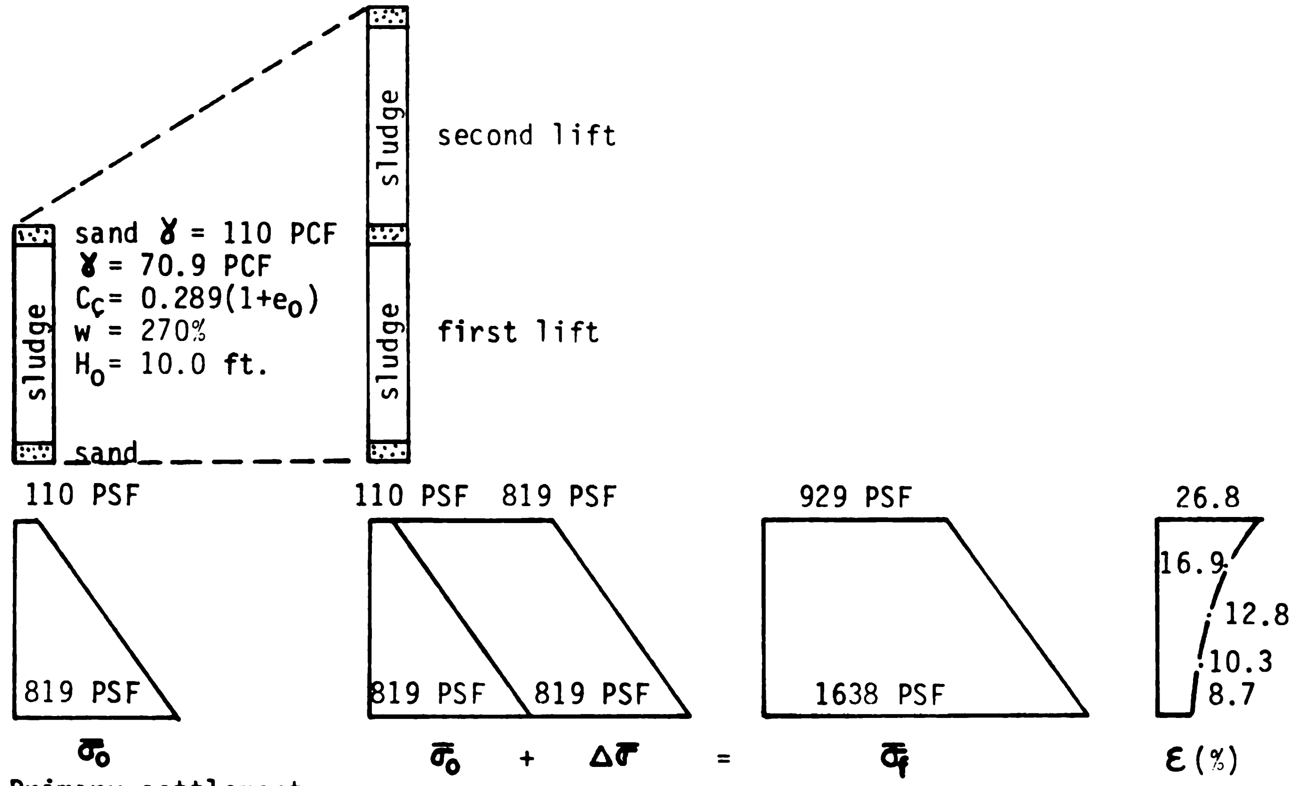
Figure 5.5 continued.

approximately 597,350 gallons of leachate, compared to 651,658 gallons for the combined sludge. These calculations used the previously described primary settlement estimates for the respective sludges.

Figure 5.5b shows an additional calculation for the time required to complete primary compression assuming 26.6 percent decomposition in the sludge. The decrease in the coefficient of consolidation (c_v) would theoretically increase the time required for primary settlement to 19.5 years. This slow drainage has implications relative to landfill stability which will be discussed in a following section.

Figure 5.6a and 5.6b present similar calculations for a configuration of 10 foot thick sludge layers separated by sand drainage layers. The settlements given in this example are for a 10 foot thick sludge layer and should therefore be compared to Figure 5.5 with that fact in mind. In addition to changes in settlement magnitudes are the decreases in time required to complete primary compression. The sand drainage layers separating 10 foot thick sludge layers will decrease the time required for primary compression by greater than a factor of 10. Secondary compression estimates in this example are based on 1 years time.

In the example in Figure 5.6 primary settlements from equation 2.5 and 2.6 compare reasonably well. It should be noted that these settlements and the resulting leachate volumes are less than the layer would actually experience due to consolidation or the layer under its' own weight. The time rate of settlement may be important in estimating the rate of leachate generation for the efficient design of leachate collection systems and in estimating the increase in stability during consolidation.



Primary settlement

$$S = \int_0^H \varepsilon \, dz \cong \varepsilon_{ave} H = \underline{17.3 \text{ inches}}$$

$$H_f = H_{of}/H_{o1} \times \Delta H_1 = \frac{120\text{in}}{0.754\text{in}} (0.2925-0.2091) = \underline{13.3 \text{ inches}}$$

Time for primary compression

$$t_p = \frac{T(H_o/2)^2}{c_v} = \frac{(1)(120/2)^2}{0.0295\text{in}^2/\text{min}} = 85 \text{ days to complete primary compression}$$

Secondary settlement in 1 year

$$H_s = C_\alpha H \log t/t_p = 0.0187(120-17.3)\log 365/85 = \underline{1.2 \text{ inches}}$$

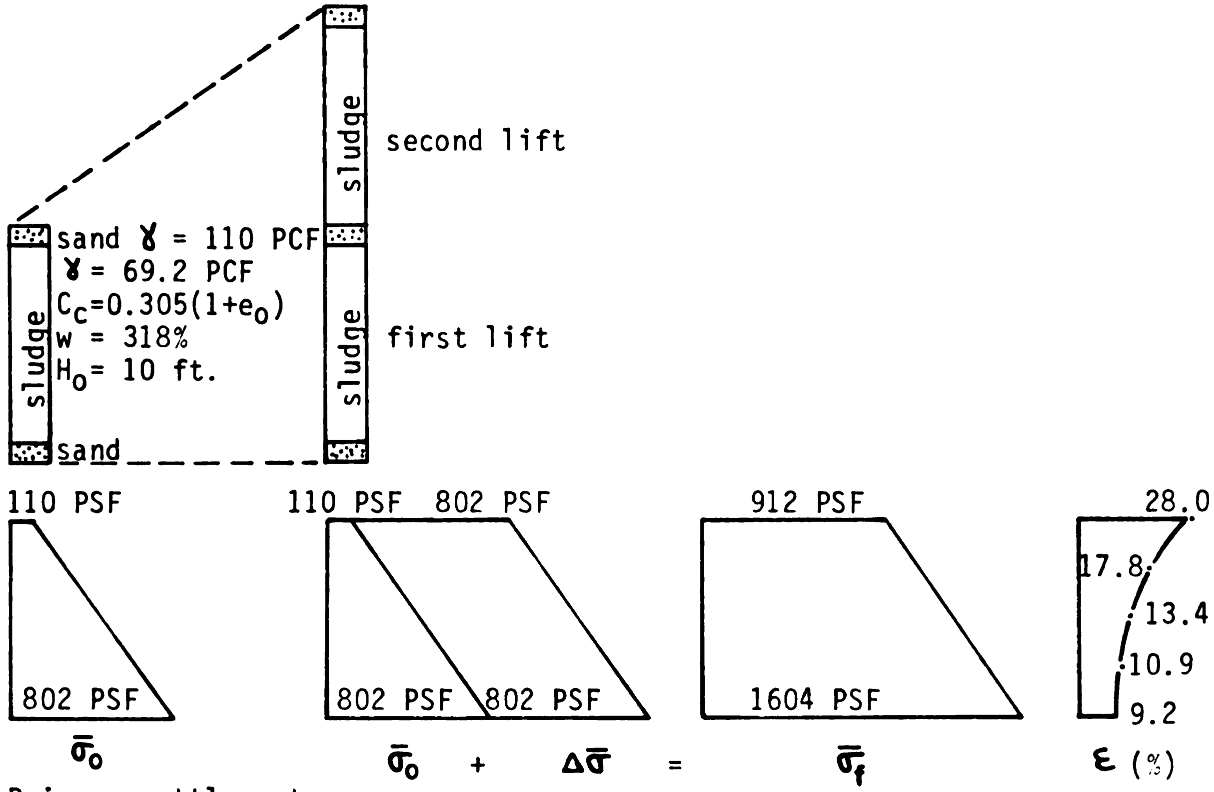
Leachate released during primary compression

1 ft^2 column

17.3in(1ft/12in)= 1.44ft^3/ft^2 = 469,737 gal/acre

(a)

Figure 5.6 Settlement predictions for a 10 foot thick layer of sludge consolidating under the weight of another 10 foot layer (a) primary sludge (b) combined sludge.



Primary settlement

$S = \int_0^H \varepsilon \, dz \cong \varepsilon_{ave} H$ = 18 inches

$\Delta H_f = H_{of}/H_{o1} \times \Delta H_1 = \frac{120\text{in}}{0.754\text{in}} \times (0.2045-0.1039)$ = 16 inches

Time for primary compression

$t_p = \frac{T(H_o/2)^2}{c_v} = \frac{(1)(120/2)^2}{0.0119\text{in}^2/\text{min}}$ = 209 days to complete primary compression

If 26.6% decomposition occurs

$t_p = \frac{T(H_{ave}/2)^2}{c_v} = \frac{(1)(95.7/2)^2}{0.00239\text{in}^2/\text{min}}$ = 1.8 years to complete primary compression

Secondary settlement in 1 year

$H_s = C_\alpha H \log t/t_p = 0.0244(120-18)\log 365/209$ = 0.6 inches

Leachate released during primary compression

1 ft^2 column

$18\text{in}(1\text{ft}/12\text{in}) = 1.5\text{ft}^3/\text{ft}^2$ = 488,706 gal/acre

(b)

Figure 5.6 continued.

Decomposition of the organic fraction has been shown to greatly increase the time required for primary consolidation. Considering Figure 2.9, there would be additional settlement of the decomposing sludge under a constant overburden stress. For 26.6 percent decomposition, the consolidated sludge layer would be expected to settle an additional 25 percent. The additional settlements for the examples presented in Figures 5.5b and 5.6b would be 9.0 feet and 2.3 feet respectively. If this is taken into account in calculating the time required for primary compression, the times are about 20 years and 1.8 years for the examples in Figures 5.5b and 5.6b, respectively.

D. Landfill Stability (shear strength parameters)

The highly fibrous nature of papermill sludges tends to make them respond to applied stresses in a plastic manner as shown in Figure 4.7. Typically, higher fiber contents result in higher initial strengths, and thus higher measured friction angles (Laza, 1971; Khattak, 1978). The amount of fiber in a primary papermill sludge is usually measured by ignition at high temperatures with the weight loss taken as the organic (fiber) fraction. Addition of biological solids from the secondary treatment processes gives an increase in the organic fraction even though little, if any fiber has been added. Comparison of Figures 4.9 and 4.11 tend to support this. The friction angle for the primary sludge, measured at 63.4 degrees, decreased to 49 degrees upon addition of secondary sludge, while the organic fraction increased from 0.49 for the primary sludge to 0.58 for the combined sludge. Accompanying the decrease in the friction angle was an increase in the apparent cohesion from 0 kg/cm^2 to 0.21 kg/cm^2.

Water content has been plotted against all around consolidation pressure in Figures 4.9b and 4.11b for primary and combined sludge, respectively. The higher organic content of the combined sludge gives it a higher water content than the primary sludge at similar consolidation pressures. There was also a greater decrease in water content of the combined sludge for a given stress increment.

Figures 4.9c and 4.11c summarize the test results in terms of total stresses by plotting undrained shear strength, c_u, against consolidation pressure. The ratio c_u/p appears to be a constant for both sludges which is typical of normally consolidated soils.

The shear strength of the sludge, in terms of effective stresses, was also evaluated by consolidated-drained (CID) triaxial tests. Since drainage is permitted during load application, measured total stresses are equal to effective stresses. This test method eliminates the development of high pore pressures, but the problem of defining failure still exists. As shown in Figures 4.12a and 4.14a the axial stress continues to increase at strains greater than 20 percent. As with $\overline{\text{CIU}}$ tests, failure was taken at 20 percent axial strain, resulting in the k_f lines in Figures 4.13 and 4.15 for primary and combined sludges, respectively. The friction angle of the primary sludge measured 33.2 degrees, while that of the combined sludge measured 23 degrees. These results are much lower than those obtained from $\overline{\text{CIU}}$ tests on the same sludge materials.

The $\bar{\phi}$ values obtained from the two test methods are summarized along with data obtained by Khattak (1978) for model sludge materials in Figure 5.7. To illustrate the significance of these test results an example analysis of the stability of the landfill cross-section shown in Figure 5.8 has been performed. Figure 5.8 shows a possible

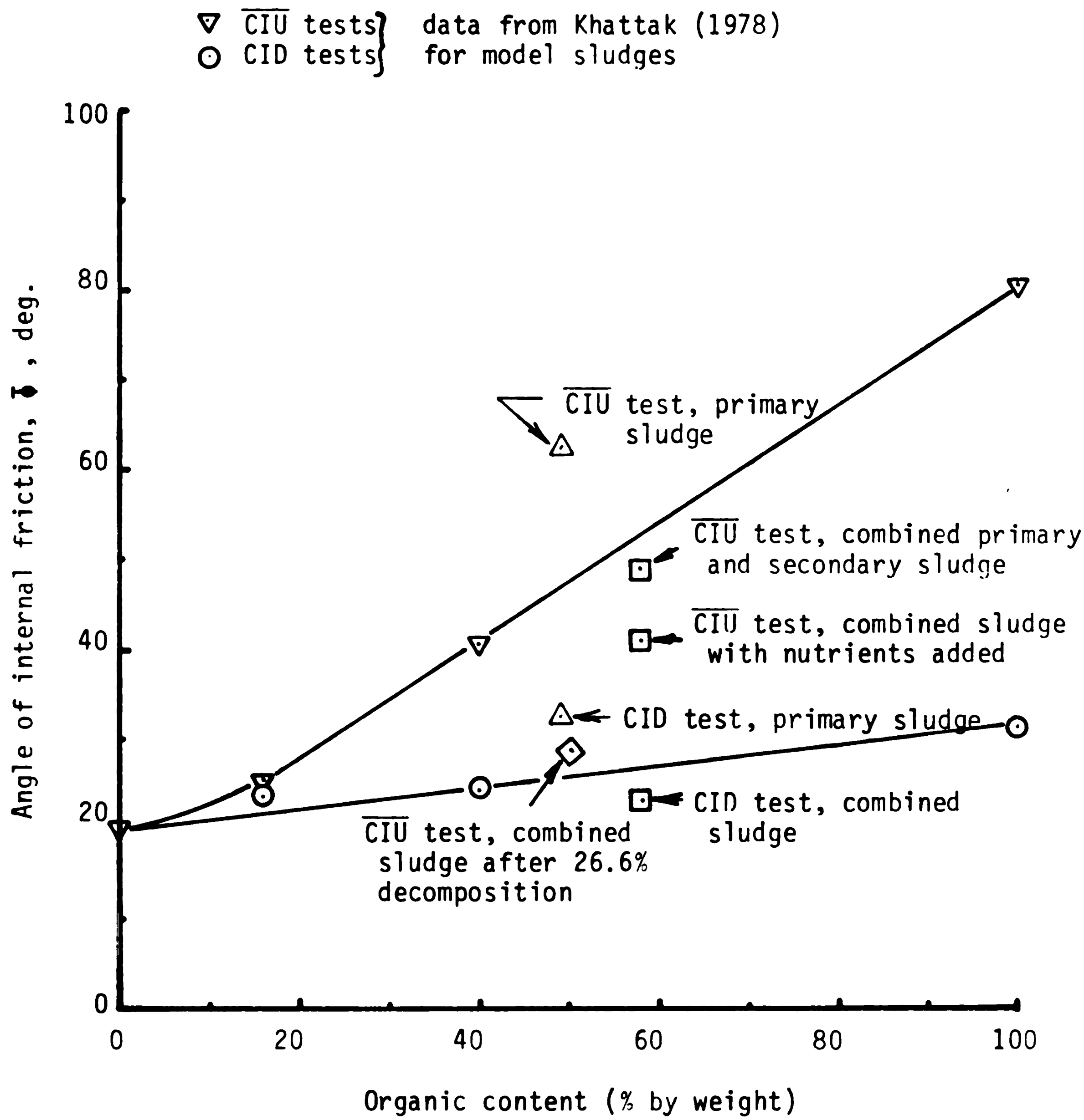


Figure 5.7 Dependence of the angle of internal friction ($\bar{\phi}$) on organic content for several sludge materials.

