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Influence of pore water composition on the compressibility of a Danish high plasticity Paleogene clay during sedimentation

Influence de la composition de l'eau interstitielle sur la compressibilité d'une argile Paléogène Danoise à haute plasticité pendant la sédimentation

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ABSTRACT: An iconic challenge in geotechnical engineering is the inability to control soil properties at construction sites. To overcome this, several efforts for soil improvement have previously been investigated. Change of pore water chemistry shows potential in strengthening soft soils, but its effects on deformation properties of stiff clays are less extensively studied. The effects of such methods on a Danish high plasticity Paleogene clay are investigated by comparing sedimentation in four different water environments varying the dominating cation to be either Na^+ and K^+ , and the total cationic charge by a factor two. At self-weight sedimentation both the charge and cation influenced the end of primary void ratio while the effect of charge disappeared with increased loading. All sedimentations curves position below the reference intrinsic compression line, indicating that reconstitution at 1.5 times the liquid limit does not result in complete destructurization in this soil. Both substituting for K^+ and increasing the charge decrease the duration of consolidation. The creep indices are insensitive to the water environment at natural stress levels but exceed previous measurements significantly at self-weight sedimentation.

RÉSUMÉ: Un défi emblématique de l'ingénierie géotechnique est l'incapacité de contrôler les propriétés du sol sur les chantiers de construction. Pour surmonter cela, plusieurs efforts d'amélioration des sols ont déjà été étudiés. Le changement de la chimie de l'eau interstitielle montre un potentiel dans le renforcement des sols mous, mais ses effets sur les propriétés de déformation des argiles rigides sont moins étudiés. Les effets de telles méthodes sur une argile paléogène danoise à haute plasticité sont étudiés en comparant la sédimentation dans quatre environnements aquatiques différents en faisant varier le cation dominant soit Na^+ et K^+ , et la charge cationique totale par un facteur deux. Lors de la sédimentation au poids propre, à la fois la charge et le cation ont influencé la fin du rapport des vides primaires tandis que l'effet de la charge a disparu avec l'augmentation de la charge. Toutes les courbes de sédimentation se situent en dessous de la ligne de compression intrinsèque de référence, indiquant que la reconstitution à 1,5 fois la limite de liquidité n'entraîne pas une destructuration complète de ce sol. La substitution de K^+ et l'augmentation de la charge diminuent la durée de consolidation. Les indices de fluage sont insensibles à l'environnement hydrique aux niveaux de stress naturel mais dépassent de manière significative les mesures précédentes à la sédimentation au poids propre.

KEYWORDS: High plasticity clay, Compressibility, Sedimentation, Soil improvement, Pore water chemistry

1 INTRODUCTION

One of the iconic challenges in geotechnical engineering is the inability to choose and control the soil properties at a construction site. Geotechnical design is, therefore, challenged when complex or unfavourable soil conditions are encountered. Such challenges have spawned an interest in investigating methods for improving soil properties. Previously, emphasis has been mainly placed on strengthening weak and soft soils, but improvement of deformation properties in stiff overconsolidated clays could provide substantial benefits in several construction projects.

Early efforts in soil improvement relied on surcharging to consolidate soil masses, thereby increasing stiffness and strength of soft soils by bringing them into an overconsolidated state. In an effort to increase the pace of consolidation Casagrande (1952) applied electro-osmosis which activates the Electrical Double Layer (EDL) in the water flow, therefore increasing the experienced permeability. Since soil improvement by consolidation relies on bringing the soil to an overconsolidated

state, this method alone could hardly provide any benefit for already overconsolidated soils. However, field application of electro-osmotic stabilization of Norwegian quick clay (Bjerrum et al. 1967) showed effects beyond that of the expelled water. These effects relate to the changing water chemistry caused by transport of ions by the electrical current. Contrary to consolidation, deformations caused by chemical changes may be applicable for improvement of overconsolidated soils as well.

