Osmotic control on the mechanical behaviour of Tennessee Valley Authority (TVA) ash

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ABSTRACT

The mechanical behavior of unsaturated granular materials such as coal fly ash (CFA) is controlled by suction. While suction is generally viewed as a function of both matric (capillarity) and osmotic (pore fluid) components, the influence of the osmotic component on the mechanical behavior of CFA (e.g., shear strength) has yet to be fully explored. In this work, the influence of osmotic suction on the shear strength of the Tennessee Valley Authority ash was investigated using direct shear tests. Test specimens were prepared at the optimum moisture content with water and a 1-molar solution of sodium chloride solution as the pore fluid. The test results show that for a given value of matric suction, a change in osmotic suction as a result of salinization lead to an increase of 32% in peak shear stress only for an applied normal stress of 100 kPa. For the same change in osmotic suction, the peak shear stresses recorded for a normal stress of 25 and 50 kPa were similar indicating that the influence of osmotic suction on the mechanical behavior of CFA differs from matric suction.

INTRODUCTION

The unsaturated behavior of granular materials including coal fly ash (CFA) is dependent on suction, which broadly consists of two main components: matric and osmotic suction.[1,2] While matric suction is dependent on the capillary effects, osmotic suction in CFA is the result of salts present in the pore fluid and therefore, osmotic suction is present in both saturated and unsaturated conditions. However, the influence of osmotic suction on the mechanical behavior of granular materials has been mostly related to unsaturated conditions.[2] The effect of matric suction on the shear strength has been extensively studied e.g. through direct shear tests, Gan and Fredlund[3] showed that the shear strength of completely decomposed fine ash tuff increased with an increase in matric suction. However, the number of studies investigating the role of osmotic suction on shear strength has been sparse. Fredlund *et al*.[2] mentioned that because the majority of engineering challenges are due to climatic variations such as fluctuations in water table which changes matric suction, the effect of osmotic suction is often ignored but its influence may be significant when there is a change in salt content. Furthermore, as mentioned in Murray and Sivakumar[4], in addition to the degree of saturation, confining pressure and fabric, a change osmotic suction (e.g. by contamination) can significantly alter shear strength and should thus be investigated.

Osmotic suction can be determined either as the difference between total and matric suction or measured by using the electrical conductivity of the pore fluid as carried out by Krahn and Fredlund[5]. The existing literature detailing the effect of osmotic suction on the strength of granular materials has not been conclusive. In investigating the strength of silty soils using unconfined compressive tests, Leong and Abuel-Naga[6] found no effect of osmotic suction on the shear strength. Mokni *et al*.[7] showed using a high plasticity clay that osmotic suction reduces shear strength whereas the opposite trend was observed in Jayathilaka *et al*.[8] when examining the behavior of a compacted clay.

As part of remediation and closure activities associated with CFA basins in the United States, dewatering operations are necessary to facilitate construction. The rationale behind dewatering is to enhance strength by excluding pore water and increasing suction which in turns lead to increase in shear strength parameters. Dewatering operations can nonetheless be more important and affect stability when water is removed from unsaturated ash basins in the presence of surrounding construction equipment or additional fill material. Changing field conditions such as leachate of salts is expected to decrease osmotic suction and compromise strength. Therefore, to investigate the effect of osmotic suction on the mechanical behavior of CFA under unsaturated conditions, this study has as main objective to maintain a constant matric suction and examine how varying the pore fluid composition alters the shear strength.

MATERIALS AND TESTING PROGRAM

SAMPLING AND PREPARATION

Coal fly ash (CFA) from the top portion of the dredge cell which did not fail in the 2008 Tennessee Valley Authority (TVA) ash spill was used in this study. The top-most 30 cm of material was scraped away to prevent contamination, after which the CFA was homogenized in a plastic cement mixer with stainless steel metal blades as per ASTM D6323-98. The samples were allowed to stand overnight and standing water was poured off before allowing the CFA to air dry.

The specific gravity of the CFA is 2.78 and the Harvard Miniature compaction curve of the CFA obtained in accordance to ASTM D1557 is shown in Figure 1. The CFA were prepared using distilled water and a 1-molar solution of sodium chloride (NaCl). The CFA were statically compacted to the optimum dry unit weight (12.3 kNm^{-3}) of the Harvard Miniature compaction curve.