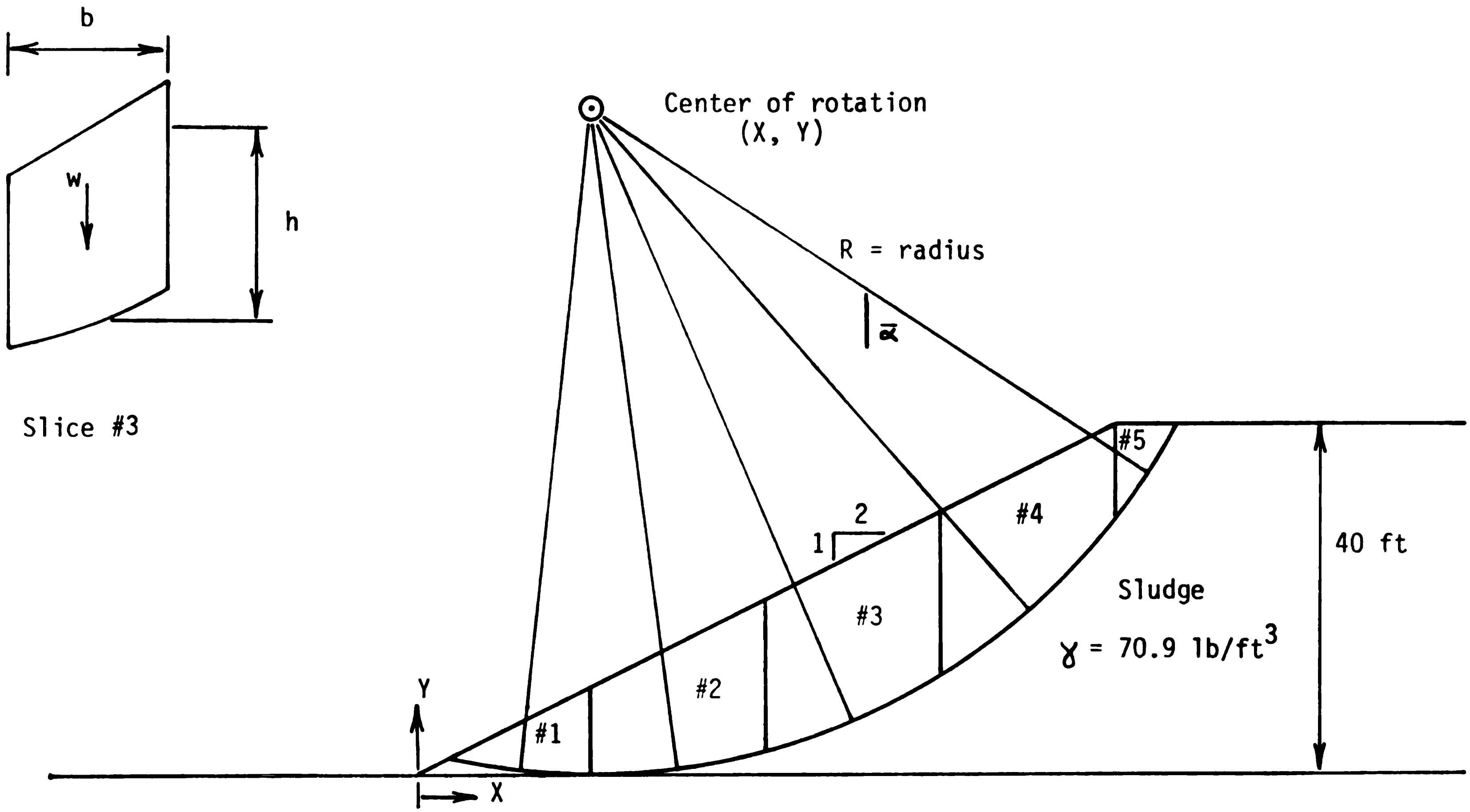


Figure 5.8 Example cross-section of a primary sludge slope with possible failure surface

cross-section along the perimeter of the landfill with a finished slope of 1 vertical to 2 horizontal. Also shown are the slices used to perform the example slope stability analysis presented in Table 5.1. The center of the critical failure circle was determined using the meods outlined in NAVFAC DM-7 (1971). The Bishop (1954) simplified method of slices was used to evaluate the stability of the slope assuming two drainage conditions. The two drainage conditions considered were a slope in which excess pore pressures coincided with the surface and one in which no excess pore pressures were present. The first condition may be an extreme case in which no drainage of the sludge has occurred and the second case exemplifies the condition of a landfill with intermediate drainage layer conpletely relieving excess pore pressures.

The results of several stability analyses for the various sludge conditions, test methods, and drainage conditions are summarized in Table 5.2. This comparison shows the influence of drainage conditions on landfill stability. Also shown is the greater dependence of overall stability on the material cohesion than on its friction angle. Due to the relatively low material weight, only a small portion of the frictional component of shearing resistance is mobilized. The results of several other stability analyses are presented in Appendix E.

Little or no field data is available to support use of the results of either test method. The measured friction angles in the $\overline{\text{CIU}}$ test for both fresh sludges appear unreasonably high. Fibers extending across potential shear planes in triaxial test samples, which are able to withstand tensile forces, may be the cause for these high friction angles. In considering the long term stability of a landfill deposit,

TABLE 5.1 STABILITY ANALYSIS FOR PRIMARY SLUDGE SLOPE USING $\overline{CIU}$ TEST RESULTS (a) FOR A SLOPE WITH EXCESS PORE PRESSURES (b) FOR A SLOPE WITH NO EXCESS PORE PRESSURES

(a)

Primary sludge: γ_m = 70.9 PCF, $\bar{\phi}$ = 63.4°, $\bar{c}$ = 0, $u = \gamma_w h$ where h corresponds to the slope surface

slice	b (ft)	h (ft)	A_2 (ft²)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	16	5.7	80.0	5.672	0	-6.05	-0.598	0.680	1.358
2	20	14.3	286.0	20.277	0	7.59	2.678	2.431	4.854
3	20	18.9	378.0	26.800	0	23.20	10.558	3.213	6.416
4	20	16.0	320.0	22.688	0	41.26	14.962	2.720	5.432
5	7	5.3	35.7	2.531	0	57.02	2.123	0.303	0.606
							Σ=29.723		

$$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$$

$$1/M_\alpha \quad (W-ub)\tan\bar{\phi} + \bar{c}b$$

slice	F_{RHS}	F_{RHS}	F_{RHS}	F_{LHS}	F_{LHS}	F_{LHS}
	(0.1)	(0.31)	(0.33)			
1	0.784	0.315	0.357	1.732	4.304	3.808
2	1.255	1.842	1.791	3.868	2.635	2.711
3	1.706	3.457	3.303	3.761	1.856	1.942
4	2.069	5.000	4.742	2.626	1.086	1.145
5	2.220	5.948	5.621	0.273	0.102	0.108
				Σ=12.260	Σ=9.983	Σ=9.714

F_{LHS} = 12.260/29.723 = 0.41 = 0.34 = 0.33

circle center (X = 20 ft, Y = 76 ft)

Factor of Safety = 0.33

TABLE 5.1 cont.

(b)

Primary sludge: γ_m = 70.9 PCF, $\bar{\phi}$ = 63.4^o, $\bar{c}$ = 0, u = γ_wh where h=0 for a drained slope

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	16	5.7	80.0	5.672	0	-6.05	-0.598	5.672	11.327
2	20	14.3	286.0	20.277	0	7.59	2.678	20.277	40.492
3	20	18.9	378.0	26.800	0	23.20	10.558	26.800	53.518
4	20	16.0	320.0	22.688	0	41.26	14.962	22.688	45.307
5	7	5.3	35.7	2.531	0	57.02	2.123	2.531	5.054
							Σ=29.723		

$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$

$1/M_\alpha \; (W-ub)\tan\bar{\phi} + \bar{c}b$

slice	F_{RHS}	F_{RHS}	F_{RHS}	F_{LHS}	F_{LHS}	F_{LHS}
	(2.0)	(4.3)	(5.08)			
1	0.889	0.945	0.953	12.738	11.980	11.885
2	1.123	1.053	1.043	36.053	38.469	38.817
3	1.312	1.102	1.074	40.777	48.561	49.831
4	1.410	1.058	1.011	32.128	42.824	44.815
5	1.382	0.934	0.874	3.657	5.412	5.782
				Σ=125.353	Σ=147.246	Σ=151.130

F_{LHS} =125.353/29.723 = 4.22   4.95   5.08

Factor of Safety = 5.08

TABLE 5.2 SUMMARY OF STABILITY ANALYSES

Sludge and Test Condition	$\bar{\phi}$ (deg.)	$\bar{c}$ (psf)	Factor of Safety * undrained slope	drained slope
Primary Sludge ($\overline{CIU}$)	63.4	0	0.33	5.08
Combined Sludge ($\overline{CIU}$)	49.0	430	1.37	4.31
Primary Sludge (CID)	33.2	238	0.75	2.44
Combined Sludge (CID)	23.0	231	0.70	1.89
Decomposed Sludge ($\overline{CIU}$)	28.7	225	0.75	2.11

* A stable slope is normally assumed when the factor of safety is greater than 1.00.

these fibers may not be held tightly enough at low consolidation pressures to yield these high friction angles. In addition, possible decomposition involving disintegration of pulp fibers,as shown in Figures 5.2b and 5.3,may reduce or eliminate the fibers' contribution to the frictional component of shearing resistance. If this is the case, the friction angle of the sludge material may approach that of the mineral component. Khattak (1978) measured the friction angle of kaolinite to be approximately 20 degrees. A value of $\bar{\Phi}$ = 28.7 degrees was measured for the combined sludge used in this research program following 26.6 percent decomposition. Figure 5.9 shows the effects of the addition of nutrients and decomposition on the deviator stress of combined sludge samples. Figure 5.10 summarizes the results of consolidated-undrained triaxial tests on the fresh combined sludge, the combined sludge after addition of nutrients, and after 26.6 percent decomposition. Table 5.2 shows the significance of decomposition on the factor of safety for the example slope considered in the calculations presented in Appendix E.

Considering the difficulty in determining an appropriate value of $\bar{\Phi}$ for the sludge, a somewhat conservative although realistic assessment of the landfill stability for design purposes may be obtained using the measured material cohesion and assuming a friction angle of 20 degrees. For field deposits, insitu measurement of the shear strength by means of a field vane may be appropriate for current sludge strengths.

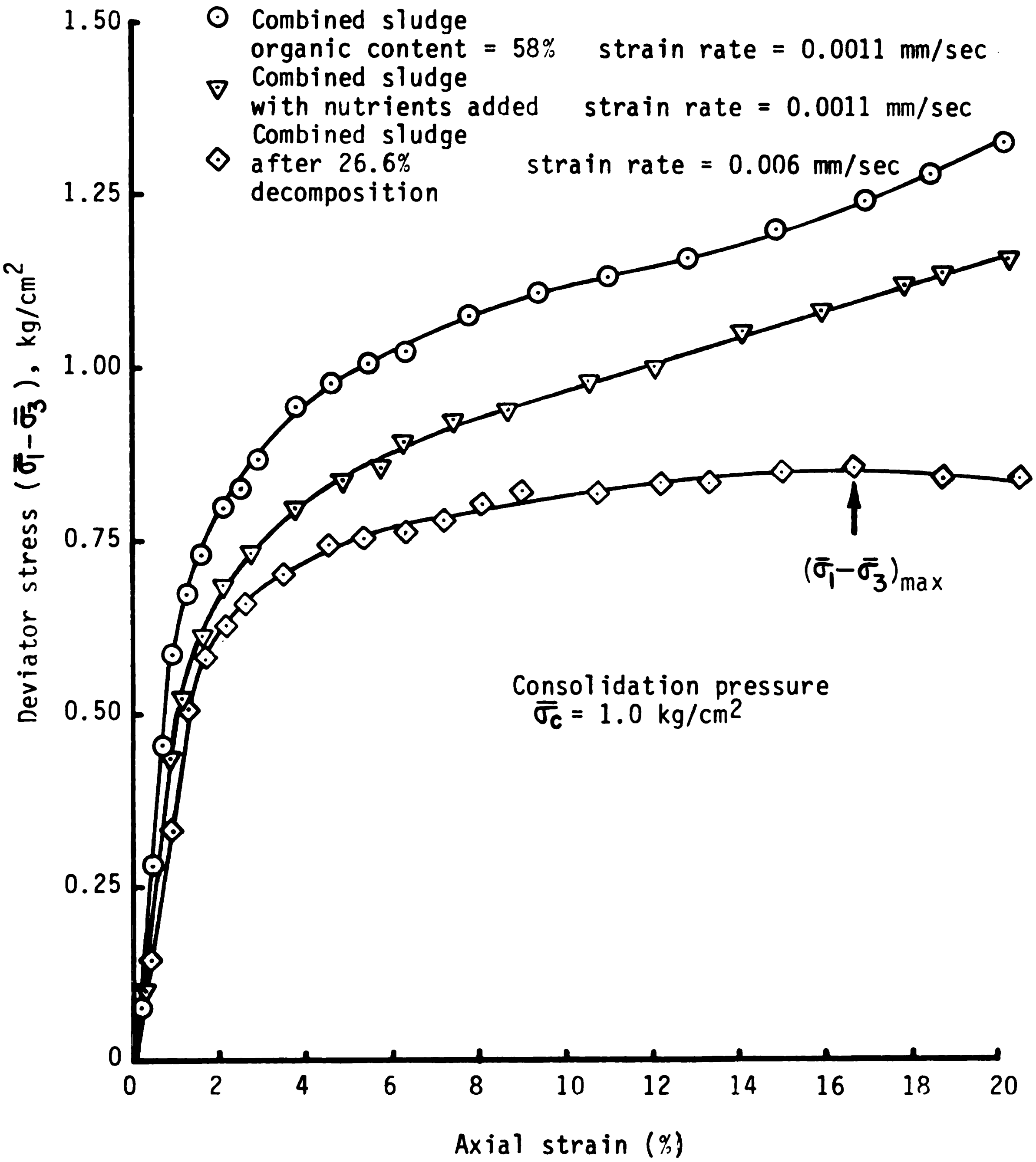


Figure 5.9 Effect of decomposition on deviator stress of combined sludge samples in the $\overline{CIU}$ test.

