Effect of Sodium Chloride on Stress-Deformation of Sand Bentonite Mixture

염분이 모래와 벤토나이트 혼합토의 응력 변형에 미치는 영향

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요 지

이 연구에서는 화학액으로서 해안가에서 쉽게 영향 받는 염분을 사용하였다. 염분 용액으로 포화된 모래 벤토나이트 혼합토를 사용하여 압밀 비배수 삼축압축 시험을 실시하였다. 변형과 강도정수를 삼축압축시험을 통하여 구속응력과 염수의 농도 변화에 따라 구하였다. 실험 결과 염수로 포화된 흙과 벤토나이트의 점착력은 염수의 농도가 증가함에 따라 증가하며 내부마찰각은 변화가 없고 탄성계수는 증가하는 것으로 나타났다.

Abstract

In this study sodium chloride solution is employed for chemicals, and several cylindrical triaxial tests are performed on the sand-bentonite mixtures saturated with sodium chloride solution. Deformation(elastic modulus, E) and strength(cohesion, c′, and angle of friction, ϕ') parameters are obtained from the triaxial tests as functions of confining pressure and sodium chloride solution concentrations. The results here indicate an increase in the value of effective cohesion with increase in the concentration of NaCl solution, which can be explained by using the Gouy-Chapman model. The value of the effective angle of shearing resistance does not show significant change with the increase in concentration of NaCl solution. The Young's modulus also increases with the increase in concentration of NaCl solution.

Keywords : Sodium chloride, Gouy-chapman theory, Soil parameters, Sand bentonite mixture, Contaminants

1. Introduction

The presence of contaminants in the subsurface causes environmental and engineering

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problems. The wide-spread use of soil-bentonite slurry as leachate barriers necessitates the study on the interaction between the contaminants and the engineering properties of these materials. Sand-bentonite mixtures are comprised of truly contrasting soils with regards to grain size, hydraulic conductivity, chemical activity and strength which, when combined in the optimum ratio, can form a seepage barrier.

There are many sources of salt water contamination such as mine tailings, leakage from brine ponds and geotechnical structures near sea. This brine can be thought of as a mixture of water molecules and Na^+ and Cl^- ions. Many studies have determined the effect of brine contamination on the hydraulic conductivity of sand-bentonite mixtures.

The purpose of this research is to study the effect of sodium chloride solution on the strength and deformation properties of a saturated sand-bentonite mixture using cylindrical triaxial cell apparatus. A series of consolidated undrained triaxial tests are conducted with different concentrations of sodium chloride and water.

2. Literature Review

Little work has been done about the stress-strain behavior of soils affected by chemicals. Evans and Fang(1988) performed the shear strength of contaminated soils and showed the decrease of the shear strength in the contaminated soils due to the presence of aniline. They did not provide elastic relations between changes of soil properties such as the internal angle of friction, cohesion, modulus and chemical concentration. The residual strength of clays is affected by their mineral composition and by the nature of their constituent and the pore fluid. Di Maio and Fenelli(1994) state that the shear strength of kaolin is not affected by the solution such as distilled water and sodium chloride solutions with given concentrations, whereas the residual strength of bentonite varies greatly due to the inward diffusion of salt water. However, most of the studies did not give the relationship between soil parameters and concentration of chemicals.

The properties of sand-bentonite mixtures are dependent on the fabric of bentonite in the mixture(Kenny et al., 1992). Since they are natural materials, bentonites vary from one source to another in regard to mineral composition, chemical state, and grain size distribution. Sodium bentonite is made up of many individual platelets. These platelets are di-polar with positive charges on the outer edges and negative charges on the flat surfaces. Its sodium cations are attracted to the negative surfaces. In comparison to bentonite, sand has little capacity to hold water and, therefore, a mixture of sand, bentonite, and water, blended to a homogeneous state, becomes one composed of dry sand and wet bentonite. As bentonite is added, sand particles are increasingly supported by the bentonite in looser frameworks, suggesting that sand is the primary load-bearing constituent of the mixture when the bentonite/sand ratio is small and that this role is increasingly shared with bentonite as bentonite/sand ratio is increased.

