

Effect of salinity on Swedish sensitive clay: a rheological perspective

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ABSTRACT: Quick clays are highly sensitive, fine-grained marine sediments that develop a metastable structure during post-glacial processes, including leaching of salt. These clays are prone to sudden failure from small perturbations, causing hazardous landslides. Natural quick clays have a natural water content that is higher than the liquid limit (LL), which defines the water content at which clay transitions from a plastic to a liquid state. However, the LL captures only a single point in the response and does not reflect the full softening behaviour. Rheological testing offers a more comprehensive characterisation, capturing elastic, viscous, and flow behaviour across a range of strain levels. This study investigates the effect of salt removal through leaching on both the LL and rheological behaviour of a natural illite-rich sensitive clay from Kärna. LL tests in remoulded state and amplitude sweep tests in both intact and remoulded states, were conducted on natural and washed samples. It was observed that LL decreased from 61% in the natural state to 52% after leaching, reflecting reduced water retention due to lower pore fluid salinity. Despite this, the slope of the LL regression remained unchanged, indicating preserved sensitivity to the chemical changes of pore fluid. Rheological results showed that the intact natural sample had a higher storage modulus and yielded at over 4 times the shear stress of the remoulded samples, while transitioning to viscous flow at a lower shear strain. The remoulded samples showed similar modulus trends, but the remoulded washed sample exhibited a more viscous response than the natural remoulded sample. These findings demonstrate how changes in pore fluid chemistry influence both the consistency and viscoelastic response of sensitive clays and support the combined use of LL and rheology for more complete behavioural assessment.

KEYWORDS: Sensitivity, clay, salinity, liquid limit, amplitude sweep, storage modulus, loss modulus, yield stress.

1 INTRODUCTION

Quick clay is a metastable, fine-grained sediment typically deposited in marine environments, and can undergo a sudden and irreversible transition from a solid-like to a liquid-like behaviour when subjected to (hydro-) mechanical disturbances (Torrance, 2012). This characteristic increases the probability for shallow landslides (e.g. Surte 1952; Tuve 1977; Stenungsund 2023). Quick clays are mainly formed in previously glaciated regions such as Scandinavia, Canada, Alaska, and northern Russia (Andersson-Sköld et al., 2005). According to Swedish standards, clay is specified as quick clay when it exhibits a sensitivity $S_t \geq 50$ and a fully remoulded shear strength below 0.4 kPa (Rankka et al., 2004).

The origin of quick clay behaviour has been closely linked to post-depositional chemical changes. Salt leaching from the pore fluid of marine clays has been identified as a key factor in the development of their sensitive and metastable structure (Rosenqvist, 1953). Subsequent studies have shown that the sensitivity of these clays is influenced by changes in the pore fluid chemistry (Bjerrum & Rosenqvist, 1956; Mitchell & Houston, 1969), particularly reductions in salinity that weaken interparticle bonds. These chemical alterations influence both the clay microstructure and its consistency characteristics.

One such consistency parameter is the liquid limit (LL), which defines the water content at which soil changes from solid to liquid state. Quick clays are typically characterised by water contents exceeding the LL (Rosenqvist, 1953). According to Wroth and Wood (1978), soils at their LL have a shear strength between 1.3 and 2.4 kPa, while quick clays show higher strength in their intact state. The LL is influenced by both clay minerals and pore fluid composition. In illite-rich marine clays, an increase in the LL has been reported in higher NaCl concentrations (Song et al., 2017), whereas kaolinite clays show different and inconsistent trends (Sridharan & Prakash, 1999; Di Maio et al., 2004; Palomino & Santamarina, 2005).

Rheological testing complements consistency-based characterisation by providing a more detailed assessment of clay behaviour under shear deformation. Rheology, defined as the study of deformation and flow in response to applied stress, has gained attention in soil mechanics and offers a quantitative means of investigating the microstructural and mechanical properties of fine-grained soils (Vyalov, 2013).