SUCTION MEASUREMENTS

To cover the entire range of suction, measurements of the compacted CFA specimens were obtained for different water contents using two different devices commercialized by the METER group: for the relatively low suction values below 100 kPa, a HYPROP measurement system (consisting of two precision mini-tensiometers) was used and for the relatively higher suction values (beyond 1000 kPa), the WP4C, a chilled mirror dew-point hygrometer was used. While the HYPROP is used to measure matric suction, measurements by the WP4C is considered to be equivalent to total suction because at such high suction range, the influence of osmotic suction is assumed to be negligible.[9] To obtain the osmotic suction of the CFA, samples were slurried at different water content and allowed to equilibrate for 24 hours. The pore fluids were then extracted and the electrical conductivity (EC) measured using an electrical conductivity meter. The osmotic suction at saturation (Ψ_{os}) was obtained from Equation (1) and for other levels of saturations, the osmotic suction (Ψ_o) was calculated as a function of their moisture content as per Equation (2) where w_s and w are respectively the gravimetric moisture content at saturation and gravimetric moisture content of the soil. The osmotic suctions of the NaCl solutions (at varying molar concentrations) were obtained by using the WP4C with the CFA samples fully saturated (i.e. matric suction equal to 0 kPa) and the recorded total suction assumed to be equivalent to osmotic suction.

$$\Psi_{os} = -0.036 * EC \quad \text{(Equation 1)}$$
$$\Psi_o = \Psi_{os} * (w_s / w) \quad \text{(Equation 2)}$$

DIRECT SHEAR TESTS

Direct shear tests were carried out on the CFA sample with dimensions of 62.4 mm (diameter) and 38.3 mm (height). The horizontal shear force was measured using a load cell accurate to ± 0.001 kN and the displacements in both vertical and horizontal directions were recorded using LVDT transducers accurate to ± 0.001 mm. The initial matric suction was kept constant by targeting the optimum moisture content of the CFA. Distilled water and a 1-molar solution of NaCl solution were used to compact the samples of CFA to achieve a unit weight within ± 15% of the optimum dry unit weight. All samples were left to equilibrate for 1 hour before testing. It was assumed that the moisture content of the CFA remained constant during compaction and shearing of the samples.

RESULTS AND DISCUSSION

SUCTION OF THE CFA SAMPLES

Figure 2 illustrates the volumetric water content and suction measured by the HYPROP and WP4C for the compacted CFA samples using distilled water. The HYPROP enables a high frequency data collection points in the wet range of 9 kPa to its upper bound of 100 kPa while the WP4C used in the dry range recorded a total of 5 data points above a suction of 1000 kPa. By combining the outputs from both HYPROP and WP4C as suggested in the work of Shokrana and Ghane[10] a complete retention curve for the CFA can be obtained by fitting the data with the commonly used Van Genuchten model.

The measured electrical conductivity EC of the sample of CFA and its respective osmotic suction at saturation, Ψ_{os} (at a volumetric water content of 53%) were respectively 446 dS/m and 16 kPa. Based on these values, the osmotic suction at different water contents were calculated and also shown in Figure 2. All values of osmotic suctions obtained from EC were lower than the suctions measured from the HYPROP and WP4C. At the optimum volumetric water content (33.5%), the matric suction recorded from the HYPROP and WP4C was 190 kPa and the osmotic suction calculated was 34 kPa, the latter corresponding to 15% of the total suction despite the aforementioned sampling and preparation technique.

The measured osmotic suctions of the fully saturated CFA samples for the molar concentrations of 0.001 to 1 in logarithmic increments are shown in Figure 3. An increase in osmotic suction is observed as the molar concentration increases, in particular a sharp rise from 440 kPa to 4630 kPa is noted as the molar concentration increases from 0.1 M to 1 M. Also plotted on Figure 3 is the change in EC as molar concentration increases.

DIRECT SHEAR TESTS

The shear stress-shear strain of the CFA samples measured at optimum water content with three different normal loads are illustrated in Figure 4 (a) – (c). The shear stress and shear strain behavior of CFA samples without the presence of NaCl solution (i.e. no osmotic suction) was used as a reference for all 3 normal stresses (25 kPa, 50 kPa and 100 kPa) considered. Irrespective of pore fluid used, an increase in normal stress lead to an increase in peak shear stress, for example with the 1 M NaCl solution, the respective peak shear stresses for the 25 kPa, 50 kPa and 100 kPa normal stresses were 63 kPa, 86 kPa and 140 kPa. The corresponding shear strains at these peak stresses were 2.5%, 2% and 2.9% and were comparatively less than those reported by Jayathilaka *et al*.[8] in their study of the mechanical behavior of compacted clay. Possible reasons for such disparities include the mineralogy of the materials tested, the normal stress applied and the shearing rate.