When sodium bentonite comes in contact with water, the bentonite swells. This occurs as water molecules penetrate the space between bentonite layers causing sodium cations to hydrate and disassociate from platelet surfaces. When dry bentonite and water are mixed, as in the case of bentonite-sand mixtures, water is drawn into the montmorillonite particles to hydrate the surfaces of elemental sheets and the cations. For the combination of sodium montmorillonite and fresh water, the fluid that enters the particles forms thick, viscous diffuse ionic layers around the sheets, causing the montmorillonite particles to swell, possibly to the extent of complete separation of the sheets. When the mixture of dry sand and bentonite combines with sodium chloride solution, less fluid is required to neutralize the negatively charged sheets, and if the ion concentration is large, or the valences of the cations are large, the separation distances between sheets will remain small and the montmorillonite particles will remain in the form of closed books. The fabric of bentonite in this case will consist of swollen but intact montmorillonite particles, surrounded by thin, viscous diffuse ionic layer, in an arrangement resembling a pile of fallen books. The objective of this study is to determine the effect of NaCl solution on the stress, strain and deformation properties of sand-bentonite mixture.

3. Soil Chemical Interactions

Interaction between soil and chemical modifies its engineering properties such as permeability, deformations and strength behavior. The clay particles usually carry a net negative charge on their surface. The cations present in the solution surrounding the clay particles are attached to the clay surface to balance the negative charge. Thus, a negative charged silicate framework surrounded by a diffuse cloud of oppositely charged ions is formed and the cations in the electrolyte tend to be uniformly distributed due to the repulsive forces between them. This is referred to as diffuse double layer(DDL). The cation concentration decreases with increasing distance from the surface of the particle. Some clay minerals have weak interlayer bonding and the expansion of the DDL can result in swelling of the soil particles. The expression for the thickness of the DDL is expressed as

$$t=\sqrt{\frac{D\kappa T}{8\pi\eta\varepsilon^2 v^2}} \tag{1}$$

where t= thickness of DDL, D=dielectric constant of the solution, κ=Boltzman constant, T=temperature, η=electrolyte concentration of the solution, ε=unit electric charge and v=cation valence of the system.

4. Materials and Experimental Methods

1) Bentonite and Sand

The bentonite used in this study is sodium rich bentonite and contains 90% of montmorillonite. The other constituents are small portions of feldspar, biotite, selenite, etc. The chemical formula is$(Al, Fe_{1.67}, Mg_{0.33})Si_4O_{10}(OH_7)Na^+Ca^{++}_{0.33}$ and other technical data is provided in Table 1. The sand is #20 sand, which passes sieve #10 and is retained by sieve #20. The specific gravity is 2.66.

Table 1. Bentonite Used in Experiment

Chemical Composition	Silica 63.02% as SiO_2 Alumina 21,08% as Al_2O_3 Iron(ferric) 3.25% as Fe_2O_3 Iron (Ferrous)0.35% as FeO Magnesium 0.67% as MgO Calcium 0.65% as CaO Crystal Water 5.64% as H_2O Trace Elements 0.72%
Moisture Content	Maximum of 10%
Dry Particle Size	65% minimum passing #200 seive
pH	1% suspension 8.0 to 10.0
Dry Bulk Density	53lbs per cubic foot

2) Sodium Chloride

For this study, pure sodium chloride is used. The sodium chloride solution is prepared by mixing sodium chloride with tap water. The concentration of the solution is the factor which determines the amount of the sodium chloride to be mixed with a weighed quantity of tap water. The mixture is well stirred with a glass rod to ensure that no precipitate is formed at the bottom of the container.

3) Sample Preparation

The sand retained on the #20 sieve is taken and weighed. The amount of bentonite to be mixed is 10% by weight of sand. The two materials are mixed thoroughly by hand. Different concentrations of sodium chloride solution are used in preparing different samples. In this study, tap water, 5% NaCl, 10% NaCl and 15% NaCl are used in the preparation of the samples. The sand-bentonite mixture is deposited in a container and an adequate amount of sodium chloride solution of known concentration is added to it. The sample is sealed in a bucket and stored in the constant humidity room for a period of 45 days to enable the materials to have interaction and be fully saturated. After above time period, the samples are taken out and excess solution is drained out by placing the samples in a plastic bucket which has small holes drilled at the bottom. A filter paper is placed at the bottom over the holes as well as on the top of the sample. Values of bulk density and relative density for various samples are shown in Table 2.