Despite the prevalence of effective stress-based geotechnical tests for hydro-mechanical characterisation of soils, some studies have demonstrated the applicability of rheological methods for probing particle scale mechanisms (e.g. Mezger, 2002; Markgraf et al., 2006; Markgraf & Horn, 2007; Markgraf & Horn, 2009). Moreover, rheological parameters have been shown to vary significantly with water content in clayey soil samples (Van Kessel & Bloom, 1998; Soltanpour & Samsami, 2011; Shakeel et al., 2020), suggesting a potential link between rheology and LL.

While LL indicates the water content at which clay transitions from a plastic to a liquid state happens, it represents only a single point on the broader mechanical response curve. Rheological testing, by contrast, provides a continuous characterisation of stress-strain behaviour, elastic stiffness (G'), viscous response (G''), and energy dissipation (loss factor) across a range of strain amplitudes. Combining these approaches provides a better understanding of clay behaviour.

Specifically for quick clays, it is crucial to focus on the impact of ionic strength on the emerging clay behaviour. Although salt leaching has been associated with the formation of sensitive clays, few studies have investigated its effect on both LL and rheological properties. This study addresses that gap by examining how salt removal influences the LL and rheological behaviour of an illite-rich natural clay from Sweden with a sensitivity $S_t > 20$. To isolate the effect of salt, tests were conducted under both natural and washed conditions, with the latter ensuring a negligible amount of salt in the pore fluid.

2 MATERIALS AND METHODS

2.1 Soil samples

Natural clay samples were collected from a depth of 8 m at the Chalmers soft soil test site near Kärå municipality (Gothenburg, Sweden) using a STII piston sampler. The sensitivity of the clay from this depth was >20 (according to the Swedish classification) with a natural water content of 75%. The pore water salinity was equal to 0.41 M and its composition is shown in detail in Table 1.

Table 1. Salt concentrations of natural Kärå clay.

| Ions | Na ⁺ | K ⁺ | Mg ²⁺ | Ca ²⁺ |
|-------------------|-----------------|----------------|------------------|------------------|
| Concentration (M) | 0.37 | 0.01 | 0.02 | 0.01 |

2.2 Liquid limit test

Reconstituted samples of natural and washed Kärå clay were prepared by drying, grinding, and sieving, with only the fraction passing through a 500 μm sieve used for the test. Washed Kärå samples were obtained by washing the soil until the electric conductivity of its pore fluid reached less than 100 $\mu\text{S}/\text{cm}$ to ensure there was a negligible amount of ions left (Palomino & Santamarina, 2005). The liquid limit (LL) was determined using the fall cone method in accordance with BS 1377-2 (BS, 1990). A cone with an angle of 30° and a mass of 80 g was utilised. Demineralised water was incrementally added to the sieved soil until the cone penetration depth fell within the 15 to 25 mm range. For each penetration within this range, a portion of the sample was oven-dried at 110 °C for 24 hours to determine its water content. A minimum of four samples with varying water contents were used to determine the LL. This step was carried out to evaluate how the presence of salt affects the LL of natural Kärå clay.

2.3 Rheometry

Soil washing was conducted by leaching Kärå clay in a Rowe cell for 4 days until there was a negligible amount of ions left in the pore fluid. While the water content of natural Kärå clay was 75%, the water content after leaching was 67%, indicating loss of volume. Rheological oscillatory tests were conducted on clay samples at their natural water content using an Anton Paar MCR302e rheometer. A parallel plate configuration with a diameter of 8 mm was utilised. In accordance with the recommendations of Markgraf et al. (2006), the gap between the plates did not exceed the plate radius, and the vertical load was kept between 1 and 2 N to ensure the contact between the sample and the plates. Size-corresponding samples of intact natural Kärå, remoulded natural Kärå, and remoulded washed Kärå underwent an amplitude sweep test at a constant frequency of 1 Hz, with an increasing shear strain amplitude varying from 0.001% to 10% for a total test duration of approximately 8 min, to minimise drying of the sample. A temperature of 20 °C was set and maintained throughout all tests. The configuration for the amplitude sweep tests is summarised in Table 2.

