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PEETER TALVISTE

Temporal changes in weak natural and artificial soils – influence on geotechnical characteristics

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Temporal changes in weak natural and artificial soils – influence on geotechnical characteristics

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Institute of Ecology and Earth Sciences, Faculty of Science and Technology, University of Tartu, Estonia.

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following published Papers, which are referred to in the text by their Roman numerals. The Papers are reprinted by kind permission of the publishers.

I Talviste, P.; Hang, T.; Kohv, M. (2012). Glacial varves at the distal slope of Pandivere–Neva ice-recessional formations in western Estonia. Bulletin of the Geological Society of Finland, 84, 7–19.

II Hang, T.; Talviste, P.; Reinson, R.; Kohv, M. (2007). Proglacial sedimentary environment in Pärnu area, western Estonia, as derived from the varved clay studies. In: P. Johansson; P. Sarala (Eds). Applied Quaternary research in the central part of glaciated terrain. Geological Survey of Finland, Special Paper 46, 79–86.

III Kohv, M.; Talviste, P.; Hang, T.; Kalm, V. (2010). Retrogressive slope failure in glaciolacustrine clay: Sauga landslide, western Estonia. Geomorphology, 124(3–4), 229–237.

IV Kohv, M.; Hang, T.; Talviste, P.; Kalm, V. (2010). Analysis of a retrogressive landslide in glaciolacustrine varved clay. Engineering Geology, 116(1–2), 109–116.

V Kohv, M.; Talviste, P.; Hang, T.; Kalm, V.; Rosentau, A. (2009). Slope stability and landslides in proglacial varved clays of western Estonia. Geomorphology, 106, 315–323.

VI Talviste, P.; Sedman, A.; Mõtlep, R.; Kirsimäe, K. (2013). Self-cementing properties of oil shale solid heat carrier retorting residue. Waste Management & Research, 31(6), 641–647.

VII Sedman, A.; Talviste, P.; Mõtlep, R.; Jõeleht, A.; Kirsimäe, K. (2012). Geotechnical characterization of Estonian oil shale semi-coke deposits with prime emphasis on their shear strength. Engineering Geology, 131–132, 37–44.

VIII Sedman, A.; Talviste, P.; Kirsimäe, K. (2012). The study of hydration and carbonation reactions and corresponding changes in the physical properties of co-deposited oil shale ash and semicoke wastes in a small-scale field experiment. Oil Shale, 29(3), 279–294.

IX Mõtlep, R.; Kirsimäe, K.; Talviste, P.; Puura, E.; Jürgenson, J. (2007). Mineralogical Composition of Estonian Oil Shale Semi-Coke Sediments. Oil Shale, 24(3), 405–422.

Author's contribution

Paper I: The author was primarily responsible for collection, evaluation and synthesis of geotechnical data, discussions and writing of the manuscript.

Paper II: The author was primarily responsible for research planning and fieldwork; collection, evaluation and synthesis of geotechnical data and writing (about 40%) of the manuscript.

Paper III: The author is responsible for field work planning and fieldwork, designing of laboratory testing program, interpretation and synthesis of obtained geotechnical data and slope stability modelling concept, and writing (about 30%) of the manuscript.

Paper IV: The author is responsible for field work planning and fieldwork, for laboratory testing program, interpretation and synthesis of obtained geotechnical data and slope stability modelling concept and writing (about 20%) of the manuscript.

Paper V: The author is responsible for planning the research, interpretation and synthesis of obtained geotechnical data and slope stability modelling, and writing (about 20%) of the manuscript.

Paper VI: The author was primarily responsible for planning original research and experimental setups, geotechnical testing and data analysis, and writing of the manuscript.

Paper VII: The author was responsible for experiment planning and fieldwork, obtaining and interpretation of geotechnical data, and for writing (about 30%) of the manuscript.

Paper VIII: The author was primarily responsible for original field experiment idea, planning and running of experiments, collection of geotechnical data, interpretation and synthesis of geotechnical data, and writing of the manuscript (about 50%).

Paper IX: The author was responsible for filed data collection, interpretation of material analysis data and writing of the manuscript (about 25%).

1. INTRODUCTION

Understanding the long-term behaviour of weak soils requires integrating data gathered at various scales and on different properties-processes. To this day standardized stability calculations provide sufficient information about stability of individual soil sites e.g slopes. However, spatial variability of the soils, short and long term processes within unstabilized sediments like geologically young clays and/or chemically-mineralogically-structurally metastable artificial soils piled up at industrial landfills, affect the reliability of predictions by introducing large uncertainties. Without knowing the degree of variability and understanding the physical and/or chemical status and reactions, it is difficult to assess the potential geotechnical stability of such formations.

In this thesis geotechnical properties of soft, highly porous, natural and artificial soils are discussed. The main topics, discussed in nine appended papers, distinguish various geochemical, geotechnical and geomorphological aspects related to the origin and dynamics of varved clays of western Estonia and oil shale retorting waste as well as processes that determine the physical-mechanical (geotechnical) properties, which influence the stability of natural and man-made deposits.

Both soil types under consideration are very porous and consist about one part of solids and two parts of voids in volume. In terms of soil mechanics both have maintained loose post-sedimentation state under considerable overburden due to geochemically determined bonding. Both soil types, in terms of time, tend to lose that bonding due to geomechanical and geochemical impacts as soon as equilibrium conditions change.

Bonding determines not only the ability of the solids to preserve their skeleton under the pressure of overburden, but also the strength by adding the cohesive component to the otherwise frictional strength of the porous granular matter. Degradation of these bonds means decrease of overall strength of frictional matter and may ultimately lead to a failure – landslide or yield of dams or waste depositories. Therefore, the knowledge of the nature and the timeframe of these processes inducing degradation of the bonds is of major importance in order to assess the long-term stability of the natural and man-made structures. By using the geochemical and geomorphological framework, together with engineering skills, the accuracy of the engineering predictions can be raised and thus, hazard to the people and environment minimized.

General goal of this thesis is to summarize and analyze geotechnical properties and long term behaviour of soft lateglacial varved clays and landfilled waste from oil shale retorting processes with respect to their environmental and compositional changes.

Specific objectives of this thesis are:

- to compare the geotechnical properties of the varved clays in Pärnu with geotechnical properties of clays in other landslide areas, and to understand the nature of the geomechanical properties of the varved clay;

- to allocate the western Estonian landslides within the framework of landslide classification by Simons et al. (2001) and Rankka et al. (2004);
- to explain the mechanism of strength decrease in varved clays at river valley slopes by applying the theory of critical state soil mechanics (Schofield and Wroth, 1968), and to show that the relatively young overconsolidated natural clays follow the framework deduced from laboratory experiments using reconstituted clay samples;
- to establish the relationship between varve thickness (together with changes in the ratio of seasonal lamina thickness within single varve) and natural water content of the varved clay;
- to construct a spatial distribution model of the varved clay units in Pärnu by applying the relationship between the varve thickness and water content on the extensive geotechnical data, and to explain some aspects of the post-glacial paleogeographical conditions in the area;
- to propose the possible methods for cementation control by describing the geochemical and geomechanical deterioration of ettringite cementation in semi-coke waste dumps and its corresponding impact to the stability of the waste heaps;
- by describing the geochemical and geotechnical aspects of black ash cementation envisage the direction of further investigations in order to obtain low permeability and high strength of black ash deposits.

2. LATE GLACIAL VARVED CLAYS: LONG TERM STABILITY OF EROSIONAL RIVER VALLEYS IN WESTERN ESTONIA

According to spatial distribution and bathymetry models of the Baltic Ice Lake in the eastern Baltic (Rosentau et al., 2009; Vassiljev et al., 2011; Vassiljev and Saarse, 2013), relatively deep water (20–40 m) conditions remained in western Estonia for at least as long as the ice margin stood at a place of a present day Salpausselkä I formations (12.3–12.1 ky BP) in southern Finland. In western Estonia this long lasting (>1000 yrs) deep-water Baltic Ice Lake stage left behind widely distributed fine-grained glaciolacustrine sediments, including rhythmically deposited clays.

Glacial varved clays with their characteristic summer (silty) and winter (clayey) laminas are suggested to reflect seasonal variations in sediment deposition in the proglacial lake (De Geer, 1884, 1940). The variability of thickness, inner structure and fabric of the varves can provide specific details about the proglacial environment, water depth and deglaciation. These changes also reflect the geotechnical properties of the clay sequences: the water content and plasticity whereas both indexes have higher values in more clayey (winter) part of the varve. More recent water-level changes of the Baltic Ice Lake near the Pärnu area have influenced the mechanical properties of the varved clay complex.

In western Estonia recent landslides can be found at lower course of Audru, Sauga and Pärnu rivers where river valley slopes dip into the glaciolacustrine plain (Fig. 1). Flat topography and low altitude led to a belief that these regions are of low landslide hazard areas (Miidel and Raukas, 2005). However, in recent decades the number of landslides in the area has grown (Kalm et al., 2002; Talviste et al., 2004; Kohv, 2005).

Recent landslides are mapped and the mechanisms that set off landslides are well analyzed (Kalm et al., 2002; Kohv et al., 2009 – PAPER V; Kohv et al., 2010 – PAPER III; Kohv et al., 2010a – PAPER IV and Kohv, 2011).

Available data, both geological and geotechnical, enable an interdisciplinary approach of the data evaluation and reveale new aspects in post-glacial geomorphology and recent landslide developments at river valleys of western Estonia.

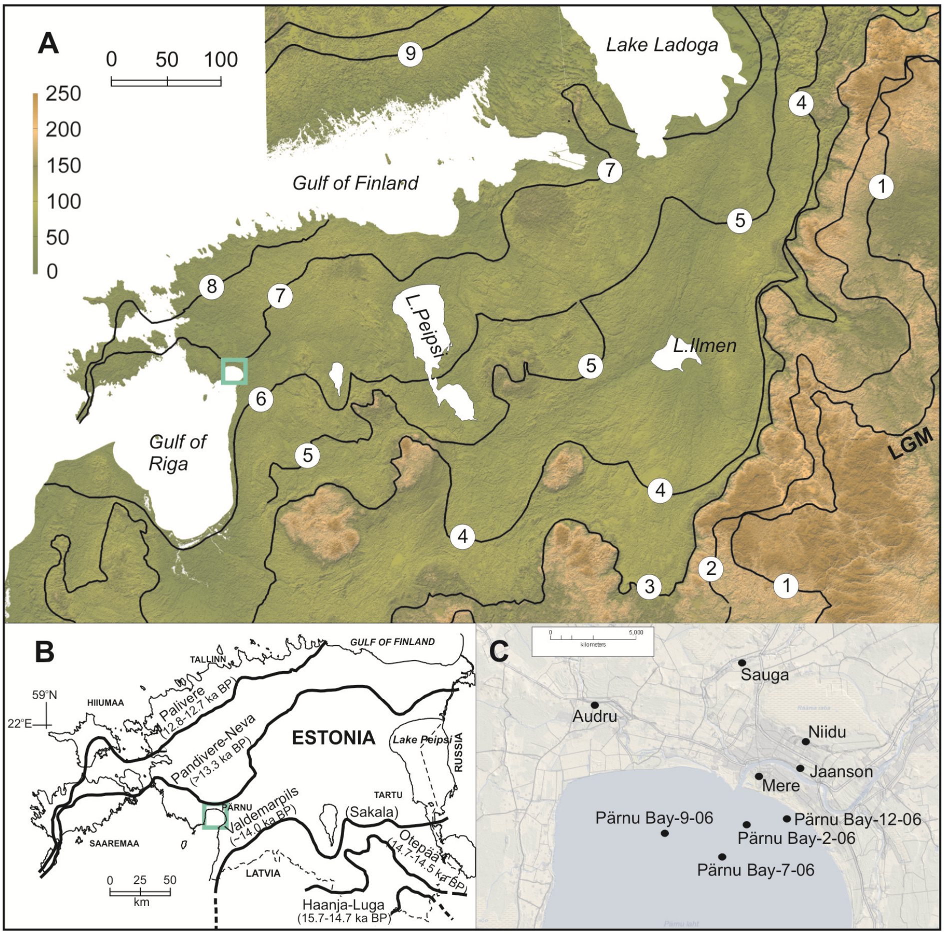

Figure 1. Location of the study area in coastal Estonia, eastern Baltic, with Late Weichselian ice-marginal formations (Kalm, 2010) (A), corresponding ages according to Kalm (2006) (B), and the positions of the discussed sites (C). Ice-marginal zones: 1 = Last Glacial Maximum (LGM), 2 = Vepsian in Karelia and western Russia (Baltija, Pomeranian), 3 = Sebezha and Krestets in Russia and Karelia (South Lithuanian), 4 = Haanja–Luga in Russia and Estonia, Linkuva in Latvia (North Lithuanian), 5 = Otepää, 6 = Valdemarpils and Sakala in Latvia and Estonia, 7 = Pandivere–Neva in Estonia, Russia and Karelia, 8 = Palivere, 9 = Salpausselkä I (Rugozero in Karelia). From Talviste et al. (2012 – PAPER I).

2.1. Geotechnical properties of the varved clay complex in Pärnu

According to geotechnical parameters (Talviste, 1988), mineralogical and chemical composition (Kattel, 1989) and varve thickness, inner structure and fabric (Hang et al., 2007 – PAPER II), the clay complex in Pärnu is divided into five units A – E (Table 1).

Table 1. Clay units distinguished in the varved clay complex in Pärnu (Hang et al., 2007 – PAPER II)

Unit	Description
A	Dehydrated greenish-grey clay, varve structure destroyed due to emergence after clay accumulation and due to soil forming processes
B	Varved clay containing a series of thin winter layer dominating clayey, hardly distinguishable seasonal couplets
C	Varved clay, varves are winter layer dominating with clearly distinguishable clayey seasonal couplets; total varve thickness is less than in unit E and is decreasing upwards. Where present, the lower boundary with unit D is sharp
D	Waterline glacial diamiction; grey massive silt-clay with dispersed grains of sand/gravel; discontinuous lateral distribution; maximum known thickness 8 m
E	Varved clay; summer layer dominating varves with clearly distinguishable seasonal layers; thickest varves of clay sequence with upwards decreasing varve thickness; unstable sedimentary environment close to the ice margin is reflected in multiple graded summer layers with rare ripples, where present the upper boundary with unit D sharp otherwise the transition from unit E to C displays continuous lamination

The corresponding characteristic geotechnical properties for units A–E are given in Table 2 (Talviste, 1988; Kattel, 1989; Eek, 1989).

Table 2. Geotechnical index properties and field vane test amplitude within the clay units in Pärnu varved clay complex.

Unit	Water content wN, %	Liquid limit 1) $wL_{(C)}$, %	Plasticity index I_P	$CaCO_3$ cont., %	Undrained shear strength, c_U, kPa	Residual shear strength, c_R, kPa	Sensitivity, $S_t = c_U / c_R$
A	30…65	80	45	–	>50	–	–
B	70…90	60…100	35…65	2.5	13…45	c_R= 2+0.28c_U (r=0.7)	S_t<5 (95%) (Fig. 11)
C	50…70	50…90	25…55	3.8	19…48		
D	30…40	30…65	10…40	10.9	24…46		
E	30…60	30…80	10…45	11.1	25…75		

1) $w_{L(C)}$ (Casagrande, 1958) is calculated from GOST 25100–95 liquid limit ($w_{L(V)}$) using the equation $w_{L(C)} = 1.24*w_{L(V)} – 2.16$ (Lemberg and Oll, 1992).

Typical geological-geotechnical section (test site Jaanson-1-09) of the varved clay in Pärnu is presented on the Figure 2 (Talviste et al., 2012 – PAPER I) with field vane test results (Kohv, 2011).

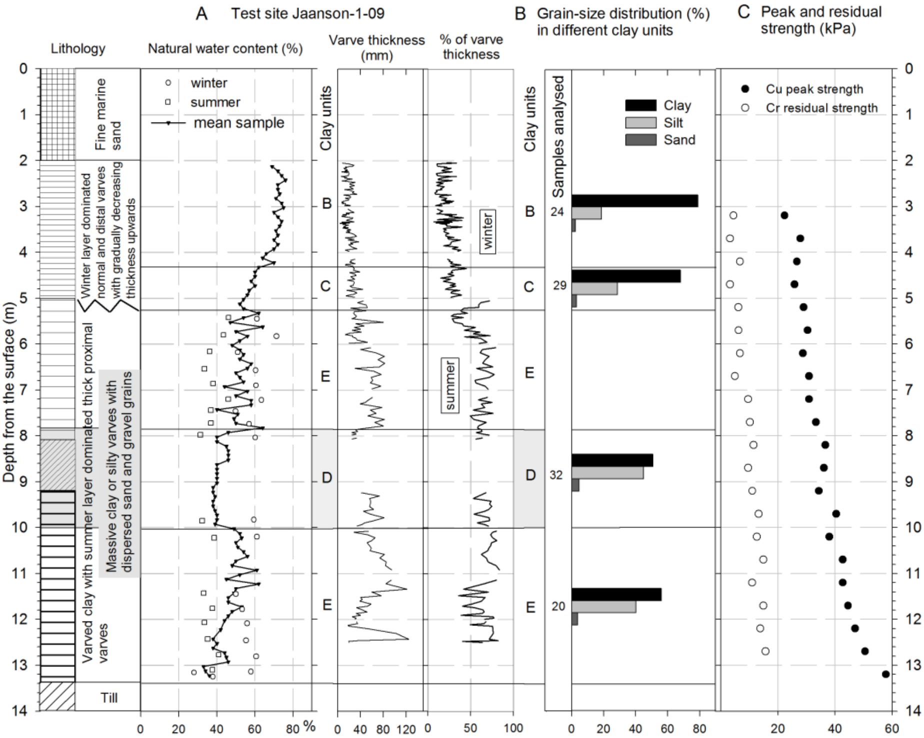

Figure 2. Lithology and different clay units distinguished according to vertical changes in the natural water content, varve thickness and ratio of seasonal layer thickness within a varve (A), generalized grain-size composition of clay units (B) and peak and residual undrained shear strength from vane tests (C). (Talviste et al., 2012 – PAPER I), field vane test results (Kohv, 2011).