Table 2. Values of Bulk Density and Relative Density for Various Samples

Samples Saturated with	Bulk Density (γ, kN/m^3)	Relative Density (D_r, %)
Tap Water	19.8	60.0
5% NaCl Solution	19.9	64.0
10% NaCl Solution	20.0	67.0
15% NaCl Solution	20.1	71.5

4) Experimental Procedure

The cylindrical triaxial system consists of MTS load frame with movable cross head to accommodate specimens of various heights. The porous stone which is kept saturated in water to drain out any clogging particles is fitted to the bottom pedestal. The preparation starts with applying silicon grease on the longitudinal direction of the split from cylindrical mold, before closing the form to prepare a 7.1cm diameter air tight hollow cylinder. A filter paper is put on the top of the sand-bentonite mixture, then the top loading platen is brought in contact with the sample and locked. The program is run on the computer with the sample dimensions and the readings obtained by the data acquisition system help to make sure that the loading platen is in contact with the sample. Lubrication is applied to the end platen to minimize friction that may cause non-uniformity of stress and deformation.

The first stage of the test is started by applying a small confining pressure of 7kPa. Then small equal increments of back pressure and cell pressure are simultaneously applied. The total back pressure applied is 210kPa. The magnitude of the back pressure is based on the recommendations by Bishop and Henkel(1957). The time period provided for saturation is sufficient for full saturation and this was confirmed by checking B value, which is found to be close to 1.0. The cell pressure is then increased to the desired confining pressure, keeping the drainage valves at the top and bottom of the sample to allow the sample to consolidate. The shear tests conducted on these samples were CTC(Cylindrical Triaxial Com-

Table 3. Moisture Content of the Samples

Samples Saturated with	Moisture Content before Testing(%)	Moisture Content after Testing(%)
Tap Water	18.6	16.5
5% NaCl Solution	17.9	15.6
10% NaCl Solution	17.4	15.3
15% NaCl Solution	16.6	15.1

pression) tests($\sigma_1 > \sigma_2 = \sigma_3$). A constant strain rate of 0.03% per minute is used. Stress-strain and pore water pressure reading are recorded automatically on the data acquisition system. The program enables the loading and unloading at specified intervals.

5. Experimental Results and Evaluation

5.1 Stress-Strain Curves

The experimental investigation included twelve consolidated-undrained tests. The samples tested include samples saturated with water, 5% NaCl solution, 10% NaCl solution and 15% NaCl solution. Each sample is separately tested under three different confining pressures, i.e., 35 kPa, 70 kPa and 175 kPa. The pore water pressure is also measured, and the effective soil parameters are computed with variation of confining stress and the concentration of sodium chloride.

The stress-strain curves obtained in the experimental investigation for the samples saturated with different concentrations of NaCl solution under the confining pressure of 35 kPa are presented in Figure 1. Similarly, the stress-strain curves for the samples saturated with different concentrations of NaCl solution under the confining pressures of 70 kPa and 175 kPa are shown in Figure 2 and Figure 3.