Table 2. Parameters of amplitude sweep tests.

| Parameter | |
|------------------------|--|
| Shear strain amplitude | $\gamma = 0.001\%$ to 10% |
| Frequency | $f = 1$ Hz |
| Temperature | $T = 20$ °C |
| Water content | Natural samples $w_0 = 75\%$ Washed sample $w_0 = 67\%$ |

3 RESULTS AND DISCUSSION

The results of the fall cone tests conducted on natural and washed Kärå clay are shown in Figure 1, where the LL was identified using a linear regression approach. According to the British Standards definition, the LL corresponds to the water content at which cone penetration reaches 20 mm. The slope of the linear regression between cone penetration and water content reflects the sensitivity of the clay for changes in the pore fluid, where a steeper slope corresponds to increased sensitivity to changes in salinity (Palomino & Santamarina, 2005).

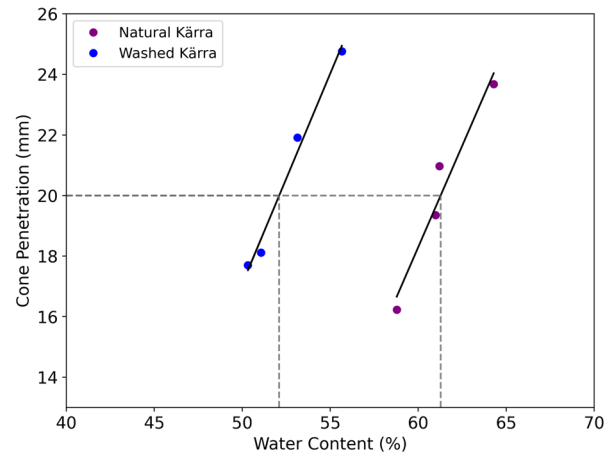


Figure 1. Cone penetration test results, and the LL based on British standards for natural and washed Kärå clay.

As shown in Figure 1, the LL of Kärå clay was 61% under natural conditions. The value decreased to 52% after soil washing, when the pore fluid contained only a negligible concentration of ions. A similar reduction in LL for natural sensitive clay after leaching was reported in previous studies (Rosenqvist, 1953; Bjerrum & Rosenqvist, 1956). Despite the decrease in LL, the sensitivity of Kärå clay to the pore fluid salinity remained unchanged, as indicated by the constant slope of the linear regression.

Figure 2 illustrates the measured shear stress as function of shear strain amplitude, where shear stress is normalised by the peak shear stress of the remoulded natural Kärå sample at $\gamma=10\%$ ($\tau_{ref,10\%} = 3.4$ kPa). The data are based on rheological tests conducted on natural Kärå clay in both intact and remoulded conditions, as well as on washed Kärå clay in the remoulded state.

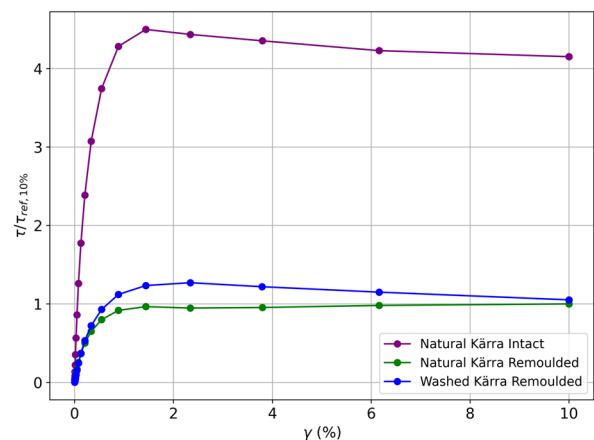


Figure 2. Normalised shear stress as a function of shear strain amplitude.

The shear stress of intact natural Kärå clay was more than 4 times greater than that of the remoulded natural sample. Both

remoulded samples, natural and washed, exhibited similar behaviour in their response to increasing shear strain amplitude (no post peak softening). For the intact natural clay, peak shear stress occurred at a shear strain of 1.4%. This behaviour is consistent with structured clays under monotonic loading, where natural fabric and interparticle bonding contribute to high peak strength followed by strain softening (Leroueil & Vaughan, 1990; Mitchell & Soga, 2005).

The different responses of the remoulded samples suggest that factors such as water content, ionic strength of the pore fluid and particle arrangement influence the behaviour under oscillatory shear.