The plasticity chart (Whitlow, 2001) of distinguished units B–E (Fig. 3) shows that subunit B is clay with very high plasticity ($w_{L(C)} > 70\%$), subunit C is clay with mainly high plasticity ($w_{L(C)} = 50$–70%) and subunits E and D are mainly clays with intermediate to high plasticity ($w_{L(C)} = 30$–70%). It is evident that the proportion of winter and summer layers within varves determines the average clay content of the subunits (Hang et al., 2007 – PAPER II), which is well illustrated in Figure 4.

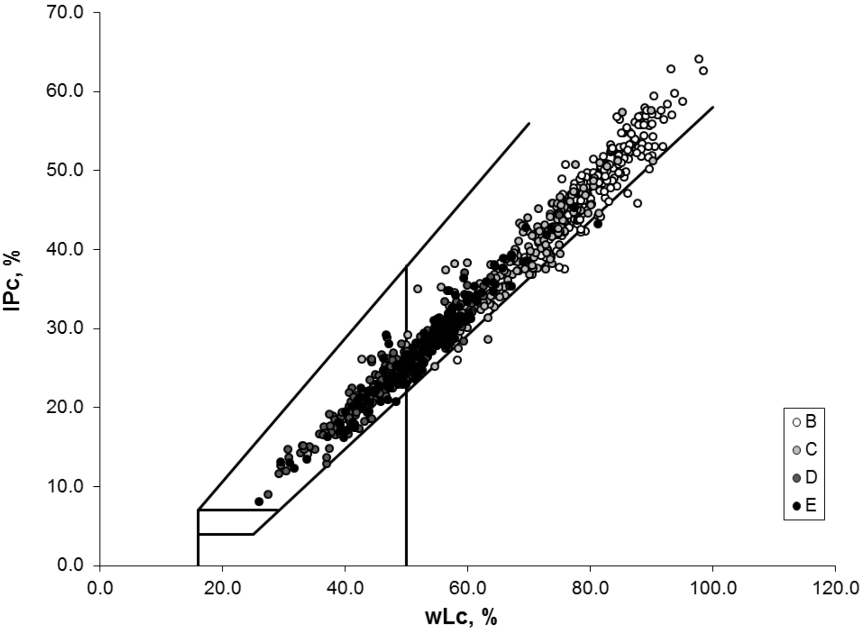

Figure 3. Plasticity chart of the varved clay units B–E in Pärnu (data from IPT Projektijuhtimine database).

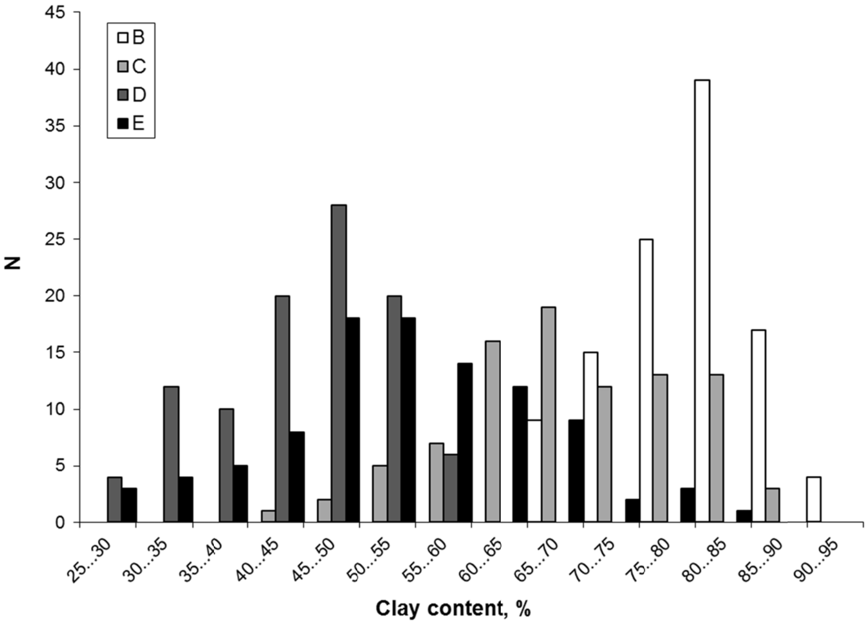

Figure 4. Average clay content (<0.002 mm) of the varved clay units B–E in Pärnu (data from IPT Projektijuhtimine database).

2.2. Comparison of varved clay complex in Pärnu with common landslide related clay deposits – stiff fissured clays and quick clays

Recorded landslide events belong into two general types (Simons et al., 2001) – undrained failure or drained failure. The first type occurs in the situation where the time of slope existence is too short for significant changes in effective stress to occur and, hence, the strength of the soil has not developed yet. These types of landslides (quoted also as short-term stability landslides) are mostly related to the fresh cuttings and are not relevant if landslides in natural slopes are discussed. The second group of landslides, referred to as long term stability landslides, occur if the time before the failure is long enough for the pore water pressures to change, thus changing effective stresses and hence the strength of the soil.

Simons et al. (2001) considered four long-term stability cases:

- first time slides in intact clays (intact clay has no structural discontinuities such as fissures, slickensides, bedding planes, slip surfaces);
- first time slides in cuttings in stiff fissured clays;
- natural slopes in stiff fissured clays;
- slides on pre-existing slip surfaces;

In addition to these, Rankka et al. (2004) shows that almost all landslides involving clays in Sweden, Norway and Canada can be designated as “quick clay” slides. Therefore, the fifth type – natural slope failures in “quick clays” – could be added.

The “quick clay” refers to clay which structure collapses completely at remoulding and which shear strength is thereby reduced almost to zero. “Quick clay” is defined as clay with sensitivity of 50 or more, and fully remoulded shear strength of less than 0.4 kPa (Rankka et al., 2004).

Most of the “quick clays” are clayey sediments deposited in sea water during last deglaciation (Rankka et al., 2004). However, clays deposited in fresh water, and which have flocculated structures and low activity, may also become “quick” due to the action of different dispersing agents (Söderblom, 1974). Söderblom (1974) also showed an example of a natural, “quick”, fresh water clay beneath peat deposits.

As far as the nature of the clay yield in “quick clays” is unique and the “quick clay” phenomena is extremely important in regions once covered by thick ice-sheet during the last glaciations, the landslides in “quick clays” are dealt as separate group of long-term stability case in present thesis.

Geotechnical properties of the varved clay units in Pärnu area, including landslide sites and some other clay deposits in Estonia and abroad are presented in the Table 3.

Table 3. Geotechnical properties of analysed clay formations and reference data of similar clays.

Description	w_N, %	E	$CaCO_3$ %	$w_{L(C)}$, %	c_U, kPa	c_R, kPa	S_t	σ_{VO}' kPa	I_{VO}	Source
London clay	22.6–25.7	0.62–0.71	–	59.9–70.6	100–300	–	–	117–455	–1.07 – –1.20	Burland, 1990
Cambrian clay, Sillamäe	17.7–21.0	0.49–0.58	–	55.1–64.6	53–354	–	–	100–300	–1.36 – –1,61	Barnekow and Talviste, 2002
Drammen river valley lean clay	30–40	0.81–1.10	–	27–38	10–30	2–3	4–10	–		Kjaernsli and Simons, 1962
Lodalen lean clay	41		–	36	40–70	10–35	2–6	–		Sevaldson, 1956
Bothkennar NC clay	50–70	1.35–1.90	–	70–80	12–50	2–10	2–9	–		Hawkins et al., 1989
Utby “quick clay” at Göta river valley	55–75	1.60–1.76	–	41–52	20–50	0.4–7	5–500	140–230	3.22–3.37	Osterman, 1963; Rankka et al, 2004
Niidu B	81	2.23	1.1–2.5	78.3	30	10	3	70	1.78	Talviste and Listra, 1988
Niidu C	68.5	1.87	8.4–12.6	67.0	30	11	2.7	85	1.68	
Niidu D	42.2	1.14	10.3–12.0	44.9	35	14	2.5	120	1.15	
Niidu E	45.6	1.24	7.8–12.8	50.9	58	14	4.1	150	1.01	
Mere B	72.3	2.00	–	85.2	41	13	3.1	80	1.02	
Mere C	58.9	1.62	–	73.3	44	19	2.3	110	0.78	
Mere D	48.4	1.32	–	60.3	–	–	–	115	0.69	
Mere E	48.5	1.32	–	56.5	51	15	3.4	150	0.90	
Audru B	78.0	2.15	–	76.8	15	2.5	3.0	40	1.69	Sedman and Talviste, 2012
Audru wet	80.7	2.21	–	65.4	16	3	2.7	60	2.58	
Sauga dry	54.8	1.51	–	80.0	46	–	–	15	0.31	Kohv et al., 2010; 2010a – PAPERS III and IV)
Sauga B	79.4	2.20	–	88.0	20	12	1.7	35	1.25	
Sauga C+E	54.6	1.48	–	50.0	16	10	1.6	65	1.87	

Burland (1990) suggested a void index $I_V = (e–e^*_{100}) / (e^*_{100}–e^*_{1000}) = (e–e^*_{100})/C_C^*)$ as a soil parameter normalizing the compression of the reconstituted (mixed and reconstituted at water content $w_L < w < 1.25–1.5w_L$ without air or oven drying) clays. In the formula the asterisk (*) means that the parameter is for reconstituted clay, the subscript means the corresponding effective stress. The term “intrinsic” has been introduced for the compression line of reconstituted clay (ICL).

According to Burland (1990) void ratio of the intrinsic clay depends on the liquid limit w_L and applied pressure. Nagaraj and Srinivasa Murthy (1986) expressed the equilibrium state between applied stress and forces between clay particles (as a half distance between the particles) via osmotic repulsive pressure and explained the physical aspects of Burland’s (1990) approach.

Comparison of intrinsic void index with void index of various well known soils suggest that during the sedimentation clay minerals are forming certain clusters of particles that are sometimes slightly cemented and based on the empirical regression line fitted to the experimental data Burland (1990) suggested a sedimentation compression line (SCL) that deviates from ICL described above (Fig.5).

Approach proposed by Burland (1990) is used in this thesis by comparison of varved clay units of western Estonia with other clay formations presented in Table 3. Vertical effective pressure σ_{VO}’ is calculated ($\sigma_{VO}' = \Sigma(\gamma \ x \ H) - u$, where γ – unit weight of the unit, H – thickness of the unit and u – pore pressure) based on the geological conditions at sites for the approximate centre of each unit.

In this context the chracteristics of the varved clays in Pärnu area (Table 3, Fig. 5) show that:

1. in general the varved clay units B–E are lying close to SCL proposed by Burland (1990);
2. the exceptions are unit C+E at Sauga landslide site and “wet” clay layer at Audru landslide site lying well above the SCL;
3. the exception is also “dry” desiccated clay layer at Sauga landslide site lying well below the SCL;
4. in general all units at Mere location are close the SCL while the units at Niidu location are lying above the SCL , units B and C are similar to unit C+E at Sauga landslide.

Soil lying below the SCL is overconsolidated due to desiccation or erosion and has smaller porosity (smaller average distance between particles) than it is necessary to compensate the effective stress at corresponding depth. If historic stresses have been large – as an example in London clay (Burland, 1990) and North Estonian Cambrian clay (Barnekow and Talviste, 2002) – the clays are heavily overconsolidated and fissured due to stress release (Fig. 5). Varved clay complex in Pärnu region often shows signs of desiccation in the upper part of the clay complex (Talviste et al., 2012 – PAPER I). Indeed, desiccated clay from Sauga landslide site (Table 3) has similar void index (0.31) as the void index in upper desiccated part of the Bothkennar clay (0.4–0.8; Burland, 1990).

However, soils lying above the SCL have higher porosity (bigger average distance between particles) compared to normal sedimentational clays and the effective stresses are partly compensated with bonds between particles or these can be classified as "quick clays" where the clay particles skeleton is relict and represents a former equilibrium (Bjerrum and Rosenquist, 1956).

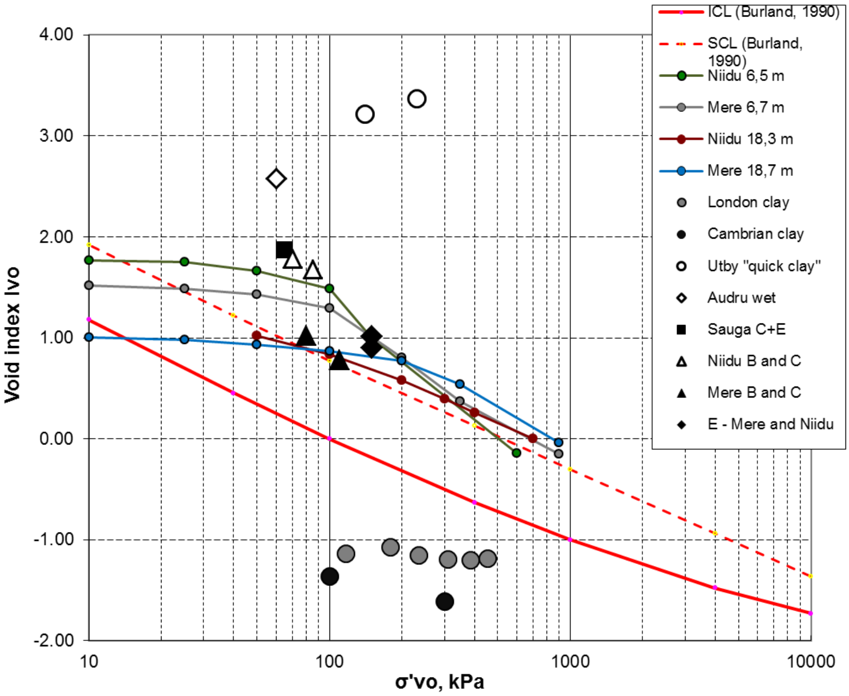

Figure 5. Oedometer compression curves of Niidu and Mere varved clays (Talviste and Listra, 1988) normalized via void index Ivo (Burland, 1990). London clay, Cambrian clay, Utby "quick clay" and important layers from landslide sites Audru and Sauga together with units B, C and E from Mere and Niidu sites are also marked.

Bonded (cemented) clays are often overconsolitaded, due to strength of the bonds, and have specific stress-strain behaviour if the strength of the bonds is exceeded (Nagaraj et al., 1994, 1998). The oedometer compression curves of samples from Niidu core at the depth 6.5 m and Mere core at 6.7 m, both samples representing unit B of varved clay complex in Pärnu, have stress-strain curve shape characteristic for cemented overconsolidated soft clays (Fig. 5).

"Quick clays" are apparently overconsolidated due to non-cemented nature of the additional bonds between the flocculated particles and groups of particles that compensate the *in-situ* stresses during the geological history. These bonds have disappeared during changed geological-climatic-hydrogeological conditions, for example as a result of leaching. Leaching affects the forces between the particles, but normally do not influence the flocculated structure as such (Brand and Brenner, 1981). On the other hand, leaching strongly affects the ability of the particles to re-flocculate after remoulding or yielding. During the rapid pore pressure changes or if the shear stress increases close to peak undrained shear strength the "card-house" like structure of clay particles collapses (Aas, 1981; Gregersen, 1981) and soil temporarily transforms into liquid like mass with minimal residual strength.

Rosenqvist (1978) proposed the following general theory for "quick clay" formation:

1. Clay size particles of non-swelling clay minerals sediment in a flocculated condition since the electrokinetic potential is low (thin electrical double layer thickness), either because the water contain salts or because of adsorption of strongly bonded counter-ions such as Fe^{3+}, Al^{3+}, Ca^{2+} and Mg^{2+}.
2. After deposition and moderate consolidation of the clay the electrokinetic potential increases (i.e. the electrical double layer expands) due to leaching, reduction of trivalent iron to bivalent iron (Fe^{3+} to Fe^{2+}) or bonding of multivalent ions to organic compounds, for example.
3. A subsequent mechanical remoulding of the clay causes a unidirection of the particles. A reflocculation thereafter is not possible because of the strong repulsive forces between the particles and it is only possible to bring the particles into contact again after a considerable reduction in the water content, i.e. consolidation.

Illite and chlorite are examples of non-swelling clay minerals whereas smectite and mixed-layer mineral illite-smectite are swelling clay minerals. All these minerals are present in varved clay complex in Pärnu (Averin, 2007; Palolill, 2007).

The concept of activity of clay minerals was introduced by Skempton (1953) based on the relation between plasticity index and clay content in clay. This relation was designated the activity of the clay, a_C, and is defined as: $a_C = IP/sf\%$, where IP is plasticity index and sf% is clay content. Skempton (1953) found the activity to be different for different clay minerals, but fairly independent of the particle size distribution. He obtained, thus, straight lines when plotting plasticity index versus clay content for each type of clay mineral. Values of activity for some types of clay minerals are (Skempton, 1953; Mitchell, 1976): Muscovite $a_C = 0.23$; Kaolinite $a_C = 0.4 - 0.5$; Smectite $a_C = 1 - 7$; Illite $a_C = 0.5 - 1$. The activity of "quick clay" is normally less than 0.5 (Mitchell, 1976). The activity of varved clay complex in Pärnu is typically >0.5 (Fig. 6). However, several samples, especially from units D and E, show a_C values at about 0.5 and could be considered close to the "quick clay" state.