The core effects of changing ion composition of pore water arise from the interaction between clay minerals and the cations in the pore water. This interaction acts on two scales. On the scale of the individual clay mineral, (Sawhney 1972) describes how the introduction of cations with low hydration energy (e.g. K^+ , Rb^+ and Cs^+) will result in clay mineral interlayer collapse and even fixation of the cations in the mineral, while cations with higher hydration energy (e.g. Mg^{++} , Ca^{++} and Sr^{++}) will result in interlayer expansion. On the inter-particle scale, the repulsion between particles is governed by the thickness of the EDL (van Olphen 1977). The thickness of the EDL will change to generate an equilibrium between the total cationic charge in the pore water

and the surface charge of the clay mineral, so that higher cationic charge produces a thinner EDL and thereby closer inter-particle spacing. Furthermore, the opposite charged edges and faces of the clay particles can result in strong attraction into structures, which persist during further compression. Additional inter-particle effects occur from bonding generated for instance by cementation of particular strong attraction related to specific cations.

In artificial samples with controlled mineralogy, (di Maio et al. 2004) and (Lodahl & Sørensen 2019) observed a correlation between pore water salinity and sustained void ratio at the same stress. The difference between the salinities decreases with stress and becomes negligible at a few MPa. Both (Sridharan et al. 1986) and (di Maio 1996) observed that increased valence led to more compressed states with Na⁺ and Li⁺ expanding the clay the most significantly. The fixation of K⁺ in the clay minerals made it more comparable to the divalent cations and resulted in a stable change of properties, as it would not be easily washed out by demineralized water. This particular role of K⁺ in improving soil stiffness and strength was utilized in field studies where they applied cation exchange with KCl in areas with a slow moving slope failure (de Rosa et al. 2016) and quick clay (Helle et al. 2018). A persisting change was observed even after flooding with freshwater, as expected.

(Sridharan et al. 1986) further noticed that Na⁺ compared to K⁺, Ca⁺⁺ and Mg⁺⁺ based bentonites would have a higher ratio of creep index (C_{ae}) to compression index (C_c) and liquid limit (w_L) as well as a lower coefficient of consolidation (c_v). Since Na⁺ is the dominating cation in marine specimens and has a higher preference for adsorption to clay minerals as described by (Mitchell and Soga 2005), there is potential for extending the cation exchange based soil improvement to stiff marine clays. In order to investigate this potential, a Danish high plasticity overconsolidated clay formation named “Røsnæs Clay” was sedimented in four different water environments and the effects on the deformation behaviour were compared.

2 METHODOLOGY

Sedimentation in four different water environments with individual properties presented in Table 1 was investigated. The sample names follow the convention: “Dominating cation”_”Cationic charge in milli elementary charges per litre”. Sedimentation from complete dissolution at five times w_L was applied to ensure that proper chemical equilibrium between the pore water and clay minerals could be established prior to compression. The alternative would have been reconstitution, which starts from mechanical mixing at 1.5 times w_L . In choosing sedimentation over reconstitution it is important to be aware of the fact that reconstitution represents the intrinsic state of the soil without structure while sedimentation may include sedimentation structure as defined by Burland (1990) and

Table 1. Ion concentration and relevant solution properties for the four water environments.

Sample	Na_278	Na_555	K_278	K_555
Na ⁺ [mol/L]	0.227	0.453	0.011	0.023
K ⁺ [mol/L]	0.011	0.022	0.227	0.453
Mg ⁺⁺ [mol/L]	0.010	0.019	0.010	0.019
Ca ⁺⁺ [mol/L]	0.010	0.020	0.010	0.020
Cl ⁻ [mol/L]	0.266	0.544	0.266	0.544
SO ₄ ⁻ [mol/L]	0.006	0.006	0.006	0.006
Cationic charge [e/L]	0.278	0.555	0.278	0.555

confirmed by Stallebrass et al (2007). The difference in structure causes a shift of the sedimentation compression line (SCL) relative to the intrinsic compression line (ICL).

Sample Na_278 represents the in-situ pore water composition of the sample material, by mimicking the average ion composition measured in leached water from 18 samples along the Fehmarn alignment, where the material for the samples was collected (Femern A/S 2013). The other three samples use the composition of sample Na_278 as a baseline and vary the cationic charge and dominating cation (K⁺ or Na⁺) to test the effects of changing EDL thickness and stronger or weaker compression of individual clay minerals. In all four water environments the concentration of SO₄⁻ was kept constant, to ensure full solubility of the salts, as CaSO₄ otherwise would precipitate.

