Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3

doi: 10.32075/17ECSMGE-2019-0265

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

Comparison of three Norwegian marine clays from a mineralogical, chemical and geotechnical approach

Comparaison minéralogique, chimique et géotechnique de trois argiles marine Norvégienne

P. Paniagua
Norwegian Geotechnical Institute/Trondheim, Norway

J.S. L'heureux
Norwegian Geotechnical Institute/Trondheim, Norway
Norwegian University of Science and Technology/Trondheim, Norway

ABSTRACT: Results of X-ray diffraction (XRD) and X-ray fluorescence (XRF) analyses of sensitive clay sediments from three particular sites in Norway are presented. The mineralogical analyses carried out on the bulk and < 6 µm fraction show that muscovite is the dominant clay mineral at all sites followed by quartz and plagioclase. The most dominant chemical elements in all soils were found to be SiO_2 and Al_2O_3. The total carbon content varies slightly between all sites with values from 0.5 to 1.25 %. Data from all three sites compare well with other Norwegian studies showing that Norwegian clays are rather inactive and with a relatively high content of clay minerals.

RÉSUMÉ: Les résultats d'analyse par diffraction des rayons X (XRD) et par fluorescence des rayons X (XRF) de sédiments argileux sensibles provenant de trois sites particuliers en Norvège sont présentés. Les analyses minéralogiques effectuées sur la masse et la fraction <6 µm montrent que la muscovite est le minéral argileux dominant à chacun des sites, suivi du quartz et du plagioclase. Les éléments chimiques les plus dominants dans tous les sols se sont révélés être SiO_2 et Al_2O_3. La teneur totale en carbone varie légèrement entre chacin des sites, avec des valeurs comprises entre 0,5 et 1,25%. Les données des trois sites se comparent bien avec d'autres études norvégiennes montrant que les argiles norvégiennes sont plutôt inactives et présentent une teneur relativement élevée en minéraux argileux.

Keywords: sensitive clay; minerals; index properties; chemistry

1 INTRODUCTION

Investigation of the mineralogy and chemistry of sensitive marine clays from Norway are quite limited eventhough such factors can have large impact on its geotechnical properties. Some mineralogical analyses of Norwegian clays have been presented by Kenney (1967), Hilmo (1989), Lunne (2002, 2003), Gylland (2013), by Syversen (2013) and Helle (2017). In this paper data collected for marine clays at Koa, Skatval and Nybakk-Slomarka (Rakkestad) in Norway are presented. The data is compared to similar data from other Norwegian and worldwide clays.

The scope of this paper is to report on the mineralogy and chemistry of these marine clays and allow to establish a link to geotechnical properties like compression and strenght reported by Paniagua et al. (2017) and L'Heureux et al. 2018.

2 SOIL STRATIGRAPHY AT THE STUDY SITES

The Nybakk-Slomarka study area is situated in southeastern Norway. Here the soil conditions are fairly homogenous and can be generalized with three layers. The top layer consists of a 0.4 m thick cropland overlying a layer of desiccated clay or dry crust underneath. The dry crust generally extends 3-4 m below the ground surface. Further down, a normally consolidated and sensitive marine clay (Rakkestad clay) is found.

The Koa site is situated in mid Norway, approximately 80 km north of Trondheim. The soil conditions in Koa show a top layer of 2.5-3 m dessicated clay (dry crust), followed by a homogenous siltig clay layer to about 21 m depth. The clay between 7-12.5 m depth is classified as quick clay following the Norwegian standards (i.e. remoulded undrained strength < 0.5 kPa).

The Skatval study site is also located in mid Norway, about 40 km north of Trondheim. The soil conditions are dominated by a top layer of 1-2 m dessicated clay, followed by a homogenous clay to about 20 m depth. The clay between 7.5-13.5 m depth is classified as quick clay.

Piezocone tests (CPTU) and soil sampling were performed at all three study sites. Cone resistance (q_t) and pore pressure ratio (B_q) vary between 600-1000 kPa and 0.8-1.1, respectively, for the clay deposit on each site (see Figure 1). Table 1 presents basic soil parameters for each site. All three clays have plasticity indices varying between 8-25 and water contents varying between 30-40%.

Table 1. Basic site properties.