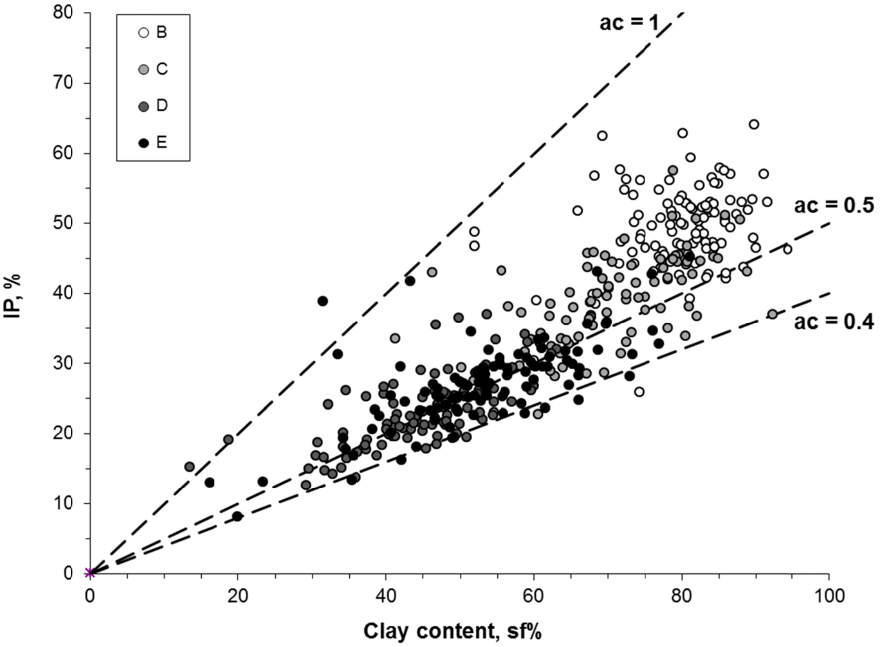

Figure 6. Activity chart of varved clay units B–E (data from IPT Projektijuhtimine database). Ativity of pure kaolinite is a_C= 0.4–0.5, illite a_C = 0.5–1 and smectite a_C = 1–7. Datasets average activity is a_C > 0.5 for all units but there are several samples, especially from units D and E, below the a_C = 0.5 line.

Void index versus effective pressure plot (Fig. 5) shows that properties of the "wet" clay layer at Audru landslide site are remarkably similar to "quick clay" analogue from Utby, Sweden (Rankka et al., 2004, Table 3). Therefore, the sensitivity of varved clay in Pärnu is analyzed in more detail.

Sensitivity (St) of the soil is defined as ratio between the undrained shear strength and remoulded shear strength and soils are grouped as follows (Whitlow, 2001):

St = 1…4 – low sensitive;
St = 4…8 – sensitive;
St = 8…16 – extra sensitive;
St > 16 – quick.

Swedish Geotechnical Institute has proposed a somewhat different classification (Rankka et al., 2004):

St <8 – low sensitivity;
St 8…30 – medium sensitivity;
St >30 – high sensitivity.

The later classification is used in Estonia (Eesti Ehitusteave, 1998, ET-1 0113-0237).

The sensitivity increases with increasing liquidity index, $IL = (w_N - w_L)/(w_L - w_P)$. An increase in liquidity index is caused by leaching, ion exchange or the action of a dispersing substance. Decrease in liquidity index is normally caused by drying, weathering or consolidation (Rankka et al., 2004). The experimental data show that the w_N/w_L ratio should exceed 1.1 if the clay is to be "quick" (Larsson and Åhnberg, 2003).

Vane tests as well the water content and Atterberg limits from the close proximity (horizontal distance <1 m, vertical distance <0.2 m) to the actual vane test location were studied by Eek (1989), 55 test pairs in total. The sensitivity versus w_N/w_L plot using dataset of Eek (1989) (Fig. 7) shows in general low sensitivity (St < 8) of varved clay complex in Pärnu. In comparison the sensitivity of the typical "quick clay" formation in Utby is much higher at the same w_N/w_L values. The overall low sensitivity of the varved clay complex in Pärnu area is further supported by analysis of a larger data-base including vane test results in Pärnu area (Fig. 8).

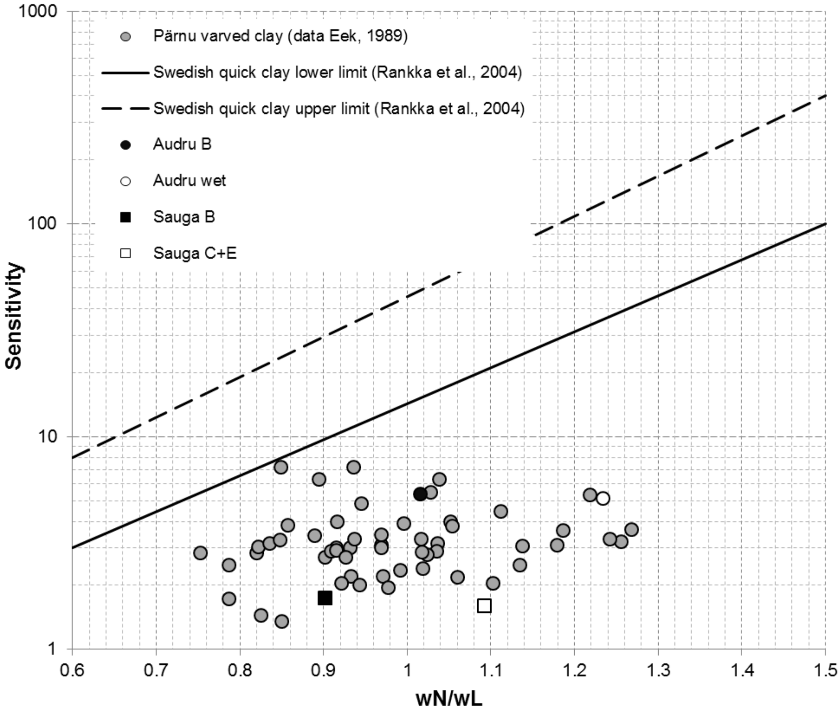

Figure 7. Sensitivity of Swedish "quick clays" (Rankka et al., 2004) compared to the sensitivity of varved clays in Pärnu (Eek, 1989). Sensitivity measured at Audru (Sedman and Talviste, 2012) and Sauga landslide (Kohv et al., 2010 – PAPER III) site is compared.

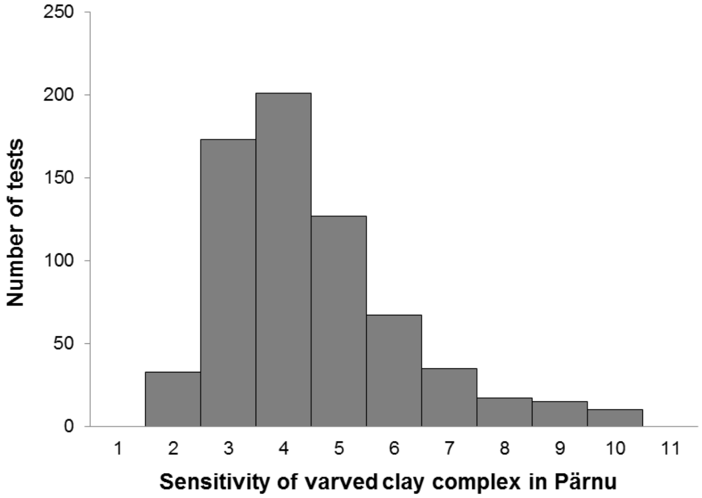

Figure 8. Sensitivity (c_U/c_R) of varved clay complex in Pärnu according to 678 vane test results (data from IPT Projektijuhtimine database).

However, about 15% of the samples have $w_N/w_L > 1.1$, potentially in the zone where "quick clay" formation may occur. In units B and C less than 15% of samples may be considered as problematic regarding the "quick clay" development. For units D and E the share of problematic samples is about 10% and only few samples have w_N/w_L ratio > 1.2 (Fig. 7, Fig. 9).

Varved clays in Pärnu are mainly soft (c_U < 40 kPa) low sensitivity clays (St < 8). They are characterized with high water content close to the liquid limit. Clay is slightly overconsolitated, overconsolidation ratio OCR = 1.3…1.6 (Kalm et al., 2002), at river valley slopes immediately after erosion even up to OCR = 2 due to stress release. Physical properties of the varved clay are similar to normally consolidated clays (like Bothkennar clay, Drammen lean clay, Burland, 1990), although the w_N/w_L ratio is usually higher compared to these analogues.

In this thesis I propose that overconsolidation is due to cemented bonds and that cementation causes the higher water content of varved clays compared to normally consolidated clays.

Nature of the bonding in the varved clays in Pärnu has not been investigated before. The hematite cement has been reported by Wu (1958), carbonates are mentioned as bonding agent in Canadian ice-lake clays (Tavenas et al., 1971). Carbonates are always present in varved clay units B–E (Tables 2 and 3), but can they form cementing bonds needs future study. Although activity chart (Fig. 6) proposes some samples, especially from lower units D and E delicate to "quick clay" formation, the w_N/w_L ratio (Fig. 9) and sensitivity is generally lower for these units.

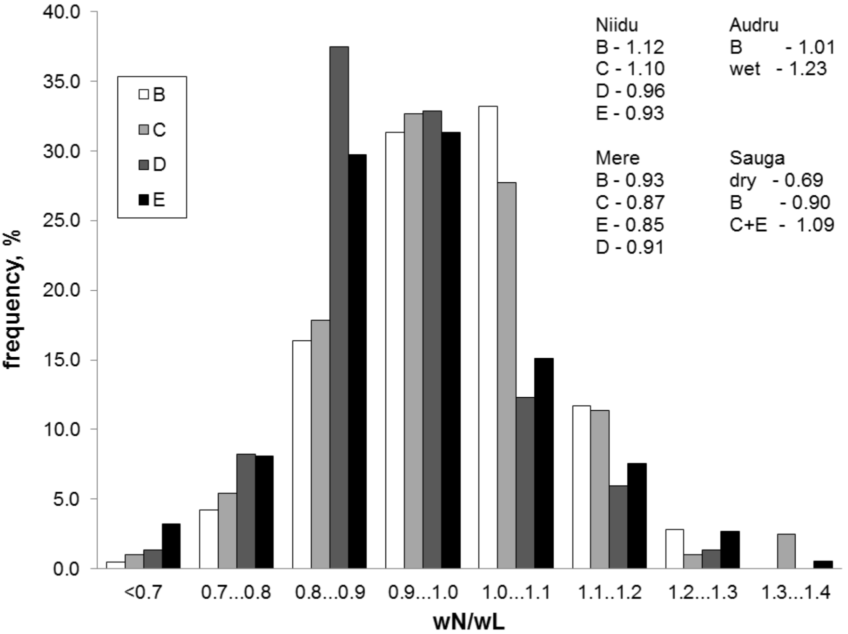

Figure 9. $w_N/w_{L(C)}$ ratio of varved clay units in Pärnu: B (214 samples), C (202 samples), D (219 samples) and E (186 samples). The corresponding values for Niidu and Mere sampling sites (Talviste and Listra, 1988) and for Audru (Kohv et al., 2010 – PAPER IV; Sedman and Talviste, 2012) and Sauga (Kohv et al., 2010 – PAPER III) landslides (landslide locations are shown in Fig.1).

Nevertheless, there is one phenomenon – wet clay at Audru landslide site remarkably differs from the whole analysed dataset (Figs. 5, 9). This 0.8…0.9 m thick (Sedman and Talviste, 2012) layer has w_N/w_L ratio of 1.24 and I_{VO} = 2.58, both considerable higher than usually in varved clays in Pärnu. Void index value is close to Utby "quick clay" values of 3.22–3.37 (Burland, 1990). The relation of the particular layer and Audru landslide is discussed later in more detail.

2.3. Analysis of landslides in Pärnu county

Recently several landslides are mapped and studied in western Estonia (Kalm et al., 2002, Talviste et al., 2004, Kohv, 2005, Kohv et al., 2009 – PAPER V). Relief in western Estonia is low lying (<20 m a.s.l.) and flat, which formed by the deposition of proglacial ice lake sediments – varved clays and overlying marine sands and/or silts. Landslides are mostly confined to the lower courses of the Pärnu, Reiu, Sauga and Audru rivers (Fig.1). The river valleys are eroded 10–15 m into the varved clays and have slopes from less than 7° to more than

20° (Kalm et al., 2002). Location and main morphological characteristics of the investigated landslides are presented in Table 4 (Kohv et al., 2009 – PAPER V).

Table 4. Location, main morphological characteristics and the classification of the landslides in Pärnu area (Kohv et al., 2009 – PAPER V).

Landslide	Coordinates	Width (m)	Length (m)	Height of scarp (m)	Time of occurrence
Audru-1	E:24°20,09` N:58°25,26`	75	36	1.2	Feb.2002
Audru-2	E:24°19,89` N:58°25,28`	8	4	0.3	Spring 2002?
Audru-3	E:24°19,89` N:58°25,28`	16	4	0.4	Spring 2002?
Sauga-1	E:24°26,41` N:58°25,72`	13	13	1.4	Spring 2002
Pärnu-1	E:24°36,29` N:58°22,70`	80	42	5.4	April 2002
Reiu-1	E:24°36,21` N:58°21,60`	8	15	1.2	2000?
Reiu-2	E:24°37,09` N:58°21,21`	23	16	1.5	Feb. 2002
Reiu-3	E:24°36,93` N:58°19,39`	22	10	2.5	2000

Three different groups of (A, B, C) of landslides were distinguished based on soil type, sediment stratigraphy, failure mechanism and size of the slides (Kohv et al., 2009 – PAPER V):

A. slides in glaciolacustrine varved clays covered by <3 m of marine sand and/or silt;
B. slides in marine sand (sand layer >3 m thick), and
C. small (width 4…15 m) slides in glaciolacustrine clay directly in the bank of the flow channel.

Small scale landslides of type C at the erosional banks of the flow channels (Kohv et al., 2009 – PAPER V) characterize the intermediate states of the strength decrease of the varved clay complex. Small landslides are typical first time slides in intact clay sequence according to Simons et al. (2001). The mechanism behind the small landslide is erosion, and the triggering effect is often related to the rapid drawdown of the water level in the river (Kohv et al., 2009 – PAPER V; Kohv et al., 2010 – PAPER III; Kohv et al., 2010a – PAPER IV, Kjaernsli and Simons, 1962). Modelling of the type C landslides shows that the failure occurs at the various strength of the varved clay – steeper slopes yield at higher strength and gentle slopes yield at lower strength (Kalm et al., 2002), in some cases at critical state strength (Kohv et al., 2010 – PAPER III; Kohv et al., 2010a – PAPER IV). Thus, this type of landslides represent soil-softening due to combination of vertical stress release and creep from overconsolidated clay stage after the erosion to the fully softened stage (or normally consolidated stage) of critical state strength

Simon et al. (2001) proposed that the first time slides in intact clay is characteristic to landslides in normally or slightly overconsolidated (due to erosion only) clays. Skempton (1970) proposed that these landslides occur at peak strength, but a later investigation by Simons et al. (2001) has shown that the overconsolidation due to erosion is minimal, meaning that peak strength is almost equal to the critical state strength.

Varved clay complex in Pärnu is overconsolidated due to bonding (OCR = 1.6), and even bigger overconsolidation ratio (up to OCR = 2) can be found in river valleys due to erosion. However, the mechanism of small landslides at river banks in western Estonia is similar to the first slides in intact clays described by Kjaernsli and Simons (1962) and Sevaldson (1956) and explained by (Simons et al., 2001). The higher overconsolidation of varved clay in Pärnu is a reason behind a possible longer delay between the erosion and actual rupture of the riverbanks. That is because two processes occur in the slope – the slow decrease in effective stress (Simons et al., 2001) and slow creep in stress concentration zones along the slip surface shear zone (Quinn, 2009) – both are leading to fully softened or critical state strength of the clay, and take time to fully develop.

Small landslides often trigger larger, type A slides at west Estonian valley slopes (Kohv et al., 2009; 2010 and 2010a – PAPERS III, IV and V). This phenomenon is common for “quick clay” slides in Canada (Quinn, 2009). According to Gregersen (1981) and Bjerrum et al. (1969) landslides in “quick clay” may develop in two ways: (a) flake-type slide takes place immediately because the initial stress level in “quick clay” is close to the critical stress level and already a small stress increase will result in a failure of a large areas simultaneously; and (b) a slide will develop retrogressively (relatively slowly) if the initial stress level in the “quick clay” is well below the critical stress. After an initial slide, shear stress builds up, reaching the highest level close behind the slip edge and a new initial slide may occur. This phenomenon may repeat itself and the slide progresses backwards in many small slides until the equilibrium is reached. Retrogressive slide may develop into flake-type slide as analysis of Rissa landslide in Norway demonstrates (Gregersen, 1981). Both well investigated large landslides in western Estonia, Audru and Sauga landslides, have occurred in many stages (Kohv et al., 2010; 2010a – PAPER IV) similarly to the retrogressive “quick clay” slides.

As varved clay complex in Pärnu is surprisingly overconsolidated despite the loose structure of the clay, the landslides in western Estonia are also comparable to the landslides in stiff fissured clays. The failures of natural slopes in stiff fissured clays can be divided into two groups – steep slope failures that occur for example along the coastline of Great-Britain and gentle slope failures that can be found in hinterland river valleys of Great-Britain (Simons et al., 2001).

Landslides in gentle slopes of stiff fissured clay develope slowly over decades preceeded by deformations and movements, sometimes visible and remarkably large before the actual rupture happens (Skempton, 1964). The slide surfaces often follow historic landslide zones of varying ages (Skempton, 1964). As shown by Skempton (1964; 1970) and Burland (1990) these slides, similarly to the slides in slightly overconsolidated or normally consolidated soils, are occurring at fully softened strength at critical state or even at residual strength if the slide surface is following the old rupture zone. Following the earlier rupture zones is also characteristic for Sauga and Audru landslides (Kohv et al., 2010; 2010a – PAPERS III and IV).

The landslides along the coastline of Great-Britain are occurring under conditions of intensive wave erosion, the slopes are unstable and irregular with average inclination between about 15° and 30° (Hutchinson, 1967). Despite the difference in soil softening process in weak cemented slightly overconsolidated clays and stiff fissured overconsolidated clays (Burland, 1990; Nagaraj, 2001) the mechanism of yielding of the coastal cliffs and small landslides at channel banks in western Estonia are surprisingly similar. Possible explanation is that:(a) the softening of fissured clay has developed to the stage where the shear stress exceed the remaining strength; (b) the more inclined the slope the bigger the remaining strength at the yielding moment.

Landslides in western Estonia, occurring in relatively young and soft but remarkably overconsolidated clays, have similarities with three major landslide types – slides in natural slopes in stiff fissured clays, natural slopes in "quick clays" and first time slides in intact clays.