The samples were created from four intact rotary cores of Røsnæs Clay sampled in a depth interval of 59-67 m below seabed along the Fehmarn alignment (Femern A/S 2014). The measured w_L in each core ranged from 76% to 122%. The entirety of these four cores was cut into pieces passing an 8 mm sieve removing a few discontinuous parts with an ash-like substance and some burrows in the process. The cuttings were mixed thoroughly in a cleaned tilting drum concrete mixer to ensure homogeneity of the batch. The batch was then divided into four portions with measurement of water content for every 500 g added to each portion to monitor possible differences between the samples. As the 32 water content measurements had a standard deviation of 0.13%, the samples were regarded as satisfactorily mixed. The water compositions in Table 1 were added to each portion respectively to achieve a water content of ~180% in which state the soil soaked for a few days in air tight containers. The soaked pieces were worked through a 425µm sieve before additional water (of the same compositions as in the previous step) was added to the samples and mixing performed with a paint mixer drill attachment. As more water was added to the samples, the water content was measured to ensure that all samples ended up at a final water content of 505 % ± 5 %. In this state the samples were stored in air tight containers for 5 months with regular mixing by the paint mixer drill attachment.

Subsequent sedimentation was performed in purpose built large diameter consolidometers, shown in Figure 1. The systems had a diameter of 190 mm and an initial sample height of 470 mm ± 2mm. Double-sided drainage was used with hydraulic connection between the cell water on either side of the sample to avoid influence of hydraulic gradients in the sedimentation process. Initial self-weight sedimentation was performed by pouring the slurry into a small water column and letting it settle until the soil water interface stabilized. From this state further loading with weights commenced from 1 kPa by a load step factor of two up to 16 kPa. From 16 kPa, a constant rate of deformation phase was carried out with rates based on the development during weighted loading to a stress level of ~100 kPa where loading with an actuator controlled by a hydraulic system was possible. Loading continued then with a step factor of two from 125 kPa to 1000 kPa. The time-curves at 1 and 2 kPa were corrupted due to unintended restrictions to the movement



Figure 1. Overview of purpose built consolidation setups.

of the top pressure head and are not included in the interpretation.

Time-curves are interpreted with the log-time method (ASTM D2435/D2435M – 11). Calculation of c_v and the time until the end of primary consolidation (t_{EOP}) follow the same standard. The void ratio (e) calculation assumes full saturation and accounts for the weight of added salt in the measured water contents.

3 RESULTS

Differences between the four water environments appear already during the self-weight sedimentation as shown in Figure 2. The samples reach three different self-weight void ratios, with Na_555 having the lowest followed by Na_278 and K_555, which have similar void ratios, and K_278, which has the highest. Additionally, the t_{EOP} also form three groups with K_555 having the lowest and Na_278 having the highest and Na_555 and K_278 grouping together inbetween.. The self-weight void ratio is therefore affected very comparably by the charge doubling and the change of cation so that the further compression caused by Na^+ over K^+ is roughly the same as doubling the charge. A similar system may be observed for the settlement time on a logarithmic scale, where the increased settlement rate from K^+ rather than Na^+ is roughly the same as doubling the charge. The settlement times may be compared directly since the average height during self-weight sedimentation are roughly the same for the four samples.

As no external stress is applied during self-weight sedimentation, the average vertical effective stress at this state is calculated from the density of the soil column as $\sigma'_v = (\gamma_{bulk} - \gamma_{water}) \cdot H/2$. Where γ_{bulk} and γ_{water} is the bulk unit weight and the unit weight of water respectively, and H is the sample height at the end of self-weight sedimentation. The calculated average stresses in the samples are 0.27 – 0.28 kPa and the water contents at the end of self-weight sedimentation are 225%, 183%, 250% and 189% for Na_278, Na_555, K_278 and K_555, respectively. The state at end of self-weight sedimentation is therefore well above w_L in agreement with the calculated load levels, which are below the limit of 2 kPa undrained shear strength, defining w_L .

