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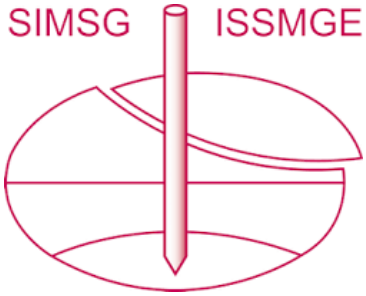

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Impact of Pore Fluid Salinity on Progressive Volume Change Behavior of Kaolin

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ABSTRACT: Geoengineering properties of fine-grained, clay mineral rich soils such as kaolin are dictated by a critical interplay of surface forces. As such, electrolytes present in the pore fluid phase of the geomaterials are expected to alter the force balance of the soil system. In this study, we demonstrate the impact of pore fluid salinity during progressive volume change behaviour of kaolin from a highly saturated state through drying, linear and volumetric shrinkage tests. Results indicated alteration in volume change and drying response of kaolin subjected to pore fluid salinity. Drying tests revealed that, the rate of reduction of moisture from the specimen varied over time. Outcomes from the linear shrinkage tests depicted that, one-dimensional shrinkage behaviour of fine-grained soils is dependent not only upon the pore fluid salinity but also on the size of the shrinkage mould used. Furthermore, volumetric shrinkage tests provided continuous evolution of moisture content and void ratio, and exhibited pore fluid dependent response.

1 INTRODUCTION

Dynamics of the moisture regime in geomaterials plays a crucial role in deciding their suitability for geotechnical engineering applications. Presence of excessive moisture beyond liquid limit tends to fluidize the material with negligible shear resistance, which may result in catastrophic consequences such as failures of tailings dams (Fourie et al. 2001), excessive post constructional settlement, stability of slope (Anderson et al. 1982), settlement of embankments (Balasubramaniam et al. 2010) etc. On the other hand, prolonged moisture loss may lead to cracking and failure of geomaterials such as bentonite used as barriers in geoenvironmental applications. As such, for a fine-grained soil system, geoengineering properties are reliant upon the microstructural parameters and the fabric, which in turn are dictated by the chemistry of the associated pore water phase (Palomino and Santamarina 2005).

Depending upon the ionic constitution of the pore water, fine-grained soil system may assume any of the following two configurations: flocculated or dispersed. In case, the ionic constituents in pore water are high, double layer is depressed and particles get attached to each other. This corresponds to overall force in the system being attractive, and a resultant flocculated state. However, if the resultant force becomes repulsive, particles are stacked parallel to each other sans any connection. This state is referred as dispersed state (Das 2008). It is, thus, evident that a clear understanding of the evolution of the fine-grained soil system during continuous change in moisture regime with different salinity levels is essential. This also enforces the idea that, dredged sediments from harbour areas, tailings need to be tested in the laboratory with pore water having similar to in place pore fluid properties, as idealized tests with deionized water to ascertain field behaviour may be misleading.

In view of the above discussions, the present study attempts to look at the evolution of morphology, drying rates and state parameters such as gravimetric moisture content, void ratio and dry density during continuous dewatering tests on a fine-grained geomaterial kaolin, subjected to two different levels of salinity of pore fluid. Longitudinal volume change behaviours for the above tests are also studied through a series of linear shrinkage tests in two moulds of different dimensions.

2 MATERIALS AND METHODS

Investigations reported in this paper pertain to a fine-grained reference geomaterial named ‘Kaolin’, commercially available as Eckalite I. Comprehensive characterization of the material is presented in Schwing (2015). The material exhibited to have a Casagrande cup liquid limit of 90, plasticity index of 54 and shrinkage limit of 35. Specific gravity of the material is 2.615. Hydrometer analysis revealed that, kaolin is predominantly rich in clay sized fraction

(86%) having some amount of silt (14%). Mineralogical analysis indicated the presence of both 1:1 and 2:1 type clay minerals (kaolinite: 52.7%, Illite-Mica: 20%), and thus some amount of swelling tendency can be expected owing to the presence of Illite.