The small, type C landslides at channel banks:

1. are "built up" by erosion and are often related to the rapid fall of water level in rivers (Kohv et al., 2009 – PAPER V) similar to the slides in intact clays (Simons et al., 2001). Though, it is not always happening at critical state strength due to higher overconsolidation of clays (OCR = 1…1.2 versus OCR = 1.6…2);
2. occur in the course of the strength softening process at the strength level, determined by magnitude of shear stress in the channel bank (hence channel bank morphology) similar to the coastal cliff ruptures in stiff fissured clays (Hutchinson, 1967). Though, the scale-difference of the slides is remarkable and can yet again be explained via differences in overconsolidation ratio (OCR > 10..20 v OCR = 1.6…2);
3. trigger larger landslides similar to "quick clay" slopes (Gregersen, 1981; Quinn, 2009; Kohv et al., 2009 – PAPER V). Though, the flake-type slides are not observed in western Estonia, it is possible, that this type of large landslide triggering mechanism is related to the bonded and therefore overconsolidated varved clays in western Estonia.

The large, type A landslides:

1. occur at fully softened critical state strength (Kohv et al., 2010; 2010a – PAPERS III and IV) similar to the landslides at gentle slopes in stiff fissured clay (Skempton, 1970; Burland, 1990) or in intact clay (Simons, 2001). Although, remarkably smaller pre-sliding deformations than expected are observed (Sedman and Talviste, 2002);
2. are retrogressive, happen in many stages similar to retrogressive slides in "quick clays". Time between the stages is from minutes or hours in case of Sauga landslide up to the years in case of Audru landslides (Kohv et al., 2010; 2010a – PAPERS III and IV), though varved clay in western Estonia is soft highly plastic clay with low sensitivity;
3. follow the former rupture zones of previous retrogressive stages similar to the stiff fissured clay slides utilizing the weaker zones of old landslides. However, the strength of the rupture zones corresponds to the undrained weakened (but not residual) strength (Kohv et al., 2010; 2010a – PAPERS III and IV) rather than to the drained residual strength characteristic of the rupture zones in stiff fissured clays (Skempton, 1970; Burland, 1990).

2.4. Analysis of the history and future of the strength in terms of stress release at erosional river valleys in western Estonia

The nature of soil behaviour – volume and strength changes – under changing stress field is described by the concept of CSSM – Critical State Soil Mechanics (Schofield and Wroth, 1968). As defined by Roscoe et al. (1958) the saturated clay is at its critical state, in drained test, if increments in shear distortion will not result changes in water content. In an ideal case a clay, whether normally consolidated or overconsolidated, will correspondingly contract or expand during drained shear until the critical state is reached, when it continues to deform under constant stress and at constant volume (Skempton, 1970). The critical state corresponds to the strength of the normally consolidated clay. The water content in this state is equal to that attained by the overconsolidated clay due to expansion before or during shear.

CSSM is based on laboratory tests performed on artificially created (reconstituted) clays. Despite the fact that natural soils differ in many ways from the reconstituted soils the theory of CSSM is widely used as a main framework in soil mechanics. The properties of natural soils are often described as deviations from the general model of CSSM due to soil structure (combination of fabric or arrangement of particles) or bonding (Skempton, 1970; Burland, 1990; Nagaraj and Miura, 2001). Based on the laboratory tests of natural undisturbed varved clay samples the empirical CSSM model of the western Estonian varved clays was evaluated (Talviste, 2002) and used beside the laboratory test results obtained by landslide analysis (Kohv et al., 2010; 2010a – PAPERS III and IV).

In case of pure, erosion related overconsolidation, the modern soil mechanics predicts that the total softening is due to swelling. Release of the effective stress leads to decompression (swelling) and new equilibrium of pore pressure starts to develop. The process takes time due to low permeability of clay but ultimately leads to lower strength. Whereas the critical state drained strength is the lowest possible strength (Burland, 1990; Skempton, 1970; Schofield and Wroth, 1968). The laboratory tests with undisturbed samples of the overconsolidated clay illustrate the strength decrease during the swelling process (e.g., Burland, 1990).

The swelling and corresponding strength decrease was also recorded in Cambrian age stiff overconsolidated clays in Sillamäe, Northern Estonia (Barnekow and Talviste, 2002). Water content has increased from initial 16…18% up to 25...28% leading to the undrained shear strength drop from $c_U >$ 200...450 kPa to the c_U = 41…51 kPa (Fig. 10) in zones with greater water content. The corresponding drop of fully softened frictional strength has been from φ' = 40° to φ' = 27 ° and residual strength has dropped from φ' = 27° to φ' = 11.8° (Fig. 11). Zone with increased water content penetrates to the depth down to 14…15 m from the sea bottom (Mets and Torn, 1997; Barnekow and Talviste, 2002) and has evolved during approximately the last 10 000 years since the last glaciation receded. It is also important to point out the high undrained strength (c_U = 500…5000 kPa) of the Cambrian clay samples lying deeper in the section and are therefore affected by fissures only.

In addition to clay swelling due to stress release Skempton (1964) indicated that water content rises close to the slip surface in stiff fissured London clay. Skempton (1970) explained this phenomenon with dilatancy and opening of fissures that lead to the increase in water content and culminate with strength decrease to the fully softened values. According to the data presented by Skempton (1964; 1970) full softening of the stiff fissured clay in slope area has developed within 30…40 years, which is relatively short period compared to the soil softening purely due to erosion in Sillamäe case. Developing shear strain in that zone of decreased strength may lead to future strength drop reaching residual strength at large strains.

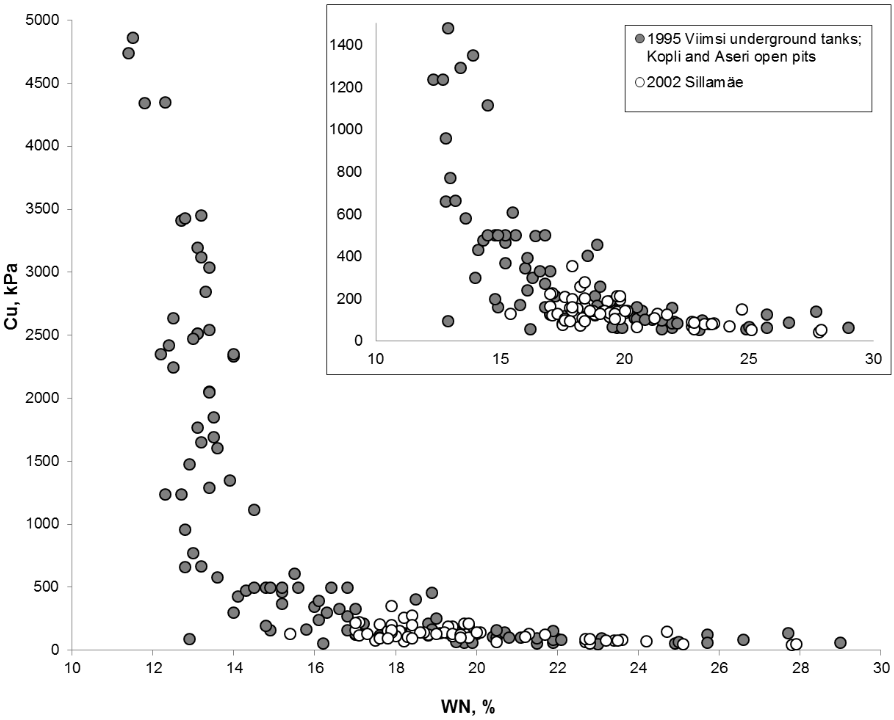

Figure 10. Relation between undrained shear strength and water content in Cambrian clay, Sillamäe (Barnekow and Talviste, 2002) compared with older dataset from Aseri, Kopli and Viimsi, northern Estonia (Mets et al., 1995). Inset shows the enlarged part of the graph.

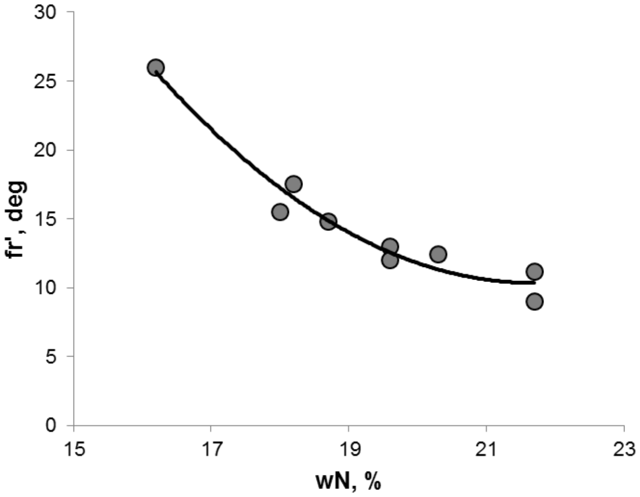

Figure 11. Relation between residual friction angle and water content in Cambrian clay, Sillamäe (Barnekow and Talviste, 2002).

Clay on river valley slopes is always at least slightly overconsolidated due to erosion (Simons et al., 2001). In western Estonia some varved clay units have additional overconsolidation due to the bonding effect between particles as stated earlier in Chapter 2.2. That has lead to the equilibrium between the stresses and particle distance in higher porosity clays compared to the normally consolidated clays (Fig. 5). It is possible that the bonding effect holds back natural swelling (Bjerrum, 1973) and soil softening after the stress release due to erosion, as the porosity and water content are already larger compared to the normal non cemented clays. However, in the slope area the conditions are different as the shear stress may in certain zones exceed the bonded shear strength of the clay (Quinn, 2009). Developing shear strain (creep) that exeed critical level in these zones will destroy the bonds between the particles. The overconsolidation caused by bonding disappears, and since cemented clay at the same stress level has looser structure compared to normally consolidated clay (Fig. 5) the soil softening can develop immediately. That kind of process tends to expand beyond initially softened zones until the whole slide surface is softened (Quinn, 2009).

It is characteristic that well investigated and analysed landslides in western Estonia (Kohv et al., 2010; 2010a – PAPERS III and IV) occur at critical state shear strength despite the fact that outside landslide areas varved clay is overconsolidated and bonded (OCR = 1.6). It is likely that possible rapid softening of overconsolidated soft clay, due to degradation of the bonds in slope zone, leads to similarities between retrogressive "quick clay" landslides and retrogressive landslides in western Estonia because the porosity and moisture content of the bonded clay exceeds the equilibrium developed during the normal consolidation. That concerns especially the thin 0.8…0.9 m thick wet clay layer at Audru landslide site about 8 m below the surface (Figs. 5, 7 and 9; Table 3). Audru landslide developed on the slope with only 10° inclination (Kohv et al., 2010a – PAPER IV). The layer "C+E" at Sauga landslide site is also more bonded than average varved clay in western Estonia (Fig. 5, 7 and 9; Table 3). The existence of more tightly bonded layers in geological sections may have played conclusive role in Sauga landslide. However, the degradation of bonds has not lead to the total strength loss similar to "quick clays" due to low sensitivity (Fig. 7; Table 3), and the retrogressive slides in western Estonia most possibly will not develop into flake-type slides.

However, the clay at the valley banks of 10…15 m deep river valleys (Kohv et al., 2009 – PAPER V) in western Estonia is more overconsolitated compared to the average slope overconsolidation. After erosion OCR value may reach 8…12 close to river bottom or 3...5 3 m below it. Erosion is never immediate but the fact that the clay strata at valley banks are released from 10…15 m thick overburden is indisputable. Therefore, the soil softening processes described above for stiff (fissured) overconsolidated clay can be relevant for varved clay in close proximity to the river.

The recent increase of landslide incidents in western Estonia (Kalm et al., 2002; Kohv et al., 2009 – PAPER V) is correlated with the rise of a potentiometric level of a confined aquifer below the varved clay complex (Kohv et al., 2010a – PAPER IV). Pressure rise in confined aquifer leads to the same effect as erosion – decreasing the effective stress above the confined aquifer (Listra and Talviste, 1988). Drawdown of the potentiometric level of the confined aquifer below the varved clay complex in Pärnu (Talviste and Listra, 1988) due to water consumption increased effective stresses in varved clays and temporarily decreased or even stopped the process of soil softening due to earlier erosion. Registered rise of the potentiometric level during the period 1993–2004 (Talviste, 2004) indicates the old depression cone has almost replenished (Kohv, 2012) due to decrease in groundwater consumption, and this has lead to the continuation of soil softening precesses and the frequency of landslides has once again increased, especially compared to the period of 1960–1990.

The following conclusions can be withdrawn:

1. Type C small landslides at western Estonian channel banks are similar to the slides in stiff fissured clays due to similarity of the soil softening process.
2. According to Barnekow and Talviste (2002) the soil softening in stiff fissured clays due to swelling is a long process and can develop deep below the surface during the long period of time. According to Skempton (1964; 1970) soil softening of stiff clays in slopes can develop remarkably faster due to dilatancy in shear zone.
3. Type A large landslides at slopes of west Estonian river valleys are similar to the retrogressive slides in “quick clays” without flake-type landslide developing. The reason for the similarity is the higher initial water content of the clay due to bonding that could possibly lead to the fast soil softening to the critical state strength when bonds are broken or disappeared.
4. Unevenly distributed shear stresses in the slope may destroy the cementing bonds when peak shear strength is exceeded by shear stress. That kind of process tends to expand farther from the softened zones until the whole slide surface is softened (Quinn, 2009). Yielding of the slope may happen in minutes or hours (Sauga landslide) or can take years (Audru landslide).
5. If the river valley forms due to erosion, the release of normal stresses and the increase of shear stresses in slope area are inevitable. That leads to inevitable soil softening in due time. As the strength at critical state is lowest possible strength for the soft clay then the friction angle at critical state determines the final slope stability. It has been proposed that under wet temperate climatic conditions landslides happen if the slope inclination is roughly ½ of critical friction angle φ’ for first time slides and ½ of the residual friction angle φ’r for the slides along old rupture

zones (Howland, 1987). That hints safe slope angles <7° for Audru landslide area and <8.5° for Sauga landslide area. Slopes before yielding were inclined correspondingly 10° and 11° (Kohv et al., 2009 – PAPER V).

6. Process of soil softening may have been stopped temporarily in 1960–1990 when the potentiometric level of the confined aquifer was drawn below the varved clay complex. The former groundwater depression cone is at the moment almost recovered and the landslide hazard is therefore increased and controlled by the natural conditions.

2.5. Correlation between the geotechnical properties of the varved clay and post-glacial conditions

Geotechnical properties of clays are defined by geological processes. The whole complex of these processes determining the geotechnical properties can be referred as "geological history" of the particular soil in contrast to "stress history" or "stress path" – terms often used if reconstituted samples are discussed (Ladd and Foott, 1974). In addition to the historical stress path the sedimentation, bonding, leaching and other factors may have played important role by influencing the geotechnical properties of the clay deposits.

During recent years a complex study explaining the proglacial sedimentary environment in Pärnu area, western Estonia was made (Veski et al., 2005; Hang et al, 2007; 2008; Rosentau et al, 2009; 2011; Vassiljev et al., 2011; Vassiljev and Saarse 2013; Talviste et al., 2012 – PAPER I). Recent study by Talviste et al. (2012 – PAPER I), partly initiated by the hypothesis that geotechnical properties of the varved clay complex in Pärnu hints temporary low water stand episodes of the Baltic Ice Lake or the Baltic Sea, most possibly after the Billingen event (Talviste, 1988a), revealed a number of evidences of that low stand in the area. It was concluded that the minimum water-level was at 0 to –2 m a.s.l. in Pärnu area and this low-stand can be attributed to the Yoldia Sea stage after the Billingen drainage event (Talviste et al., 2012).

The low-stand in the Baltic Sea, well below the upper surface of the varved clay in the northern part of Pärnu (+5…10 m a.s.l.), explains the desiccation of the uppermost cover of the varved clays – unit A in Table 1. The unit A is missing in southern part of Pärnu, where the upper surface of the varved clays lies at elevation +2…–3 m a.s.l (Fig. 12).

The varved clay surface displays a gentle scarp at a distance of ca 3 km onshore from the current shoreline, where the altitude of the clay surface increases from 0 to 4 m (Fig. 12). According to geotechnical studies (Kohv et al., 2010a – PAPER IV) and supported by varve investigations in a few sections (Hang et al., 2007 – PAPER II; Hang et al., 2008; 2010), the clay layer above this scarp exhibits a full series of clay units (A–E) distinguished in the proglacial clay section in the Pärnu area (Fig. 12). Below the scarp, in areas adjacent to the current coastline, unit A is missing in the clay sections and unit B is rather varying in thickness and is probably incomplete. Further offshore to Pärnu Bay, unit B is more completely represented and unit A is missing (Hang et al., 2008; 2010). Such a succession in clay facieses together with the erosional discontinuity in the upper contact of clay sequences point to possible erosional origin of the clay surface (Fig. 12) and proposes the corresponding paloeshoreline at ca 0 m a.s.l.