The grouping from Figure 2 changes as the external load increases. Samples Na_278 and K_278 find a similar line at >200 kPa and samples Na_555 and K_555 form a lower and upper bound, respectively. The general variation between all four samples is much smaller at >200 kPa and the trend, therefore, less distinct. It would seem that the charge is less influential at higher stresses, while the dominating cation still influences the response. After 500 kPa three distinct parallel SCLs appear, as shown in Figure 3. These SCLs finds comparable C_c of 0.85, 0.79, 0.79 and 0.88 for samples Na_278, Na_555, K_278 and K_555 respectively. These C_c are noticeably higher than the ICL by (di Remigio et al. 2021), which have $C_c=0.68$ in the same stress range. Figure 3 shows that all of the SCLs position below the ICL at 1000 kPa. It is here important to highlight the direct comparability between sample Na_278 and the ICL, as they use

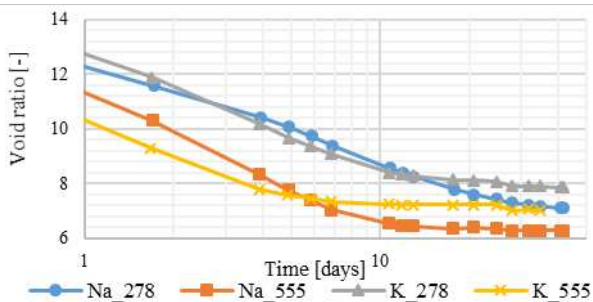


Figure 2. Time-curves from self-weight sedimentation

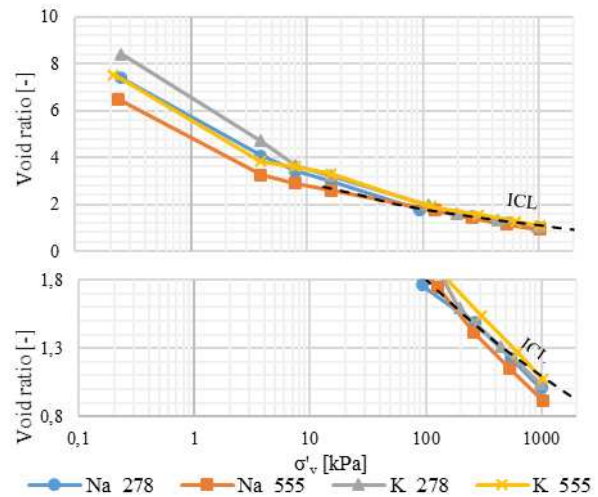


Figure 3. Compression curves for the four sedimentation environments, including ICL by (di Remigio et al. 2021).

the same water composition. It should therefore, be expected that the SCL would position together with or above the ICL, contrary to the observation.

The approach towards a straight SCL for each of the tested samples is conceptually similar but differs from that expected of natural and reconstituted soils without significant unstable structure by having a decreasing C_c with stress. However, the ICL by (di Remigio et al. 2021) shows a similar approach towards its straight-line trend.

Figures 4a and b show that the subtrend from Figure 2, regarding the time component of the consolidation, persists at higher load levels, as both K_278 and K_555 have higher c_v and lower t_{EOP} compared to Na_278 and Na_555 respectively.

Sample K_555 with both double cationic charge and K^+ as the dominating cation shows both significantly higher c_v and significantly lower t_{EOP} compared to the other samples, which fall within a more narrow band.

The range of c_v from 68 samples of natural Røsnæs clay based on the tests reported by (Kinslev et al. 2019) is indicated by a dashed line in Figure 4a. These measurements show a generally decreasing c_v with increasing stress. At comparable stress (>100 kPa) the range of the natural sample is in line with that measured here. From the self-weight sedimentation until 8

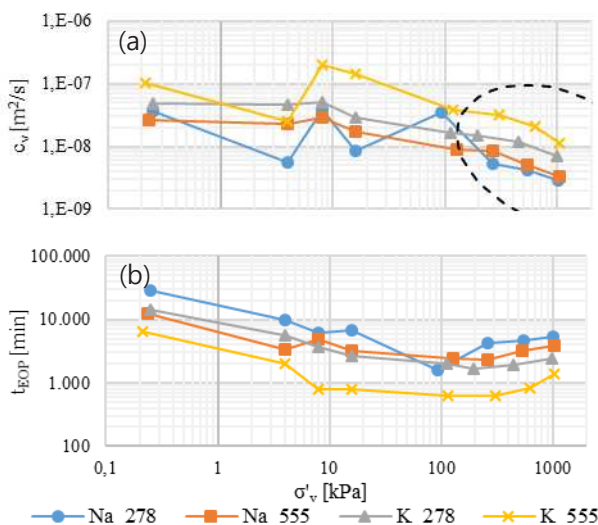


Figure 4. Development of (a) c_v and (b) t_{EOP} with stress for the four different water environments. A dashed line marks the previous measurements of c_v on natural Røsnæs Clay from tests presented by (Kinslev et al. 2019)