According to the retention curve shown in Figure 2, the matric suction at which the direct shear tests were carried out was 33 kPa. Compared to the initial ion content of the CFA samples, the addition of 1M NaCl solution during compaction induced a significantly higher osmotic suction (4680 kPa). The shear stress-shear strain response as a result of an increase in osmotic suction for a given matric suction depends on the normal stress applied. This observation differs from what is usually reported in unsaturated soil (e.g. Garakani *et al*.[11]) where an increase in osmotic suction leads to an increase in peak stress. In our study, this trend has been recorded only when a normal stress of 100 kPa was applied and an increase of 32% in peak stress was attributed to the increase in osmotic potential. In contrast, with the relatively lower normal stresses of 25 kPa and 50 kPa, no change in peak stresses were noted. While a decrease in relative movement of CFA particles upon the addition of NaCl solution is expected to enhance the peak stress, its dependency on normal stress using CFA suggests that beneath a given normal stress, the addition of NaCl offers no resistance to the relative movement of particles. The effect of increasing osmotic suction for a given matric suction on the normal strain at the three normal stresses is illustrated in Figure 4 (d) – (f). For the CFA samples subjected to a normal stress of 50 kPa and 100 kPa, an initial contractive behavior (decrease in normal strain) was observed with an increase in osmotic suction. For the 25 kPa normal stress applied, no difference in normal strain of the samples was observed during the shearing process as osmotic suction increased.

CONCLUSIONS

Direct shear tests were carried out on compacted coal fly ash samples using distilled water and 1M sodium chloride solution at optimum dry unit weight of the Harvard Miniature compaction curve. The matric and osmotic suctions were obtained from the retention curve and electrical conductivity respectively. The ratio of matric to osmotic suction using the sodium chloride solution was 1: 24. Test results showed that samples subjected to normal stresses of 25 kPa and 50 kPa had no effect on the peak stress whereas samples subjected to a normal stress of 100 kPa had an increase in peak stress.

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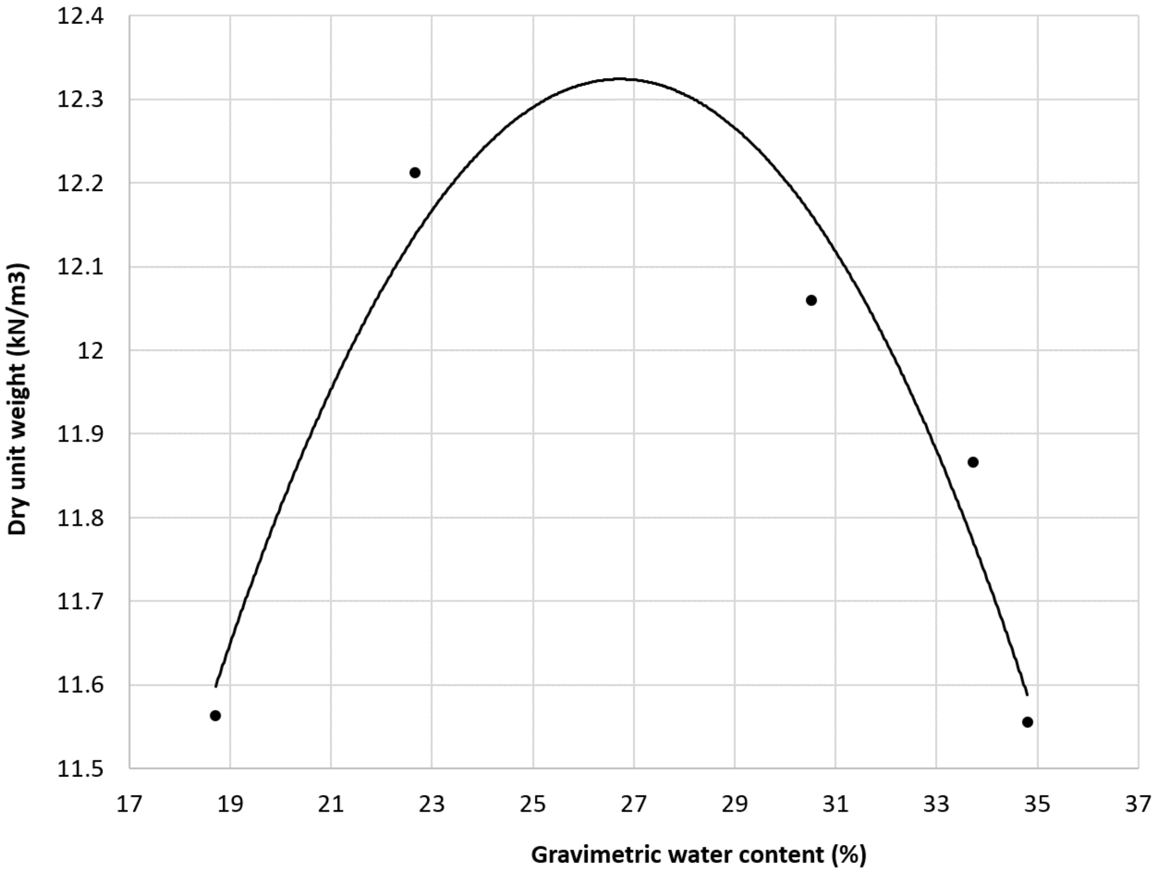