NaCl solutions, prepared with deionized (DI) water at two concentration levels of 0.2 m and 1.0 m (1 mol of NaCl by weight per kg of DI water), were used to saturate the material over and around the liquid limit. Kaolin samples mixed with the respective solutions were left in a desiccator for a period of 24 hr in order to allow uniform distribution of moisture throughout the specimen, following which, drying tests were performed in a sample cup of 70 mm diameter with continuous logging of weight. This enabled monitoring of temporal evolution of average moisture in the specimen. Based on Corte and Higashi (1960) model, gravimetric moisture content vs. time (w vs. t) curves were fitted from experimental data. First derivative of this curve with respect to time furnished temporal progress of drying rate (*dw/dt* vs. *t*) for the samples.

Linear shrinkage tests involved kaolin samples in 150 mm and 250 mm long moulds at two respective pore fluid concentrations (AS 1289.3.4.1, R2016), and are used to establish one dimensional volume change behaviour of the material. Moreover, soil shrinkage characteristic curve (SSCC) correlates a water content related variable to a pore volume related variable (Cornelis et al. 2006) such as void ratio and moisture ratio (Tariq and Durnford 1993, Groenevelt and Grant 2001) or specific volume and water content (Braudeau et al. 1999). Volumetric shrinkage tests for the samples were carried out in rings of 70 mm diameter. Weight and dimensions of the specimen were recorded in regular intervals for evaluation of water content and volume. Diameters of the specimen were measured along four directions spaced at angular intervals of 45°, and five measurements of height were undertaken along each diameter. This enabled calculation of average volumes of specimen at several stages of the test, at which moisture contents of the specimen were also appraised from the weights recorded. Specimens were pictured during each set of measurement to keep track of evolution of morphology during the tests. Fredlund et al. (2002) model as presented below was used to fit the water content (w) ~ void ratio (e) data for the test.

$$e(w) = a\left[\frac{w^C}{SL_{GE}^C} + 1\right]^{\frac{1}{C}} \quad (1)$$

where, *a* and *c* are fitting parameters representing minimum void ratio, and curvature of the shrinkage curve, respectively. SL_{GE} is the shrinkage limit as per the definitions in geotechnical engineering (Leong and Wijaya 2015).

A clear distinction in notations used should be made in studies involving saline pore fluids in geomaterials; in this paper 'gravimetric moisture content' has been used for reporting and should not be confused with 'gravimetric fluid content'.

3 RESULTS AND DISCUSSIONS

As discussed earlier, rates of drying over time (*dw/dt* vs. *t*) for kaolin with tap water, 0.2 m and 1.0 m NaCl solution were evaluated as the first derivative of the gravimetric moisture content vs. time curve fitted with a Corte and Higashi (1960) model and presented in Figure 1. A distinct three-staged behaviour could be observed in Figure 1. The first stage shows steady change in *dw/dt* over time, followed by a transitional stage, and an eventual varying stage.

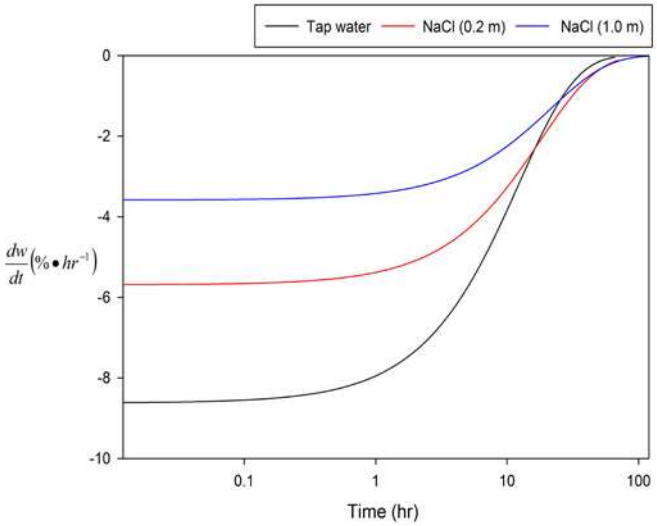

Figure 1. Rate of drying (first derivative of evolution of moisture content over time) with time for the kaolin specimen with tap water, 0.2 m NaCl solution and 1.0 m NaCl solution

