Salinity effects on the behaviour of Eckalite Australian kaolin clay

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Offshore wind turbine foundations are commonly installed in seabed soils with saline pore water filling the voids, where salt–clay mineral interactions may influence the mechanical parameters. This work examines Australian kaolin clay (Eckalite) reconstituted with aqueous solutions of sodium chloride (NaCl), calcium chloride ($CaCl_2$), magnesium chloride hexahydrate ($MgCl_2 \cdot 6H_2O$), sodium sulfate (Na_2SO_4), and potassium chloride (KCl) at concentrations of 0.05, 0.5, 1, and 2 Mol/l. The experimental program comprises pH measurements, liquid limit (LL) and plastic limit (PL) tests, and Enslin-Neff water absorption measurements to characterise the coupled chemical and geotechnical characteristics of the considered soil. Results are presented relative to specimens prepared with deionised water and compared across salt types and concentrations to establish consistent trends relevant to saline offshore ground conditions.

1 Introduction

Pore fluid chemistry affects clay behaviour because ionic strength, cation valence, and pH-dependent surface charge control diffuse double-layer interactions and interparticle forces, governing aggregation and fabric [1–3]. Kaolin fabric is sensitive to physico-chemical conditions due to pH-dependent edge charge and seawater-type alkalinity effects on edge-face associations [4, 5]. Increasing electrolyte concentration compresses the double layer, and divalent cations promote stronger associations than monovalent ions [3]. Accordingly, Atterberg limits can vary with salt type and concentration, exhibiting non-monotonic trends and, in some cases, overall decreases in the liquid and plastic limits depending on salt chemistry [6, 7]. Since oven drying removes water but not dissolved salts, the calculated gravimetric water content differs from a "fluid content" measure that accounts for the saline pore fluid, which can shift the observed trends [8, 9]. Enslin-Neff water absorption complements LL and PL as a standardised indicator of material-water interaction rather than porosity alone [10, 11]. For kaolin, it is useful to evaluate multiple electrolytes within a single consistent programme because ion type and concentration can produce different responses even within the same molarity range. Many kaolin studies focus on LL/PL alone, while water absorption behaviour and the pore-fluid chemistry that develops after clay contact are less often reported together within the same dataset. The present work, therefore, combines salt-corrected LL/PL with Enslin-Neff water absorption and pH measurements of both fluids and kaolin suspensions across multiple mono- and divalent salts over the concentration range from 0.05–2 Mol/l to support ion-specific interpretation relevant to saline offshore conditions.

2 Experimental program

Eckalite Australian kaolin clay was mixed as a slurry using deionised water, and aqueous salt solutions representative of saline offshore pore fluids [12]: NaCl, $CaCl_2$, $MgCl_2 \cdot 6H_2O$, Na_2SO_4, and KCl. For each salt type, concentrations of 0.05, 0.5, 1, and 2 Mol/l were prepared. The pH-value was determined in accordance with DIN EN ISO 10390:2022-08 [13] for (i) the prepared salt solutions and (ii) kaolin suspensions, to quantify pore fluid chemistry and its evolution upon interaction with the clay mineral.

Liquid and plastic limits were determined in accordance with DIN EN ISO 17892-12:2020 [14]. The LL and PL of standard kaolin mixed with distilled water were measured as 79.35 and 41.63, respectively. Water contents for saline specimens were corrected to account for dissolved salts remaining after oven drying, following BS 1377-2:1990 [15]. The corrected water content w_f was calculated from the measured gravimetric water content w in percentage using

$$\mathrm{w_f} = \frac{1000\,\mathrm{w}}{1000 - \frac{q}{\rho_f}\left(1 + \frac{w}{100}\right)}, \tag{1}$$

where q is the salt content per litre of fluid and ρ_f is the density of the mixing fluid.

Enslin-Neff water absorption was measured according to DIN 18132:2012 [10] using the corresponding salt solution. Cumulative absorption was recorded at fixed time intervals up to 2 hours and reported as a percentage of the initial dry mass.