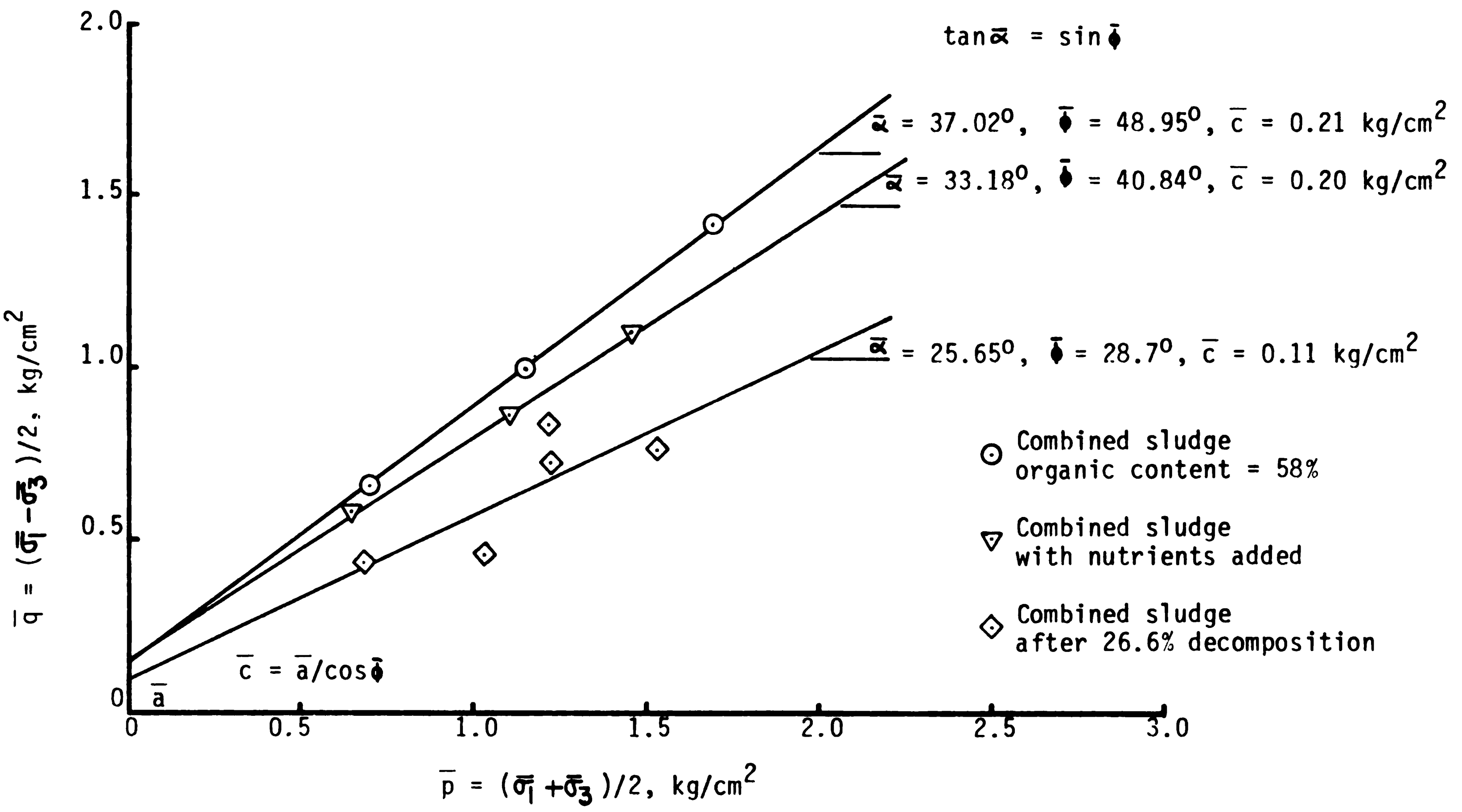


Figure 5.10 Summary of consolidated-undrained triaxial tests, k_f lines, effective stress basis.

CHAPTER VI

SUMMARY AND CONSLUSIONS

The summary and conslusions are presented in the areas of : (1) physical properties, (2) engineering properties, (3) decomposition effects on sludge properties and landfill performance, and (4) suggested field instrumentation and monitoring.

A. Physical Properties

Physical properties of the papermill sludge were measured in order to better evaluate differences in engineering behavior of the sludge materials. Physical properties included water content, unit weight, organic content, specific gravity, and pH. These properties were influenced most by differences in the organic content. Higher organic contents of the combined sludge resulted in higher water contents (lower solids contents), lower unit weights and lower specific gravities. The pH of the sludge was influenced by pretreating agents used prior to dewatering, and pH changes served to indicate microbial activity. Decreased pH values were generally associated with activity of acid forming anaerobic bacteria. A reduction in the organic fraction was also observed for decomposing sludge samples.

B. Engineering Properties of the Sludges

Stress deformation behavior of the sludge was observed in terms of the consolidation behavior and shear strength parameters of the sludge materials.

One-dimensional consolidation tests utilizing a range of compressive loads, from 0.1 to 10 kg/cm^2, measured the sludge response to applied stress. The results, summarized in terms of strain versus pressure, showed that the combined sludge with its higher initial water content was more compressible than the primary sludge. Use of the compression index for prediction of ultimate settlements for two possible landfill configurations showed the combined sludge to be slightly more compressible than the primary sludge. Ultimate settlement estimates based on MacFarlane's (1969) method utilizing single increment load tests were less than those predicted using the compression index.

The rate of consolidation, which is dependent on sludge permeability, was compared for the two sludges by means of the coefficient of consolidation. These results showed that the primary sludge would compress approximately twice as rapidly as the combined sludge for typical field loading conditions. Estimates of the coefficient of consolidation, c_v, were obtained from the Taylor square root of time construction for each load increment during the consolidation test. These results also allowed indirect determination of the coefficient of permeability k. Over the range of applied loads (0.1 to 10 kg/cm^2), k for the primary sludge ranged from 2.5×10^{-6} to 8.0×10^{-9} cm/sec while k for the combined sludge varied from 1.3×10^{-6} to 1.1×10^{-9} cm/sec. Also, use of drainage layers at 10 foot intervals would decrease the theoretical time required for primary consolidation by a factor of 10 or more for the layer configurations discussed.

Two variations to the standard consolidation test procedure included the single increment and rapid load increment (quick) procedures. Single load increment tests yielded results which differed from other test methods in some instances. Rapid load increment tests and standard 24 hour increment tests gave nearly identical results.

Shear strength of the fresh and partially decomposed sludge was measured by consolidated-undrained ($\overline{CIU}$) and consolidated-drained (CID) triaxial tests. Stress-strain curves showed that large strains were required to fully mobilize the available sludge strength. This implies that unacceptably large deformations may occur before overall instability develops. Experimental data, summarized in terms of $\bar{p}$ - $\bar{q}$ plots provided the angle of internal friction and cohesion on an effective stress basis and water content and undrained strength versus all-around consolidation pressure. The $\overline{CIU}$ tests gave a friction angle for the fresh primary sludge equal to 63 degrees as compared to 49 degrees for the combined sludge. However, a cohesion intercept of 0.21 kg/cm^2 for the combined sludge gives it a slightly higher strength at low overburden pressures. The CID test yielded friction angles of 33 degrees and 23 degrees for the primary and combined sludges, respectively. Nutrients added to the combined sludge to aid decomposition lowered the $\bar{\Phi}$ value from 49 degrees to about 40 degrees for the undrained tests. Decomposition of 27 percent lowered the friction angle from 40 degrees to about 29 degrees.

Using these strength parameters, several stability analyses were performed on a typical slope for the undrained and drained conditions. Due to the low sludge unit weight the material cohesion was found to have more influence on stability than the friction angle. Also, the drainage condition was found to be the most important factor relative to stability of the example slopes.

C. Decomposition Effects on Sludge Properties

Decomposition of the sludge organic fraction reduces the amount and strength of interlocking fibers in a sludge mass. This decomposition also generates various gases which may be effectively trapped in low permeability sludge. Decomposition of 27 percent lowered the c_v value to 20 percent of its original value. This decrease in c_v resulted in tripling the time required for completion of primary compression for the example configurations. In addition, 27 percent decomposition will result in a 25 percent increase in settlement and will generate a similar amount of additional leachate.

A reduction in sludge stability resulting from decomposition was difficult to determine accurately and may be dependent on the test method employed. Stability would be highly dependent on drainage conditions. A large decrease in permeability as a result of decomposition might effectively trap pore water and gas, thus altering the effective stress in the sludge mass. These factors may contribute to additional settlement, increased leachate generation, production of foul odors, and a reduction in shear strength and thus stability.

D. Suggested Field Instrumentation and Monitoring

It is recommended that instrumentation be installed to monitor the behavior during construction and initial filling of a future landfill cell. The field observations can be used to select the best analysis methods. Settlement plates consisting of steel or aluminum plates with riser pipes could be installed at convenient elevations during sludge placement. The initial and subsequent elevations of the top of the riser pipes would be monitored to provide data on the landfill settlement. This information would be used to compare settlement estimates based on consolidation test results. Landfill settlements, tabulated over a period of time, would provide information on secondary compression and effects of sludge decomposition. In addition, this data would help evaluate the effectiveness of leachate collection systems.

Pore pressure transducers installed at various elevations near the settlement plates could measure the reduction in pore pressures as consolidation progresses. These devices could also indicate the point where pressures have decreased to a level sufficient to allow placement of an overlying lift of sludge without creating an unstable condition. The development of gas pressures, such as those observed in decomposing lab samples, could also be recorded at an early stage of decomposition.

BIBLIOGRAPHY

Alexander, J. A., Wardwell, R. E., and Charlie, W. A., "Gas Generation from Combined Papermill Sludges," Presented at the Northeast Regional Meeting, N. C. A. S. I., Boston, Mass., 1978.

Al-Khafaji, A. W. N., "Decomposition Effects on Engineering Properties of Fibrous Organic Soils," Unpublished Ph.D. Thesis, Michigan State University, East Lansing, Michigan, 1979.

Al-Khafaji, A. W. N., and Andersland, O. B., "Ignition Test for Soil Organic-Content Measurement," Journal of the Geotechnical Engineering Division, ASCE, Vol. 107, No. GT4, April, 1981.

American Society for Testing and Materials, Book of ASTM Standards, Parts 11 and 15, Philadelphia, Pennsylvania.

Andersland, O. B., and Charlie, W. A., "A Cut Slope in Consolidated Papermill Sludge," Proceedings of the Conf. on Insitu Measurement of Soil Properties, Vol. 1, American Society of Civil Engineers, 1975.

Andersland, O. B., Charlie, W. A., and Marshall, D. W., Second Annual Report to the U.S. Environmental Protection Agency, Division of Engineering Research, Michigan State University, East Lansing, Michigan, 1973.

Andersland, O. B., Khattak, A. S., and Al-Khafaji, A. W. N., "Effect of Organic Material on Soil Shear Strength," in Laboratory Shear Strength of Soil, ASTM STP 740, R. N. Yong and F. C. Townsend, eds., American Society for Testing and Materials, 1981.

Andersland, O. B. and Laza, R. W., "Permeability of High Ash Papermill Sludge," Journal of the Sanitary Engineering Division, ASCE, Vol. 98, No. SA6, pp. 927-936, 1972.

Andersland, O. B., Vallee, R. P., and Armstrong, T. A., "An Experimental High Ash Papermill Sludge Landfill," First Annual Report to the U.S. Environmental Protection Agency, Division of Engineering Research Michigan State University, East Lansing, Michigan, 1972.

Bishop, A. W.,"The Use of the Slip Circle in the Stability Analysis of Slopes," Geotechnique, London, 5:7-17, 1954.

Bishop, A. W. and Henkel, D. J., The Measurement of Soil Properties in the Triaxial Test, Edward Arnold, Ltd., London, 1962.

Bowles, J. E., Engineering Properties of Soils and Their Measurement, McGraw-Hill, Inc., 1978.

Charlie, W. A., Wardwell, R. E., and Andersland, O. B., "Leachate Generation from a Sludge Disposal Area," Journal of the Environmental Engineering Division, ASCE, Vol. 105, No. EE5, Proc. Paper 14884, October, 1979, pp. 947-960.

Charlie, W. A., Wardwell, R. E., and Cooper, S. R., "Engineering Properties of Combined Primary and Secondary Papermill Sludge," N. C. A. S. I., Central-Lake-States Regional Meeting, Chicago, Ill., 1979.

"Design Manual - Soil Mechanics, Foundations, and Earth Structures," NAVFAC DM-7, Mar., 1979, Naval Facilities Engineering Command, Department of the Navy, San Bruno, California.

Eastman, J. A., Personal Communication, 1978 and 1980.

Gibson, R. E. and Lo, K. Y., "A Theory of Consolidation for Soils Exhibiting Secondary Compression," Norwegian Geotechnical Institute, Publication 41, Oslo, Norway, 1961.

Gillespie, W. J., Gellman, I. and Janes, R. L., "Utilization of High Ash Papermill Waste Solids," Proc. 2nd Mineral Waste Utilization Symposium, IITRI, Chicago, Ill., 1970.

Gillespie, W. J., Mazzola, C. A., and Gellamn, I., "Landfill Disposal of Papermill Waste Solids," Presented at the 7th Technical Association of the Pulp and Paper Industry Air and Water Conference, Minneapolis, Minn., June 7-10, 1970.

Hanrahan, E. T., "Investigation of Some Physical Properties of Peat," Geotechnique, 4:3:108-123, 1954.

Khattak, A. S.,"Mechanical Behavior of Fibrous Organic Soils," Unpublished Ph.D. Thesis, Michigan State University, East Lansing, Michigan, 1978.

Lambe, T. W., "A Mechanistic Picture of Shear Strength in Clay," Proc. ASCE Res. Conf. on Shear Strength of Cohesive Soils, 1960.

Laza, R. W., "Permeability and Shear Strength of Dewatered, High Ash Content Pulp and Papermill Sludge," Unpublished Ph.D. Thesis, Michigan State University, East Lansing, Michigan, 1971.

Lea, N. D. and Brawner, C. O., "Highway Design and Construction over Peat Deposits in the Lower Mainland of British Columbia," Highway Res. Board, Res. Rec., No. 7, Washington, D.C., 1963.

MacFarlane, I. C., ed., Muskeg Engineering Handbook, University of Toronto Press, 1969.

McKinney, R. E., Microbiology for Sanitary Engineers, McGraw-Hill Book Co., Inc., 1962.

Miner, R. A. and Marshall, D. W., "Biological Sludge Dewatering Practices in the Pulp and Paper Industry," Presented at the 13th Annual Purdue Industrial Waste Conference, 1975.

Perloff, W. H. and Baron, W., Soil Mechanics Principles and Applications, Ronald Press, 1976.

Perpich, W. M., "Design Considerations for Land Disposal of Paper and Pulpmill Sludge," T.A.P.P.I. Environmental Conference, Atlanta, Georgia, 1976.