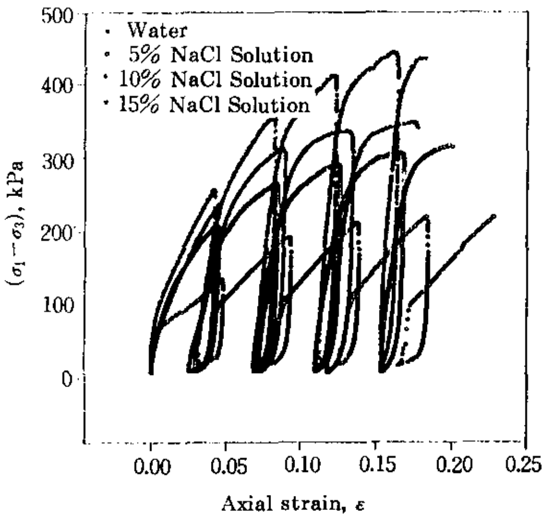

Fig 1. $(\sigma_1-\sigma_3)$vs. Axial Strain, ε; σ_3=35kPa

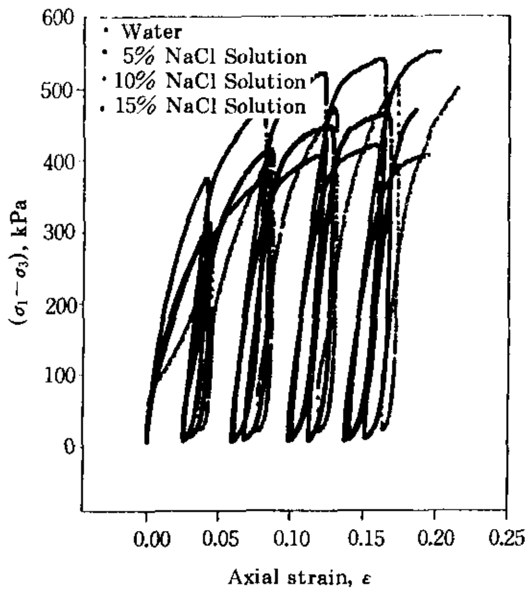

Fig 2. $(\sigma_1-\sigma_3)$vs. Axial Strain, ε; σ_3=70kPa

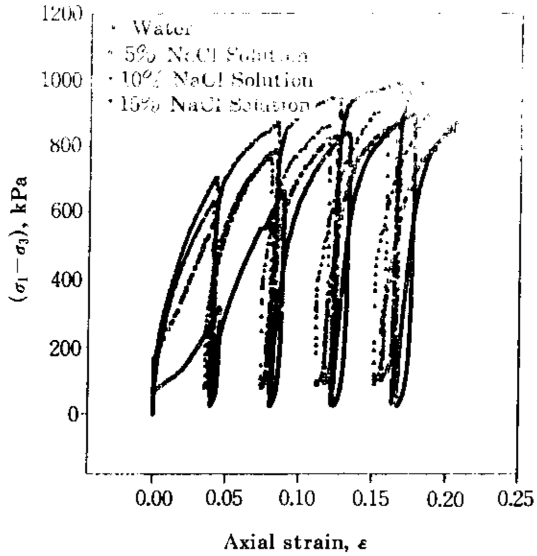

Fig 3. $(\sigma_1-\sigma_3)$vs. Axial Strain, ε; σ_3=175kPa

By comparing these curves, it is concluded that the strength of the sand-bentonite mixture increases with the increase in the concentration of NaCl solution. This finding is similar to what other researchers have found previously (Moum and Rosenquist, 1961; Woo and Moh, 1977; and Di Maio and Fenelli, 1994). Moum and Rosenquist also found that the shear strength of the soil increases with the increase in the concentration of the NaCl solution.

The above results can be explained by the cation exchange capacity and the diffuse double layer(DDL) theory. The bentonite used in the mixture is sodium-rich and the NaCl solution is used as the chemical for saturating the mixture. The attraction between the electropositive Na^+ and the negatively charged clay platelets increases when the mixture comes in contact with sodium chloride solution. This results in a decrease in the thickness of the DDL, leading to a flocculated soil structure and a corresponding increase in the strength.

According to equation (1), as the electrolyte concentration in the pore fluid increases, the thickness of DDL tends to decrease. A tendency towards a more flocculated structure is caused by the decrease in the thickness of the DDL. In principle, the fluid composition may influence the thickness of the double layer (Lambe, 1960), the type and size of the elementary aggregates (Stawinski et al., 1990) and the interparticle forces. The type and size of particle aggregates seem to play an important role in the behavior of sodium-montmorillonite suspensions.

5.2 Strength Parameters

From the results obtained in the experimental investigation, stress paths are plotted according to the concentration of NaCl solution used in saturating the sand-bentonite mixtures so as to obtain the values of effective cohesion, c´ and effective angle of shearing resistance, ϕ'.

Based on the results, it can be stated that the value of c´ increases as the concentration of NaCl solution used to saturate the sand-bentonite mixture is increased (Figure 4). As the thickness of the DDL decreases, there is a tendency for the soil structure to be flocculated and this reduces the interparticle repulsion. For the combination of sodium bentonite and a saline solution, less fluid is required to neutralize the negatively charged sheets, and if the ion concentration is large, or the valences of the cations are large, the separation distances between sheets will remain small and the montmorillonite particles will remain in the form of closed books(Kenney et al, 1992). Also, the rate of increase in c´ is reduced as the percentage of NaCl solution increases.