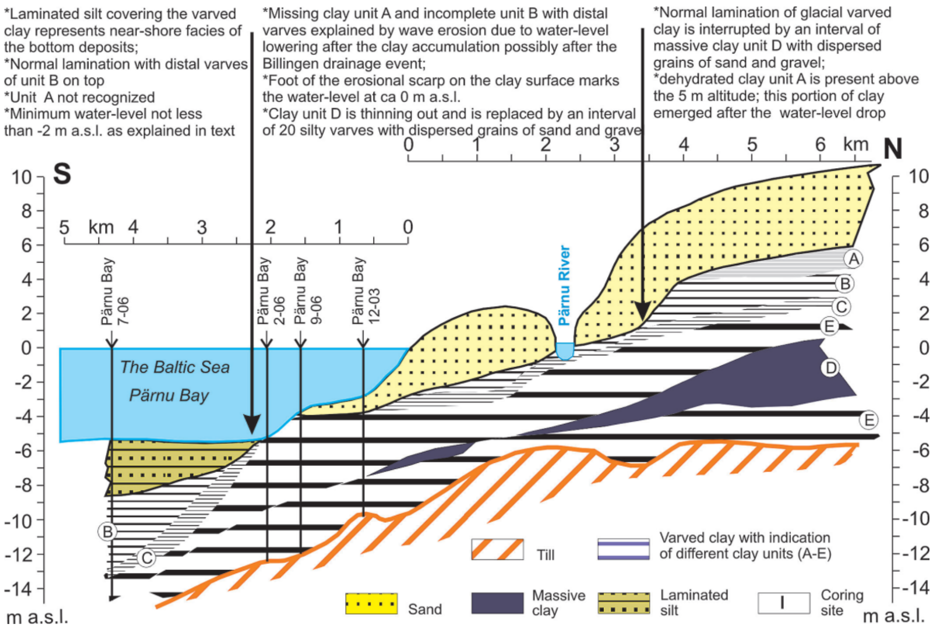

Figure 12. Principle cross section through the town of Pärnu to Pärnu Bay based on the logs of geotechnical cores (database of IPT Projektijuhtimine OÜ) in the town and logs of cores in Pärnu Bay Talviste et al. (2012 – PAPER I). Based on data from Hang et al. (2007 – PAPER II) and Hang et al. (2008), location of coring sites in Fig.1.

The hypothesis of selective erosion of the clay surface in Pärnu is also supported by a good correlation between the thickness of the clay complex and the height of the clay surface (Fig. 13). Relationships between the height of the lower clay surface and the thickness of clay shows two groups of data sets, both reflecting an increase in sediment thickness with decreasing height (Fig. 13). Linear trends for both groups of data show high r^2 values (0.75 and 0.77) and a rather similar slope component (Fig. 13). The best characteristic for differentiating between two groups is the height of the upper clay surface at 2 m a.s.l. Accordingly, at sites where the clay surface is above 2 m line the clay sequence is regularly thicker than in the areas with the corresponding surface below 2 m line. Nearly parallel trend lines reveal a difference in clay thickness of about 4 m between the two statistically defined groups. It is proposed that the clay sections with the upper clay surface below 2 m.a.s.l. have suffered from post sedimentary erosion of about 4 m. Four metres is also the height of aforementioned erosional scarp in the clay surface (Fig. 12). It is also proposed that during the fall of the water level and the following low-stand, wave erosion reached the bottom and the upper portion of clay was eroded. The clay surface above the scarp emerged during the water level low-stand and due to periodic freezing-melting cycles and accompanying chemical and soil forming processes, the ca 2 m thick upper clay interval lost its varve structure and is recognized as desiccated clay of unit A.

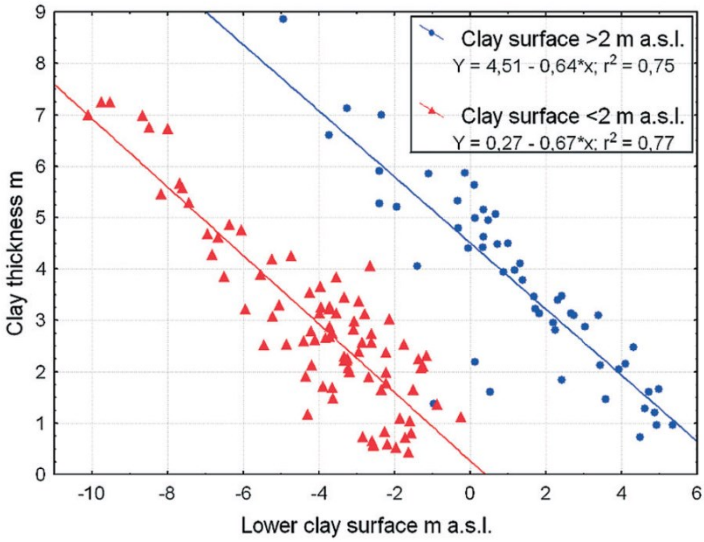

Figure 13. The relationship between the height of the lower clay boundary and the thickness of the clay complex in 151 geotechnical cores in the town of Pärnu (Talviste et al., 2012 – PAPER I).

The gradual upper contact of clay unit B with the Holocene bottom deposits of the Baltic Sea in the deeper (>7 m) part of Pärnu Bay indicates that the unit B is fully represented there and that wave erosion during the lowest water-level period after clay accumulation did not reach depth of ca –7 to –8 m. As calculated from wave lenght data (Kask and Kask, 2004), and derived from the distribution of Holocene bottom deposits (Lutt, 1987; Hang et al., 2008), about 5 m deep water column is critical for the wave-induced sediment transport/ erosion in Pärnu Bay. For this to be true, the water level in the bay could not have dropped below –2 m with the corresponding wave erosion down to –7 m, a.s.l. Consequently, the lowest water-level in the Pärnu Bay after the Billingen drainage event can be placed to an altitude of 0 to –2 m, which is rather similar to the earlier proposed Yoldia Sea minimum level in the Pärnu area between 3 and 0 m a.s.l. (Veski et al., 2005; Rosentau et al., 2009; 2011).

The geotechnical sampling locations Mere and Niidu (Fig. 1) are representing areas between the erosional scarp and shore line and north from the scarp, upper surface of clay sequence at elevation –3 m and 5 m a.s.l., respectively. The sand layer covering varved clay in both locations is ca 5 m thick that leads to the equal (comparable) present in-situ effective stresses at the clay surface and at comparable depth measured from clay surface. Despite the similar in-situ stress level all clay units B–E at Niidu sampling location have considerably higher w_N/w_L values compared to the Mere sampling location units B–E (Fig. 9). It is also important to point out that units B and C at Niidu sampling location have clearly formed a bonded structure, while the evident bonding effect for units B and C at Mere sampling site is missing (Fig. 5). This can be explained with the erosion of the upper clay portion at Mere site by simply stating that the clay sediment close to the upper clay surface at Mere location should be compared with clay at 4 m depth from the upper clay sequence at Niidu site. However, we can not exclude the possibility that the bonding occurred during the Yoldia Sea water level low-stand and is related with emerged areas located north from the scarp of the clay upper surface. At the same period of time erosion of upper 4 m south from the scarp took place. Later clay has been compressed under the pressure of at least 5 m of marine sand, compaction of bonded and non-bonded clay on both sided of the scarp has lead to the different compression degree resulting in different w_N/w_L ratio.

As the bonding of the clay may have an important role in landslide development at river valleys of western Estonia, the geochemical nature of the bonding is something that needs further research. That also may provide the answer when the bonding took place: before the Billingen drainage event during the actual sedimentation of varved clays, or later, during the water level low-stand at Yoldia Sea stage when the clay surface partly emerged and was influenced by periodic freezing-melting cycles.

The activity chart (Fig. 6) hints that in addition to the overall varve thickness changes and winter and summer layer ratio changes within yearly cycle (Hang et al., 2007) the clay mineralogy may have been changed. Whether or not that needs further research and depends in our opinion on the possibility to derive palaeogeographic conclusions from that information.

3. SHALE OIL PROCESSING WASTES: COMPOSITION AND CEMENTATION WITH IMPLICATIONS TO THE LONG TERM STABILITY

Oil shale is a low quality fossil fuel that can be found all over the world for example in Australia, Brazil, China, Jordan and USA (e.g., Andrews 2008; Dyni 2006; Hrayshat, 2008; Johnson et al., 2004; Schmidt, 2003; Wang et al. 2012). Effective and sustainable usage of oil shale type fuels is, however, complicated due to its low calorific value and large amount of solid waste (40–85% of the fuel) remaining after the shale processing. This is nearly an order of magnitude more ash remaining than in typical coal fuel processing.

Large-scale exploitation of oil shale is operational only in Estonia where kerogenous oil shale (kukersite) is burnt in Thermal Power Plants (TPP) as well as retorted to produce shale oil (Ots, 2006). The mineral matter content of oil shale can be as high as 80–90%, but usually stays between 40–50%. The main residue from the oil shale industry is TPP ash, and shale-oil processing residues semi-coke and black ash. At the current production rate each year 5–7 Mt of ash and nearly 1 Mt of semi-coke are formed in Estonia (Statistics Estonia, 2010).

Oil shale processing wastes have been investigated and used for construction (cement, road construction, building materials), agricultural purposes, as fuel additive and water treatment sorbent (e.g. Pets et al., 1985; Hanni, 1996; Paat, 2002; Trikkel et al., 2008; Kaasik et al., 2008; Kõiv et al., 2010). However, the secondary use of this waste is limited to less than 5% of its annual production, and thus, most of the waste is landfilled. Total ash amount in the depositories is about 300 Mt (Mõtlep et al., 2007 – PAPER IX; Mõtlep et al., 2010).

Estonian oil shale industry employs different methods for waste disposal. Oil shale ash from power plants is transported by hydraulic transport in slurry at water/solid ratio 20:1 to the plateau-like sedimentation ponds with current height of >40 m at large power plants (Fig. 14). In contrast, shale oil processing residue semi-coke is disposed by dry dumping, i.e. it was transported to semi-coke landfills by conveyer belts/wagons in earlier decades and by trucks today forming landfills with maximum height reaching about 120 m (Fig. 15). Amounts of the black ash, the other shale oil processing residue, have been so far much smaller compared to TPP ash/semicoke and until now this residue has been deposited together with TPP ash in sedimentation plateaus.

Figure 14. Plateau-like sedimentation ponds of TPP ash in Kohtla-Järve, slope ratio 1:1 of the pond can be seen (photo Pille Sedman).

Figure 15. Semi-coke landfill in Kohtla-Järve. In front the old deposited semi-coke with visible cementation degradation close to the surface. In the center the new deposition plateau with visible compaction can be seen and in the back the stormwater sedimentation ponds are visible (authors photo).

TPP ash is known to exhibit good self-cementing properties on disposal due to high content of free lime and other reactive Ca-silicate and Ca-sulphate mineral phases in ash. These phases form on hydration and through subsequent carbonation reactions a lithified mass – ashrock (e.g. Mõtlep et al., 2010; Pihu et al., 2012; Sedman et al., 2012b – PAPER VIII), which allows build-up of high and steeply sloped (slope ratio up to 1:1, Fig. 14) depositories. Shale-oil extraction residue semi-coke shows much weaker self-cementing properties compared to TPP ash (Sedman et al. 2012a – PAPER VII). Most of semi-coke waste is deposited at two main dumping sites in the vicinity of shale-oil plants near the towns of Kohtla-Järve and Kiviõli. These landfills form artificial heaps more than 120 m high and occupy an area of more than 2.5 ha. The larger dumping site at Kohtla-Järve holds approximately 83 Mt and the smaller site at Kiviõli 19 Mt of semi-coke (Veski, 2005). Composition and behaviour upon hydration of black ash has not studied before as it has been deposited together with TPP ash, which has good self-cementing properties by itself. TPP ash and semi-coke are both considered as hazardous wastes (Riigi Teataja RT I 2004, 23, 155) mainly due to the high alkalinity of leachate water and in addition, due to the organic compounds in semi-coke. Particularly the semi-coke waste dumps are among the most serious residual pollution sources posing threat to nature and human health. Tang and Otsa (2003) have thoroughly studied the environmental impact of semi-coke. Their main conclusions indicate that semi-coke sediments contain several environmentally toxic organic compounds, such as bitumoids, including shale-oil residues (0.6–2%), phenols and PAHs (polycyclic aromatic hydrocarbons). The main threat is the alkaline-toxic leachate from semi-coke dumps that can infiltrate through the deposits into the environment. Therefore, landfill design and deposition methods must:

- firstly, ensure the low permeability of the landfill body to minimize the infiltration of leachate,
- secondly, confirm high mechanical stability of the deposits to reduce the possibility of a failure and consequent pollution of the environment.

3.1. Semi-coke

Semi-coke is a blackish granular material which contains both mineral and organic part that forms as a solid residue in so called Kiviter retorting process in the absence of oxygen. During the coking in Kiviter process the maximum temperature reaches 350–400 °C (Kann et al., 2004; Koel, 1999). At the last stage of the retorting process semi-coke is heated to 900 °C in aerobic conditions to burn out as much of the organic material as possible (Soone and Doilov, 2003). However, the residence time of combustion stage is short and it does not guarantee the total decomposition of organics. As a result the retorting residue contains 6–10% of organics. The organic part contains mainly kerogen residues, shale-oil remains, bitumoids, but also environmentally hazardous compounds like PAHs and phenols (Tang and Otsa, 2003).

Phase composition of semicoke is defined by amplitude of temperatures at different stages of its thermal treatment.Mineral transformations during coking stage are minimal and only clay minerals start to dehydrate. At temperatures 500 °C and above various sulfur compounds (mainly in the form of pyrite and/or marcasite – FeS_2) start to decompose. The sulfur released by pyrite decomposition and the free CaO released from partial pyrolysis of calcium carbonate react and form CaS type phase, whereas the uncompleted decomposition process of pyrite may produce mackinawite [FeS] type phases (Mõtlep et al. 2007 – PAPER IX).

At the final step of retorting the temperatures of 900–1000 °C are applied to burn off the organic matter/coke in solid residue. In this process a slag-like material forms, which consists of amorphous glass phase at the expense of the decomposition and melting of alumosilicate minerals (clays) and new-formed Ca-silicates – melilite, cement minerals like belite [β-C2S], merwinite, etc., that form in reactions between free Ca- and Mg-oxides derived from the decomposition of dolomite (decomposition starts at ~860 °C) and calcite (decomposition at ~950 °C), and alumosilicates (mainly clay minerals and K-feldspar) and less quartz. Moreover, mineral composition of slag lumps found in semi-coke indicates that temperatures as high as 1400–1500 °C can occur locally during this stage and the diffuse maximum from amorphous phase scattering in measured X-ray difractograms indicates the average quantity of non-crystallised matter to be as high as 10(20)% (Mõtlep et al., 2007 – PAPER IX).

As a result the semi-coke in the waste dump site is a complex mixture, which contains alongside with transformed matter also pieces of macroscopically unaltered oil shale that shows only slight signs of thermal decomposition, lumps-pieces of partly altered carbonate rock together with lumps of melted slag and about 6–10% of organics. It is also very porous material composed of irregular pieces of coked oil-shale particles of variable size mixed with particles of partially or completely unchanged oil shale. Coked particles are characterized by high intragranular porosity (Fig. 16).

In general, the shale-like, conglomerate-like and poorly sorted structural types of semi-coke are distinguished (Fig. 19). The geotechnical index properties of the semi-coke structural types are summarized in Table 5.

The content of organics in retorting residue is one of the factors determining the later geotechnical properties of the deposited semi-coke. Organics content determines the extremely high liquid limit (w_L) values of the residue (Fig. 17), despite to non-existing plastic (or clay-like) behaviour of the semi-coke.

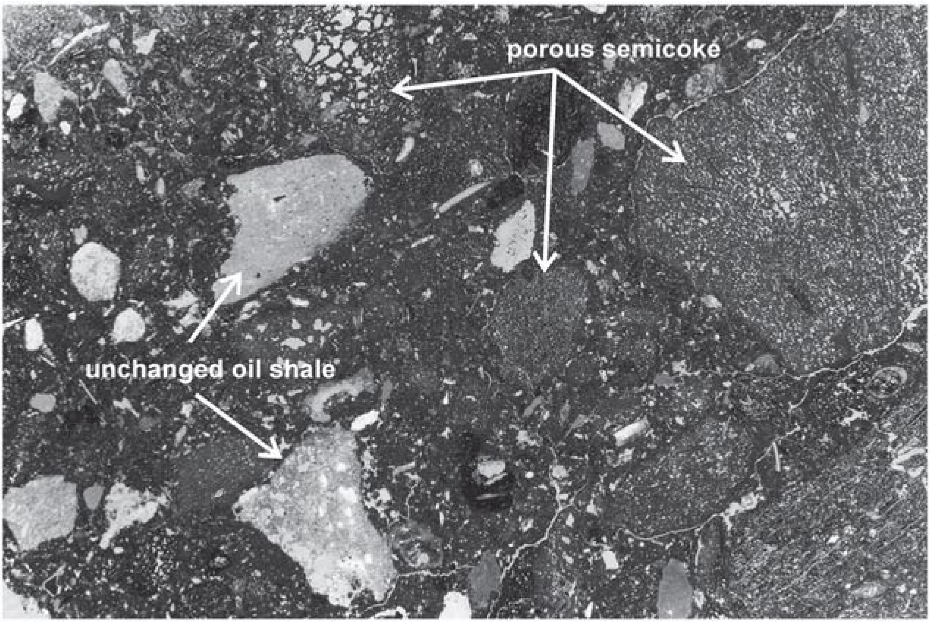

Figure 16. Optical microscopy photograph of semi-coke (Sedman et al., 2012a – PAPER VII).

Table 5. Average dry density (ρd), apparent specific gravity of solids (Gs), water content (w), void ratio (e) and degree of saturation (S) of the conglomerate-like, shale-like and well graded remolded and undisturbed semi-coke samples (Sedman et al., 2012a – PAPER VII).