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3 Results and discussion

3.1 pH-measurements

Table 1 summarises the pH results for both the prepared fluids (salt solutions) and the corresponding kaolin-fluid suspensions. Across 0.05–2 Mol/l salt solutions, the prepared pore fluids spanned near neutral to strongly alkaline pH, with a clear dependence on salt type. $CaCl_2$ produced the most alkaline solutions. As molarity increased, Na_2SO_4 remained approximately neutral; NaCl and $MgCl_2{\cdot}6H_2O$ showed an overall reduction in pH, while KCl shifted the pH of the solution toward acidic values at higher concentrations. After contact with kaolin, the pH of the suspension (reported after 60 min of shaking) differed from that of the corresponding fluids and was generally weakly influenced by concentration, with salt-dependent deviations at higher molarity. At 0.05 Mol/l, all suspensions were acidic, whereas at higher molarity the pH range broadened from acidic toward neutral and, for selected electrolytes, alkaline conditions. All measurements were conducted at approximately 21–23 °C. The pH of distilled water and the corresponding slurry were measured as 8.21 and 5.75, respectively.

Table 1. pH measurements of the prepared fluids and kaolin-fluid suspensions.

Mol/l	NaCl fluid	NaCl suspension	$CaCl_2$ fluid	$CaCl_2$ suspension	$MgCl_2.6H2O$ fluid	$MgCl_2.6H2O$ suspension	Na_2SO_4 fluid	Na_2SO_4 suspension	KCl fluid	KCl suspension
0.05	8.71	4.74	9.49	5.07	8.25	4.65	7.95	5.11	7.23	4.48
0.5	7.95	4.62	10.63	4.72	8.07	4.69	7.92	4.85	7.15	4.65
1	7.04	4.42	10.62	8.24	7.82	5.05	7.55	5.03	6.89	4.38
2	7.27	4.39	10.51	9.68	6.98	4.50	7.78	4.92	6.89	4.58

3.2 Liquid limit

Figure 1 shows that the liquid limit of Eckalite kaolin generally decreases with increasing salt concentration, although the response depends on salt type. For NaCl and KCl (Figures 1a and 1e), the suspension pH remains acidic over the full concentration range, and LL decreases only moderately with increasing molarity. $MgCl_2{\cdot}6H_2O$ (Figure 1c) also keeps the suspension in the acidic to near-transition range, yet produces the largest LL reduction. In contrast, $CaCl_2$ (Figure 1b) changes the pH regime from acidic at low concentration to alkaline at high concentration, while LL first decreases strongly and then shows a slight recovery at 2 Mol/l. Na_2SO_4 (Figure 1d) remains close to the transition range around pH 5 and likewise exhibits a non-monotonic LL trend at high concentration. Overall, the LL reduction is consistent with diffuse double-layer compression as ionic strength increases, reducing repulsive interactions and the amount of water associated with the clay at the liquid state [2, 3, 6, 7, 16]. The stronger decrease caused by $CaCl_2$ and $MgCl_2{\cdot}6H_2O$ compared with NaCl and KCl further indicates the role of cation valence [3, 6, 7]. The pH results nevertheless show that this is not a diffuse-double-layer effect alone. Since most suspensions remain at or below the transition range around pH 5, the LL decrease for NaCl, KCl, and $MgCl_2{\cdot}6H_2O$ is consistent with double-layer compression acting together with changes in edge–face association, leading to a less open fabric [4, 5]. The $CaCl_2$ and Na_2SO_4 results suggest that, at high concentration, pH-related changes in edge charge and salt-specific interactions begin to compete with the general double-layer effect, explaining the non-monotonic LL response [4, 6, 7].