Perpich, W. M. and Zimmerman, E., "Major Components of Pulp and Papermill Residues," First Annual Conf. of Applied Res. and Prac. on Municipal and Industrial Waste, Madison, Wisconsin, Sept., 1978.

Terzaghi, K., Theoretical Soil Mechanics, John Wiley and Sons, Inc., New York, 1943.

Terzaghi, K. A. and Peck, R. B., Soil Mechanics in Engineering Practice, 2nd ed., John Wiley and Sons, Inc., New York, 1967.

Vallee, R. P., "A Field Consolidation Study of High Ash Papermill Sludge," Unpublished Ph.D. Thesis, Michigan State University, East Lansing, Michigan, 1973.

Vallee, R. P. and Andersland, O. B., "Field Consolidation of High Ash Papermill Sludge," Journal of the Geotechnical Engineering Div., ASCE, Vol. 100:GT3:309-327, 1974.

Wahls, H. E., "Analysis of Primary and Secondary Consolidation," Journal of the Soil Mechanics and Found. Div., ASCE, 88:SM6:207-231, 1962.

Wu, T. H., Soil Mechanics, Allyn and Bacon, Boston, 1976.

APPENDIX A

TABLE A.1 WATER CONTENT OF SLUDGE SAMPLES

Primary Sludge		Combined Sludge	
276%	271%	319%	316%
281%	278%	326%	337%
290%	279%	333%	318%
267%	252%	307%	316%
258%	274%	333%	314%
274%	267%	321%	295%
271%	269%	316%	308%
270%	276%	316%	309%
273%	257%	average =	318%
	247%		
average =	270%		

Values were measured in conjunction with other tests during the research program.

TABLE A.2 COMPACTED UNIT WEIGHT OF SLUDGE MATERIALS

Volume of container = 0.100 cubic feet

	Primary Sludge		Combined Sludge	
wt. wet sludge + tare (gm)	5726	5714.5	5648	5640
tare wt. (gm)	2506	2507.0	2506	2506
sludge wt. (gm)	3220	3207.5	3142	3134
unit wet wt. (PCF)	71.0	70.7	69.3	69.1
average water content (%)	276	281	319	326
unit dry wt. (PCF)	18.9	18.6	16.5	16.2

TABLE A.3 ORGANIC CONTENT DETERMINATIONS

Primary Sludge		Combined Sludge
49.0%	49.0%	58.0%
54.0%	48.0%	59.0%
50.0%	48.0%	59.0%
47.9%	48.7%	59.0%
46.0%	48.0%	58.0%
49.0%	48.2%	57.4%
	48.2%	57.5%
average =	49.0%	average = 58.0%

TABLE A.4 SPECIFIC GRAVITY OF SLUDGE MATERIALS

		Primary Sludge		
1.	Wt. flask + water + sludge	677.5	677.0	686.10
2.	Temperature, ^{o}C	23.0	22.0	22.00
3.	Wt. flask + water	673.4	673.4	680.60
4.	Wt. evap. dish + dry sludge	274.9	273.7	277.85
5.	Wt. evap. dish	266.3	266.2	266.30
6.	Wt. dry sludge	8.6	7.5	11.55
7.	W_w = 6 + 3 - 1	4.5	3.9	6.05
8.	G_s^w = 6/7	1.91	1.92	1.91

average specific gravity = 1.91

		Combined Sludge		
1.	Wt . flask + water + sludge	678.50	675.90	680.00
2.	Temperature, ^{o}C	25.00	25.00	22.00
3.	Wt. flask + water	673.10	673.00	673.30
4.	Wt. evap. dish + dry sludge	282.18	272.40	280.30
5.	Wt. evap. dish	270.80	266.20	266.20
6.	Wt. dry sludge	11.38	6.20	14.10
7.	W_w = 6 + 3 - 1	5.98	3.30	7.40
8.	G_s^w = 6/7	1.90	1.88	1.90

average specific gravity = 1.89

TABLE A.5 pH DETERMINATIONS

	8/27/79	11/6/79	3/29/80
Primary Sludge	11.9	10.3, 8.6	9.7
Combined Sludge	11.9	8.3, 8.1	7.6

Sample procured on 8-27-79, pH measured at Nekoosa Papers Water Quality Center.

Sample storage in sealed containers at $4^{o}C$.

TABLE A.6 DAILY MEASUREMENT OF SLUDGE PROPERTIES AT NEKOOSA PAPERS, 1979

February				March			
Solids Content %		Ash Content %		Solids Content %		Ash Content %	
20	22	41	40	26	24	55	45
26	22	55	36	22	24	36	46
27	25	54	40	21	21	40	43
24	22	48	44	22	25	44	48
24	23	47	42	23	24	43	42
43	20	79	40	20	24	39	49
40	23	81	44	20	26	45	48
36	22	72	44	20	22	39	42
22	22	38	42	21	22	45	41
20	21	37	38	26	20	45	39
20	24	32	43	26	22	47	32
21	22	38	38	22	26	32	38
18	22	39	44	25	23	40	39
22	24	35	43	22	24	37	43
ave. = 24		ave. = 46		ave. = 23		ave. = 42	

June				July			
Solids Content %		Ash Content %		Solids Content %		Ash Content %	
42	23	72	35	21	24	42	66
28	22	53	32	23	28	39	49
26	19	40	34	--	28	--	44
24	23	33	37	--	28	--	40
26	24	38	38	--	24	--	39
26	22	40	29	28	22	50	40
22	22	35	29	26	28	43	44
24	24	36	36	22	24	44	38
23	25	32	38	24	28	41	44
24	26	38	35	23	22	43	35
20	24	36	34	--	20	--	34
25	24	40	35	24	29	43	49
25	24	41	40	24	24	42	40
20	24	31	41	22	26	37	48
22	20	28	36	24	29	47	57
ave. = 24		ave. = 37		ave. = 25		ave. = 45	

Source: Nekoosa Papers Inc.
Note: Solids content measured at 110°C for about 17 hours
Ash content measured at 550°C for about 3 hours

TABLE A.6 cont.

August

Solids Content %		Ash Content %	
24	34	42	59
26	32	40	53
28	31	44	55
34	22	66	36
24	27	38	38
24	24	39	38
26	20	45	34
32	24	52	50
36	24	61	43
34	23	65	44
31	26	64	50
30	25	53	49
31	22	48	39
26	22	62	43
31	26	66	45
	22		37
ave. = 27		ave. = 48	

September

Solids Content %		Ash Content %	
22	22	41	45
20	22	37	46
21	22	40	36
30	21	55	46
24	26	55	57
26	22	48	43
29	27	68	45
23	27	67	64
24	18	58	34
--	20	--	43
--	24	--	50
28	24	54	49
26	23	33	47
28	24	54	48
24	26	49	50
ave. = 24		ave. = 49	

October

Solids Content %		Ash Content %	
24	22	46	44
28	26	48	49
26	24	52	45
--	26	--	46
24	26	44	53
22	24	46	48
24	26	50	53
20	26	46	54
24	25	45	54
24	28	54	45
24	28	46	57
26	26	52	55
26	23	48	50
26	26	43	53
22	24	39	50
	21		39
ave. = 25		ave. = 48	

November

Solids Content %		Ash Content %	
27	26	54	45
23	26	50	53
25	22	52	45
27	22	52	44
27	23	51	48
21	22	48	44
24	23	56	44
26	22	60	41
38	25	73	47
29	24	60	48
30	25	62	48
31	23	60	47
28	22	57	43
26	26	48	43
24	28	41	51
ave. = 26		ave. = 51	

TABLE A.6 cont.

December	
Solids Content %	Ash Content %
24	44
23	42
22	41
22	36
24	41
26	42
24	42
25	44
23	49
27	49
24	44
25	33
25	49
27	59
ave. 24	44

APPENDIX B

Preparation of samples for decomposition

Total Combined Sludge Sample Weight = 4500 grams

water content = 309%

W_s = 1100 grams
W_w = 3400 grams

organic content = 58%

organic material = 638 grams
mineral material = 462 grams

Approximate amount of carbon:

Cellulose $C_2H_{10}O_5$ molecular weight = 162
Carbon C molecular weight = 72

72/162 = 44.4%
Cellulose contains about 44% carbon

A small portion of the biological solids derived from secondary sludge would also contain carbon.

Assume that the combined sludge contains 45% carbon

638 gms (0.45) = 287 grams of carbon in above sample

Use a carbon to nitrogen ratio of 20

C/N = 20 = 287/20 = 14.36 grams of nitrogen

Use a phosphorous to nitrogen ratio of 1/6

P/N = 1/6 = 14.36/6 = 2.39 grams of phosphorus

Use a ratio of all other nutrient to nitrogen of 1/15

(all other)/N = 1/15 = 14.36/15 = 0.96 grams of all other nutrients

TABLE B.1 NUTRIENT PROPORTIONS FOR DECOMPOSING SLUDGE SAMPLES

Nutrient	Source	Percent of Desired Nutrient	Desired Weight
Nitrogen	NH_4Cl	26.19%	54.81 gms
Phosphorous	K_2HPO_4	17.89%	13.36 gms
Magnesium	$MgSO_4$ (70% pure)	20.2%	6.79 gms
Calcium Chloride	$CaCl_2$	63.89%	1.50 gms
Iron	$FeCl_3$	20.66%	4.65 gms
pH Buffer (Sodium Bicarbonate)	$NaHCO_3$	100.00%	5.70 gms

Component	Wt. grams	% Dry Wt.
Dry sludge solids	1100.00	87.6
NH_4Cl	54.81	4.4
K_2HPO_4	13.36	1.1
$MgSO_4$	6.79	0.5
$CaCl_3$	1.50	0.1
$FeCl_3 \cdot 6H_2O$	4.65	0.4
$NaHCO_3$	70.00	5.6
Seeding Material	4.00	0.3
	1255.11	100.0

APPENDIX C

TABLE C.1 QUICK CONSOLIDATION TEST DATA

Primary Sludge Q-P1

Initial dry density = 19.8 PCF
Dry sample weight = 27.0 grams
Final dry density = 41.7 PCF

Initial water content = 290%
Final water content = 107%

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	61	0.1	46	0.1	93
0.25	133	0.25	69	0.25	142
0.5	195	0.5	92	0.5	199
1.0	278	1.0	123	1.0	268
2.0	380	2.0	155	2.0	346
4.0	456	4.0	185	4.0	415
8.0	500	8.0	213	8.0	467
1445.0	650	15.0	237	15.0	507
load 0.8 kg/cm^2		load 1.6 kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	112	0.1	109	0.1	98
0.25	170	0.25	167	0.25	153
0.5	232	0.5	231	0.5	210
1.0	313	1.0	315	1.0	291
2.0	408	2.0	416	2.0	396
4.0	494	4.0	521	4.0	509
8.0	557	8.0	607	8.0	612
15.0	601	13.0	641	15.0	679
16.0	604				
unload 1.6 kg/cm^2		unload 0.8 kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	29	0.1	21	0.1	22
0.25	35	0.25	27	0.25	26
0.5	41	0.5	35	0.5	30
1.0	48	1.0	47	1.0	35
2.0	54	2.0	60	2.0	43
4.0	60	4.0	74	4.0	48
8.0	62	8.0	87	8.0	52
15.0	64	15.0	95	15.0	55
				30.0	56

TABLE C.1 cont.

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	45	0.1	85	0.1	41
0.25	55	0.25	120	0.25	57
0.5	66	0.5	160	0.5	79
1.0	82	1.0	216	1.0	113
2.0	98	2.0	292	2.0	161
4.0	117	4.0	389	4.0	225
8.0	137	8.0	490	8.0	302
13.0	152	15.0	564	15.0	363
				30.0	415
unload 3.2 kg/cm^2		unload 0.4 kg/cm^2			
0.0	0	0.0	0		
15.0	122	30.0	327		

TABLE C.2 QUICK CONSOLIDATION TEST DATA

Primary Sludge Q-P2

Initial dry density = 18.2 PCF
Dry sample weight = 25.2 grams
Final dry density = 42.6 PCF

Initial water content = 274%
Final water content = 102.8%

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	265	0.1	80	0.1	90
0.25	337	0.25	130	0.25	123
0.5	410	0.5	184	0.5	178
1.0	514	1.0	256	1.0	252
2.0	642	2.0	347	2.0	344
4.0	773	4.0	437	4.0	437
8.0	855	8.0	510	8.0	517
load 0.8 kg/cm^2		load 1.6 kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	95	0.1	78	0.1	96
0.25	148	0.25	133	0.25	133
0.5	207	0.5	193	0.5	179
1.0	289	1.0	271	1.0	244
2.0	387	2.0	372	2.0	335
4.0	495	4.0	490	4.0	447
8.0	589	8.0	600	8.0	565
		9.0	614		
unload 1.6 kg/cm^2		unload 0.8 kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	27	0.1	19	0.1	18
0.25	31	0.25	26	0.25	22
0.5	36	0.5	32	0.5	27
1.0	40	1.0	41	1.0	33
2.0	45	2.0	54	2.0	40
4.0	48	4.0	67	4.0	46
7.0	49	7.0	78	8.0	51
		8.0	80		

TABLE C.2 cont.

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	38	0.1	66	0.25	42
0.25	48	0.25	92	0.5	60
0.5	59	0.5	122	1.0	88
1.0	76	1.0	166	2.0	130
2.0	99	2.0	229	4.0	188
4.0	130	4.0	309	8.0	262
8.0	170	8.0	406	15.0	329
9.0	177	12.0	463	17.0	342
10.0	184	13.0	474	18.0	348
11.0	190				
13.0	200				
14.0	205				
15.0	210				

unload 3.2 kg/cm^2		unload 0.4 kg/cm^2	
0.0	0	0.0	0
12.0	100	17.0	246

TABLE C.3 CONVENTIONAL CONSOLIDATION TEST DATA

Primary Sludge C-P1

Initial dry density = 18.5PCF
Dry sample weight = 24.15 grams
Final dry density = 42.2 PCF

Initial water content = 289%
Final water content = 107.5%

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	70	0.1	50	0.1	141
0.25	132	0.25	64	0.25	196
0.5	190	0.5	77	0.5	264
1.0	255	1.0	92	1.0	344
2.0	321	2.0	110	2.0	440
4.0	366	4.0	126	4.0	525
8.0	393	11.0	151	10.0	606
609.0	625	17.0	160	16.0	636
		35.0	176	30.0	666
		60.0	191	60.0	695
		120.0	210	125.0	726
		190.0	223	264.0	759
		446.0	254	351.0	771
		641.0	266	472.0	780
		1395.0	289	683.0	791
				1425.0	804
load 0.8 kg/cm^2		load 1.6 kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	127	0.1	146	0.1	181
0.25	193	0.25	202	0.25	264
0.5	255	0.5	253	0.5	345
1.0	313	1.0	304	1.0	439
2.0	373	2.0	366	2.0	567
4.0	401	4.0	452	4.0	710
8.0	414	12.0	584	9.0	837
15.0	423	15.0	595	15.0	900
30.0	431	34.0	619	30.0	970
84.0	444	76.0	640	60.0	1021
160.0	453	146.0	656	98.0	1053
392.0	473	227.0	668	239.0	1109
666.0	592	638.0	702	582.0	1156
777.0	604	1410.0	737	1424.0	1193
1490.0	635	1420.0	741		

TABLE C.3 cont.

time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)	time (min)	dial reading (in. x 10^4)
unload 1.6 kg/cm^2		unload 0.8 kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
1444.0	48	1432.0	161	0.1	29
				0.25	35
				0.5	44
				1.0	54
				2.0	63
				4.0	69
				8.0	74
				19.0	79
				39.0	82
				60.0	83
				115.0	88
				236.0	92
				537.0	98
				1440.0	103
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	40	0.1	106	0.1	33
0.25	52	0.25	152	0.25	44
0.5	64	0.5	204	0.5	57
1.0	76	1.0	277	1.0	75
2.0	87	2.0	373	2.0	99
4.0	96	4.0	497	4.0	130
8.0	103	8.0	636	9.0	173
15.0	111	15.0	707	15.0	202
33.0	119	36.0	770	30.0	241
60.0	127	63.0	798	60.0	277
139.0	140	92.0	812	115.0	307
227.0	149	123.0	819	227.0	338
431.0	165	271.0	838	1430.0	414
581.0	175	420.0	848		
1430.0	201	508.0	852		
		1465.0	933		
unload 3.2 kg/cm^2					
0.0	0				
1420.0	108				

TABLE C.4 SINGLE LOAD INCREMENT CONSOLIDATION TEST DATA

Primary Sludge SI-P1

Initial dry density = 19.5 PCF
Initial water content = 267%
Dry sample weight = 27.3 grams
Final water content = 194%
Final dry density = 26.0 PCF

load 0.1-0.4 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	154
0.25	222
0.5	301
1.0	407
2.0	539
4.0	670
8.0	769
15.0	829
30.0	879
60.0	920
120.0	956
197.0	985
384.0	1018
525.0	1032
1190.0	1066
1476.0	1079
1580.0	1082
2607.0	1107

Primary Sludge SI-P2

Initial dry density = 18.5PCF
Initial water content = 285%
Dry sample weight = 25.6 grams
Final water content = 171%
Final dry density = 28.7 PCF

load 0.1-0.8 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	249
0.25	423
0.5	572
1.0	770
2.0	1007
4.0	1242
8.0	1419
16.0	1523
30.0	1580
60.0	1628
134.0	1676
240.0	1709
370.0	1732
595.0	1756
1296.0	1791
1616.0	1802

TABLE C.4 cont.