Even though both samples showed a strain-softening response without a distinct peak, the remoulded washed sample maintained a slightly higher shear stress over a longer strain range before softening. Since the leaching process was conducted in a Rowe cell under constant effective stress, the observed differences are unlikely to result from changes in grain size distribution. As a consequence, different interactions may occur at the inter-particle and intra-particle levels within the clay matrix, which might contribute to the observed differences, along with the lower initial water content of the washed sample. The distinct behaviour can be linked to their difference in salt-concentration. Thus, both water content and pore water chemistry affect the mechanical response of Kärä clay.

Figure 3 shows the variation of storage and loss moduli as functions of shear strain for natural Kärä clay in both intact and remoulded state, as well as for washed Kärä clay in the remoulded state. The same tests as Figure 2 were used to quantify the storage (G') and loss (G'') moduli, respectively representing the elastic and the viscous components (e.g. Markgraf et al., 2006).

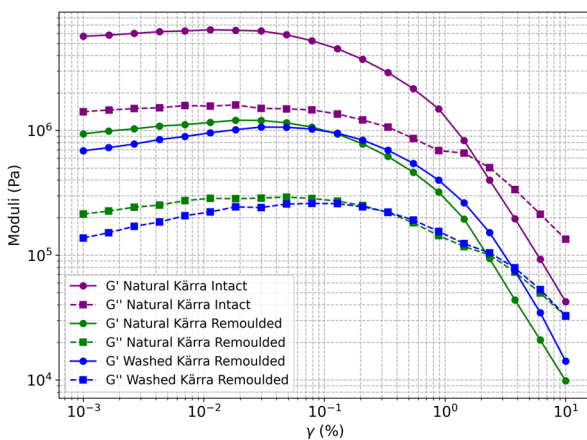


Figure 3. Storage and loss moduli as functions of shear strain.

As shown in Figure 3, the storage modulus (G') exceeded the loss modulus (G'') at low shear strain for all samples before the transition to viscous regime ($G' = G''$) happens, a typical trend for soft soils also reported by Markgraf et al. (2006).

The intact natural Kärä clay exhibited higher G' values compared to both remoulded samples. A similar pattern was observed for G'' . The lower value in both moduli may be attributed to the lower ionic strength and changes in clay microstructure. In fact, the higher initial moduli in the intact clay reflect its geologically-induced structured nature, where interparticle bonding and fabric contribute to an elastic response. Upon remoulding, the change in the microstructure leads to lower G' and G'' , indicating a softer and more viscous material.

Loss factor as a function of shear strain for natural and washed Kärä clay is shown in Figure 4. The loss factor which

characterises the viscoelastic behaviour of a material, is defined by Equation (1). An elastic response is seen when $\tan \delta < 1$, whereas a predominantly viscous behaviour is exhibited when $\tan \delta > 1$. The transition between the two states occurs when $\tan \delta = 1$, indicating the point at which the material transitions from solid-like (elastic) to fluid-like (viscous) behaviour as shear strain increases (Markgraf et al., 2006).

$$\tan \delta = G''/G' \quad (1)$$

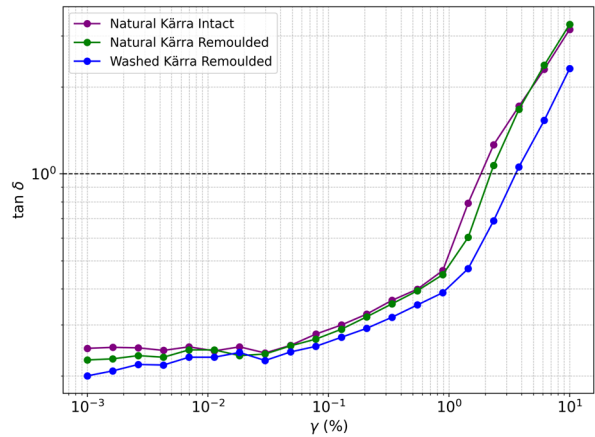


Figure 4. Loss factor as a function of shear strain.

As seen in Figure 4, the transition occurred at a higher shear strain for the remoulded natural sample, compared to the intact natural state. A similar trend was observed for the remoulded washed sample in comparison with the remoulded natural sample. The natural clay with higher salt concentration transitioned to viscous state in lower shear strain amplitude in comparison to the washed sample, indicating influence of the salt-concentration on the transition zone and the clay behaviour.