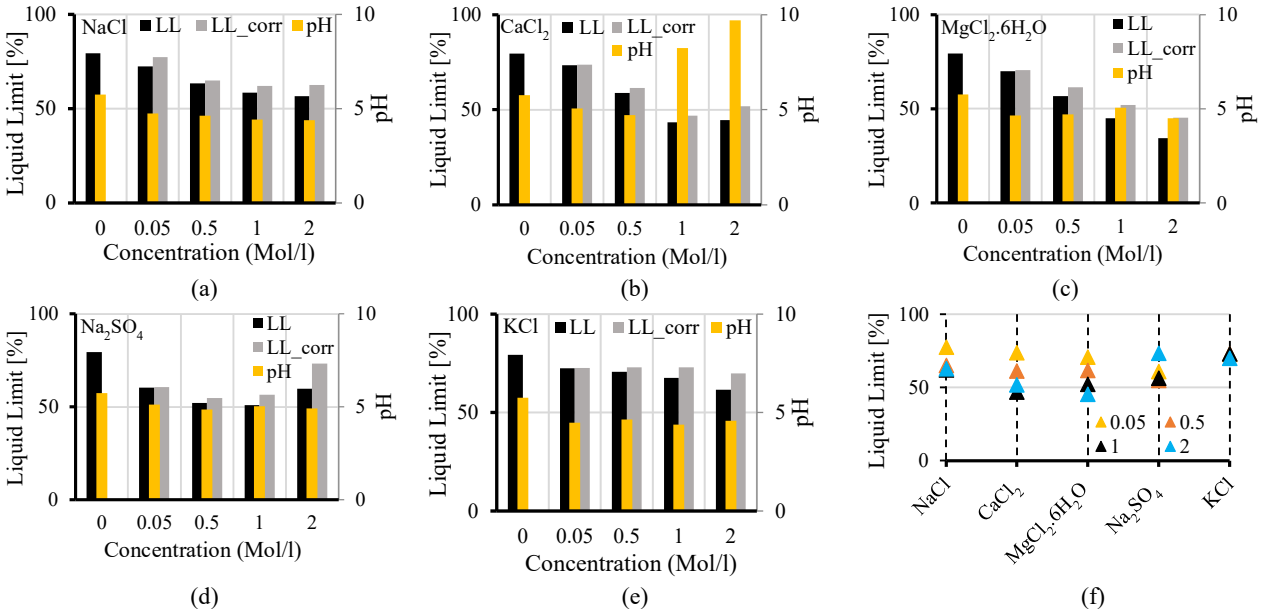

Figure 1. Liquid limit (LL) and corrected liquid limit (LL_corr) and pH for kaolin prepared with (a) NaCl, (b) $CaCl_2$, (c) $MgCl_2{\cdot}6H_2O$, (d) Na_2SO_4, and (e) KCl; (f) comparison of LL_corr as a function of concentration (Mol/l).

3.3 Plastic limit

Figure 2 indicates that the plastic limit is influenced by both salt concentration and salt type, although the overall variation is smaller than that observed for the liquid limit. For NaCl and KCl (Figure 2a and 2e), PL shows only a slight downward trend with increasing concentration, while the suspension pH remains acidic. A more pronounced decrease is observed for the divalent chlorides, particularly $MgCl_2 \cdot 6H_2O$ (Figure 2c), showing that PL is more sensitive in the presence of higher-valence cations. $CaCl_2$ (Figure 2b) likewise leads to a clear reduction in PL, despite the shift in suspension pH from acidic at low concentration to alkaline at high concentration. By contrast, Na_2SO_4 (Figure 2d) stays close to the transition range around pH 5 and displays a non-monotonic pattern, with PL decreasing initially and then rising again at higher concentration. In general, the reduction in PL with increasing salinity is consistent with diffuse double-layer compression and decreasing adsorbed water, while the stronger effect of the divalent salts reflects the additional influence of cation valence [2, 3, 6, 7, 16]. The pH measurements further indicate that the response is not governed by ionic strength alone. Because most suspensions remain within the acidic to near-transition range, the limited PL variation for NaCl and KCl suggests that the plastic state is less responsive to pore-fluid chemistry than the liquid state. In contrast, the stronger response of $CaCl_2$ and $MgCl_2 \cdot 6H_2O$, together with the non-monotonic behaviour of Na_2SO_4, points to a combined contribution of ionic strength, cation valence, and pH-related fabric modification [4–7].