Primary Sludge SI-P3

Initial dry density = 18.8 PCF
Initial water content = 284%
Dry sample weight = 26.3 grams
Final water content = 144%
Final dry density = 34.2 PCF

load 0.1-1.6 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	552
0.25	750
0.5	955
1.0	1230
2.0	1556
4.0	1883
8.0	2136
15.0	2275
30.0	2364
60.0	2419
120.0	2465
225.0	2501
355.0	2527
580.0	2555
1281.0	2594
1597.0	2606

Primary Sludge SI-P4

Initial dry density = 20.1 PCF
Initial water content = 258%
Dry sample weight = 27.8 grams
Final water content = 115%
Final dry density = 39.6 PCF

load 0.1-3.2 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	545
0.25	838
0.5	943
1.0	1230
2.0	1599
4.0	1994
10.0	2427
15.0	2555
30.0	2693
60.0	2771
120.0	2824
219.0	2859
580.0	2904
1149.0	2930
1605.0	2945

TABLE C.5 QUICK CONSOLIDATION TEST DATA

Combined Sludge Q-P1

Initial dry density = 16.7 PCF
Dry sample weight = 22.88 grams
Final dry density = 39.5 PCF

Initial water content = 333%
Final water content = 115.6%

time (min)	dial reading (in.x10^{4})	time (min)	dial reading (in.x10^{4})	time (min)	dial reading (in.x10^{4})
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
1.0	348	0.1	38	0.1	160
2.0	378	0.25	54	0.25	270
4.0	398	0.5	76	0.5	360
8.0	406	1.0	95	1.0	460
15.0	409	2.0	111	2.0	635
30.0	413	4.0	118	4.0	845
70.0	421	8.0	125	8.0	980
759.0	445	15.0	133	15.0	1041
				26.0	1080
				30.0	1083
				45.0	1113
load 0.8 kg/cm^2		load 1.6 kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	92	0.1	74	0.1	88
0.25	138	0.25	112	0.25	126
0.5	187	0.5	152	0.5	168
1.0	249	1.0	209	1.0	227
2.0	334	2.0	285	2.0	304
4.0	431	4.0	380	4.0	404
8.0	528	8.0	504	8.0	523
15.0	603	15.0	616	15.0	635
		30.0	716		
unload 1.6 kg/cm^2		unload 0.8 kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	27	0.1	12	0.1	13
0.25	33	0.25	16	0.25	16
0.5	39	0.5	21	0.5	19
1.0	46	1.0	27	1.0	23
2.0	53	2.0	36	2.0	27
4.0	61	4.0	47	4.0	32
8.0	66	8.0	60	8.0	37
15.0	69	15.0	71	15.0	41

TABLE C.5 cont.

time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	40	0.1	68	0.1	31
0.25	50	0.25	90	0.25	38
0.5	60	0.5	114	0.5	49
1.0	75	1.0	148	1.0	67
2.0	94	2.0	194	2.0	93
4.0	121	4.0	264	4.0	133
8.0	157	8.0	356	8.0	191
15.0	197	15.0	454	15.0	258
30.0	252	32.0	569	30.0	341
unload 3.2 kg/cm^2		unload 0.4 kg/cm^2			
0.0	0	0.0	0		
15.0	112	60.0	333		

TABLE C.6 QUICK CONSOLIDATION TEST DATA

Combined Sludge Q-P2

Initial dry density = 16.7 PCF
Dry sample weight = 23.1 grams
Final dry density = 41.8 PCF

Initial water content = 316%
Final water content = 106%

time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	201	0.1	71	0.1	73
0.25	258	0.25	115	0.25	124
0.5	319	0.5	165	0.5	176
1.0	400	1.0	239	1.0	253
2.0	489	2.0	335	2.0	357
4.0	587	4.0	445	4.0	476
6.0	633	6.0	505	6.0	545
		7.0	528	7.0	571
load 0.8 kg/cm^2		load 1.6kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	74	0.1	64	0.1	54
0.25	122	0.25	106	0.25	81
0.5	176	0.5	154	0.5	114
1.0	254	1.0	220	1.0	161
2.0	359	2.0	313	2.0	233
4.0	490	4.0	440	4.0	331
6.0	572	8.0	586	8.0	462
8.0	627	10.0	635	12.0	547
9.0	648	12.0	672	15.0	594
		14.0	703	21.0	664
				25.0	701
unload 1.6 kg/cm^2		unload 0.8kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	19	0.1	14	0.1	13
0.25	23	0.25	19	0.25	17
0.5	28	0.5	24	0.5	21
1.0	33	1.0	31	1.0	26
2.0	40	2.0	42	2.0	31
4.0	46	4.0	57	4.0	39
6.0	50	8.0	75	8.0	47
		12.0	86	12.0	51
		15.0	92	13.0	52
		16.0	94		
		18.0	96		

TABLE C.6 cont.

time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	24	0.1	36	0.1	18
0.25	31	0.25	51	0.25	23
0.5	40	0.5	67	0.5	29
1.0	51	1.0	89	1.0	40
2.0	69	2.0	124	2.0	56
4.0	93	4.0	175	4.0	81
8.0	126	8.0	250	8.0	122
16.0	172	15.0	337	15.0	173
26.0	203	28.0	436	37.0	267
31.0	217	42.0	498	69.0	330
35.0	227	61.0	551	71.0	333
40.0	237	63.0	555		
41.0	239				
unload 3.2 kg/cm^2		unload 0.4 kg/cm^2			
0.0	0	0.0	0		
41.0	110	51.0	242		

TABLE C.7 CONVENTIONAL CONSOLIDATION TEST DATA

Combined Sludge C-C1

Initial dry density = 16.8 PCF
Dry sample weight = 23.3 grams
Final dry density = 41.6 PCF

Initial water content = 307%
Final water content = 106%

time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)
load 0.1 kg/cm^2		load 0.2 kg/cm^2		load 0.4 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	176	0.1	47	0.1	48
0.25	233	0.25	69	0.25	69
0.5	296	0.5	92	0.5	92
1.0	382	1.0	123	1.0	124
2.0	488	2.0	159	2.0	163
4.0	587	4.0	198	4.0	207
8.0	659	8.0	235	8.0	252
15.0	704	15.0	267	15.0	290
30.0	741	30.0	299	30.0	333
683.0	863	60.0	332	60.0	373
		120.0	364	120.0	414
		240.0	399	291.0	467
		667.0	455	703.0	523
		1473.0	504	1440.0	568
load 0.8 kg/cm^2		load 1.6 kg/cm^2		load 3.2 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	55	0.1	59	0.1	48
0.25	78	0.25	79	0.25	65
0.5	104	0.5	102	0.5	84
1.0	141	1.0	135	1.0	112
2.0	187	2.0	181	2.0	149
4.0	244	4.0	238	5.0	217
8.0	304	8.0	305	8.0	260
15.0	358	16.0	377	16.0	332
30.0	410	30.0	436	32.0	402
65.0	464	66.0	501	60.0	459
168.0	529	121.0	547	127.0	519
257.0	560	180.0	577	199.0	551
367.0	585	240.0	597	249.0	566
462.0	601	517.0	653	510.0	615
635.0	625	728.0	677	692.0	634
838.0	643	912.0	692	1459.0	678
1441.0	678	1453.0	720		

TABLE C.7 cont.

time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)	time (min)	dial reading (in.x10^4)
unload 1.6 kg/cm^2		unload 0.8 kg/cm^2		reload 1.6 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	15	0.1	10	0.1	7
0.25	18	0.25	12	0.25	10
0.5	21	0.5	15	0.5	13
1.0	24	1.0	18	1.0	17
2.0	29	2.0	23	2.0	22
4.0	34	5.0	31	4.0	27
11.0	41	12.0	39	8.0	32
15.0	43	20.0	44	15.0	35
30.0	47	81.0	57	30.0	38
137.0	55	188.0	63	65.0	40
258.0	58	443.0	71	128.0	43
678.0	61	648.0	76	241.0	46
1437.0	63	1458.0	84	652.0	50
				1420.0	53
reload 3.2 kg/cm^2		load 6.4 kg/cm^2		load 10.0 kg/cm^2	
0.0	0	0.0	0	0.0	0
0.1	15	0.1	24	0.1	14
0.25	20	0.25	34	0.25	19
0.5	25	0.5	47	0.5	23
1.0	33	1.0	64	1.0	30
2.0	42	2.0	89	2.0	40
4.0	54	4.0	123	4.0	55
8.0	64	8.0	167	8.0	74
16.0	72	15.0	215	19.0	107
30.0	78	33.0	282	30.0	128
62.0	85	60.0	331	60.0	174
113.0	91	120.0	382	120.0	198
254.0	100	240.0	427	181.0	218
598.0	113	394.0	456	351.0	250
1450.0	129	620.0	483	587.0	274
		1430.0	527	1425.0	306
unload 3.2 kg/cm^2		unload 0.4 kg/cm^2			
0.0	0	0.0	0		
1435.0	126	1450.0	325		

TABLE C.8 SINGLE LOAD INCREMENT CONSOLIDATION TEST DATA

Combined Sludge SI-C1

Initial dry density = 16.4 PCF
Initial water content = 333%
Dry sample weight = 22.9 grams
Final water content = 222%
Final dry density = 23.1 PCF

load 0.1-0.4 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	175
0.25	250
0.5	336
1.0	452
2.0	601
4.0	760
8.0	893
15.0	988
30.0	1063
60.0	1121
123.0	1174
233.0	1219
594.0	1282
1163.0	1324
1619.0	1351

Combined Sludge SI-C2

Initial dry density = 16.4 PCF
Initial water content = 321%
Dry sample weight = 22.9 grams
Final water content = 192%
Final dry density = 26.4 PCF

load 0.1-0.8 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	286
0.25	409
0.5	542
1.0	729
2.0	969
4.0	1233
8.0	1462
15.0	1610
30.0	1715
63.0	1791
120.0	1843
252.0	1896
353.0	1919
636.0	1957
1255.0	1990
1687.0	2013

TABLE C.8 cont.

Combined Sludge SI-C3

Initial dry density = 16.1 PCF
Initial water content = 321%
Dry sample weight = 22.2 grams
Final water content = 158%
Final dry density = 30.9 PCF

load 0.1-1.6 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	427
0.25	593
0.5	775
1.0	1009
2.0	1304
4.0	1638
8.0	1955
15.0	2184
30.0	2354
60.0	2459
120.0	2530
268.0	2591
368.0	2614
651.0	2649
1270.0	2680
1710.0	2700

Combined Sludge SI-C4

Initial dry density = 16.6 PCF
Initial water content = 316%
Dry sample weight = 23.2 grams
Final water content = 126%
Final dry density = 37.5 PCF

load 0.1-3.2 kg/cm^2

time (min)	dial reading (in.x10^4)
0.0	0
0.1	496
0.25	714
0.5	934
1.0	1221
2.0	1573
4.0	1973
8.0	2371
15.0	2689
30.0	2969
60.0	3118
121.0	3216
353.0	3322
451.0	3342
1374.0	3413
1961.0	3436

APPENDIX D

TABLE D.1 TRIAXIAL TEST DATA

Primary Sludge CU-P1

Consolidation press. = 1.0 kg/cm^2
Strain rate = 0.0067 cm/min

Water content* = 144%
Dry density* = 30.9 PCF

$\bar{\sigma}_{1f}$ = 1.715 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.05 kg/cm^2

u_f = 0.95 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.57

c_u = 0.833 kg/cm^2

c_v = 1.8x10^{-4} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.000	1.00
2.88	0.0889	0.09	0.195	1.108	0.91
9.30	0.1143	0.24	0.473	1.399	0.76
10.82	0.1270	0.32	0.612	1.422	0.68
11.90	0.1397	0.38	0.751	1.435	0.62
13.53	0.1651	0.45	1.029	1.474	0.55
14.61	0.2032	0.51	1.447	1.483	0.49
15.25	0.2388	0.57	1.836	1.463	0.43
16.77	0.3556	0.65	3.116	1.471	0.35
17.85	0.4572	0.70	4.229	1.479	0.30
18.61	0.5588	0.74	5.342	1.475	0.26
19.53	0.6883	0.78	6.760	1.476	0.22
20.28	0.7645	0.80	7.595	1.493	0.20
20.99	0.9119	0.82	9.209	1.495	0.18
21.21	1.0109	0.85	10.294	1.463	0.15
22.56	1.1684	0.88	12.018	1.489	0.12
23.70	1.3487	0.90	13.994	1.506	0.10
24.78	1.4732	0.91	15.356	1.537	0.09
26.51	1.6256	0.92	17,026	1.598	0.08
30.91	1.9050	0.95	20.086	1.715	0.05