In the incipient stages of drying of geomaterials, there is a continuous hydraulic connection existing between the atmosphere and the moisture font in the geomaterials. This results in a faster rate of reduction in soil moisture through transportation of liquid molecules to atmosphere dependent upon several factors such as temperature, relative humidity, boundary conditions etc. With the progressive loss of moisture, soil grains come close to each other, and there is reduction in void space available in the soil skeleton. This essentially hinders the interconnectedness of the paths for moisture transport, which results in a reduced hydraulic conductivity of the system in response to densification. Concurrently, a stiff crust of lower hydraulic conductivity develops on the surface, which inhibits faster rate of moisture loss.

Soil suction, in simple words, can be described as its affinity for water (Wray 1984). A reduction in

soil moisture prompts to an increment in matric suction. Also, when there are solutes in the pore fluid, osmotic suction also contributes to the total suction. With dewatering, liquid phase separates from the soil progressively, leaving behind solutes and a concentrated pore fluid. This attributes to increased value of osmotic suction, as well. All the factors described above lead to a reduced drying speed and mode of drying is dominated by transfer of vapours. This corresponds to the second stage of drying. The final stage of drying is associated with a slow and rather steady rate of moisture loss (Mishra et al. 2017). A clearly distinctive drying behaviour was observed for kaolin with varied pore fluid chemistry. Increased salinity in the pore fluid reduced the drying speed in the initial stages of dewatering. However, the curves asymptotically merge towards the end stage of dewatering.

Linear shrinkage tests for the kaolin samples saturated with 0.2 m and 1.0 m NaCl solution, in two moulds of similar cross section but different lengths (150 mm and 250 mm) were performed as per the relevant codal provisions (AS 1289.3.4.1, R2016), and the results are presented in a graphical form in Figure 2. It can readily be noticed that, with increase in concentration of pore fluid from 0.2 m to 1.0 m, linear shrinkage of kaolin reduced. Furthermore, at similar pore fluid concentrations, kaolin samples in shorter moulds exhibited higher linear shrinkage.

Table 1 presents evolution of surficial morphology of the kaolin samples with different pore fluid solutions at several stages of drying. In the beginning, volumetric changes as radial shrinkage at the edges of the samples were observed. This occurred simultaneously with evaporation and volume loss from the surface of the sample. As the dewatering progressed, curvatures in the exposed surface of the samples could be observed. Precipitation of the salts and flocs were also noticed in concluding stages of drying in case of kaolin samples with highly saline pore fluid.

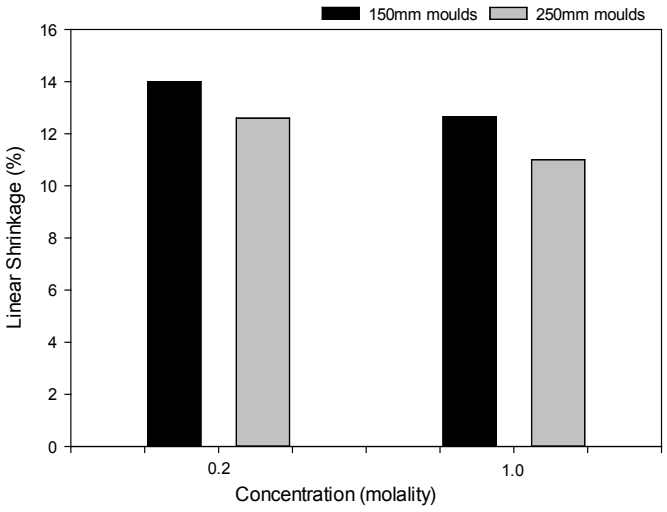

Figure 2. Linear shrinkage tests for kaolin with 0.2m and 1.0m NaCl as pore fluid solution in 150 mm and 250 mm molds

Figure 3 (a) and (b) demonstrate void ratio and dry density plotted against gravimetric moisture content during a progressive shrinkage test, respectively. Void ratio vs. gravimetric moisture content data for kaolin seemed to follow a bilinear path with a short curvilinear transition. It is worth mentioning that, tests started with kaolin being highly saturated with pore fluid beyond liquid limit. The curves followed 100% saturation line from the beginning of the test, and then transitionally deviated having constant volume irrespective of any changes in moisture content.