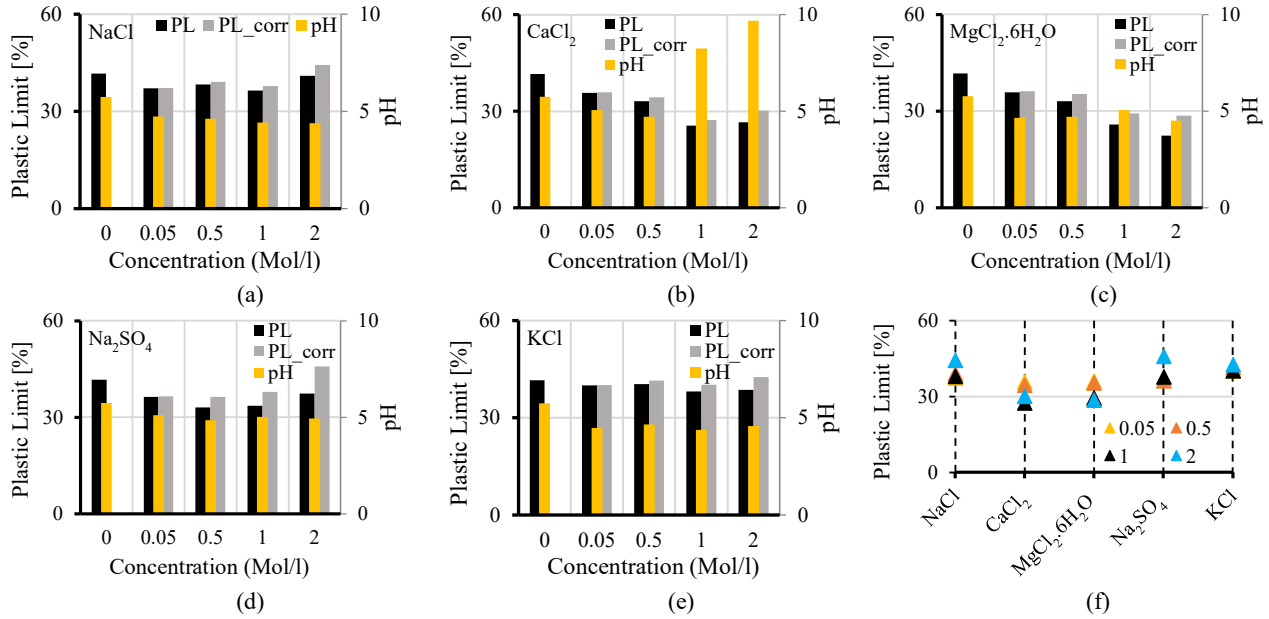

Figure 2. Plastic limit (PL), corrected plastic limit (PL_corr) and pH for kaolin prepared with (a) NaCl, (b) $CaCl_2$, (c) $MgCl_2 \cdot 6H_2O$, (d) Na_2SO_4, and (e) KCl; (f) comparison of PL-corr as a function of concentration (Mol/l).

3.4 Enslin-Neff water absorption

Figure 3 illustrates that the Enslin–Neff water absorption of the kaolin depends strongly on both salt type and concentration. For NaCl (Figure 3a) and $MgCl_2 \cdot 6H_2O$ (Figure 3c), absorption remains below the deionised-water reference and decreases progressively with increasing concentration, indicating reduced fluid accessibility within the kaolin fabric. This is consistent with the corresponding reductions in LL and PL, particularly for $MgCl_2 \cdot 6H_2O$, which shows the strongest decrease in both absorption and consistency limits. KCl (Figure 3e) remains closest to the deionised-water reference throughout the test, in agreement with the comparatively small changes observed in LL and PL. By contrast, $CaCl_2$ and Na_2SO_4 (Figure 3b and 3d) exhibit non-monotonic behaviour at higher concentration, consistent with the less systematic trends observed in the consistency limits. Overall, the results indicate that increasing ionic strength generally reduces fluid uptake, while divalent cations exert the strongest influence. The deviations observed for $CaCl_2$ and Na_2SO_4 at high concentration further suggest an additional effect of pH changes after clay–solution interaction.