Parameter	Skatval	Koa	Rakkestad
Unit weight γ (kN/m³)	19.4	19.4	18.5
Water content w (%)	32	30	35
Sensitivity St (-)	5-50	13-63	5-150
Plasticity index IP (-)	11-17	8-25	8-17
Overconsolidation ratio OCR (-)	2-4	3-4	2-6
Clay content CC (%)	35-43	50-53	40-47

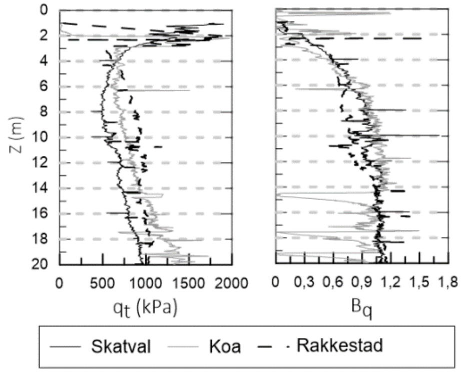

Figure 1. CPTU tests at each site.

3 LABORATORY TESTS

Selected samples were studied at the NGU laboratory in Trondheim, Norway. The analyses included: a) mineralogical analyses on the bulk and the < 6 μm fraction using x-ray diffraction method (XRD), b) chemical analyses using the x-ray fluorescence method (XRF), and c) carbon analysis i.e. Total Carbon (TC) and Total Organic Carbon (TOC). Additionaly, standard and advanced laboratory testing (triaxial tests, oedometer tests and direct simple shear tests) were performed on high quality block samples from these sites. The results are presented in Paniagua et al. (2017) and L'Heureux et al. (2018).

4 TEST RESULTS

Table 2 shows the results of the XRD analysis. Muscovite dominates over chlorite in the < 6 μm fraction for Koa and Skatval clays, and the bulk fraction for Rakkestad clay. The muscovite content in weight is comparable with the quartz content for the bulk fraction of all clays. This trend would be different in terms of volume since muscovite are flat and elongated particles. Hence there is much more muscovite per volume than quartz, something that might affect the physical properties of the clay. Table 3 presents the results of the XRF analysis which represent around 99% of the chemical compounds. SiO_2 dominates for both fractions (i.e. < 6 μm and bulk) in all clays.

Table 2. Results of the XRD analysis. Results are presented as %weight.

Site	Depth (m)	Fraction	Quartz	K-feldspar	Plagioclase	Calcite	Dolomite	Hornblende	Muscovite	Chlorite
Koa	5.00	< 6 µm	16.0	3.0	12.0	8.0	1.0	6.0	41.0	13.0
	5.40		19.0	2.0	13.0	8.0	1.0	7.0	39.0	11.0
	6.10		17.0	3.0	12.0	8.0	1.0	6.0	41.0	12.0
	6.85		13.0	3.0	10.0	7.0	1.0	5.0	49.0	12.0
	7.60		15.0	3.0	11.0	8.0	1.0	6.0	44.0	12.0
	8.40		19.0	3.0	12.0	8.0	1.0	7.0	39.0	11.0
	8.85		15.0	3.0	11.0	7.0	1.0	6.0	45.0	12.0
	6.85	Bulk	30.0	4.0	18.0	6.0	traces	3.0	30.0	9.0
	8.85		23.0	3.0	16.0	7.0	2.0	5.0	35.0	9.0
Skatval	3.25	< 6 µm	11.0	6.0	14.0	1.0	1.0	9.0	45.0	13.0
	3.50		18.0	7.0	18.0	1.0	1.0	8.0	37.0	10.0
	4.55		13.0	5.0	14.0	1.0	1.0	9.0	46.0	11.0
	5.40		11.0	6.0	14.0	1.0	1.0	6.0	47.0	14.0
	6.50		14.0	7.0	15.0	2.0	1.0	7.0	43.0	11.0
	6.90		13.0	6.0	14.0	1.0	1.0	7.0	45.0	13.0
	7.25		13.0	5.0	15.0	2.0	1.0	8.0	45.0	11.0
	7.60		13.0	4.0	15.0	2.0	1.0	9.0	44.0	12.0
	4.55	Bulk	29.0	3.0	22.0	2.0	2.0	6.0	27.0	9.0
	7.25		30.0	3.0	22.0	3.0	2.0	6.0	26.0	8.0
	7.60		29.0	4.0	22.0	3.0	1.0	6.0	26.0	9.0
Rakkestad	5.25	Bulk	22.0	2.0	16.0	traces	1.0	4.0	46.0	9.0
	6.20		30.0	4.0	18.0	1.0	traces?	4.0	36.0	7.0
	6.35		24.0	4.0	17.0	1.0	1.0	4.0	40.0	9.0
	10.20		23.0	5.0	16.0	traces	1.0	4.0	43.0	8.0
	10.25		26.0	2.0	17.0	1.0	1.0	3.0	41.0	9.0
	11.30		23.0	4.0	16.0	1.0	traces?	4.0	44.0	8.0
	12.20		25.0	4.0	17.0	traces	1.0	4.0	41.0	8.0
	12.40		24.0	4.0	16.0	1.0	traces?	3.0	44.0	8.0
	15.05		24.0	2.0	17.0	1.0	1.0	4.0	44.0	7.0