* water content and dry density after consolidation

TABLE D.2 TRIAXIAL TEST DATA

Primary Sludge CU-P2

Consolidation press. = 1.0 kg/cm^2
Strain rate = 0.0075 cm/min

Water content* = 148%
Dry density* = 30.9 PCF

$\bar{\sigma}_{1f}$ = 1.598 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.10 kg/cm^2

u_f = 0.90 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.60

c_u = 0.749 kg/cm^2

c_v = 9.5x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.000	1.00
1.18	0.0127	0.02	0.141	1.065	0.98
6.77	0.0381	0.19	0.424	1.294	0.81
9.05	0.0508	0.27	0.565	1.376	0.73
11.31	0.0711	0.37	0.792	1.435	0.67
12.61	0.0914	0.41	1.018	1.486	0.59
15.04	0.1727	0.53	1.922	1.529	0.47
16.28	0.2794	0.60	3.053	1.533	0.40
17.26	0.3759	0.65	4.183	1.537	0.35
18.23	0.4826	0.70	5.371	1.539	0.30
18.77	0.6096	0.74	6.784	1.516	0.26
19.42	0.6985	0.76	7.773	1.526	0.24
20.39	0.8331	0.80	9.271	1.529	0.20
20.83	0.9093	0.80	10.119	1.544	0.20
21.37	1.0109	0.81	11.250	1.552	0.19
22.07	1.0871	0.83	12.098	1.563	0.17
22.83	1.2548	0.86	13.964	1.550	0.14
23.80	1.4046	0.88	15.631	1.562	0.12
24.56	1.5697	0.90	17.469	1.555	0.10
26.08	1.7983	0.90	20.012	1.598	0.10

* water content and dry density after consolidation

TABLE D.3 TRIAXIAL TEST DATA

Primary Sludge CU-P3

Consolidation press. = 2.5 kg/cm^2
Strain rate = 0.0070 cm/min

Water content* = 116%
Dry density* = 37.1 PCF

$\bar{\sigma}_{1f}$ = 4.259 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.04 kg/cm^2

u_f = 2.46 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.58

c_u = 2.110 kg/cm^2

c_v = 6.9×10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.000	0.0000	0.00	0.000	2.500	2.50
1.504	0.0203	0.03	0.242	2.590	2.47
5.410	0.0330	0.15	0.393	2.782	2.35
10.008	0.0406	0.27	0.483	3.028	2.23
14.119	0.0508	0.42	0.604	3.205	2.08
22.666	0.0737	0.77	0.876	3.531	1.73
25.858	0.0940	1.01	1.118	3.540	1.49
31.376	0.1448	1.30	1.722	3.762	1.20
33.540	0.1778	1.47	2.114	3.662	1.03
35.920	0.2591	1.67	3.081	3.621	0.83
38.625	0.3734	1.83	4.440	3.629	0.67
40.897	0.4699	2.00	5.587	3.595	0.50
42.304	0.5588	2.09	6.645	3.576	0.41
44.251	0.7112	2.16	8.457	3.587	0.34
46.739	0.8890	2.26	10.571	3.591	0.24
48.903	1.0414	2.32	12.383	3.615	0.18
52.582	1.2065	2.36	14.346	3.751	0.14
55.828	1.3462	2.39	16.007	3.869	0.11
60.805	1.5138	2.43	18.001	4.067	0.07
65.781	1.6815	2.46	19.994	4.259	0.04

* water content and dry density after consolidation

TABLE D.4 TRIAXIAL TEST DATA

Primary Sludge CU-P4

Consolidation press. = 2.5 kg/cm^2
Strain rate = 0.0071 cm/min

Water content* = 118%
Dry density* = 36.6 PCF

$\bar{\sigma}_{1f}$ = 3.968 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.035 kg/cm^2

u_f = 2.465 kg/cm^2

$\bar{B}$ = 98%

A_f = 0.62

c_u = 1.976 kg/cm^2

c_v = 5.3×10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	2.500	2.50
1.75	0.0406	0.04	0.142	2.602	2.46
6.27	0.0584	0.14	0.508	2.868	2.36
13.31	0.0787	0.36	1.077	3.217	2.14
17.52	0.0914	0.57	1.415	3.345	1.93
24.12	0.1245	0.93	1.941	3.511	1.57
28.75	0.1702	1.25	2.300	3.550	1.25
32.63	0.2565	1.55	3.000	3.534	0.95
35.22	0.3429	1.74	4.004	3.520	0.76
36.97	0.4293	1.83	5.013	3.537	0.67
38.36	0.5131	1.95	5.992	3.494	0.55
39.56	0.6147	2.06	7.178	3.438	0.44
40.85	0.6833	2.10	7.979	3.470	0.40
43.63	0.8788	2.22	10.263	3.477	0.28
47.32	1.0871	2.30	12.696	3.573	0.20
48.62	1.1836	2.35	13.823	3.571	0.15
50.28	1.2852	2.39	15.010	3.599	0.11
54.72	1.4884	2.43	17.382	3.761	0.07
60.08	1.6993	2.46	19.844	3.972	0.04
61.00	1.7297	2.47	20.200	4.005	0.03

* water content and dry density after consolidation

TABLE D.5 TRIAXIAL TEST DATA

Combined Sludge CU-C1

Consolidation press. = 0.92 kg/cm^2
Strain rate = 0.0066 cm/min

Water content* = 165%
Dry density* = 29.0 PCF

$\bar{\sigma}_{1f}$ = 1.351 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.03 kg/cm^2

u_f = 0.89 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.67

c_u = 0.661 kg/cm^2

c_v = 3.2x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	0.920	0.92
0.98	0.0152	0.01	0.210	0.984	0.91
3.68	0.0330	0.10	0.443	1.098	0.82
6.19	0.0533	0.19	0.701	1.197	0.73
7.77	0.0737	0.26	0.969	1.244	0.66
9.79	0.1219	0.35	1.602	1.302	0.57
10.71	0.1600	0.43	2.091	1.286	0.49
11.90	0.2235	0.48	2.935	1.317	0.44
12.93	0.2870	0.53	3.803	1.335	0.39
13.47	0.3505	0.57	4.624	1.326	0.35
14.01	0.4140	0.60	5.476	1.326	0.32
14.82	0.5410	0.66	6.975	1.307	0.26
15.36	0.6045	0.69	7.796	1.306	0.23
16.07	0.7315	0.73	9.405	1.295	0.19
16.72	0.8585	0.76	11.047	1.289	0.16
17.47	0.9982	0.80	12.877	1.276	0.12
18.56	1.1760	0.81	14.913	1.309	0.11
19.64	1.3411	0.86	16.964	1.298	0.06
21.21	1.5316	0.88	19.332	1.339	0.04
21.80	1.5723	0.89	20.199	1.351	0.03

* water content and dry density after consolidation

TABLE D.6 TRIAXIAL TEST DATA

Combined Sludge CU-C2

Consolidation press. = 1.75 kg/cm^2
Strain rate = 0.0063 cm/min

Water content* = 142%
Dry density* = 33.7 PCF

$\bar{\sigma}_{1f}$ = 2.140 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.14 kg/cm^2

u_f = 1.61 kg/cm^2

$\bar{B}$ = 98%

A_f = 0.81

c_u = 1.000 kg/cm^2

c_v = 3.7x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.750	1.75
0.39	0.0254	0.02	0.358	1.763	1.73
1.47	0.0457	0.06	0.634	1.813	1.69
4.00	0.0635	0.14	0.875	1.944	1.61
6.32	0.0762	0.20	1.055	2.076	1.55
9.36	0.1016	0.34	1.454	2.186	1.41
12.77	0.1397	0.55	1.952	2.253	1.20
14.71	0.1778	0.63	2.425	2.328	1.12
16.12	0.2159	0.72	2.940	2.347	1.03
17.47	0.2794	0.76	3.882	2.403	0.99
19.37	0.3810	0.98	5.389	2.312	0.77
20.94	0.4826	1.13	6.728	2.263	0.62
21.91	0.5842	1.20	8.035	2.245	0.55
22.61	0.6604	1.27	9.047	2.211	0.48
23.59	0.7874	1.33	10.844	2.190	0.42
25.10	0.9500	1.40	13.000	2.188	0.35
25.86	1.0465	1.46	14.780	2.144	0.29
27.70	1.2598	1.55	17.311	2.127	0.20
29.54	1.4351	1.61	19.761	2.134	0.14
30.19	1.5037	1.61	20.659	2.155	0.14

* water content and dry density after consolidation

TABLE D.7 TRIAXIAL TEST DATA

Combined Sludge CU-C3

Consolidation press. = 2.5 kg/cm^2
Strain rate = 0.0062 cm/min

$\bar{\sigma}_{1f}$ = 3.103 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.275 kg/cm^2

u_f = 2.225 kg/cm^2

Water content* = 126%
Dry density* = 35.8 PCF

$\bar{B}$ = 100%

A_f = 0.79

c_u = 1.414 kg/cm^2

c_v = 2.5x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	2.500	2.50
0.83	0.0457	0.03	0.228	2.543	2.47
2.08	0.0813	0.09	0.578	2.592	2.41
5.48	0.1270	0.21	0.879	2.769	2.29
10.98	0.1473	0.38	1.213	3.077	2.12
15.96	0.1727	0.55	1.630	3.335	1.95
20.77	0.2108	0.90	2.215	3.393	1.60
23.80	0.2616	1.08	2.950	3.459	1.42
25.75	0.3124	1.32	3.685	3.369	1.18
27.70	0.3759	1.36	4.553	3.473	1.14
28.56	0.4267	1.45	5.255	3.438	1.05
30.40	0.5537	1.59	6.925	3.407	0.91
31.38	0.6426	1.96	8.127	3.084	0.54
33.22	0.7188	1.85	10.466	3.275	0.65
33.76	0.8712	1.89	11.301	3.252	0.61
34.30	0.9601	1.95	12.470	3.199	0.55
36.03	1.1125	2.04	14.391	3.182	0.46
37.22	1.2649	2.12	16.479	3.123	0.38
39.27	1.4427	2.20	18.817	3.114	0.30
40.46	1.5723	2.23	20.571	3.106	0.27

* water content and dry density after consolidation

TABLE D.8 TRIAXIAL TEST DATA

Primary Sludge CD-P1

Consolidation press. = 1.0 kg/cm^2
Strain rate = $5.4x10^{-4}$ cm/min

Water content* = 149%
Dry density* = 32.1PCF

$\bar{\sigma}_{1f}$ = 2.452 kg/cm^2

c_v = $6.3x10^{-5}$ cm^2/sec

$\bar{\sigma}_{3f}$ = 1.0 kg/cm^2

Volume after consolidation =123.93 cm^3

load (kg)	displacment (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.000	0.0000	0.00	0.000	1.000	1.00
0.887	0.0114	0.10	0.143	1.063	1.00
2.543	0.0254	0.30	0.297	1.182	1.00
3.516	0.0356	0.40	0.417	1.252	1.00
7.076	0.0597	0.70	0.674	1.506	1.00
8.288	0.0864	1.10	0.976	1.593	1.00
15.309	0.1118	1.40	1.245	2.095	1.00
7.786	0.1524	2.00	1.734	1.555	1.00
8.482	0.1778	2.30	2.021	1.606	1.00
9.683	0.2489	3.30	2.881	1.692	1.00
12.496	0.3708	4.80	4.294	1.891	1.00
15.580	0.5410	6.80	6.098	2.108	1.00
17.473	0.6553	8.20	7.385	2.241	1.00
21.044	0.8331	10.20	9.399	2.488	1.00
22.396	0.9220	11.20	10.462	2.578	1.00
28.022	1.1938	13.90	13.147	2.963	1.00
30.943	1.3462	15.40	14.826	3.155	1.00
32.999	1.4834	17.00	16.434	3.288	1.00
37.543	1.6434	18.50	18.182	3.585	1.00
41.763	1.8009	19.90	20.001	3.850	1.00

* water content and dry density after consolidation

TABLE D.9 TRIAXIAL TEST DATA

Primary Sludge CD-P2

Consolidation press. = 2.5 kg/cm^2
Strain rate = 5.2×10^{-4} cm/min

$\bar{\sigma}_{1f}$ = 3.984 kg/cm^2

$\bar{\sigma}_{3f}$ = 2.5 kg/cm^2

Water content* = 120%
Dry density * = 38.2 PCF

$c_v = 6.4 \times 10^{-5}$ cm^2/sec

Volume after consolidation = 97.07 cm^3

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	2.500	2.50
0.90	0.0102	0.20	0.125	2.572	2.50
4.21	0.0254	0.40	0.323	2.837	2.50
8.31	0.0381	0.50	0.481	3.165	2.50
12.12	0.0777	1.07	1.000	3.471	2.50
15.47	0.1245	1.40	1.574	3.737	2.50
16.23	0.1905	2.35	2.476	3.798	2.50
20.29	0.2718	3.40	3.579	4.123	2.50
23.59	0.3496	4.17	4.500	4.384	2.50
31.27	0.5131	6.20	6.582	4.998	2.50
35.92	0.6350	7.65	8.148	5.367	2.50
41.98	0.7620	9.05	9.745	5.884	2.50
45.66	0.8738	10.30	11.279	6.127	2.50
51.93	0.9906	11.50	12.749	6.614	2.50
58.21	1.0877	12.52	14.000	7.100	2.50
67.30	1.2853	14.40	16.215	7.799	2.50
70.97	1.3462	15.05	16.934	8.084	2.50
75.74	1.4478	16.10	18.292	8.438	2.50
78.33	1.5062	16.75	19.091	8.630	2.50
83.09	1.5850	17.55	20.130	8.984	2.50

* water content and dry density after consolidation

TABLE D.10 TRIAXIAL TEST DATA

Combined Sludge CD-C1

Consolidation press. = 1.0 kg/cm^2
Strain rate = 3.99×10^{-4} cm/min

$\bar{\sigma}_{1f}$ = 2.452 kg/cm^2

$\bar{\sigma}_{3f}$ = 1.0 kg/cm^2

Water content* = 183%
Dry density* = 27.2 PCF

c_v = 4.6×10^{-5} cm^2/sec

Volume after consolidation = 114.70 cm^3

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.000	1.00
0.89	0.0254	0.20	0.183	1.063	1.00
1.62	0.0470	0.50	0.446	1.115	1.00
2.12	0.0660	0.80	0.688	1.150	1.00
2.85	0.1046	1.20	1.147	1.201	1.00
3.26	0.1270	1.60	1.445	1.231	1.00
3.55	0.1613	2.10	1.888	1.251	1.00
4.34	0.2600	3.40	3.200	1.307	1.00
5.99	0.3734	5.10	4.654	1.423	1.00
6.73	0.4293	5.80	5.372	1.475	1.00
7.86	0.5639	7.60	6.915	1.555	1.00
10.35	0.7637	10.20	9.400	1.729	1.00
12.20	0.9246	12.00	11.467	1.854	1.00
12.76	0.9804	12.70	11.972	1.894	1.00
13.68	1.0503	13.50	12.888	1.957	1.00
14.51	1.1278	14.40	13.729	2.014	1.00
15.90	1.2459	15.90	15.256	2.108	1.00
18.12	1.3973	17.70	17.200	2.256	1.00
20.15	1.5481	19.00	18.923	2.387	1.00
21.17	1.6248	19.95	20.000	2.452	1.00