Figure 1: Harvard Miniature compaction curve

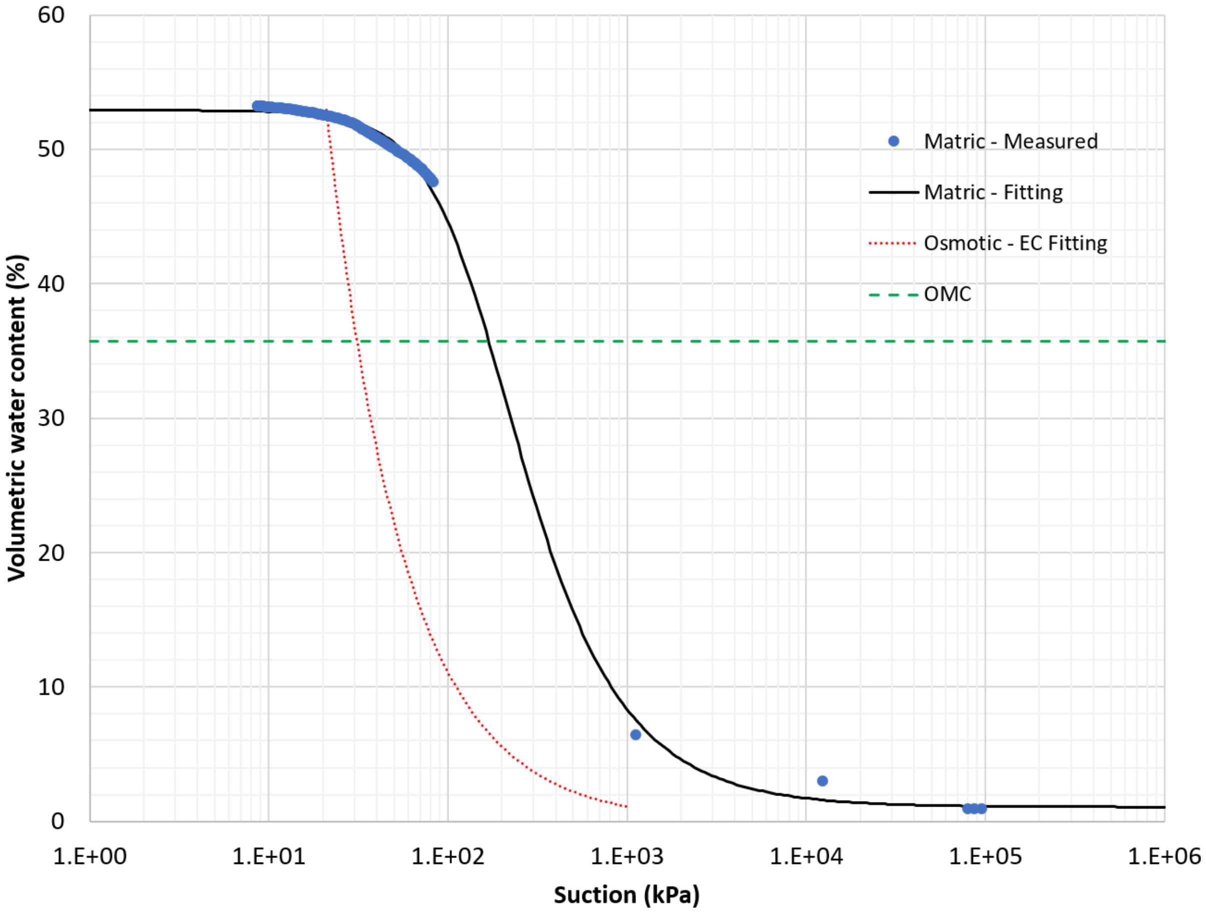

Figure 2: Retention curves of coal fly ash