Table 3. Results of the XRF analysis. Results are presented as %.

Site	Depth		SiO_2*	Al_2O_3*	Fe_2O_3*	TiO_2*	MgO*	CaO*	Na_2O*	K_2O*	MnO*	P_2O_5*	Loss of ignition*
Koa	5.00	< 6 µm	48.60	18.50	8.56	0.82	4.27	4.51	1.26	4.64	0.11	0.14	7.69
	6.80		48.30	19.10	8.83	0.82	4.24	4.22	1.12	4.94	0.11	0.14	7.85
	8.35		47.10	18.70	8.50	0.84	4.07	4.60	1.12	4.83	0.11	0.14	8.11
	8.85		48.70	18.60	8.43	0.80	4.02	4.29	1.13	4.75	0.11	0.14	7.81
Skatval	3.25	< 6 µm	48.70	19.00	9.41	0.83	5.13	2.25	1.53	4.87	0.10	0.17	6.46
	4.54		51.30	18.60	9.51	0.86	5.25	2.19	1.62	4.63	0.10	0.16	5.53
	7.34		50.20	18.50	9.60	0.85	5.25	2.25	1.58	4.66	0.10	0.16	5.47
	7.62		50.90	18.70	9.70	0.86	5.31	2.34	1.64	4.67	0.10	0.17	5.47
Rakkestad	5.25	Bulk	56.10	17.90	7.74	0.84	3.20	1.73	1.61	4.44	0.12	0.22	5.28
	6.20		61.00	15.90	6.66	0.78	2.74	2.14	1.82	3.76	0.11	0.22	4.47
	6.35		58.00	17.40	7.34	0.83	3.05	1.78	1.80	4.21	0.12	0.23	4.80
	10.20		57.10	17.50	7.49	0.84	3.06	1.72	1.80	4.30	0.12	0.22	4.87
	10.25		58.20	17.00	7.19	0.84	2.95	1.88	1.72	4.11	0.12	0.23	4.90
	11.30		56.20	17.80	7.57	0.80	3.16	1.79	1.64	4.41	0.12	0.21	5.26
Koa	6.85	Bulk	56.50	15.70	6.91	0.84	3.42	4.74	1.85	3.33	0.11	0.17	5.72
	8.85		54.00	16.60	7.30	0.81	3.61	4.68	1.66	3.76	0.11	0.16	6.39
Skatval	4.55	Bulk	59.80	15.50	6.98	0.83	3.86	3.22	2.19	3.13	0.09	0.17	3.94
	7.25		59.70	15.20	6.82	0.83	3.78	3.42	2.22	3.06	0.09	0.17	3.87
	7.60		59.60	15.50	7.01	0.84	3.91	3.44	2.24	3.12	0.09	0.18	3.93

The mineralogical composition agrees with the Norwegian sensitive (i.e. Selnes, Manglerud III, Åsrum I) and non-sensitive clays (Sandnes I & II) reported by Kenney (1967). As Helle (2017) mentions, the clay minerals are layered silicate minerals (phyllosilicates) with a definite crystal structure and chemical composition. Norwegian clays mainly consist of low-active (non-swelling) illite/muscovite and chlorite of the main groups of clay minerals (i.e. kaolinite, smectite, vermiculite, illite/muscovite and chlorite). (Rosenqvist 1955, 1975; Løken 1968).