* water content and dry density after consolidation

TABLE D.11 TRIAXIAL TEST DATA

Combined Sludge CD-C2

Consolidation press. = 1.75 kg/cm^2
Strain rate = 2.2x10^{-4} cm/min

$\bar{\sigma}_{1f}$ = 4.76 kg/cm^2

$\bar{\sigma}_{3f}$ = 1.75 kg/cm^2

Water content* = 166%
Dry density* = 30.9 PCF

c_v = 2.7x10^{-5} cm^2/sec

Volume after consolidation = 98.88 cm^3

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.750	1.75
0.10	0.0127	0.15	0.095	1.758	1.75
0.29	0.0229	0.40	0.229	1.774	1.75
0.76	0.0610	1.30	0.689	1.811	1.75
1.21	0.0965	2.10	1.127	1.849	1.75
1.42	0.1067	2.30	1.236	1.865	1.75
3.81	0.2159	4.45	2.241	2.064	1.75
4.39	0.2515	5.15	3.130	2.112	1.75
5.32	0.2997	6.10	3.800	2.190	1.75
7.79	0.3912	7.50	4.938	2.395	1.75
10.71	0.5258	9.30	6.419	2.641	1.75
13.63	0.6629	11.10	8.133	2.886	1.75
14.82	0.7442	12.30	9.224	2.988	1.75
17.96	0.8738	13.90	10.752	3.252	1.75
20.39	0.9931	15.70	12.279	3.463	1.75
21.53	1.0732	16.40	12.996	3.559	1.75
25.97	1.2370	18.10	14.867	3.929	1.75
28.24	1.3894	20.00	16.893	4.119	1.75
33.22	1.5443	21.45	18.763	4.525	1.75
36.03	1.6535	22.70	20.088	4.760	1.75

* water content and dry density after consolidation

TABLE D.12 TRIAXIAL TEST DATA

Combined Sludge CD-C3

Consolidation press. = 2.5 kg/cm^2
Strain rate = 3.45×10^{-4} cm/min

Water content* = 141%
Dry density* = 35.1 PCF

$\bar{\sigma}_{1f}$ = 5.889 kg/cm^2

$c_v = 4.4 \times 10^{-5}$ cm^2/sec

$\bar{\sigma}_{3f}$ = 2.5 kg/cm^2

Volume after consolidation = 87.57 cm^3

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	2.500	2.50
0.10	0.0076	0.00	0.112	2.508	2.50
0.51	0.0490	0.60	0.673	2.544	2.50
0.70	0.0635	0.80	0.863	2.560	2.50
1.08	0.0813	1.00	1.116	2.592	2.50
1.48	0.1041	1.40	1.403	2.626	2.50
3.98	0.1512	1.93	2.000	2.838	2.50
7.23	0.2296	2.89	3.000	3.107	2.50
11.14	0.3150	4.20	4.382	3.424	2.50
13.04	0.3975	5.30	5.548	3.569	2.50
15.31	0.4890	6.50	6.631	3.742	2.50
19.10	0.5982	7.70	8.075	4.207	2.50
22.72	0.7562	9.37	10.000	4.280	2.50
26.07	0.8382	10.25	11.259	4.519	2.50
29.97	0.9831	11.56	13.000	4.777	2.50
33.11	1.0770	12.70	14.362	4.979	2.50
38.52	1.2099	13.79	16.000	5.332	2.50
42.09	1.3824	15.00	17.316	5.550	2.50
45.33	1.4313	16.00	18.875	5.727	2.50
48.25	1.5124	16.73	20.000	5.889	2.50

* water conent and dry density after consolidation

TABLE D.13 TRIAXIAL TEST DATA

Combined Sludge with Nutrients CU-CN1

Consolidation press. = 1.0 kg/cm^2
Strain rate 0.0065 cm/min

Water content* = 163%
Dry density* = 29.9 PCF

$\bar{\sigma}_{1f}$ = 1.224 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.07 kg/cm^2

u_f = 0.93 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.81

c_u = 0.577 kg/cm^2

c_v = 4.3x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.000	1.00
0.40	0.0178	0.03	0.032	1.002	0.97
1.19	0.0279	0.07	0.096	1.026	0.93
3.54	0.0508	0.15	0.284	1.134	0.85
5.41	0.0762	0.26	0.433	1.172	0.74
6.56	0.1016	0.33	0.522	1.192	0.67
7.68	0.1397	0.41	0.609	1.199	0.59
8.66	0.1778	0.46	0.683	1.223	0.54
9.31	0.2286	0.51	0.729	1.219	0.49
10.22	0.3048	0.57	0.794	1.224	0.43
10.87	0.3937	0.63	0.834	1.204	0.37
11.79	0.5334	0.69	0.891	1.201	0.31
12.33	0.6172	0.73	0.920	1.190	0.27
12.71	0.7112	0.76	0.936	1.176	0.24
13.52	0.8636	0.80	0.975	1.175	0.20
14.23	1.0414	0.84	1.006	1.166	0.16
15.09	1.1938	0.88	1.045	1.165	0.12
15.90	1.3462	0.90	1.078	1.178	0.10
16.82	1.4859	0.91	1.114	1.204	0.09
18.07	1.6764	0.93	1.162	1.232	0.08

* water content and dry density after consolidation

TABLE D.14 TRIAXIAL TEST DATA

Combined Sludge with Nutrients CU-CN2

Consolidation press. = 1.75 kg/cm^2
Strain rate = 0.0063 cm/min

$\bar{\sigma}_{1f}$ = 1.968 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.235 kg/cm^2

u_f = 1.515 kg/cm^2

Water content* = 139%
Dry density* = 34.2 PCF

$\bar{B}$ = 100%

A_f = 0.87

c_u = 0.867 kg/cm^2

c_v = 2.7x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.750	1.75
0.23	0.0127	0.02	0.170	1.751	1.73
0.68	0.0305	0.06	0.346	1.752	1.69
2.33	0.0508	0.11	0.585	1.850	1.64
5.99	0.0762	0.21	0.909	2.081	1.54
9.23	0.1041	0.38	1.298	2.198	1.37
12.33	0.1524	0.56	1.938	2.291	1.19
13.74	0.1905	0.68	2.514	2.289	1.07
14.61	0.2311	0.80	3.107	2.238	0.95
15.26	0.2794	0.88	3.790	2.206	0.87
16.07	0.3429	0.97	4.663	2.174	0.78
16.88	0.4191	1.07	5.667	2.129	0.68
17.91	0.5461	1.18	7.298	2.081	0.57
18.83	0.6731	1.28	9.043	2.029	0.47
20.02	0.8661	1.38	11.611	1.980	0.37
20.72	1.0160	1.42	13.587	1.960	0.33
21.69	1.1786	1.47	15.629	1.946	0.28
22.45	1.3208	1.49	17.440	1.947	0.26
23.10	1.3970	1.50	18.510	1.963	0.25
23.91	1.5240	1.52	20.404	1.962	0.23

* water content and dry density after consolidation

TABLE D.15 TRIAXIAL TEST DATA

Combined Sludge with Nutrients CU-CN3

Consolidation press. = 2.5 kg/cm^2
Strain rate = 0.0060 cm/min

Water content* = 126%
Dry density* = 35.1 PCF

$\bar{\sigma}_{1f}$ = 2.566 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.35 kg/cm^2

u_f = 2.15 gk/cm^2

$\bar{B}$ = 100%

A_f = 0.97

c_u = 1.108 kg/cm^2

c_v = 2.8x10^{-5} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	2.500	2.50
0.12	0.0254	0.05	0.272	2.461	2.45
0.43	0.0508	0.11	0.648	2.429	2.39
0.97	0.0762	0.15	0.984	2.436	2.35
4.63	0.1143	0.27	1.532	2.638	2.23
12.06	0.1524	0.51	2.080	3.048	1.99
18.56	0.2286	0.86	3.219	3.248	1.67
21.10	0.3048	1.12	4.359	3.187	1.38
22.72	0.3810	1.28	5.421	3.145	1.22
24.02	0.4572	1.42	6.518	3.091	1.08
24.56	0.5334	1.54	7.477	2.995	0.96
25.10	0.6096	1.63	8.574	2.925	0.87
26.62	0.7620	1.81	10.630	2.820	0.69
27.27	0.8890	1.91	12.480	2.727	0.59
28.02	1.0160	1.98	14.331	2.670	0.52
29.00	1.1481	2.04	16.130	2.638	0.46
29.43	1.2827	2.11	17.929	2.553	0.39
30.08	1.3589	2.12	18.785	2.568	0.38
31.16	1.4859	2.15	20.670	2.564	0.35
31.27	1.5240	2.16	21.184	2.547	0.34

* water content and dry density after consolidation

TABLE D.16 TRIAXIAL TEST DATA

Combined Sludge after Partial Decomposition CU-CD1

Consolidation press. = 1.0 kg/cm^2
Strain rate = 0.0036 cm/min

Water content* = 115%
Dry density* = 37.0 PCF

$\bar{\sigma}_{1f}$ = 1.106 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.25 kg/cm^2

u_f = 0.75 kg/cm^2

$\bar{B}$ = 100%

A_f = 0.88

c_u = 0.428 kg/cm^2

c_v = 7.7x10^{-6} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.000	1.00
0.68	0.0203	0.04	0.187	1.006	0.96
2.16	0.0381	0.10	0.395	1.047	0.90
4.89	0.0635	0.19	0.715	1.140	0.81
7.51	0.1016	0.30	1.240	1.205	0.70
8.66	0.1397	0.33	1.706	1.249	0.67
9.41	0.1778	0.43	2.166	1.197	0.57
10.01	0.2159	0.46	2.626	1.203	0.54
10.71	0.2794	0.50	3.502	1.203	0.50
11.47	0.3683	0.54	4.536	1.205	0.46
11.74	0.4318	0.57	5.326	1.186	0.43
12.39	0.5842	0.62	7.208	1.162	0.38
13.31	0.7366	0.68	8.989	1.144	0.32
13.47	0.8915	0.70	10.770	1.118	0.30
13.85	0.9652	0.71	12.221	1.117	0.29
14.12	1.0693	0.72	13.370	1.112	0.28
14.66	1.2962	0.74	15.000	1.108	0.26
15.09	1.3589	0.75	16.673	1.106	0.25
15.15	1.5418	0.77	18.756	1.067	0.23
15.47	1.7018	0.77	20.552	1.066	0.23

* water content and dry density after consolidation

TABLE D.17 TRIAXIAL TEST DATA

Combined Sludge after Partial Decomposition CU-CD2

Consolidation press. = 1.75 kg/cm^2
Strain rate = 0.0035 cm/min

Water content* = 100%
Dry density* = 41.8 PCF

$\bar{\sigma}_{1f}$ = 1.950 kg/cm^2

$\bar{B}$ = 100%

$\bar{\sigma}_{3f}$ = 0.50 kg/cm^2

A_f = 0.86

u_f = 1.25 kg/cm^2

c_u = 0.725 kg/cm^2

c_v = 6.8x10^{-6} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	1.750	1.75
4.63	0.0762	0.25	0.918	1.840	1.50
10.44	0.1143	0.43	1.382	2.082	1.32
12.71	0.1524	0.57	1.835	2.104	1.18
14.93	0.1930	0.69	2.317	2.139	1.06
16.77	0.2540	0.82	3.142	2.132	0.93
17.96	0.3302	0.94	4.085	2.085	0.81
18.18	0.3505	0.95	4.278	2.088	0.80
19.58	0.4775	1.08	5.898	2.034	0.67
20.39	0.5588	1.12	6.175	2.038	0.63
20.72	0.6350	1.16	7.636	2.006	0.59
20.99	0.7112	1.18	8.527	1.991	0.57
21.42	0.7620	1.19	9.181	2.000	0.56
22.07	0.8560	1.25	10.250	1.966	0.50
21.75	0.9271	1.25	11.112	1.931	0.50
22.07	1.1049	1.29	13.221	1.877	0.46
22.07	1.2700	1.32	15.227	1.815	0.43
22.07	1.3487	1.32	16.044	1.801	0.43
22.18	1.5240	1.35	18.242	1.742	0.40
21.96	1.6891	1.37	20.055	1.679	0.38

* water content and dry density after consolidation

TABLE D.18 TRIAXIAL TEST DATA

Combined Sludge after Partial Decomposition CU-CD3

Consolidation press.= 2.5 kg/cm^2
Strain rate = 0.0035 cm/min

Water content* = 101%
Dry density* = 40.7 PCF

$\bar{\sigma}_{1f}$ = 2.046 kg/cm^2

$\bar{B}$ = 100%

$\bar{\sigma}_{3f}$ = 0.39 kg/cm^2

A_f = 1.27

u_f = 2.11 kg/cm^2

c_u = 0.828 kg/cm^2

c_v = 5.8x10^{-6} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.000	0.00	0.000	2.500	2.50
4.31	0.0381	0.22	0.430	2.588	2.28
8.92	0.0635	0.42	0.717	2.717	2.08
12.61	0.1016	0.61	1.144	2.786	1.89
14.99	0.1397	0.79	1.571	2.771	1.71
16.61	0.1905	0.97	2.189	2.698	1.53
18.45	0.2413	1.17	2.861	2.619	1.33
19.96	0.3175	1.34	3.778	2.541	1.16
20.29	0.3810	1.46	4.583	2.432	1.04
21.26	0.4572	1.57	5.508	2.375	0.93
22.50	0.6096	1.73	7.178	2.272	0.77
23.59	0.7620	1.83	8.998	2.214	0.67
24.78	0.9525	1.92	11.265	2.161	0.58
25.64	1.1176	2.01	12.935	2.096	0.49
26.29	1.2776	2.05	14.799	2.061	0.45
27.91	1.4605	2.11	16.962	2.057	0.39
28.24	1.5850	2.11	18.453	2.046	0.39
28.46	1.6383	2.11	19.125	2.045	0.39
28.67	1.6891	2.12	19.647	2.037	0.38
28.78	1.7272	2.12	20.169	2.032	0.38

* water content and dry density after consolidation

TABLE D.19 TRIAXIAL TEST DATA

Combined Sludge after Partial Decomposition CU-CD4

Consolidation press. = 3.0 kg/cm^2
Strain rate = 0.0036 cm/min

Water content* = 110%
Dry density* = 37.0 PCF

$\bar{\sigma}_{1f}$ = 1.483 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.58 kg/cm^2

u_f = 2.42 kg/cm^2

$\bar{B}$ = 100%

A_f = 2.68

c_u = 0.452 kg/cm^2

c_v = 2.2x10^{-6} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	3.000	3.00
0.24	0.0254	0.06	0.165	2.956	2.94
1.34	0.0508	0.27	0.462	2.821	2.73
3.46	0.0762	0.46	0.755	2.775	2.54
5.50	0.1016	0.63	1.014	2.742	2.37
7.88	0.1397	0.87	1.433	2.661	2.13
9.20	0.1778	1.07	1.910	2.547	1.93
10.39	0.2286	1.28	2.558	2.412	1.72
10.93	0.2794	1.46	3.185	2.264	1.54
12.06	0.4318	1.87	4.894	1.915	1.13
13.09	0.5842	2.08	6.546	1.757	0.92
13.58	0.7366	2.23	8.227	1.622	0.77
14.34	0.8890	2.31	9.965	1.573	0.69
14.77	1.0414	2.39	11.702	1.502	0.61
15.09	1.1176	2.42	12.557	1.483	0.58
15.53	1.1938	2.46	13.412	1.460	0.54
15.63	1.3462	2.50	15.121	1.408	0.50
16.28	1.4986	2.54	16.830	1.386	0.46
16.45	1.6510	2.57	18.610	1.346	0.43
16.77	1.8034	2.61	20.177	1.306	0.39

* water content and dry density after consolidation

TABLE D.20 TRIAXIAL TEST DATA

Combined Sludge after Partial Decomposition CU-CD5

Consolidation press. = 3.0 kg/cm^2
Strain rate = 0.0034 cm/min

Water content* = 100%
Dry density* = 39.1 PCF

$\bar{\sigma}_{1f}$ = 2.295 kg/cm^2

$\bar{\sigma}_{3f}$ = 0.77 kg/cm^2

u_f = 2.23 kg/cm^2

$\bar{B}$ = 100%

A_f = 1.46

c_u = 0.763 kg/cm^2

c_v = 4.3x10^{-6} cm^2/sec

load (kg)	displacement (cm)	pore pressure (kg/cm^2)	axial strain (%)	$\bar{\sigma}_1$ (kg/cm^2)	$\bar{\sigma}_3$ (kg/cm^2)
0.00	0.0000	0.00	0.000	3.000	3.00
5.71	0.0254	0.13	0.231	3.268	2.87
8.44	0.0381	0.25	0.397	3.337	2.75
13.52	0.0762	0.55	0.869	3.386	2.45
15.47	0.1143	0.82	1.377	3.245	2.18
17.64	0.1651	1.17	1.970	3.036	1.83
19.64	0.2286	1.42	2.789	2.912	1.58
20.99	0.3556	1.54	4.472	2.859	1.46
21.96	0.4318	1.76	5.419	2.690	1.24
22.50	0.5842	1.96	7.313	2.495	1.04
23.59	0.7366	2.08	9.116	2.416	0.92
24.34	0.8890	2.16	11.010	2.352	0.84
24.78	0.9652	2.18	11.971	2.342	0.82
24.99	1.0414	2.22	13.219	2.293	0.78
25.43	1.1176	2.23	14.045	2.295	0.77
25.53	1.2192	2.26	15.172	2.251	0.74
25.43	1.3030	2.31	16.299	2.175	0.69
25.75	1.3716	2.32	17.126	2.169	0.68
25.97	1.5240	2.37	18.854	2.100	0.63
25.75	1.6002	2.38	19.906	2.059	0.62

* water content and dry density after consolidation

APPENDIX E

TABLE E.1 STABILITY ANALYSIS FOR COMBINED SLUDGE SLOPE USING $\overline{CIU}$ TEST RESULTS (a) FOR A SLOPE WITH EXCESS PORE PRESSURES (b) FOR A SLOPE WITH NO EXCESS PORE PRESSURES.