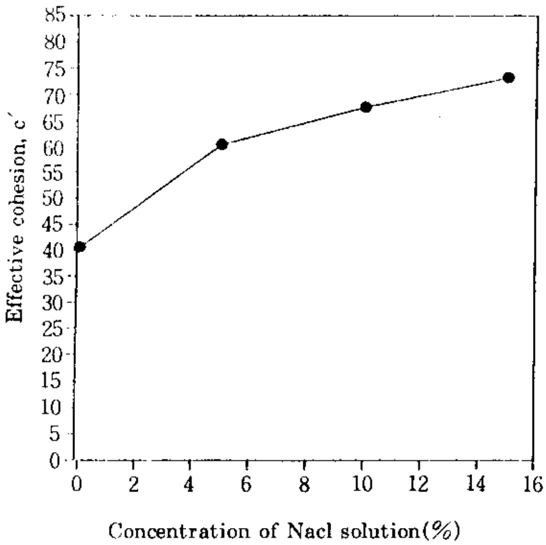

Fig 4. Effective cohesion vs. concentration of NaCl solution

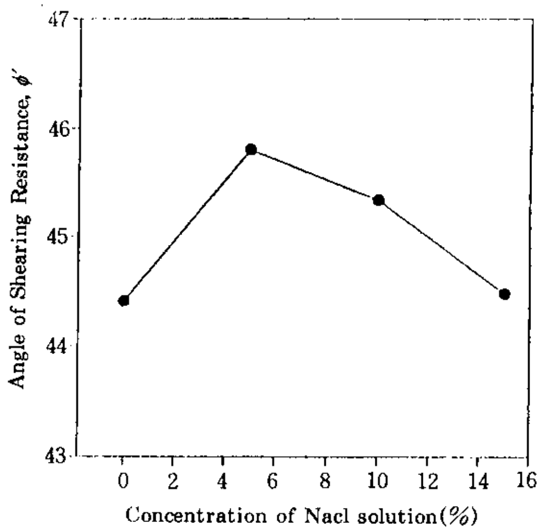

Fig 5. Angle of shearing resistance vs concentration of NaCl solution

The previous results also show that the effective angle of shearing resistance, ϕ' does not show appreciable change for the different concentrations of NaCl solution (Figure 5).

5.3 Young's Modulus

Values of Young's modulus are summarized in table 4. From this table, it can be concluded that the value of E increases with the increase in concentration of NaCl solution and also with the increase in confining pressure.

Table 4. Values of Young's Modulus, E, for the Tested Samples

Samples Saturated with	Confining Pressure, σ_3	Young's Modulus,
Tap Water	35 kPa 70 kPa 175 kPa	12482.56 kPa 19370.94 kPa 87734.74 kPa
5% NaCl Solution	35 kPa 70 kPa 175 kPa	16191.86 kPa 33235.88 kPa 124863.26 kPa
10% NaCl Solution	35 kPa 70 kPa 175 kPa	19152.64 kPa 44542.04 kPa 130000.00 kPa
15% NaCl Solution	35 kPa 70 kPa 175 kPa	46982.00 kPa 27569.71 kPa 277333.50 kPa

The material parameters K_h and n are calculated using the $E-\sigma_3$ plots and equation (2).

$$E_i = K_h\ P_a(\sigma_3/P_a)^n \tag{2}$$

where, K_h and n represent material parameters, σ_3 is the confining pressure, P_a is the atmospheric pressure used to express the results in a nondimensional form.

The values obtained are plotted against the concentration of NaCl solution in Figures 6 and 7 to find out any change in their values due to the concentration of NaCl solution. The curves obtained indicate that the value of K_h decreases up to the samples saturated with 5% NaCl solution, then for samples saturated with 10% NaCl solution and 15% NaCl solution, it increases. The value of n remains almost the same for all the concentrations of NaCl solution. The results obtained do not suggest a particular trend.