Figure 2 presents the TC and TOC data as a distribution along the depths. Skatval clay values of TOC and TC are lower than those for Koa and Rakkestad clays. The total carbon content is the highest for Koa clay, however, the total organic carbon content is the highest for Rakkestad clay.

5 COMPARISON WITH INDEX DATA

Figure 3 summarizes the index and mineralogy data for Koa, Skatval and Rakkestad clay. Data for Rakkestad clay include several boreholes and therefore is large variation. In general, all three clays show similar properties. Between 7,5-15 m depth, the clay at Koa tends to show a higher unit weight, lower water content, higher sensitivity, lower plasticity index and lower activity than Skatval and Rakkestad clays; eventhough its content of clay minerals is similar (varies between 40-60%). However, the correlation is not clear. Figure 4 presents a further analysis of the index data and clay minerals for the clays of this study and other Norwegian clays.

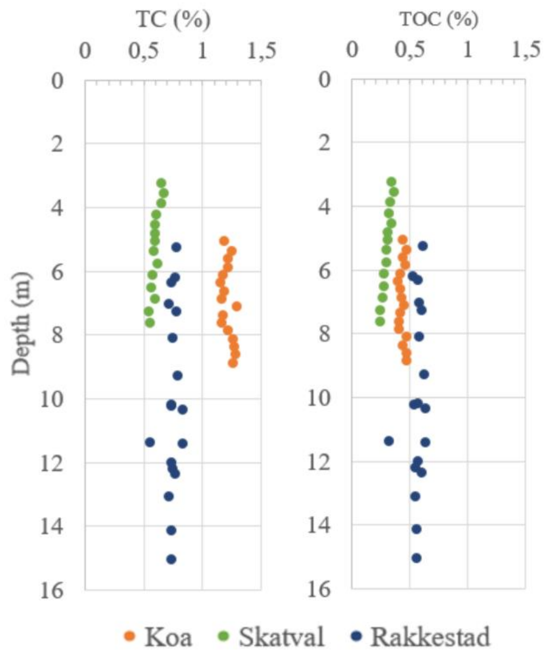

Figure 2. Measurements of TC and TOC.

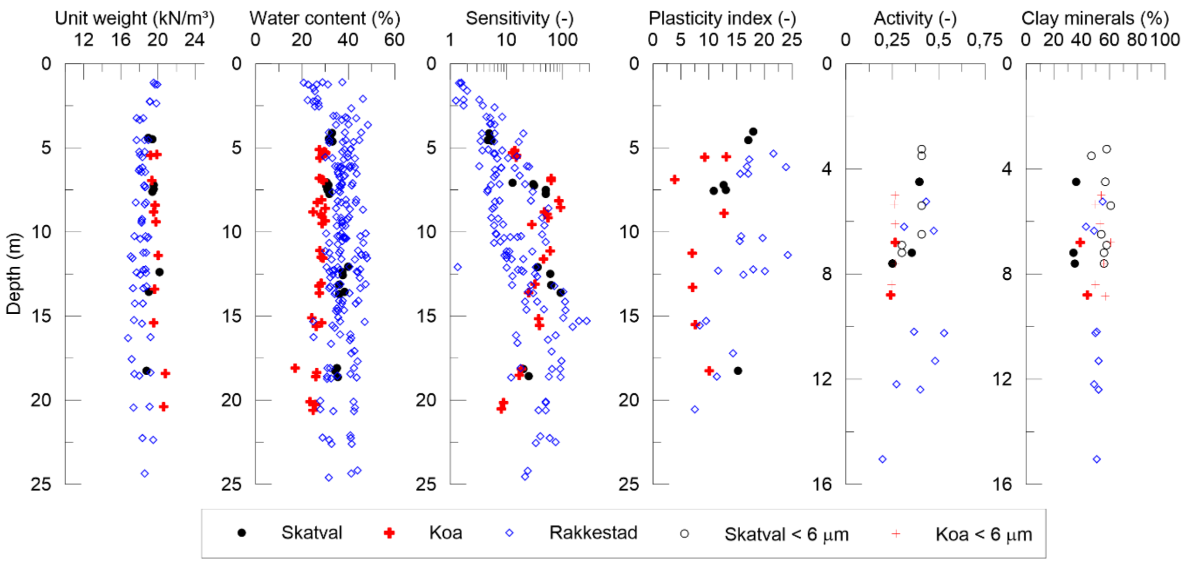

Figure 3. Variation with depth of index and mineralogy data for Koa, Skatval and Rakkestad clay