(a)

Combined sludge: γ_m = 69.2 PCF, $\bar{\phi}$ = 49°, $\bar{c}$ = 430 PSF, u = γ_wh where h corresponds to the slope surface

slice	b (ft)	h (ft)	A_2 (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	16	5.5	80.0	5.536	6.88	-6.13	-0.591	0.544	7.506
2	20	14.5	290.0	20.068	8.60	7.65	2.671	1.972	10.869
3	20	19.5	390.0	26.988	8.60	22.38	10.276	2.652	11.651
4	20	17.0	340.0	23.528	8.60	40.39	15.246	2.312	11.260
5	7.7	7.2	46.2	3.197	3.31	55.76	2.643	2.883	6.626
							Σ = 30.245		

$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$ $\qquad$ $1/M_\alpha\,(W-ub)\tan\bar{\phi} + \bar{c}b$

slice	F_{RHS}	F_{RHS}	F_{RHS}	F_{LHS}	F_{LHS}	F_{LHS}
	(1.35)	(1.36)	(1.37)			
1	0.903	0.904	0.905	8.309	8.303	8.297
2	1.105	1.104	1.103	9.840	9.848	9.855
3	1.249	1.247	1.244	9.327	9.345	9.363
4	1.314	1.310	1.306	8.570	8.597	8.623
5	1.267	1.262	1.257	5.230	5.251	5.272
				Σ=41.276	Σ=41.344	Σ=41.411
			F_{LHS} =	41.276/30.245 = 1.36	1.37	1.37

Circle center (X = 21.5 ft, Y = 75 ft) see Figure 5.8 $\qquad$ Factor of Safety = 1.37

TABLE E.1 cont.

(b)

Combined sludge: $\gamma_m = 69.2$ PCF, $\bar{\phi} = 49^o$, $\bar{c} = 430$ PSF, $u = \gamma_w h$ where h=0 for a drained slope

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	16	5.5	80.0	5.536	6.88	-6.13	-0.591	5.536	13.248
2	20	14.5	290.0	20.068	8.60	7.65	2.671	20.068	31.686
3	20	19.5	390.0	26.988	8.60	22.38	10.276	26.988	39.646
4	20	17.0	340.0	23.528	8.60	40.39	15.246	23.528	35.666
5	7.7	7.2	46.2	3.197	3.31	55.76	2.643	3.197	6.988
							Σ=30.245		

$$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}} \qquad 1/M_\alpha (W-ub)\tan\bar{\phi} + \bar{c}b$$

slice	F_{RHS} (4.35)	F_{RHS} (4.31)	F_{LHS}	F_{LHS}
1	0.966	0.966	13.714	13.717
2	1.026	1.027	30.873	30.864
3	1.025	1.026	38.665	38.630
4	0.933	0.935	38.227	38.162
5	0.781	0.783	8.944	8.921
			Σ=130.423	Σ=130.294

F_{LHS} = 130.423/30.245 = 4.312   4.31   Factor of Safety = 4.31

TABLE E.2 STABILITY ANALYSIS FOR PRIMARY SLUDGE SLOPE USING CID TEST RESULTS (a) FOR A SLOPE WITH EXCESS PORE PRESSURES (b) FOR A SLOPE WITH NO EXCESS PORE PRESSURES

(a)

Primary sludge: γ_m = 70.9 PCF, $\bar{\phi}$ = 33.2°, $\bar{c}$ = 238 PSF, u = $\gamma_w h$ where corresponds to the slope surface

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\alpha$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	16	5.7	80.0	5.672	3.81	-6.05	-0.598	0.680	4.253
2	20	14.3	286.0	20.277	4.76	7.59	2.678	2.431	6.351
3	20	18.9	378.0	26.800	4.76	23.20	10.558	3.213	6.862
4	20	16.0	320.0	22.688	4.76	41.26	14.962	2.720	6.540
5	7	5.3	35.7	2.531	1.67	57.02	2.123	0.303	1.864
							Σ=29.723		

$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$ $\qquad$ $1/M_\alpha (W-ub)\tan\bar{\phi} + \bar{c}b$

slice	F_{RHS}	F_{RHS}	F_{LHS}	F_{LHS}
	(2.0)	(0.75)		
1	0.960	0.902	4.340	4.713
2	1.034	1.106	6.139	5.740
3	1.048	1.263	6.548	5.434
4	0.967	1.327	6.760	4.928
5	0.819	1.276	2.277	1.461
			Σ=26.154	Σ=22.275

F_{LHS} = 26.154/29.723 =0.88 $\qquad$ 0.75 $\qquad$ Factor of Safety = 0.75

Circle center (X = 20 ft, Y = 76 ft) see Figure 5.8

TABLE E.2 cont.

(b)

Primary sludge: γ_m = 70.9 PCF, $\bar{\phi}$ = 33.2^{o}, $\bar{c}$ = 238 PSF, u = γ_wh where h=0 for a drained slope

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	W sin$\bar{\alpha}$ (kips)	W-ub (kip/ft)	(W-ub)tan$\bar{\phi}$ + $\bar{c}b$ (kip/ft)
1	16	5.7	80.0	5.672	3.81	-6.05	-0.598	5.672	7.520
2	20	14.3	286.0	20.277	4.76	7.59	2.678	20.277	18.029
3	20	18.9	378.0	26.800	4.76	23.20	10.558	26.800	22.297
4	20	16.0	320.0	22.688	4.76	41.26	14.962	22.688	19.607
4	7	5.3	35.7	2.531	1.67	57.02	2.123	2.531	3.322
							Σ=29.123		

$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$ $\quad\quad$ $1/M_\alpha \,(W-ub)\tan\bar{\phi} + \bar{c}b$

slice	F_{RHS}	F_{RHS}	F_{RHS}	F_{LHS}	F_{LHS}	F_{LHS}
	(2.0)	(2.45)	(2.44)			
1	0.960	0.966	0.966	7.834	7.782	7.783
2	1.034	1.027	1.027	17.428	17.563	17.561
3	1.048	1.024	1.025	21.275	21.767	21.758
4	0.967	0.928	0.929	20.266	21.131	21.115
5	0.819	0.768	0.769	4.057	4.323	4.318
				Σ=70.860	Σ=72.567	Σ=72.535

F_{LHS} = 70.680/29.723 = 2.38 $\quad$ 2.44 $\quad$ 2.44

Factor of Safety = 2.44

TABLE E.3 STABILITY ANALYSIS FOR COMBINED SLUDGE SLOPE USING CID TEST RESULTS (a) FOR A SLOPE WITH EXCESS PORE PRESSURES (b) FOR A SLOPE WITH NO EXCESS PORE PRESSURES

(a)

Combined sludge: γ_m = 69.2 PCF, $\bar{\Phi}$ = 23.0^{o}, $\bar{c}$ = 231 PSF, u = $\gamma_w h$ where h corresponds to the slope surface

slice	b (ft)	h (ft)	A_2 (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\Phi} + \bar{c}b$ (kip/ft)
1	15.0	6.7	75	5.190	3.465	-9.12	-0.823	0.510	3.681
2	20.0	14.8	296	20.483	4.620	4.48	1.600	2.013	5.474
3	20.0	20.0	400	27.680	4.620	20.91	9.879	2.720	5.775
4	20.0	18.5	370	25.604	4.620	39.41	16.255	2.516	5.688
5	8.9	7.2	61	4.208	2.056	56.98	3.528	0.414	2.232
							Σ=30.439		

$$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\Phi}}{F_{RHS}}$$

$$1/M_\alpha\,(W-ub)\tan\bar{\Phi} + \bar{c}b$$

slice	F_{RHS} (0.50)	F_{RHS} (0.70)	F_{LHS}	F_{LHS}
1	0.853	0.891	4.317	4.131
2	1.063	1.044	5.149	5.242
3	1.237	1.151	4.668	5.019
4	1.312	1.158	4.337	4.914
5	1.257	1.053	1.776	2.119
			Σ=20.246	Σ=21.425

Circle center (X = 24 ft, Y = 72 ft)
see Figure 5.8

F_{LHS} = 20.246/30.439 =0.67   0.70

Factor of Safety = 0.70

TABLE E.3 cont.

(b)

Combined sludge: γ_m = 69.2 PCF, $\bar{\phi}$ = 23.0^o, $\bar{c}$ = 231 PSF, u = $\gamma_w h$ where h=0 for a drained slope

slice	b (ft)	h (ft)	A_2 (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\bar{\alpha}$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	15.0	6.7	75	5.190	3.465	-9.12	-0.823	5.190	5.668
2	20.0	14.8	296	20.483	4.620	4.48	1.600	20.483	13.315
3	20.0	20.0	400	27.680	4.620	20.91	9.879	27.680	16.369
4	20.0	18.5	370	25.604	4.620	39.41	16.255	15.604	15.488
5	8.9	7.2	61	4.208	2.056	56.98	3.528	4.208	3.842
							Σ=30.439		

$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$ $\qquad$ $1/M_\alpha \; (W-ub)\tan\bar{\phi} + \bar{c}b$

slice	F_{RHS} (1.5)	F_{RHS} (1.90)	F_{RHS} (1.89)	F_{LHS}	F_{LHS}	F_{LHS}
1	0.943	0.952	0.952	6.014	5.954	5.955
2	1.019	1.014	1.014	13.066	13.126	13.124
3	1.035	1.014	1.014	15.814	16.145	16.139
4	0.952	0.914	0.915	16.264	16.937	16.923
5	0.782	0.732	0.733	4.912	5.247	5.240
				Σ=56.070	Σ=57.409	Σ=57.382

F_{LHS} = 56.070/30.439 = 1.84 $\qquad$ 1.89 $\qquad$ 1.89

Factor of Safety = 1.89

TABLE E.4 STABILITY ANALYSIS FOR A DECOMPOSING SLUDGE SLOPE USING $\overline{CIU}$ TEST RESULTS (a) FOR A SLOPE WITH EXCESS PORE PRESSURES (b) FOR A SLOPE WITH NO EXCESS PORE PRESSURES

(a)

Partially decomposed combined sludge: γ_m = 74.9 PCF, $\bar{\phi} = 28.7^o$, $\bar{c}$ = 225 PSF, $u = \gamma_w h$ where h corresponds to the slope surface

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	$W\sin\alpha$ (kips)	W-ub (kip/ft)	$(W-ub)\tan\bar{\phi} + \bar{c}b$ (kip/ft)
1	15.6	5.2	78	5.842	3.51	-7.70	-0.783	0.975	4.044
2	20.0	14.6	292	21.871	4.50	6.14	2.339	3.650	6.498
3	20.0	19.5	390	29.211	4.50	22.00	10.943	4.875	7.169
4	20.0	17.3	346	25.915	4.50	39.95	16.641	4.325	6.868
5	8.0	7.2	49	3.655	1.80	56.01	3.030	0.610	2.134
							Σ=32.170		

$$M_\alpha = \cos\alpha + \frac{\sin\alpha \tan\bar{\phi}}{F_{RHS}}$$

$$1/M_\alpha (W-ub)\tan\bar{\phi} + \bar{c}b$$

slice	F_{RHS} (1.5)	F_{RHS} (0.83)	F_{RHS} (0.75)	F_{LHS}	F_{LHS}	F_{LHS}
1	0.942	0.903	0.893	4.292	4.480	4.528
2	1.033	1.065	1.072	6.289	6.102	6.060
3	1.064	1.174	1.201	6.738	6.105	5.971
4	1.001	1.190	1.235	6.861	5.771	5.560
5	0.862	1.106	1.164	2.476	1.930	1.833
				Σ=26.657	Σ=24.388	Σ=23.951

Circle center (X = 22 ft, Y = 74.8 ft)
see Figure 5.8

F_{LHS}=26.657/32.170=0.83   0.76   0.75

Factor of Safety = 0.75

TABLE E.4 cont.

(b)

Partially decomposed combined sludge: γ_m = 74.9 PCF, $\bar{\phi}$ = 28.7^o, $\bar{c}$ = 225 PSF, u = γ_wh where h=0 for a drained slope

slice	b (ft)	h (ft)	A (ft^2)	W (kip/ft)	$\bar{c}b$ (kip/ft)	$\bar{\alpha}$ (deg)	W sin$\bar{\alpha}$ (kips)	W-ub (kip/ft)	(W-ub)tan$\bar{\phi}$ + $\bar{c}b$ (kip/ft)
1	15.6	5.2	78	5.842	3.51	-7.70	-0.783	5.842	6.708
2	20.0	14.6	292	21.871	4.50	6.14	2.339	21.871	16.474
3	20.0	19.5	390	29.211	4.50	22.00	10.943	29.211	20.493
4	20.0	17.3	346	25.915	4.50	39.95	16.641	25.915	18.688
5	8.0	7.2	49	3.655	1.80	56.01	3.030	3.655	3.801
							Σ=32.170		

$$M_\alpha = \cos\bar{\alpha} + \frac{\sin\bar{\alpha}\tan\bar{\phi}}{F_{RHS}}$$

$$1/M_\alpha \, (W-ub)\tan\bar{\phi} + \bar{c}b$$

slice	F_{RHS} (1.5)	F_{RHS} (2.1)	F_{LHS}	F_{LHS}
1	0.942	0.956	7.121	7.017
2	1.033	1.022	15.943	16.117
3	1.064	1.025	19.262	19.996
4	1.001	0.934	18.670	20.008
5	0.862	0.775	4.411	4.903
			Σ=65.407	Σ=68.041

F_{LHS} = 65.407/32.170 = 2.03 2.12

Factor of Safety = 2.11