Semi-coke sample	ρ_d, g/cm^3	G_S	w, %	e	S, %
Conglomerate-like					
Undisturbed	0.82	2.24	69.8	1.7	90
Remolded, unsaturated	0.87		31.7	1.6	45
Remolded, quasi-saturated	1.04		49.1	1.2	95
Shale-like					
Undisturbed	0.72	2.22	86.9	2.1	92
Remolded, unsaturated	0.75		47.6	2.0	53
Remolded, quasi-saturated	0.77		87.8	1.9	104
Poorly sorted					
Undisturbed	0.84	2.43	41.0	1.9	52
Remolded, unsaturated	1.15		24.3	1.1	53
Remolded, quasi-saturated	1.00		43.6	1.4	74

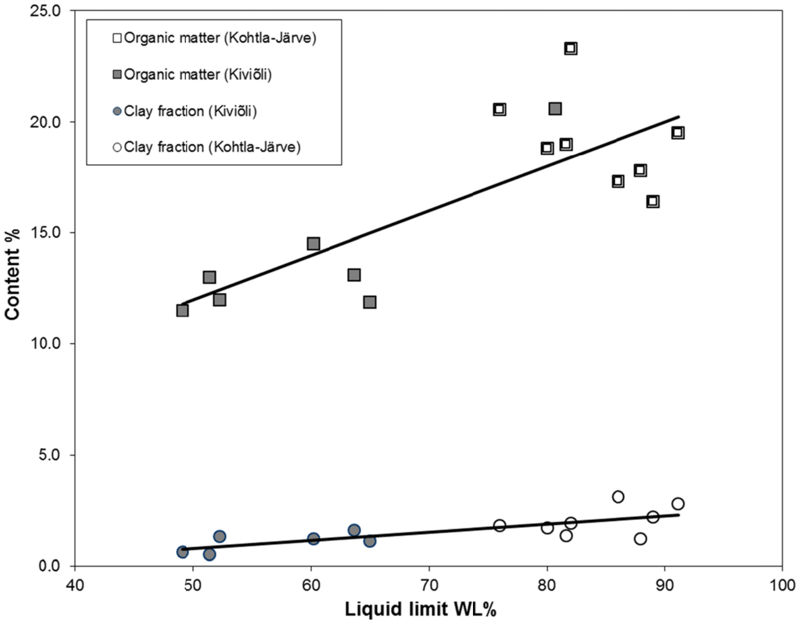

Figure 17. The relation between the liquid limit and organics content of the semi-coke. Kohtla-Järve dump site data by Talviste et al., (2004) and Talviste et al., (2008); Kiviõli dump site data by Sedman and Talviste (2005). Content of clay fraction (<0.002 mm) is very limited, below 3% and liquid limit is solely depending on the organics content.

According to the grain-size distribution (Sedman et al., 2012a – PAPER VII) semi-coke can always be classified as "*silty sand*" based on various geotechnical standards as it contains fines (particles <0.06 mm) less than 40%. Exception is shale-like semi-coke that can sometimes be classified as silt. According to Hough (1969) the void ratio of various non-organic sands, silts and silty sands in loose state does not exceed e = 0.8…1.1, depending on the content of fines. Yet, semi-coke is also characterized by extremely high void ratio that reaches e values at 1.7…2.1. Based on the published data (Swiss Standard SN 670 010b) the maximal void ratio is 0.69 and 2.26 for nonorganic and organic silts or silty clays respectively. Hence, the high organic content is one of the determining factors of the high post-depositional void ratio of the semi-coke.

Tests results presented in Table 5 indicate that the organic content can not be solely responsible for high void ratio. It is evident that once cemented semi-coke sample is remoulded and granulated, the high void ratio of the material can not be emulated. The second factor determining the extremely high post depositional void ratio of semi-coke can be the fast cementation of the oil retorting residue, starting immediately if water is added (Mõtlep et al., 2007 – PAPER IX). In addition, the post depositional cementation of the semi-coke has the major role in preserving the initial high void ratio. The void ratio in semi-coke is around e = 2, which means that 1 m^3 of semi-coke in the waste dump contains 1/3 solids and 2/3 voids in volume (Fig. 22), filled with air or water and without rapid cementation a natural compaction due to increasing overburden exerted pressure should take place.

Conglomerate like and poorly-graded semi-coke contains significant amount of altered limestone and melted slag lumps with increased internal porosity. However, the effect of secondary porosity to the high porosity of the semi-coke is not evident. Particles with secondary porosity belong into the fraction >2 mm. The shale-like semi-coke, containing less than 2% of fraction >2 mm has in average higher undisturbed porosity compared to conglomerate like or poorly-graded semi-coke containing more of fraction >2 mm.

3.1.1. Cementation of semi-coke deposits

Mineral phases formed in oil shale retorting/semi-coking process are unstable in atmospheric conditions. Deposition of spent shale from coking process in waste dumps initiates the mineral transformation, predominantly hydration and carbonation. The dominant hydration product of semi-coke is secondary ettringite – $Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$, which forms up to 30% of crystalline phases in hydrated and cemented semi-coke sediment (Mõtlep et al., 2007 – PAPER IX). According to scanning electron microscopy analysis, the pore space between discrete semi-coke particles becomes filled with ettringite masses, which forms long needle-like crystal webs binding particles together (Fig.18; Mõtlep et al., 2007 – PAPER IX; Sedman et al., 2012a – PAPER VII).

The formation of ettringite occurs as a result of the reaction between CaO formed at thermal decomposition of limestone/dolomite with Al-compounds derived from the partial decomposition of clay minerals and/or feldspars, and with the sulfur compounds and/or CaS (oldhamite), left in ash after the combustion process of organic matter or formed through decomposition of pyrite/carbonate phases, respectively. The precipitation kinetics of ettringite is rapid. In laboratory experiments (Myneni et al., 1998) the nucleation of ettringite crystallites is fast and the white ettringite precipitate appears immediately after mixing of CaO and $Al_2(SO_4)_3$ solutions. However, ettringite formation in semi-coke deposits under atmospheric conditions is much slower and the ettringite formation occurs over two-three weeks. Although nucleation can be assumed to begin in matter of hours, the crystalline ettringite appearance takes days or weeks. Controlling factors of ettringite precipitation are dissolved Ca^{2+}, Al^{3+} and SO_4^{2-} ion concentrations and their activities, which depend on ionic strength of the semi-coke pore-water. Unlike to oil shale TPP ash plateau sediments, where the most probable inhibiting factor of ettringite formation is sulphate or aluminium deficiency depending on combustion technology (e.g. Liira et al., 2009), in semi-coke deposits the controlling agent seems to be the availability of CaO and/or $Ca(OH)_2$ that are readily susceptible to chemical reactions. In semi-coke sediment it is probable that at the presence of high sulfate activity all free Ca will be bound to form ettringite (Mõtlep et al., 2007 – PAPER IX).

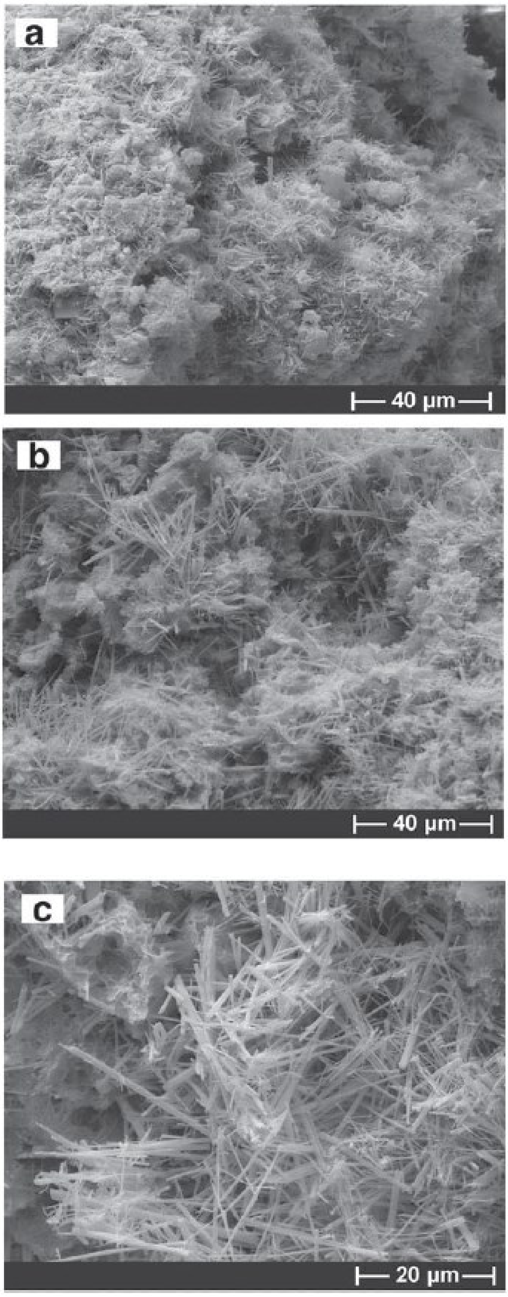

Figure 18. SEM photographs of semi-coke. Semi-coke is a highly porous material with various sized ettringite crystals (a), (b) in its pores. Needle-like ettringite crystals form irregular cement in the pores (c) (Sedman et al., 2012a – PAPER VII).

Most prominent difference of the semi-coke compared to TPP ash deposits with good cementation properties is the absence of portlandite $Ca(OH)_2$ and hydrocalumite $Ca_2Al(OH)_7 \cdot 3H_2O$ – common constituents in TPP ash sediments (e.g. Mõtlep et al., 2010). Though, high pH (12–13) of initial semi-coke leachates suggests the presence of some amount of portlandite in semi-coke, but its quantity remains probably below 1% that is under the detection limit of X-ray diffraction analyses (Mõtlep et al., 2007 – PAPER IX, Sedman et al., 2012a – PAPER VII). The presence of small amount of portlandite (~0.6%) in semi-coke was confirmed by titration experiment where semi-coke leachate pH was measured at different sediment–water ratios. The pH value in oversaturated solution respect to portlandite is 12.4 at 25 °C and the portlandite content in semi-coke matter was found from saturation – undersaturation equilibrium (Mõtlep et al., 2007 – PAPER IX,). The restricted occurrence of portlandite would suggest also limited carbonation of the semi-coke sediments that is important with respect to formation of stable cementation bonds in semi-coke sediment.

Cementation of semi-coke by massive precipitation of ettrinigite serves two purposes. Firstly, ettringite formation is responsible for strength development in deposits (Sedman et al., 2012a – PAPER VII; Sedman 2013). The uniaxial compressive strength of the hydrated TPP ash sediment can reach up to 19 MPa (Talviste, 2008) due to carbonation reactions and hydration-recrystallization of secondary Ca-silicate phases that control the pozzolanic properties of the ash. Hydration and solidification of semi-coke sediment, on the other hand, results in the uniaxial compressive strength of only about 1.2 MPa in average (Sedman and Talviste, 2005) but given also cohesive component of the semi-coke shear stenght via bonding (Sedman et al., 2012a – PAPER VII) it ensures mechanical stability of the semi-coke waste dumps.

Secondly, pore space closure due to precipitation of ettringite (and probably of other minor carbonate and Ca-silicate hydration phases) causes significant reduction of hydraulic conductivity to less than 10^{-8} $m \cdot s^{-1}$ of the compacted and hydrated semi-coke. This should minimize the infiltration through the deposits and therefore reduces the risk of contamination. It is important that the isolation properties of the more than 5 m thick cemented semi-coke waste deposits meet the requirements of the European Union Landfill Directive.

There are known cases where waste deposit yields were caused by liquefaction of waste material, for example in coal mine waste piles in Canada (e.g., Dawson et al., 1998; Hungr et al., 2002). Dawson et al. (1998) found that static collapse of saturated or nearly saturated sandy gravel cohesionless layers within the coal mine waste dumps may be responsible for the initial failure. Indeed, the structure of semi-coke deposits established before year 2002 is heterogeneous and consists of layers with different strength properties (Figure 19).

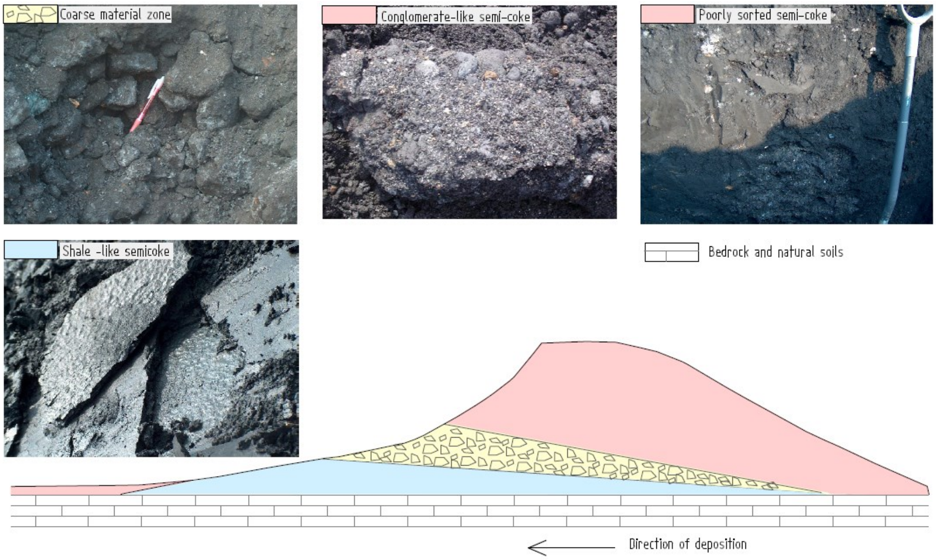

Figure 19. Principal scheme of the semi-coke dump and distinguished semi-coke structural types.

Until the early 2000s semi-coke was carried to the top of the waste heaps by wagons and washed down with water (Kattai, 2003). This transportation method caused separation of the material – coarser material settled at the foot of the heaps, forming the conglomerate-like structure, while finer material was flushed further, forming the shale-like structure of the material. Some of the material was left unsorted near the loading source. However, it can be assumed that the liquefaction in semi-coke dumps is unlikely to occur due to the cohesive component controlling possible liquefaction (Sedman et al., 2012a – PAPER VII) as bonding guarantees some strength even after the decrease in frictional component which is the main mechanism in liquefaction process.

3.1.2. Stability of semi-coke cementation

Crucial factor for the stability of semi-coke cementation (that is its strenght and isolation properties) is the stability of ettringite. We can distinguish geochemical and geomechanical aspects controlling the ettringite bonding inside the waste dump.

Geochemical stability of the ettringite is sensitive towards pH of the environment (Mõtlep et al., 2007 – PAPER IX; Sedman et al., 2012a – PAPER VII). In alkali and sulfate-rich solutions ettringite is the most stable phase of the $Ca(OH)_2$–$Al_2(SO_4)_3$–H_2O system. Ettringite is stable at pH values >10.7, but in lower pH values ettringite dissolves incongruently to gypsum, (amorphous) Al-hydroxide and Ca-aluminate type phases (Myneni et al., 1998). At high pH values one of the solubility products of the ettringite is portlandite.

However, at high CO_2 partial pressure and relatively low pH level, ettringite decomposes into sulfates and aragonite $CaCO_3$ with vaterite γ-$CaCO_3$ as an intermediate phase (Nishikawa et al., 1992). Moreover, decomposition of ettringite (decomposition rate) is also influenced by temperature and the content of different compounds found in deposit. At high temperatures mono-sulfoaluminate $Ca_4Al_2(SO_4)(OH)_{12}\cdot 6H_2O$ phase is stable over ettringite, whereas according to Pajares et al. (2003) ettringite solubility is inhibited on the presence of $CaCO_3$ (calcite) and cement clinker-minerals: belite C2S, alite C3S etc. Those phases have the capacity to buffer solution pH to the critical levels attaining ettringite stability. However, in natural systems, where the deposits are open to atmospheric CO_2, the buffering capacity of these phases on environment pH is lost with time and if the pH drops below 10.7 ettringite becomes unstable and starts to decompose.

Weathering of semi-coke deposits is well evident by appearance of loose layer (up to 0.3 m in thickness) on old waste dumps. TPP ash and semi-coke co-deposition experiments (Sedman et al., 2012b – PAPER VIII) indicated ettringite decomposition starting in the uppermost 0.2–0.3 m thick layer already after 3–4 month exposure of the deposits to ambient open environment. Ettringite disappeared completely in the uppermost 0.2–0.3 m thick loose layer of the sediment after one year at open conditions and had resulted in precipitation of secondary calcite and gypsum that, however, does not contribute to the material (re-)cementation. Nevertheless, the experimental setups revealed a secondary cementation zone with increased ettringite content just below loose zone at 0.4–0.6 m depth. This cementation zone is most probably related to pH profile development within sediment due to progression of carbonation reactions controlled by slow diffusion of atmospheric CO_2 (Sedman et al., 2012b – PAPER VIII). At this depth the portlandite (and secondary Ca-silicate phases) are still buffering the system pH above 10.7, which supports the secondary precipitation of ettringite. It is evident that depth of the weathering (that is destruction of ettringite) will increase with time if the surface will be left to open conditions for prolonged time, but its advance will be exponentially slower with increasing depth and surface weathering do not possess threat to overall stability of semi-coke depositories.

Geochemical stability of ettringite is also sensitive towards temperature. At temperatures 70 °C and above the formation of ettringite is hindered and already available ettringite starts to decompose (Pourchez et al., 2006). As indicated by Puura (2006) the heating areas occur in semi-coke heaps and the typical situations of heating can be mapped. It is suggested (Puura, 2006) that heating can be related with coarse material zones (Fig. 19) formed during the semi-coke transportation and dumping until the early 2000s and can occur in deeper deposits, especially if compared with weathering and pH related ettringite degradation zones. The extent of the zones with totally destroyed ettringite cemenation around the heated spots is later monitored during the actual remediation of the old waste dumps and is as extreme as 10…25 m in depth and 100×300 m in plane (Talviste, 2012). The cemetation loss has resulted with formation of different cohesionless residue depending on the distance from the heated spot (Talviste, 2012).

Geomechanical aspects of the bonding degradation are related to the mechanical crushing of the secondary cementing minerals (ettringite). At the effective normal stress of 800 kPa the break down of ettringite minerals in the semi-coke has lead to the decrease in strength compared to the strength at lower stresses (Sedman et al., 2012a – PAPER VII). The volume changes of the semi-coke measured in confined conditions in oedometer (Talviste et al., 2008) reveal the nature of the ettringite crushing. In soil mechanics the three phases forming the soil system – gas, liquid and solids – are considered non-compressible under the small stresses. Thus, the volume changes are due to tighter packing of solids in response to an increase in effective stresses. Since the process results in decreasing volume of voids between the solids, the compaction achieved with gradual loading is exponentially decreasing. The corresponding curves expressing compressibility are clearly non-linear in effective stress versus relative deformation or in effective stress versus void ratio scales and are considered to be nearly linear if effective stress is expressed in logarithmic scale (Whitlow, 2001). However, the confined compression tests of semi-coke results in nearly linear effective stress versus void ratio relationship and definite non-linear relation when stress is expressed in logarithmic scale (Fig. 20). In this thesis I propose that the ettringite crystals start to break as the first loads are applied and the crushing of crystals continues with increasing load. Finally that leads to the stage where large portion of ettringite bonds is crushed. The final measured relative compression of 5.0…16.4% at the effective stress of 1100 kPa (Talviste et al., 2004; Sedman and Talviste, 2005) is large and the break-down of brittle ettringite bonds in lower strata of the dump site is imminent if the semi-coke heap rises in height. The shear strength model of semi-coke at increasing effective stresses can be stated in terms of frictional and cohesive components as proposed on Fig. 21.