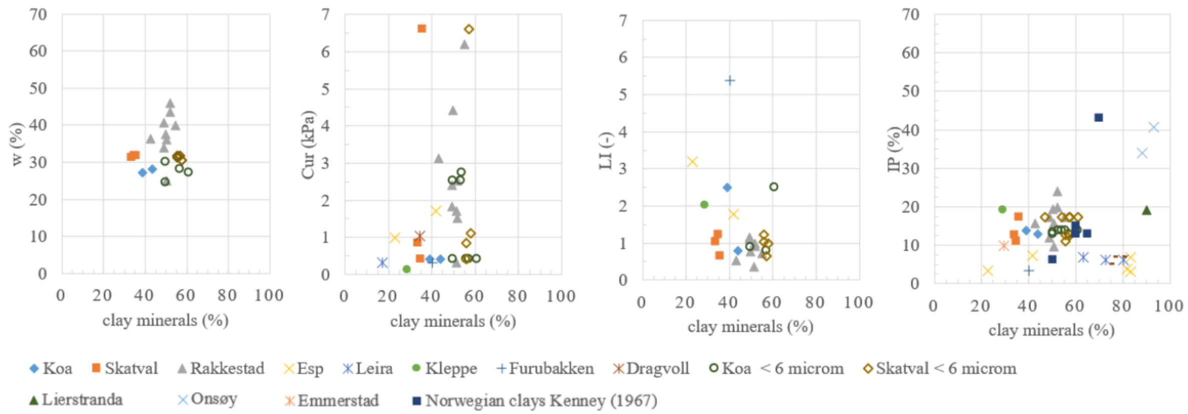

Figure 4. Correlation between clay minerals and water content (w), remoulded shear strength (c_{ur}), liquidity index (LI) and plasticity index (IP) for clays in this study and other Norwegian clays.

Figure 4 illustrates the amount of clay minerals and index data like water content (w), remoulded shear strength (c_{ur}), liquidity index (LI) and plasticity index (IP) for the clays presented in this study and Norwegian clays presented by Kenney (1967), Syversen (2013) and Helle (2017).

The data collected in the present study show a variation in water content between 25-45% which corresponds to a variation range of clay minerals between 35-65%.

For c_{ur} < 0.5 kPa (limit that defines quick clays in Norway), the % clay minerals varies between 20-60% and this range seems to narrow to about 35-55% for sensitive clays (c_{ur} < 2 kPa) and non-sensitive clays (c_{ur} > 2 kPa).

The majority of the values for liquidity index are below 1.5, however, the % clay minerals seems not to have an influence on LI values for Norwegian clays.

Low plasticity clays (IP < 10) show a wide range (between 20-85%) of % clay minerals; medium plasticity clays (10 < IP < 20) shows a narrower range of % clay minerals varying between 35-65%. There are few data with high plasticity clays for the analyzed data that is not possible to conclude the % clay minerals effect on it.

Locat et al. (1984) correlate the amount of phyllosilicates (clay minerals) and amorphous materials on bulk samples to the Atterberg limits and plasticity index (*IP*). Liquid limits (w_L), plastic limits (w_P) and *IP* increase due to increased content of phyllosilicates and amorphous materials. We cannot observed a particular trend with the Norwegian data, however, the amorphous content is not analized in the recent collected data.

6 COMPARISON WITH OTHER CLAYS IN THE WORLD

The results presented herein are compared to values reported in the literature for various clays from different parts of the world. Figures 5 and 6 present the relation between percentage of clay minerals and the clay fraction determined in bulk and clay fraction (i.e. fraction < 6 µm and fraction < 2 µm), respectively. The results show that Norwegian clays have a very high clay minerals content compared to other clays in the world. The lower content of clay minerals from Koa and Skatval respect to the rest of Norwegian clays may be due to the different fraction size that was analyzed. Typical clays from mid Norway (i.e. Leira, Esp, and Dragvoll) show the lowest clay fraction of the Norwegian clays. The highest content of clay minerals is observed for Onsøy and Lierstranda clays (when the bulk fraction was analysed).