Figure 5 shows the variation of the normalised storage modulus (G'/G'_0) with normalised shear rate ($\dot{\gamma}/\dot{\gamma}_{ref,10\%}$) expressed as a ratio of the G' to the initial storage modulus (G'_0) of each sample. The dashed lines represent fits using a logarithmic shear-rate sensitivity model based on Einav & Randolph (2005).

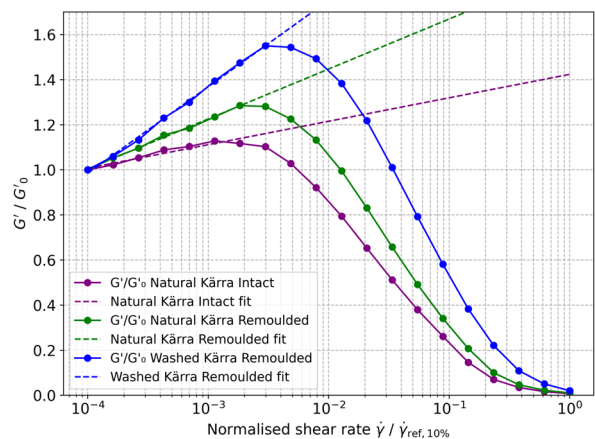


Figure 5. Normalised storage modulus as a function of normalised shear strain.

The slope was calculated based on the initial tangent and accounted for the rate effect which ranged from 0.1 to 0.4 which was double the magnitude reported by on Einav & Randolph (2005). All samples exhibited an initial increase in the normalised storage modulus at small shear rate levels, indicating a degree of hardening. The slope of this increase was highest for the remoulded washed sample and lowest for the

intact natural sample. Moreover, the peak occurred at different normalised shear rate amplitudes in the analysed samples, reflecting differences in their structural resistance to deformation. Natural intact Kärä clay shows transition at smaller shear rate amplitudes than the natural remoulded sample, confirming the metastable nature of the intact natural quick clay. The significantly higher shear rate amplitude at which transition occurs for the washed remoulded sample can be ascribed either to the lower water content of the washed sample with respect to the natural one or to the pore fluid effect. Further analyses are required to elucidate this point.

4 SUMMARY AND CONCLUSIONS

Liquid limit and amplitude sweep tests were conducted to study the consistency and rheological response of a soft sensitive Swedish clay. The aim was to examine how salt removal through washing affects the behaviour of illite-rich Kärä clay under natural and washed conditions in intact and remoulded state.

The LL of Kärä clay was 61% under natural conditions. This value decreased to 52% after washing, when the pore fluid contained only a negligible concentration of ions. Despite the decrease in the LL, the sensitivity of Kärä clay to the pore fluid remained unchanged, as indicated by the similar slope of the linear regressions for natural and washed material.

The amplitude sweep tests showed that the intact natural Kärä sample exhibited higher storage modulus and shear stress compared to the remoulded samples, due to the presence of a preserved fabric. After remoulding, this structure was altered and rearranged, resulting in reduced storage and loss moduli, diminished peak of shear stress, and a delayed transition to viscous behaviour.

The remoulded washed sample exhibited a more viscous response than the natural remoulded sample. This was reflected in larger loss modulus, and a more abrupt post-yield softening. These behaviours are likely linked to the lower salt concentration in the washed sample, which weakened particle interlocking.

All samples initially exhibited hardening at low shear rates, followed by softening as shear rate increased. The steeper hardening effect in the remoulded natural Kärä with respect to the intact one highlighted a lower structural resistance to deformation of the intact sample, confirming the metastable nature of intact quick clay.

Overall, the findings highlighted the effects of salinity on the viscoelastic and shear behaviour of illite-rich sensitive clay under varying physical and chemical conditions. Rheometry, as employed in this study, was proved to be an effective method for capturing these responses. Additionally, rheometry requires only a small amount of material and offers a rapid and user-friendly approach to evaluating the rheological behaviour of clay.

5 ACKNOWLEDGEMENTS

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