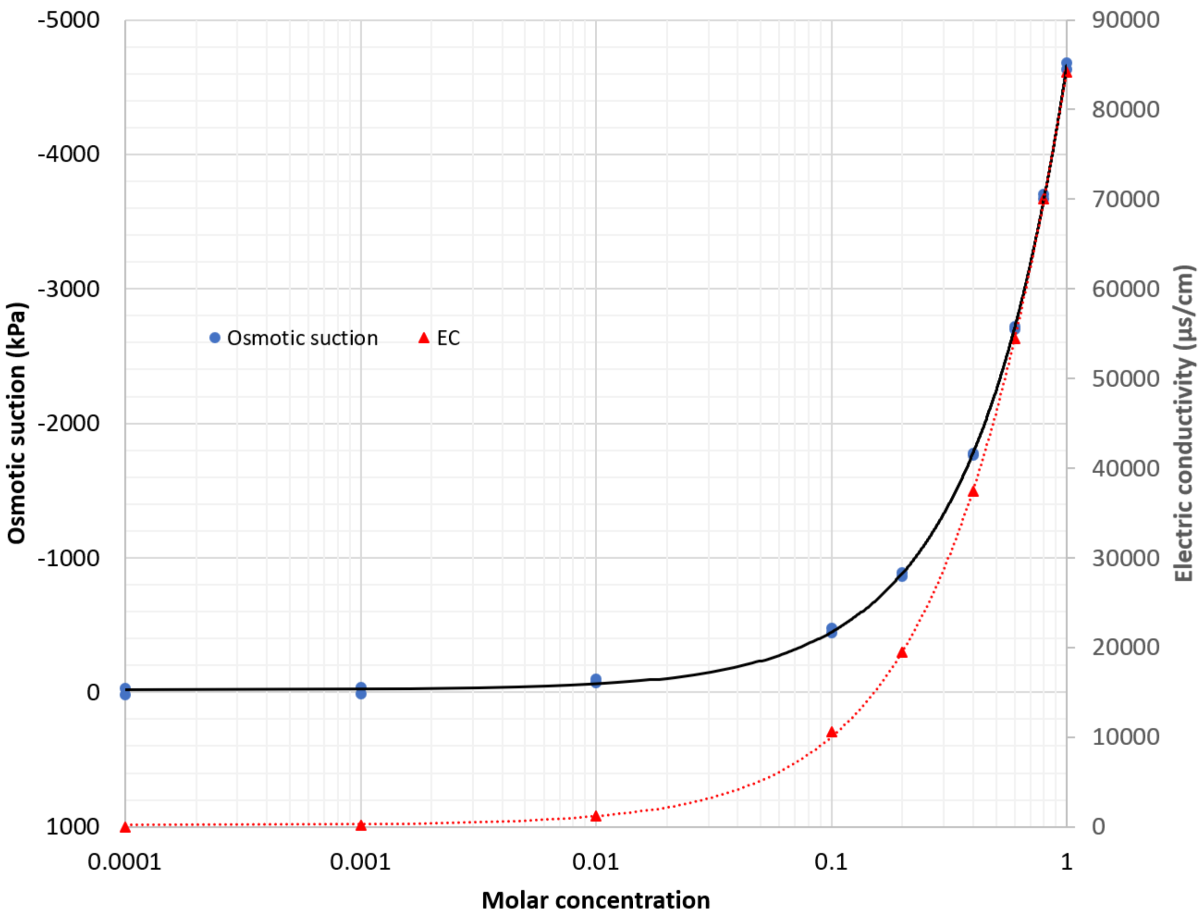

Figure 3: Change in osmotic suctions and electric conductivity of saturated CFA samples for varying molar concentrations