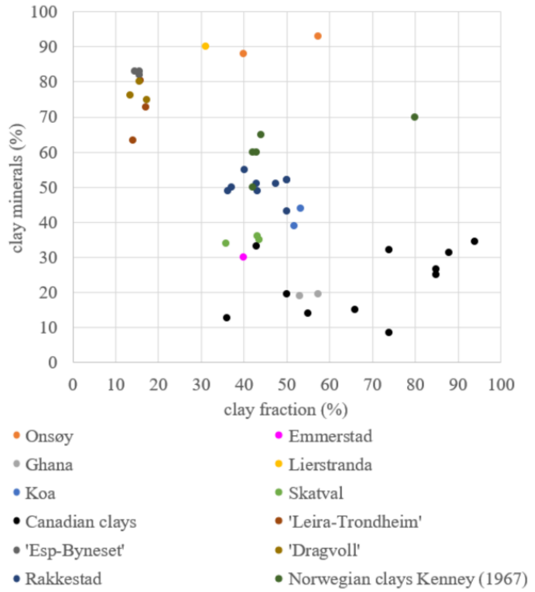

Figure 5. Clay minerals (bulk) vs. clay fraction.

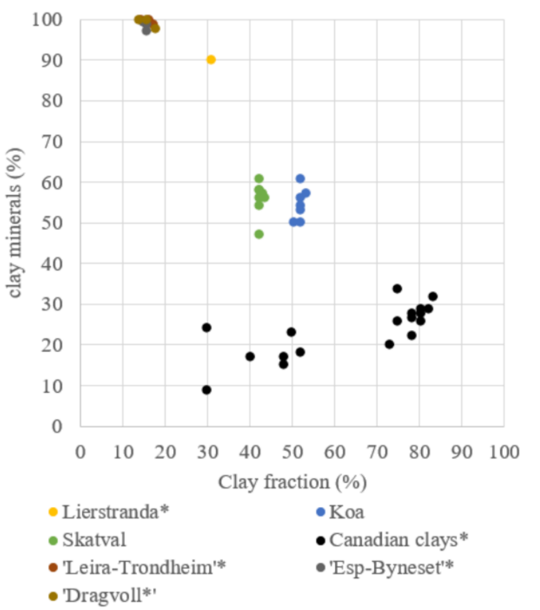

*Figure 6. Clay minerals (in fraction < 6 µm and *fraction < 2 µm) vs. clay fraction.*

Chlorite is the abundant clay mineral in Canadian clays followed by illite and mixed-layer clay minerals consisting of vermiculite (Locat & St. Gelais, 2014). Canadian clays show higher plasticity (up to 52%), and a higher clay content (up to 83%) than found in Norwegian clays.

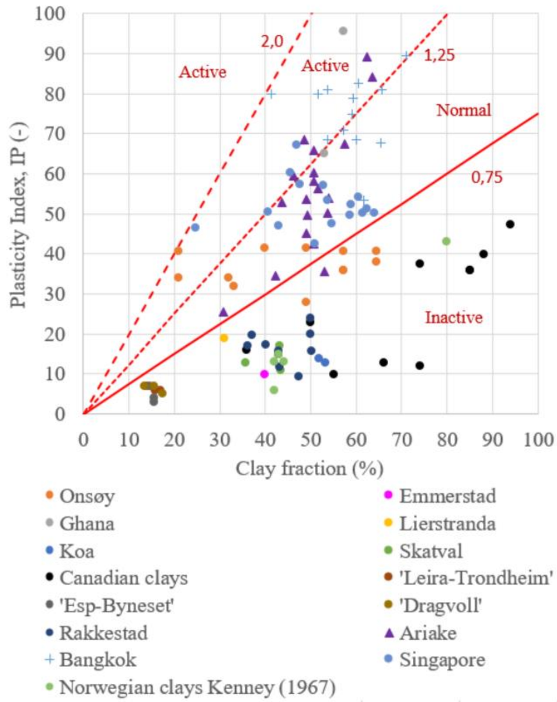

Figure 7. Plasticity index vs. clay fraction

Figure 7 shows the relation between plasticity index IP and clay fraction. The slope of the lines in red defines the activity of clays (A). According to Skempton (1953), significant volume change during swelling and shrinkage of clay is a function of plasticity index and colloidal clay present in the soil. The activity A is defined as the ratio of plasticity index to the percentage of clay-size (i.e. clay fraction = particles of size less than 0.002 mm). Activity is derived conveniently from slope of straight line: a steeper slope represents greater activity. A soil with activity lower than 0.75 is classified as inactive. When the activity values varies between 0.75 and 1.25, the soil is classified as normal. Soil with values higher than 1.25 are classified as active. Some clay minerals like kaolinite, illite and montmorillonite have activity values of 0.38, 0.9 and 7.2, respectively. Clay minerals with kaolinite, a stable clay mineral, will have low activity, whereas those soils with montmorillonite, known to be a type subject to large volume changes depending on available water, will have a high activity value.