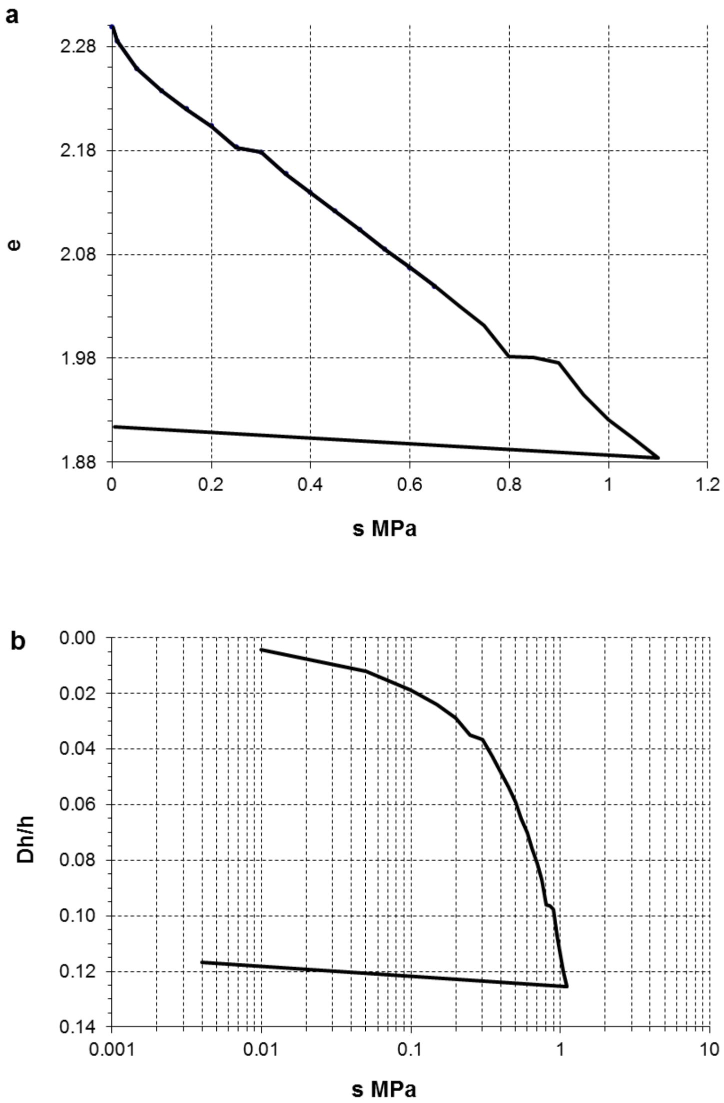

Figure 20. Confined compression test results (semi-coke) in (a) linear and (b) logarithmic stress scale (Talviste et al., 2004). Linear e = f (σ) is explained with ettringite bonds gradually breaking down during the loading.

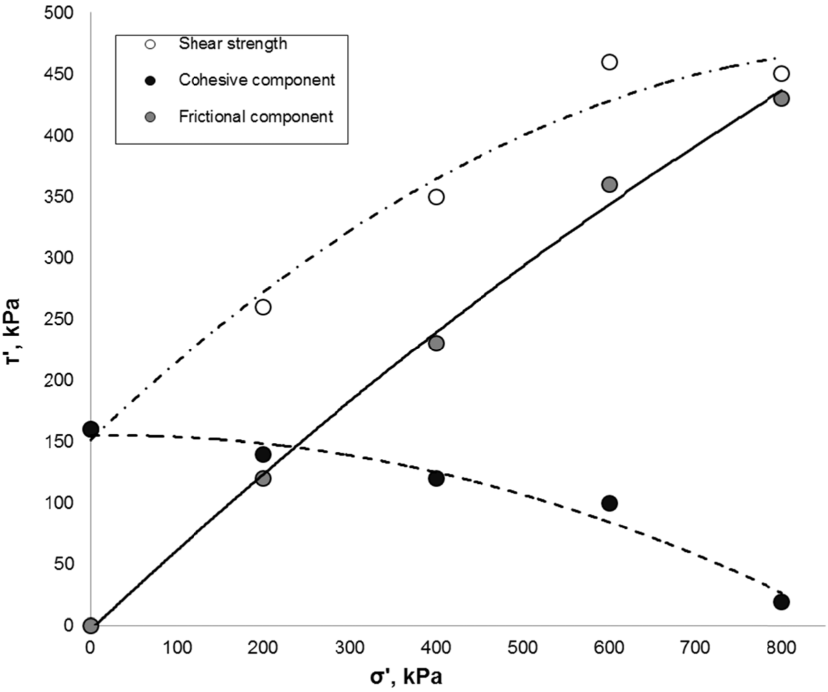

Figure 21. Principal scheme of frictional and cohesive component of the shear strength of the cemented semi-coke under the increasing load of overburden.

3.1.3 Semi-coke cementation controls

With the degradation of semi-coke cementation the permeability of the material increases and strength decreases (Sedman et al., 2012 – PAPER VII). In order to control the objectives of safe landfill design, low permeability and mechanical stability, the degradation of semi-coke cementation needs to be controlled. Crucial factor for the cementation control is reduction of the void ratio. Smaller void ratio marks smaller permeability, both for water and air, thus better protection against geochemical degradation of ettringite due to leaching or temperature rise and self-combustion. Smaller void ratio also marks smaller mechanical deformations due to increasing stress below the gradually increasing overburden and possible lesser extent of broken stringier crystals, hence higher residual strength of the semi-coke. In principal, two possibilities exist for void ratio reduction – mechanical compaction or co-deposition of semi-coke with TPP ash and/or black ash. Both, mechanical compaction and co-deposition should be done as soon as possible after semi-coke is transported to the dumping site in order to benefit from later semi-coke cementation.

Mechanical compaction with industrial vibratory rollers reduced void ratio of semi-coke to the values of e = 1.25...1.30 (Talviste, 2005). The positive side effect of the compaction is increase in landfill capacity while retaining the designed shape (Fig. 22). After 2005 the new solid deposition technology was implemented. Semi-coke from the retorting process is transported to the plateaus by trucks and placed in 0.5...0.7 m thick layers and compacted, ensuring homogenous structure, high strength and low permeability of the whole deposit (Fig. 15).

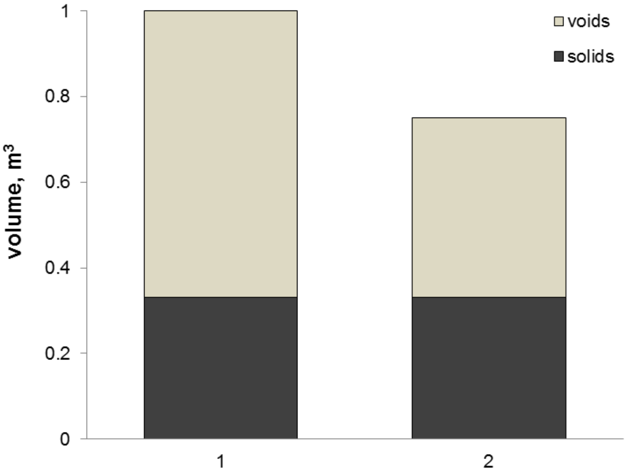

Figure 22. Void ratio e = 2.0 before (1) and e = 1.25 after (2) semi-coke compaction.

Field-scale co-deposition experiments (Sedman et al., 2012b – PAPER VII) show that mixing of coarse-grained poorly sorted semi-coke material having large (>50–100 µm) interconnected pores and fine-grained TPP ash with >50% particles with grain size <0.1 mm, results in deterioration of isolation and strength properties if the TPP ash and semi-coke ratio is higher than 1:4. Intensive secondary mineralization, especially delayed formation of ettringite (e.g., Taylor et al., 2001) causes expansion and cracking of the material which leads to higher permeability.

3.2. Solid heat carrier retorting residue – black ash

Solid heat carrier shale-oil extraction residue – black ash – is significantly different by its physical properties and composition compared with semi-coke and more similar to TPP ash. It is fine-grained fly ash-like material that contains only a few percent of residual organics because during the solid heat carrier process the initial semi-coke like residue is heated up in the presence of oxygen and directed back to the retort chamber to provide additional heat to the retorting process. The composition, physical properties and possible environmental impacts of TPP ash and semi-coke have been studied in the last decades (e.g. Kuusik et al., 2004; Kuusik et al., 2005; Kahru & Põllumaa 2006;

Mõtlep et al., 2007 – PAPER IX; Uibu et al., 2009; Mõtlep et al., 2010; Bitjukova et al., 2010; Pihu et al., 2012; Kuusik et al., 2012), but properties of solid heat carrier shale oil retorting waste have not been addressed in detail before. Need for black ash investigation is motivated by the employment of new powerful SHC retorts (Petrotert, Enefit technologies) for shale-oil production. As a consequence the share of this waste will increase and so far black ash has been deposited alongside with TPP ash at major oil producers as lesser constituent, then in future the share of this type of ash will increase or even dominate in general ash flow.

Black ash is a quite well sorted fine-grained granular material where particles <125 µm in diameter comprise in average about 70%, and only <5% consisted of gravel fraction (mostly <5 mm in diameter) (Fig. 23, Talviste et al., 2013 – PAPER VI). Mineral composition of crystalline phases of black ash is characterized by calcite, quartz, K-feldspar, and dolomite which reflect the composition of oil shale. Presence of calcite and especially dolomite in the black ash suggest that thermal decomposition of the carbonate phases typical to TPP ash formed at temperatures in excess of 800 °C was not completed in solid heat carrier retorting process. Calcite, which constitutes typically 30–50% of the mineral matter in oil shale composes about 30% of phases in black ash (Talviste et al., 2013 – PAPER VI). Calcite starts to decompose at 620 °C having maximal decomposition rate at 895–900 °C (Lvov, 2002). Furthermore, black ash still contains about 7% of dolomite that starts to decompose at about 500 °C and is completed at about 860 °C indicating that temperatures during burnout of the organic material were not kept long enough to allow its decomposition. However, black ash contains considerable amount of carbonate mineral decomposition-reaction products – periclase (MgO), lime (CaO), secondary Ca-Mg silicates (e.g., belite C2S) and oldhamite (CaS) of which many are unstable and reactive (Talviste et al., 2013 – PAPER VI). CaS forms at the expense of sulphur released by pyrite decomposition, organic material pyrolysis and the free CaO released from partial decomposition of carbonate minerals.

The geotechnical index properties of black ash and black ash-water mixtures 5 days after mixing are summarized in Table 6. Ash-water volume ratio was 2:1 for ASHa mixture and 1:2 for ASHw mixture (Talviste et al., 2013 – PAPER VI).

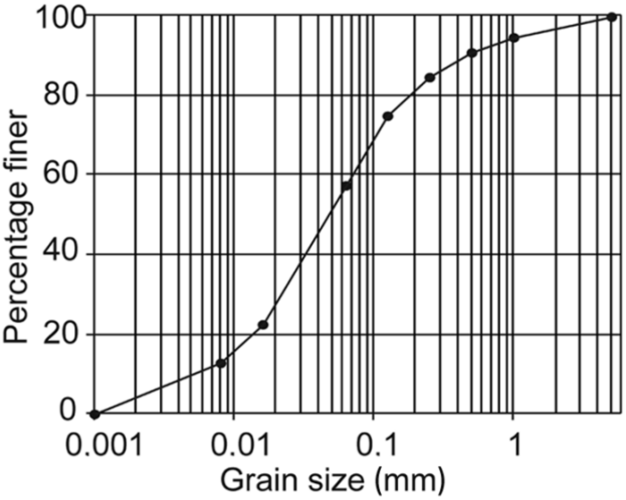

Figure 23. The average grain size distribution curve of the fresh black ash (Talviste et al., 2013 – PAPER VI).

Table 6. Average dry density (ρd), apparent specific gravity of solids (Gs), water content (w), void ratio (e) and degree of saturation (S) of the black ash, mixed with water, 5 days after mixing (Talviste et al., 2013 – PAPER VI; Talviste et al., 2011).

	ρ_d, g/cm^3	G_S	w, %	e	S, %
Black ash	1.01	2.43	0	1.41	0
Black ash water mixture in air ASHa	1.33	2.50	25	0.92	69
Black ash water mixture in water ASHw	1.18	2.53	47	1.16	99

It is important to point out the lower void ratio of black ash water mixtures compared to void ratio of non-compacted semi-coke (Fig. 24). According to the grain-size distribution (Fig. 23) the semi-coke is a typical "*silt*" based on various geotechnical standards as it contains fines (particles <0.06 mm) more than 40% and has rather small clay content (ratio of fractions <0.002mm/<0.06 mm is less than 10%). According to Hough (1969) the void ratio of various non-organic sands, silts and silty sands in loose state does not exceed e = 0.8…1.1 and the void ratio of black ash e = 0.92…1.16 which corresponds well with the low organic content 1.05…2.45% (Talviste, 2011) of black ash. Void ratio of ASHa is smaller compared to void ratio of ASHw due to the different mixing conditions. By adding two parts of water to one part of black ash mixing is happening at submerged conditions, full saturation of black ash voids with water is achieved at e = 1.16 (Table 6) and mixture is covered with excess water. By adding one part of water to two parts of black ash mixing is happening in wet conditions with no excess water.

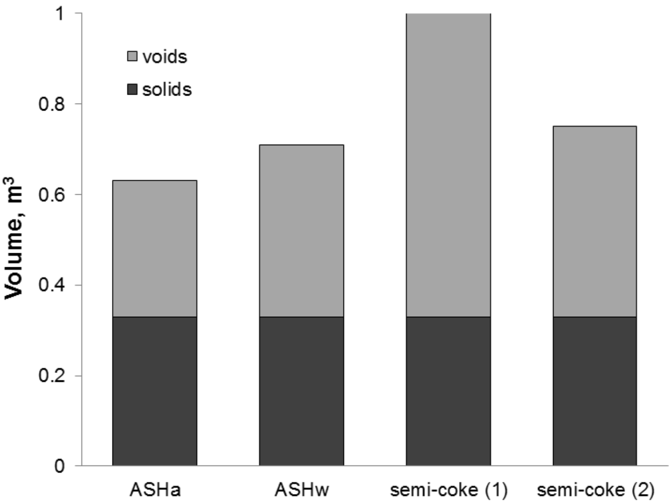

Figure 24. Void ratio of black ash in water mixture at ratio 2a:1w in air (ASHa) e = 0.92;, Black ash water mixture 1a:2w ratio in water (ASHw) e = 1.16; semi-coke 1, before compaction e = 2.0; and semi-coke 2, after compaction e = 1.25.

3.2.1 Hydration, cementation and stability of black-ash

Black ash contains several reactive phases (e.g. lime, belite) that react with water and have potential cementation properties. Ash contains notably low amount (<5%) of lime (CaO) suggesting that carbonation reactions do not contribute much to the stabilization of the sediment. However, black ash contains considerable amount of cement clinker minerals belite and ferrite which form C-S-H gel-like mass providing cementation of the material. Hydration of ferrite (C4AF) occurs rather quickly, but its contribution to the strength is rather subdued (6–8 MPa in pure compound), whereas the belite hydration in cement pastes occurs over 60–90 days, but its final strength peaks at about 40 MPa for pure compound (Mindess et al. 2003). Moreover, upon long term hydration black ash develops another binding phase – hydrocalumite. As the result, the black ash mortars show uniaxial compressive strength values >6 MPa after 90 days after curing in ambient air conditions (Fig. 25; Talviste et al., 2013 – PAPER VI).

Black ash is by physical characteristics and composition somewhat similar to TPP ash formed in circulating fluidized bed combustion (CFBC) operating at about 800–900 °C. However, surprisingly the uniaxial compressive strength values of the black ash mortars are higher compared with CFBC ash mortars that reach maximum 4 MPa (Arro et al., 2009). At the same time the content of potential binding phases in black ash is 10–15% lower compared to CFBC ash (e.g. Bitjukova et al., 2010). The reasons for that difference lie probably in somewhat different composition of the binding phases. Although there are some similarities as the slacking of lime to portlandite and its subsequent carbonation into calcite, and formation of hydrocalumite; also conceptual differences can be seen. There is no evidence of massive precipitation of ettringite and gypsum in black ash in contrast to all TPP ash types (including CFBC ash) and semi-coke, where both phases are common (Mõtlep et al., 2007 – PAPER IX; Mõtlep et al., 2010; Pihu et al., 2012). Also experiments did not show expansion and cracking of the samples which is a common process accompanying intensive formation of ettringite (Bland et al., 1987) in TPP ash (Pihu et al., 2012) and in coal fly ash (e.g. Anthony et al., 2002). Instead, the cementation of black ash leads to the small but steady decrease of voids volume, expressed as void ratio decrease (Fig. 26).

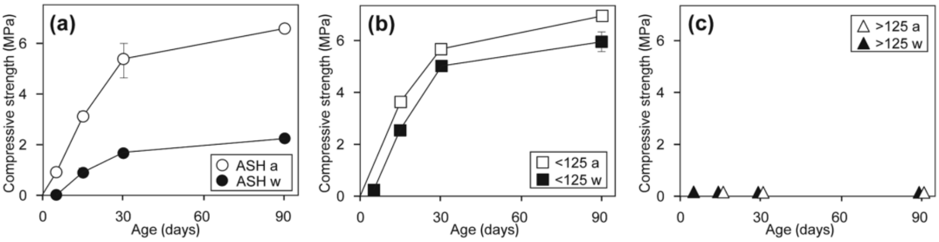

Figure 25. Compressive strength values of unsorted black ash (a), fine fraction <125 µm (b) and coarse fraction >125 µm (c) after 5, 15, 30 and 90 days. Average values and error bars (Talviste et al., 2013 – PAPER VI). (a) – aged in ambient air, (w) – aged in water.