Table 1. Morphology of the samples during progressive drying[1]

KDNC0.2	KDNC1.0
121%	90%
109%	73%
95%	62%
66%	45%
38%	22%
17%	7%
0%	0%

[1]Gravimetric water contents are in percentage indicated in the samples

Eventually, it can be observed that the kaolin specimen with 1.0 molal NaCl as pore fluid reached a lower void ratio compared to the one with 0.2 molal NaCl solution.

The data points fit well with Fredlund et al. (2002) model, as evident from Figure 3 (a). When dry densities of the sample were plotted against gravimetric moisture content during progressive dewatering, as shown in Figure 3 (b), a similar bilinear trend was also observed. The curves followed zero air void line and then with a short curvilinear transition deviated to yield constant dry densities regardless of any further changes in gravimetric moisture content. It can also be noted that, the specimen saturated with 1.0 molal NaCl solution furnished a nearly constant higher dry density during near completion of the test.

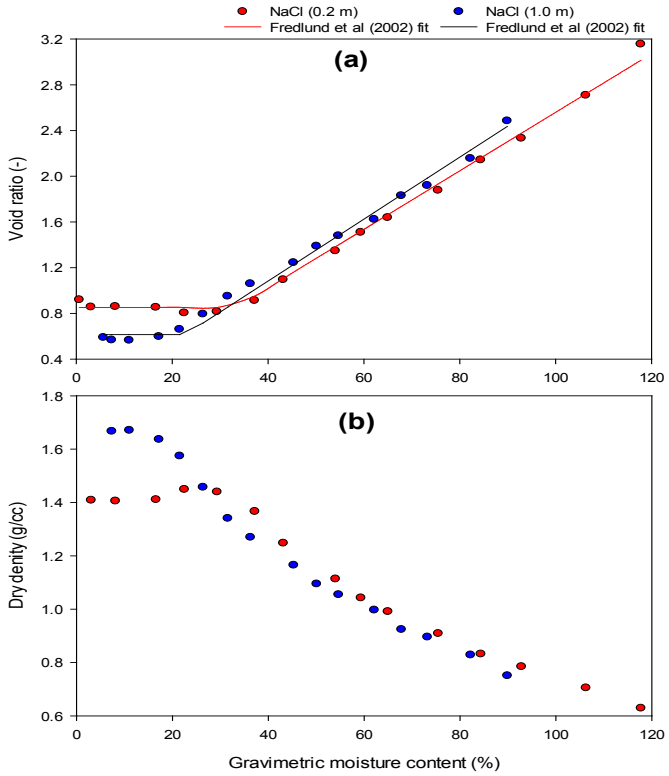

Figure 3. (a) Void ratio vs. gravimetric moisture content (b) dry density vs. gravimetric moisture content for kaolin with 0.2m and 1.0m NaCl as pore fluid solution

4 CONCLUSIONS

The investigations reported in this paper, highlighted the importance of pore fluid chemistry vis-a-vis some of the observable geophysical properties of a reference fine-grained geomaterial, kaolin. There were marked alterations in drying and volume change behaviour of kaolin having NaCl solution at 0.2 and 1.0 molality as pore fluids. Increase in concentration of pore fluid reduced the overall drying rate, minimal void ratio at the end of shrinkage tests and one-dimensional linear shrinkage, while resulting in higher dry densities at the end of the shrinkage tests. Length of the moulds also impacted linear shrinkage behaviour; at the same concentration of pore fluid samples in short mould yielded high linear shrinkage. Therefore, dredged sediments from harbour areas, tailings and similar fine particle rich porous systems need to be tested in the laboratory with pore water having similar to in place pore fluid properties, as idealized tests with deionized water to ascertain field behaviour may be misleading. Further experimental investigations are required to adjudge the claims, and to ascertain pore fluid dependence of fine-grained porous media in a better manner.

5 ACKNOWLEDGEMENTS

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