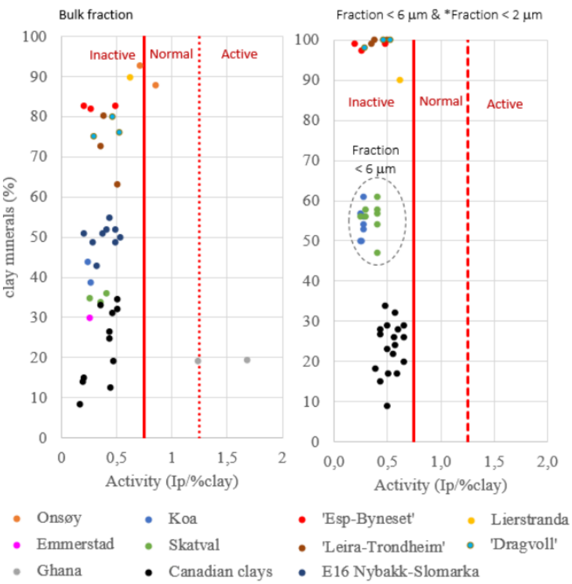

Figure 8. Clay minerals vs. activity of the clays

According to Figures 7 and 8, the Koa, Skatval and Rakkestad clays classify as inactive. This also applies for Canadian clays and the rest of Norwegian clays presented in the figures. The exception is Onsøy clay which has values classifying as inactive, normal and active. Ghana clay, Bangkok clay and some values of Ariake clay fall into active classification. An upper bound of A = 2 is identified for the data shown.

Figure 8 shows the relation between percentage of clay minerals and activity of clays determined in the bulk and clay fraction (i.e. fraction < 6 µm and fraction < 2 µm), respectively. Norwegian clays have a higher percentage of clay minerals than Canadian clays, even though both are classified as inactive. This difference is then defined by the lower plasticity index of the Norwegian clays. Clays from mid Norway tend to have a low plasticity (beacuse of its high silt content) and a high content of clay minerals observed when either the bulk or clay fraction are studied. Koa, Skatval and Rakkestad clays show a content of clay minerals varying between 35-55% when the bulk fraction is analysed. This variation increases to 50-60% in Koa and Skatval clays eventhough the fraction < 6 µm was studied. One might expect a higher clay mineral content is the fraction < 2 µm was studied.

Organic matter absorbs water and causes clay-sized particles to aggregate forming an open fabric. This may cause an increase in water content and plasticity, and a decrease in the total unit weight. However, when comparing TOC with water content for the soil data collected in the present study, no particular impact of the total organic carbon content was seen on the water content.

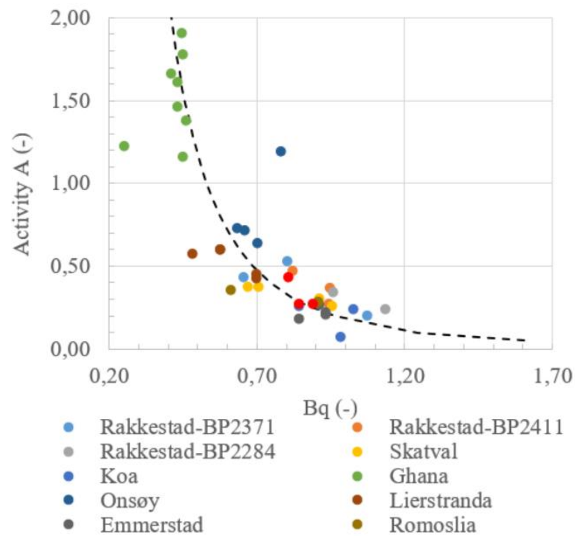

Figure 9. Comparison between the pore pressure parameter B_q and the activity (A) of the various clays in this study.