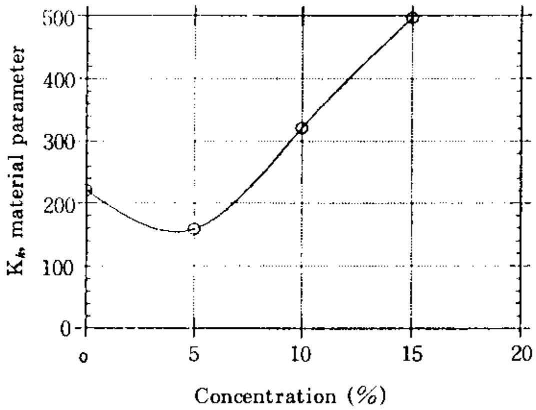

Fig 6. Material parameter, K_h vs. concentration of NaCl solution(%)

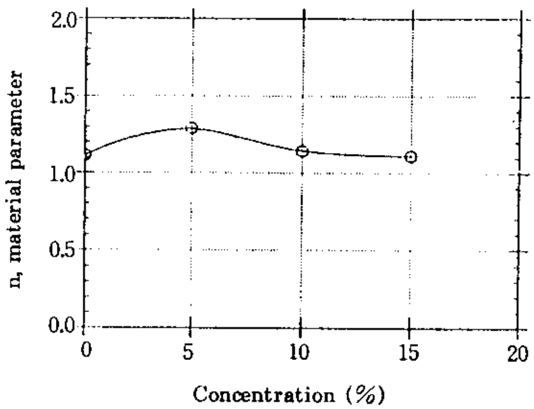

Fig 7. Material parameter, n vs. concentration of NaCl solution(%)

6. Suggestion for Stability Analysis

Since the early 1920s when Terzaghi pioneered the concept of effective stress, it has been well recognized that the volume change and shear strength characteristics of saturated soils are governed by the effective stress classically defined as the difference between the applied stress and the pore water pressure. The classical definition of effective stress has , however, been found to be inadequate in explaining the volume change and shear strength properties because it considers the saturation with water. Therefore, the concept of physico-chemical effect on the soil strength needs to be considered in the case, for example, of the waste landfill dike stability because leachate easily affects the liner materials. In this study, sodium chloride is used for the pioneer test as a possible contaminant source. The chemical waste and municipal waste leachate can be tested in the same manner. When dike stability is analyzed, the soil parameters need to be modified as a function of chemical concentration as shown in equation

$$\phi'(c) = a$$
$$c'(c) = b_1 + b_2 c + b_3 c^2 \quad (3)$$

where, a, b_1, b_2, and b_3 are the coefficients determined through triaxial tests, and c is the chemical concentration. Since the internal friction angle did not change considerably, it is constant. The equation (3) is based on the test results of sodium chloride. In the case of other leachate materials, the coefficients need to be modified. Also, the internal friction angle may not be constant.

When slope stability analysis is performed, the equation (4) is commonly used. However, the zone which is affected by leachate or contaminant fluid under the free surface of dike needs to be modified as equation (5)

$$F_s = \frac{c' + \sigma'_n \tan\phi'}{\tau} \quad (4)$$

$$F_s = \frac{c'(c) + \sigma'_n \tan\phi'(c)}{\tau} \quad (5)$$

where, F_s is safety factor, τ is shear stress.

7. Conclusions

The results of the study presented lead us to the following conclusions:

1) From the review of the literature and the present experimental research, it is concluded that the strength of soil depends on both the composition of the soil and the concentration of the chemical used to saturate it. In these experiments, it is shown that the strength of the mixture of sodium bentonite and sand increase as the concentration of NaCl solution increases.
2) The results obtained in this study can be explained utilizing the Gouy-Chapman DDL model in response to saturation with different concentrations of NaCl solution. The

substitution of electro positive sodium ion causes the attractive forces between the cation and negatively charged clay platelet to increase. This causes a decrease in the DDL thickness and the corresponding increase in the undrained shear strength.

3) The results here indicate an increase in the value of effective cohesion with increase in the concentration of NaCl solution, which can be explained by using the Gouy-Chapman model. With the increase in the concentration of the electrolyte solution, the soil structure becomes more flocculated. Thus, the cohesion value increases.
4) The value of the effective angle of shearing resistance does not show significant change with the increase in concentration of NaCl solution. This may be due to the dense nature of the samples tested.
5) The results obtained in this study show that the value of Young's modulus increases with the increase in the confining pressure. The Young's modulus also increases with the increase in concentration of NaCl solution.
6) The results obtained in this study can provide a methodology for including the effect of NaCl on the stress-strain-strength behavior of soils. They can be used in the stability analysis and design of geotechnical structures founded on soils affected by waste leachate.

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