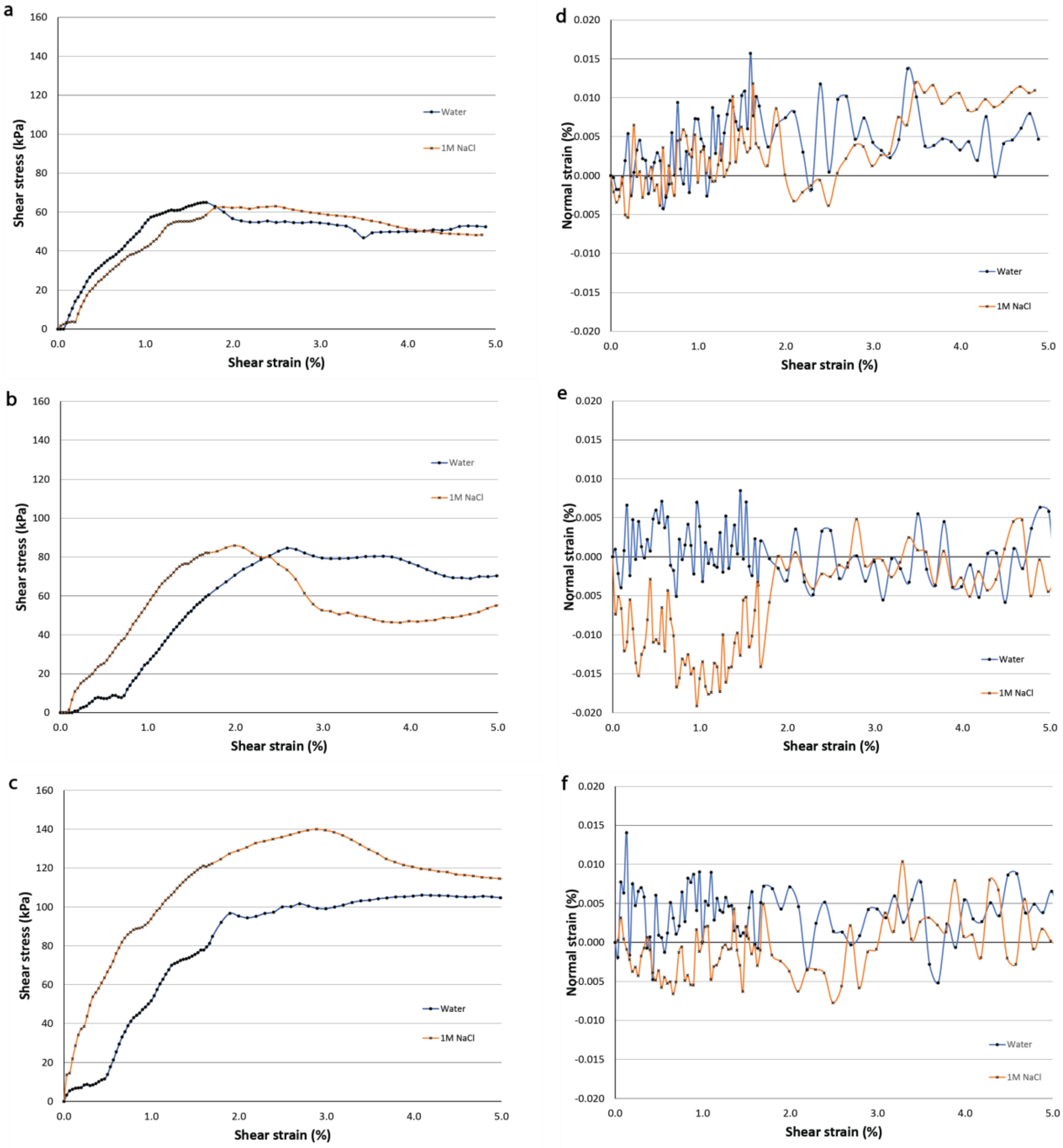

Figure 4: Stress-Strain behavior of coal fly ash using different pore fluids at normal stresses of 25 kPa (a and f), 50 kPa (b and e) and100 kPa (c and f)