kPa samples Na_555 and K_278 show no stress dependency of c_v while samples Na_278 and K_555 contain significant scatter. After 8 kPa, c_v starts decreasing in samples Na_555, K_278 and K_555, with a close to constant slope for increasing stress. The stress dependency of sample K_555 is slightly higher than that of samples Na_555 and K_278. Sample Na_278 shows no consistent trend at any point due to significant scatter.

The effect of the water environment on C_{ae} is shown in Figures 5 and 6. Figure 5 shows the development of C_{ae} with stress, which clearly has an order of magnitude jump from self-weight sedimentation to stresses representing a more common state. At the self-weight sedimentation and 4 kPa load step there is a clear distinction between the samples of high and low cationic charge, with the high charge leading to lower C_{ae} . Beyond that, the results show no consistent grouping between either cationic charge or dominating cation. In general, the creep indices at self-weight sedimentation for all samples and at 4 kPa for samples Na_278 and K_278 are much higher than any of the previously reported measurements on natural samples (Kinslev et al. 2019). The samples of low cationic charge exceed the previous measurements by a factor >20, while the samples of high cationic charge exceed by a factor >10 at the self-weight sedimentation.

As the stress increases, the creep indices converge towards values much closer to those previously measured in natural Røsnæs Clay. At stresses above 100 kPa all but sample Na_278 seem to have stabilized on a comparable trend of decreasing C_{ae} with increasing stress. Sample Na_278 reach that same state but one load step later. All but sample Na_278 show similar C_{ae} when approaching 1000 kPa, where the average C_{ae} for the three samples is 0.01, while sample Na_278 lies slightly higher, at 0.017. The development of C_{ae} towards a decreasing trend is different for each of the samples with Na_278 and K_555 dropping close to zero at 16 and 4 kPa, respectively, before rising again. Sample Na_555 has similar behaviour, but dropping only just below 0.02 before rising again. Sample K_278 shows a slight steady decrease throughout the test.

As mentioned and shown in Figure 3, C_c decreases as stresses increase. Due to the relation between primary and secondary index identified by (Kinslev et al. 2019) for natural Røsnæs Clay, the high C_{ae} values at low stresses might be compensated by the higher C_c . Figure 6 illustrates the link between C_{ae} and C_c for each of the samples, with comparison to the envelope ratio of $C_{ae}/C_c = 0.04$ observed by (Kinslev et al. 2019). Only stress points with a well defined C_c are plotted in Figure 6 except for

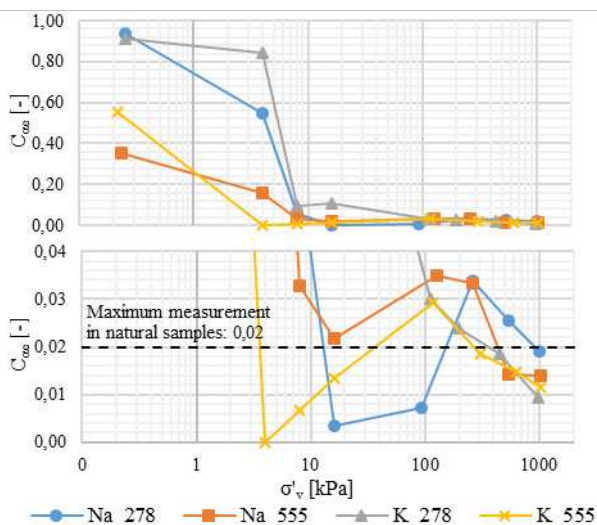


Figure 5. Development of the C_{ae} with stress. Indication of maximum measurement in natural Røsnæs Clay reported by (Kinslev et al. 2019).