The Enslin–Neff results help explain why LL and PL do not respond only to salinity level, but to the combined effects of ionic strength, cation type, and pH-dependent fabric changes. The closer agreement with LL than with PL further indicates that fluid accessibility within the evolving fabric is strongly related to the liquid-state threshold [10, 11].

4 Conclusion

In conclusion, the experimental program confirms that pore-fluid salinity and ionic composition influence the index properties of Australian Eckalite kaolin. Across chloride solutions, increasing molarity produced a systematic reduction in liquid limit and a less pronounced decrease in plastic limit, with divalent cations generating the strongest effect. After clay-solution contact, pH shifted toward lower values in most cases (notably at 0.05 Mol/l), while $CaCl_2$ at higher molarity

moved into alkaline conditions, showing that clay-fluid interaction changes the chemical environment governing interparticle bonding and can contribute to non-linear responses at higher salinities. Collectively, the results demonstrate that offshore and saline-ground assessments should be based on site representative pore-fluid chemistry rather than freshwater assumptions, and that ion type must be considered when interpreting consistency parameters for design.

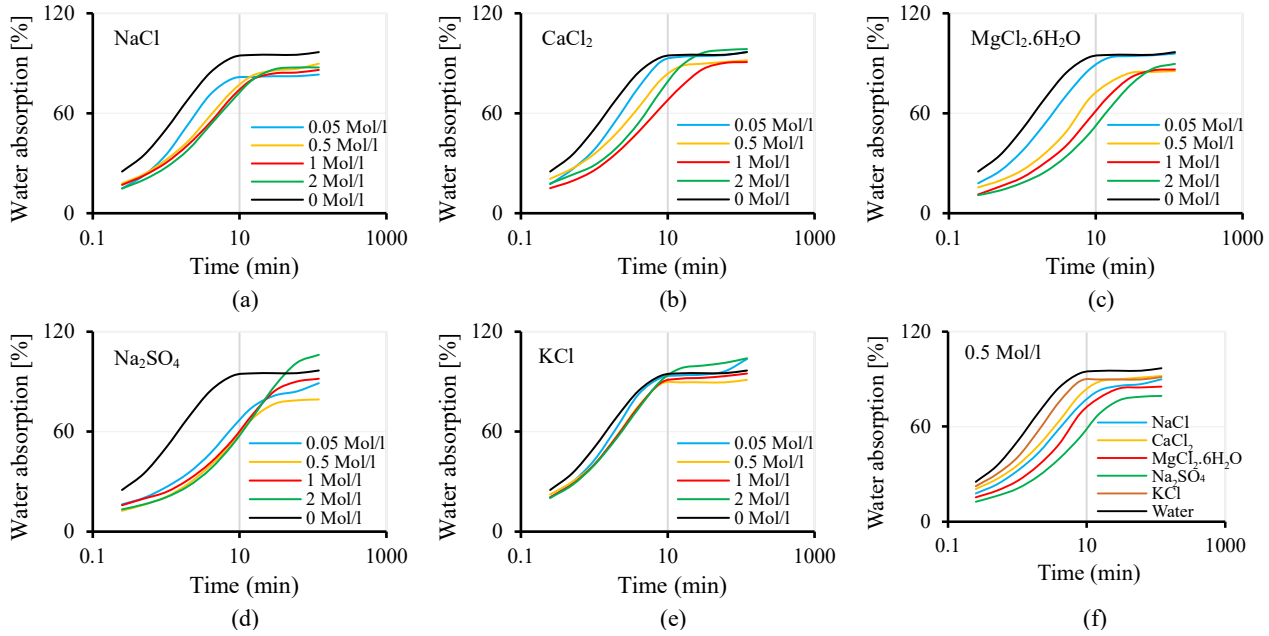

Figure 3. Enslin-Neff water absorption of kaolin prepared with (a) NaCl, (b) $CaCl_2$, (c) $MgCl_2 \cdot 6H_2O$, (d) Na_2SO_4, and (e) KCl solutions; (f) comparison of water absorption for all solutions at 0.5 Mol/l and water.

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