7 COMPARISON WITH CPTU PARAMETERS

The cone penetrometer is a widely used instrument in geotechnical engineering in Norway and elsewhere in the world. However, few studies have looked into the impact of mineralogy and/or clay content on the CPTU response in soils. Figure 9 compares the measured activity of the clays in the present database with the pore pressure parameter B_q measured from the CPTU tests. There seems to be a trend of increasing B_q with a lowering of the activity in the clay. This means that the lower the activity of the clay, the higher the pore pressure generation will be at a given depth in a clay deposit. The best fit equation shown on Figure 10 is given by the relationship [1], however, more research is needed before making further conlusions.

$$B_q = 0.53 \text{ x } (\text{Activity})^{-0.37} \quad n=42;\ r^2=0.72 \quad [1]$$

8 CONCLUSIONS

The present paper summarizes the mineralogical, chemical and physical data collected for Koa clay, Skatval clay and Rakkestad clay. The data has been compared to similar data from other Norwegian and worldwide clays. In general, Norwegian clays are inactive and with a relatively high content of clay minerals. Further analysis of the presented data must include a cross-correlation study with field data (i.e. CPTU) and laboratory data collected at the sites. This might give a better background for answering the uncertainties regarding the database scatter, the similarities / differences between the clay types and will help in establishing reliable correlations for soil parameter determination.

9 REFERENCES

Bo, M.W., Arulrajah, A., Sukmak, P. & Horpibulsuk, S. 2015. Mineralogy and geotechnical properties of Singapore marine clay at Changi. Soils and Foundations 55(3):600-613.

Gylland A., Long M., Emdal, A. & Sandven, R. 2013. Characterisation and engineering properties of Tiller clay. Engineering Geology 164: 86-100.

Hilmo, B.O., 1989. The Mineral Composition, Chemistry of Colloids and Mechanical Properties of Marine Sensitive Clays. PhD Thesis NTNU, Trondheim.

Horpibulsuk, S., Shibuya, S., Fuenkajorn, K., Katkan, W. 2007. Assessment of engineering properties of Bangkok clay. Can. Geotech. J. 44 (2), 173–187.

Kenney, T.C. 1967. The influence of mineral composition on the residual strength of natural soils. In *Proceedings of the Geotechnical Conference*, Oslo, Norway. pp. 123-129.

Locat, J. & St-Gelais, D. 2014. Nature of sensitive clays from Quebec. In Landslides in sensitive clays: From geoscience to risk management, pp. 25-37

Locat, J., Lefebvre, G. & Ballivy, G. 1984. Mineralogy, chemistry, and physical properties interrelationships of some sensitive clays from Eastern Canada. Canadian Geotechnical Journal 21: 530-540.

Lunne, T. 2002. Engineering properties of lean Lierstranda clay. In: Coastal Geotechnical Engineering in Practice.

Lunne, T., Long, M., and Forsberg, C.F. 2003. Characterisation and engineering properties of Onsøy clay. Proc. Int. Works. on Charact. Eng. Prop. of Natural Soils, pp. 395–428.

Løken T. 1968. Kvikkleiredannelse og kjemisk forvitring i norske leirer. NGI Publ. 75, pp. 1-9.

NGI. 2014. Ghana Laboratory Testing. 9756 Geotechnical Report Part B. Report 20140080-01-R. 23.10.2014.

Paniagua, P., L'Heureux, J-S., Caroll, R., Kåsin, K., Sjursen, M. and Amundsen, H. 2017. Evaluation of sample disturbance of three Norwegian clays. Proc. 19th ICSMGE, Seoul: 481-484. www.issmge.org

L'heureux J.-S., Gundersen A.S., D'Ignazio M., Smaavik T.F., Kleven A., Rømoen, M., Karlsrud K., Paniagua P. & Hermann S. 2018. Impact of sample quality on CPTU correlations in clay – Example from the Rakkestad clay. Proc. CPT 2018 Delft.

Rosenqvist IT (1955) Investigations in the clay-electrolyte-water system. NGI Publ. 9, pp. 1-125.

Syversen, F.S.G. 2013. Et studie av den mineralogiske sammensetningen i norske sensitive leirer med et geoteknisk perspektiv. MSc thesis, Universitet i Oslo.