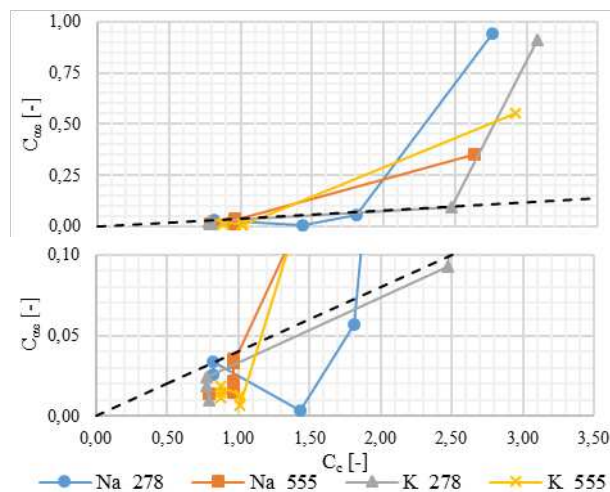


Figure 6. Relation between C_{ae} and C_c including envelope line by (Kinslev et al. 2019).

the C_c at the self-weight sedimentation, which is a lower bound estimate. The C_{ae}/C_c ratio at self-weight sedimentation far exceeds the envelope ratio and despite the C_c here being lower bound estimates, C_c would still have to be underestimated by a factor 7-20 in order to fall inside the envelope. Apart from the point at self-weight sedimentation, Figure 6 shows that the envelope ratio from natural Røsnæs Clay also makes a good upper boundary for the resedimented samples. As the samples approach their final C_c of ~0.8, samples Na_555, K_278 and K_555 cluster together at roughly half the envelope ratio while sample Na_278 is much closer to the envelope line. This is the natural effect of what is seen in Figure 5 combined with the low variation in final C_c . At the lower stress stages, the more gradual development of C_c in samples Na_278 and K_278, shown in Figure 3, is also illustrated in Figure 6 as they have a more gradual approach towards their final location opposite to samples Na_555 and K_555, which reach their final location more or less immediately after self-weight sedimentation.

Figures 5 and 6 show that C_{ae} seems to be generally less affected by the specific water environment while it is significantly influenced by the low stress levels associated with self-weight sedimentation.

4 DISCUSSION

The influence of the water environment on the sedimentation compression behaviour of Røsnæs Clay is evident from the presented data. The most immediately noticeable effect is on the self-weight sedimentation, where a consistent grouping based on cationic charge and dominating cation appears. The sustained void ratio at self-weight decreases with increasing charge and domination of Na^+ relative to K^+ . The decrease of void ratio from these changes has roughly the same magnitude. The compression from increased charge is in accordance with previous observations by (di Maio et al. 2004) and (Lodahl and Sørensen 2019). However, the more compressed state from Na^+ relative to K^+ contradicts the observations on artificial clays by (Sridharan et al. 1986) and (di Maio 1996) who both observed significant expansion from Na^+ domination relative to K^+ , Ca^{++} and Mg^{++} . On the other hand, (Bjerrum 1967) and (Helle et al. 018) observed a shift of the normal consolidation line with introduction of K^+ in Norwegian quick clay. Both (Sridharan et al. 1986) and (di Maio 1996) studied pure bentonites with close to 100% smectite content, while the clay mineralogy of Røsnæs Clay is ~20% smectite, 30-60% illite and 20-50% kaolinite according to (di Remigio et al. 2021) and clay mineralogy of Norwegian Quick Clay has 60-90% illite and close to no smectite

according to (Helle 2017). It would therefore seem that the extreme expansion from Na^+ observed by (Sridharan et al. 1986) and (di Maio 1996) is related to the smectite content. As described by (Sawhney 1972) and (di Maio 1996) K^+ can fixate in the smectite structure causing “illitization”, which compresses the individual clay minerals, thereby causing the significant difference observed here by (Sridharan et al. 1986) and (di Maio 1996). However, when the mineral composition is already illitic this effect diminishes, which complies with the observations. At the inter-particle scale, it seems that K^+ domination creates stable bonding structure, which shifts the state line as seen in the results by (Bjerrum 1967) and (Helle et al. 2018), which is not observed in the pure smectites as the expansion of individual clay particles dominated the bulk response. Since the influence from K^+ domination persists with increased loading, the argument of increased structure would seem to apply to the resedimented Røsnæs Clay. An explanation based on stable bonding structure over fabric is preferred since (Bjerrum 1967) and (Helle et al. 2018) observed the effect in intact clays where the fabric is generally locked by mechanical forces and therefore cannot change as argued by (Wilkinson 2011). Contrary to the cation domination effect, the influence from the cationic charge disappears as the consolidation stress increases. (Lodahl and Sørensen 2019) also observed this with samples of different charge becoming less distinguishable from one another as the consolidation stress increased.

All the generated SCLs eventually position below the intrinsic compression line for the same soil formation reported by (di Remigio et al. 2021). As they have higher C_c , they seem to continue this trend if loaded further. This contradicts the observations by (Burland 1990) and (Stallebrass et al. 2007), who present evidence that the sedimentation compression line contains more structure than the corresponding intrinsic compression line and therefore is able to sustain a higher void ratio at the same stress. This only applies for comparison of these different compression methods on the same water environment. Therefore, a comparison between the ICL and sample Na_278, which have the same water environment, is expected to display sedimentation structure relative to the ICL. As mentioned, this is not the case, since it positions together with the other samples below the ICL. This observation could suggest that the reconstitution method applied by (di Remigio et al. 2021) was not sufficiently destructive to completely remove the soil structure, while the dissolution at a water content above 500 % for five months did indeed result in complete destruction. Additionally, it is possible that the applied resedimentation method did not mimic closely enough the natural sedimentation process and therefore did not allow sedimentation structure to develop. However, the self-weight settlement time for sample Na_278 was more than 30 days, which is about twice that observed by (Stallebrass et al. 2007) for sedimentation to roughly the sample height of the very comparable London Clay, where sedimentation structure was observed. It would therefore seem that it is not the time component of the applied method that caused the lack of structure. (Stallebrass et al. 2007) started sedimentation from 2.5 times higher water content and let the sedimentation occur in four layers, but it seems unlikely that that alone would make the behaviour change from non-structured to structured. No matter what, it seems that Røsnæs Clay does not produce significant sedimentation structure compared to the intrinsic state, which is in accordance with observations by (Kinslev et al. 2021) that the majority of natural samples of Røsnæs Clay has a sensitivity of unity.

The general shape of the sedimentation compression lines for Røsnæs Clay compares to the relevant ICL, but diverges from the general shape presented by both (Burland 1990) and (Stallebrass et al. 2007) (among many others), by displaying a significantly decreasing C_c as stresses increase. This shape is more comparable to the response seen during destructuration from a

metastable structure. As neither the SCL or ICL contain any metastable bonding structure the odd shape is more likely an effect of the low stress level, although (Stallebrass et al. 2007) report a conventional shape of increasing C_c until a constant value in the same stress range as the ICL.

In addition to the influence on the sustained void ratio, the water environment also affects the settlement time and c_v . The clearest illustration of this is in the self-weight sedimentation where K^+ relative to Na^+ and higher charge increases the pace of consolidation. Unlike with the void ratio state, both effects persist as stresses increase. This agrees with the observations by (Sridharan et al. 1986) although on a much smaller scale, which again likely is related to the mineralogy of the investigated samples. The increased c_v in K^+ relative to Na^+ can partly be ascribed to the higher void ratios, but as samples Na_278 and K_278 have very comparable SCLs, but still an offset between their development of c_v , this cannot be the only reason. Since the SCLs have very comparable shapes, the individual volumetric compressibility of the samples may be assumed the same. The differences in c_v must therefore be related to permeability, which is dominated by a combination of the size of the pores and the tortuosity of flow path through the samples. With this in mind, the dependency of c_v on the cationic charge neatly relates to a more compressed EDL allowing for a greater portion of the pore space to activate in water dissipation.

It is reasonable to expect that the clay slurries had reached an equilibrium state of cation exchange prior to sedimentation due to the long period of storage at a water content above 500%, the effects seen from the different environments at low stresses would therefore not be the results of ongoing changes in the interlayer cations or thickness of EDL, but rather the settlement of particles of different properties. The low cationic charge samples represent slurries where the particles have higher repulsive forces compared to the samples of high cationic charge. This is caused by the thicker EDL in samples Na_278 and K_278 compared to samples Na_555 and K_555. At self-weight this repulsion is strong enough to influence the clay structure but as stresses increase the mechanical forces dominate and dictate the structure. On top of that, the K^+ based samples generate a stronger inter-particle bonding, which causes a structure based parallel shift of the respective SCLs. Furthermore, any K^+ fixation will decrease the size of the individual clay particles and thereby will increase their density. Along with the shorter interaction radius a faster consolidation time is seen as the result.

While clear effects from the water environment are seen for the primary compressibility, the creep deformations are generally unaffected in the normal stress range (≥ 4 kPa), where the boundary line from natural Røsnæs Clay proposed by Kinslev et al. (2019) also apply to the resedimented samples. The lack of reaction to dominating cation, as was observed by (Sridharan et al. 1986) on pure smectite, may again be related to the illite content in the Røsnæs Clay. At self-weight sedimentation the increased C_{ae} relative to previous measurements could be related to a greater instability in the particle arrangement from the very open structure, which would also explain the low cationic charge leading to relative higher C_{ae} as they have less strong interaction between clay particles and a more open structure due to the larger EDL.

The development of C_{ae} contains significant variation at low stresses but finds a unifying trend of decreasing C_{ae} with stress after ~ 200 kPa. This reduction does not relate to changes in C_c , which is more or less constant from this stress level. At the final stress level of 1000 kPa all but sample Na_278 converge to roughly $C_{ae} = 0.01$, while sample Na_278 lies slightly higher at 0.017. This suggests that both changing the dominating cation and cationic charge reduces C_{ae} although the effects are not cumulative as sample K_555, with both double charge and changed cation, does not show further reduction than samples Na_555 or K_278.

The fact that the observation of (Sridharan et al. 1986) of increases C_{ae}/C_c ratio for Na^+ domination caused by a much higher C_{ae} is not observed in Røsnæs Clay may again be ascribed to the difference in mineralogy causing the “illitization” from K^+ to have a negligible influence in this more illite prone clay.

5 CONCLUSIONS

The present study clearly shows how sedimentation of a natural high plasticity clay is affected by the water environment in which the process is taking place. Two effects from alternating cation composition were investigated by changing the dominating cation between Na^+ and K^+ and changing the total cationic charge by a factor two while maintaining the relative distribution of cations. These changes influenced both the overall compression and the time component of the consolidation.

The overall compressibility is influenced by both cationic charge and dominating cation at self-weight sedimentation, where Na^+ and higher charge result in a more compressed state compared to K^+ and lower charge, respectively. At higher stresses, the effect of charge disappears but the effect from dominating cation is maintained and believed to relate to stable bonding structure. All sedimentation compression lines from this study position below the relevant intrinsic compression line. This questions the level of destructure used for producing an intrinsic compression line as one of the studied samples has the same water composition as that used for intrinsic compression line and still positions below despite any sedimentation structure. It is therefore argued that only negligible sedimentation structure is generated in the presented resedimentations of Røsnæs Clay and that the natural structure is not completely removed by regular remoulding in this clay type.

For the time component both increasing charge and changing for K^+ instead of Na^+ increase the coefficient of consolidation and reduce the time to reach end of primary consolidation. These effects persists at increasing stress.

The creep behaviour is not consistently influenced by the pore water composition, but extreme creep indices are achieved at self-weight sedimentation, far beyond the values that would be expected from the compression index at this stress level. For higher stresses a 0.04 ratio between the creep and compression index constitutes a suitable upper bound, similarly to what has previously been observed in natural Røsnæs Clay.

Differently from observations of in-situ application of cation exchange the difference between the tested cationic environments is small, which is proposed to be caused by the structural rearrangement that is possible during sedimentation. This allows the particles to find a different equilibrium of the inter-particle structure than what is seen in-situ. The in-situ structure is locked from mechanical forces resulting in the cation exchange leading to increased bonding only, instead of a combination of bonding and reorientation.

With the different sedimentation structures generated in this study, it is possible to investigate the effects from the water environment beyond the sedimentation compression by changing the pore water chemistry during different stress paths. In particular it is expected that unloading after compression will enhance the diffusion process and actively enhance the modification of the pore water chemistry and, since the mechanical forces are reduced, allow for the chemical forces to influence the structure more effectively.

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