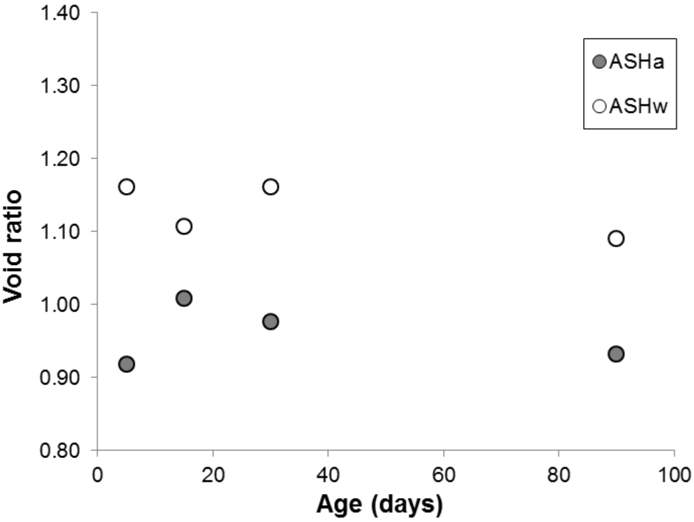

Figure 26. Void ratio decrease during cementation of black ash. Void ratio is calculated based on test data (Talviste et al., 2013 – PAPER VI; Talviste et al., 2011).

There are tree processes that, as an outcome, are resulting in decreased void ratio: (a) tighter packing of grains due to compression, (b) sedimentation of new minerals in the pore space and (c) decrease of specific gravity of the solid phase. As tested samples were held under the constant zero pressure (Talviste et al., 2013 – PAPER VI) compression seems unlikely. Moreover, as the expansion of the black ash samples was originally expected similar to semi-coke TTP ash mixtures (Sedman et al., 2012a – PAPER VIII), the volume changes of samples were monitored with no changes observed during the test (Talviste et al., 2013 – PAPER VI). Specific gravity of ash-water mixtures is higher compared to the specific gravity of black ash (Table 6). That leads to the explanation that decreased void ratio indicates precipitation of cementing minerals into voids similar to sandstone lithification. It is important, that precipitated minerals in black ash do not expand voids but form bonds between solid particles and the absence of massive ettringite and gypsum precipitation in black ash is probably the key factor in that. The proposed hypothesis needs further study with scanning electron microscopy from samples taken during the various phases of black ash cementation.

The absence of abundant ettringite in black ash is probably caused by sulphate deficiency. Ettringite forms mainly due to the reaction of Ca-aluminate or Si-Al glasses with sulphate which is provided by dissolution of anhydrite and/or gypsum. Ettringite precipitation is favoured by high sulphate concentrations, and it is stable at sulphate activities above $5 \cdot 10^{-4.5}$. Fresh black ash contains only traces of anhydrite and most of the sulphur occurs in oldhamite (Talviste et al., 2013 – PAPER VI). Although oldhamite is readily dissolved in water and sulphur becomes oxidised to thiosulphate and sulphate (Kann et al., 2004), the concentration is probably not high enough for ettringite formation. If the sulphate concentration in pore solution is low, monosulphate forms instead or ettringite transforms to monosulphate. However, monosulphate is not easily detectable in the XRD spectrum, and it is unclear to which extent it contributes to the strength development.

As indicated on Figure 27 the compressive strength of black ash may be a function of initial void ratio. Black ash water 2:1 mixture (ASHa) has a smaller initial void ratio compared to black ash water 1:2 mixture (ASHw) and although reasons behind void ratio rise of ASHa between 5th and 15th day are unknown, the relation between void ratio and compression strength is evident. While the void ratio decreases in the mixture, possibly indicating increasing amount of cementing minerals, the initial void ratio indicates distance between the particles prior to bonding. It is possible that the same amount of cement forms different strength depending on the distance between the particles. If true, the strength of black ash can be controlled via initial void ratio (porosity).

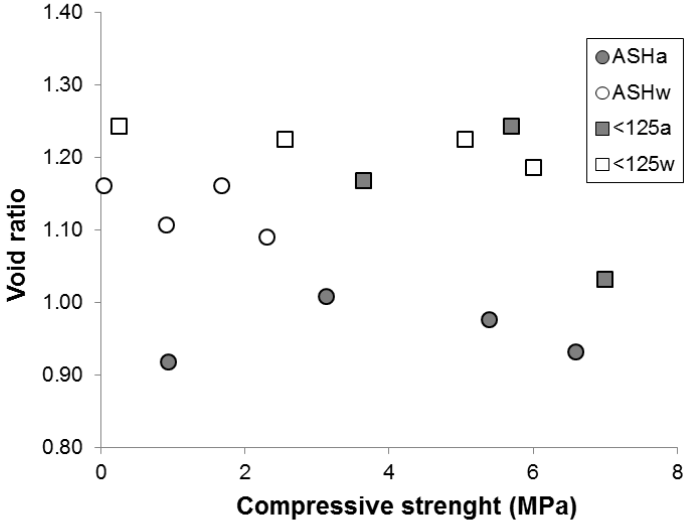

Figure 27. Relation between void ratio and compressive strength. Compressive strength increases with time (Fig. 25) but the relation hints that there might be a connection between the initial void ratio and finally achieved compressive strength.

The relation between the void ratio and compressive strength for black ash fraction <0.125 mm is similar – the strength increases as the void ratio decreases. The higher strength despite the higher initial void ratio is explained by smaller void dimensions, hence smaller particle distances in the generally finer granular materials.

Nevertheless, a good cementation behaviour of the analyses of cementing phases in black ash suggests that although the content of binding phases is lower compared to other oil shale wastes, in long term the cementation bonds are more stable due to hydration of belite and low content of unstable ettringite, which becomes decomposed at pH <10 and would cause stability issues of the waste depositories. The possibilities of strength control via initial void ratio and use of different fractions of black ash, as well as cementation bonds composition and location in the voids needs further study as it may influence the re-use of black ash.

4. CONCLUSIONS

The varved clay in western Estonia and oil shale retorting waste are complicated materials in terms of engineering as both have their geomechanical properties changing in response to changing environment. However, utilization of methodical approaches of various geological disciplines, allowed better understanding of the nature of the temporal changes of geotechnical properties.

The following conclusions can be drawn from the current thesis:

1. Varved clays in Pärnu are mainly soft ($c_U < 40$ kPa) low sensitivity clays ($St < 8$). They are characterized with high water content close to the liquid limit. Clays are slightly overconsolidated.
2. Although activity chart (Fig. 8) suggest that some samples are similar to "quick clay" formation, the w_N/w_L ratio (Fig. 12) and sensitivity does not indicate the phenomenon of "quick clays" in Pärnu area.
3. The overconsolidation of varved clays in Pärnu area is due to cemented bonds and that has led to the higher water content than normal. Nature of the bonding in varved clays in Pärnu is not investigated but carbonate mineralization could be considered as possible cementing agent.
4. The recent landslides in Pärnu area have several yielding mechanisms and in some aspects are similar to the landslides in "quick clays" and in other aspects to the landslides in overconsolidated clays. Geotechnical properties of the clay units, namely the water content and over-consolidation ratio, are determining the rupture mechanism.
5. The nature of soil softening to the fully softened critical state strength can be discussed in context of erosion related stress and creep, which follow shear stresses in slope area. Timeframes for the soil softening are from minutes (in Sauga landslide case) to the years (in Audru landslide case) and decades (in the stiff fissured clay slopes) up to the thousands of years (stiff fissured clay in Sillamäe without significant shear stresses in massive clay beds).
6. The soil softening is inevitable and the question is not if the slopes steeper then critical would fail, but when they fail. The critical slope inclination of ½ from the critical state friction angle can be suggested for practical use.
7. Low-stand of Yoldia Sea in the Pärnu Bay can be placed to an altitude of 0 to –2 m, which is rather similar to the earlier proposed minimum level in the Pärnu area between 3 and 0 m a.s.l. (Veski et al., 2005; Rosentau et al., 2009; 2011).
8. The formation and spatial distribution of desiccated clay unit A can be discussed and explained as emerged from the sea during the water level low-stand after the Billingen event.
9. Semi-coke is a high porosity material due to high organic content and geochemical reactions starting immediately if mixed with water. The high

void ratio is held up by ettringite bonding. However, the ettringite bonding is unstable due to geochemical degradation and geomechanical crushing.

10. Initial porosity of semi-coke is probably controlled by compaction. Smaller initial void ratio leads to lower permeability, hence lower geochemical degradation rates of ettringite and lower compressibility, hence lower geomechanical crushing of ettringite.
11. Attempts to control the initial porosity of semi-coke by adding fine TTP ash in order to fill the large scale voids of semi-coke did lead to expansion of the mixtures if the TTP ash content exceeded 20–25% in the mixture.
12. Black ash exhibits self-cementing properties when mixed with water reaching compressive strength values >6 MPa. Most of the strength was gained during the first 30 days, and further increase was only minor.
13. The self-cementing properties of black ash are controlled mainly by the hydration of belite, precipitation of secondary calcite and, to the lesser extent, by hydrocalumite. This type of cementation can be considered chemically stable.
14. The possibility that the strength of black ash could be controlled via initial void ratio or by use of different fractions of black ash needs further assessment. The composition of cementation bonds and their location in the voids needs further study as it is important for possible re-use of black ash.

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SUMMARY IN ESTONIAN

Nõrkade savi- ja tehispinnaste geotehnilised omadused

Käesolev doktoritöö uurib suure poorsusega nõrkade looduslike ja tehispinnaste füüsikalis-mehaanilisi omadusi, nagu pinnaseosakeste paigutuse tihedus, veejuhtivus, kokkusurutavus ja tugevus, mis määravad tsementatsiooniliste sidemete tekkimise ja püsivuse. Töös käsitletakse kahe äärmuslike omadustega pinnase, hilisjääaja viirsavi ja põlevkivitööstuse jäätmehoidlate settelasundite geotehnilisi omadusi muutuvates välistingimustes. Füüsikalistest ja keemilistest omadustest tingituna on need setendid potentsiaalselt ebastabiilsed ning muuhulgas altid maalihete või varingute tekkimisele.

Uurimuse eesmärkideks oli 1) selgitada hilisjääajal settinud viirsavide geotehnilisi omadusi ning ruumilis-ajalise muutumise seost maalihetega Pärnu piirkonnas (Kohv *et al.*, 2009; Kohv *et al.*, 2010, 2010a); 2) kirjeldada keskkonnatingimusi, mis on kujundanud viirsavide omadusi (Hang *et al.*, 2007; Talviste *et al.*, 2012); 3) selgitada välja põlevkiviõli tootmisel tekkivate tahkete jäätmete – poolkoksi ja musta tuha – tsementeerumise kontrollivõimalused, lähtudes uudismineralisatsiooni käigus moodustuvate geokeemiliste sidemete tugevuse mehaanilisest mudelist; eesmärgiks on saavutada püsiva tugevusega ladestu ning madal veejuhtivus (Mõtlep *et al.*, 2007; Sedman *et al.*, 2012, 2012a; Talviste *et al.*, 2013).

Pärnu piirkonna viirsavilasund on geotehniliste parameetrite (Talviste, 1988), mineraloogilise ja keemilise koostise (Kattel, 1989) ning varvide iseloomu (Hang *et al.*, 2007) alusel jagatud viieks faatsieseks. Poorsusindeksi (Burland, 1990) kaudu normaliseeritud viirsavide omadused näitavad nende vastavust sedimentoloogilise tihenemise sõltuvusele (*sedimentation compression line* – SCL). Siiski esineb viirsavi lasundis ka märgatavalt erineva poorsusega tsoone, mille geotehnilised omadused hälbivad tihenemissõltuvusest. Kui tihenemissõltuvusega ennustatust väiksema poorsusega viirsavi asub reeglina lasundi ülemises osas ja selle tekkimine on seotud savi pindmise kuivamisega, siis eeldatust suurema poorsusega savikihindid paiknevad näiliselt seaduspäratult. Nii puuduvad suurema poorsusega tsoonid nendes viirsavi läbilõigetes, mis paiknevad rannajoone läheduses, Pärnu põhjaosas on suurenenud poorsusega osad viirsavide kompleksi läbilõigete ülaosas, töös analüüsitud maalihete piirkonnas läbilõike kesk- või alaosas. Pärnu ümbruses on viirsavi geotehnilised omadused määratud hilisjääaegsete geoloogiliste protsesside poolt. Viirsavi omaduste uuring näitas, et Billingeni katastroofi järgne madal veeseis ulatus Pärnu ümbruses tasemeni 0…–2 m alla merepinna (Talviste *et al.*, 2012). Sellega on Pärnu linna lõunaosas kaasnenud viirsavikompleksi valikuline *ca* 4 m paksune erosioon ning kogu linna piirides on viirsavipinnasesse moodustunud *ca* 4 m kõrgune astang. Valikuline erosioon seletab ka erinevat veesisalduse ja voolavuspiiri suhet osades Pärnu viirsavikihtide läbilõigetes, mis võib olla võtmeks, et seletada tsementatsiooniliste sidemete puudumist näiteks praeguse rannajoone lähedastes läbilõigetes. Madala veetaseme perioodil oli viirsavi pealispind Pärnu linna põhjaosas Läänemere veetasemest kõrgemal ning sealsed tingimused soodustasid kuivamiskooriku tekkimist.

Üldreeglina seostatakse sedimentatsioonilisest tihenemissõltuvusest ehk normaalsest tihedusest suuremat poorsust tundlike (Bjerrum ja Rosenquist, 1956) või tsementatsiooniliste sidemetega savidega (Nagaraj *et al.*, 1994; 1998). Viirsavi kolloidaktiivsusteguri, veesisalduse ning voolavuspiiri suhte ja pinnaste tundlikkuse analüüs näitab, et kuigi teatud tunnuste järgi võib viirsavides esineda tundlikke tsoone, ei esine need tunnused reeglina koos. Ka tundlikkuse otsemäärangud pigem ei kinnita tundlike savide esinemist uuringuala viirsavide hulgas. Eespool kirjeldatud suurema poorsusega tsoonid viirsavilasundis on käesolevas uuringus seostatud tsementatsiooniliste sidemetega. Sidemete iseloom ei ole teada, kuid sarnaselt Kanada viirsavidega (Tavenas *et al.*, 1971) võib tegemist olla karbonaatse tsementatsiooniga.

Lääne-Eestis registreeritud ja viirsavidega seotud maalihked jagunevad kahte suurde gruppi: väikesed lihked jõgede kallastel ja suured lihked oru veerul (Kohv *et al.*, 2009). Võrdlus teiste samalaadsete savides toimunud maalihetega maailmas (Hutchinson, 1967; Skempton, 1970; Gregsen, 1981; Simons *et al.*, 2001; Quinn, 2009) näitas järgmist. Esiteks, väikesed maalihked on nagu lihked normaaltihenenud savideski seotud veetaseme järskude langustega veekogus (jões). Need toimuvad ületihenenud savide lihetega sarnaselt tugevuse kahanemise faasis ning vallandavad samamoodi kui tundlike savide maalihked sageli järgnevaid suuri maalihkeid. Teiseks, suured maalihked toimuvad ületihenenud savide lihetega sarnaselt savi kriitilise tugevuse juures ja on nagu tundlikes savides toimuvad lihkedki mitmeastmelised ning lihkepinnad jälgivad tsoone, kus on varem purunemisi toimunud. Teoreetilises plaanis on savi tugevuse kahanemine peale koormuse vähenemist loomulik protsess (Burland, 1990; Skempton, 1970; Schofield ja Wroth, 1968). See on seotud dekompressioonil tekkiva negatiivse poorirõhu tõttu pooriruumi tagasi imatava niiskusega. Sellise protsessi ilmekaks näiteks on Kambriumi vanusega ületihenenud mikropragulise sinisavi veesisalduse suurenemine ja tugevuse vähenemine, mis on toimunud peale viimase jääaja liustike taandumist (Barnekow ja Talviste, 2002). Nõlvades võivad nihkepingete poolt esile kutsutud dilatatsioon ja mikropragude avanemine seda protsessi oluliselt kiirendada ning viia tugevuse kahanemise kõigest 40–50 aasta jooksul kriitilise tugevuseni (Skempton ,1970). Lääne-Eesti jõgede kallastel, väikeste maalihete toimumise tsoonis, on viirsavi jõe erosiooni tõttu oluliselt ületihenenud ning ülal kirjeldatuga sarnaselt jõgede kallastel savi tugevus kahaneb.

Nõlvadel toimub nendes tsoonides, kus savi poorsus ja veesisaldus on tsementatsiooniliste sidemete mõjul suuremad, savi tugevuse kahanemine nihkepingete mõjul purunevate tsementatsiooniliste sidemete katkemisena (Quinn, 2009). Nõlvas tekkivad nihkepinged võivad teatud tsoonides ületada nihketugevuse, sel juhul purustab arenev nihkedeformatsioon aja jooksul keemilised sidemed, mille tõttu nihkepinged vähenenud tugevusega tsoonidega külgnevatel aladel suurenevad. See võib viia iseseisvate maaliheteni (nt Audru maalihe) või kutsuda esile kiirelt areneva suure mitmeastmelise maalihke, mis järgneb esmasele väikesele maalihkele kaldatsoonis (nt Sauga maalihe).

Oluline on siinjuures asjaolu, et erinevalt ületihenenud savist ei ole tugevuse vähenemiseks vajalik täiendava vee imamine savisse, kuna purunemiseelse seisundi veesisaldus on tavapärasest suurem. Sarnaselt erosiooniga vähendab efektiivpingeid põhjaveehorisondi survetaseme tõus pinnases, ja vastupidi, põhjavee survetaseme langus suurendab efektiivpingeid (Listra ja Talviste, 1988). Seega võivad hiljuti Pärnu ümbruses sagenenud maalihked olla seotud aastatel 1960–1990 intensiivse veetarbimise tagajärjel moodustunud põhjavee depressioonilehtri täitumisega, kui põhjavee tarbimine kiiresti langes. Orud, kus voolavad Lääne-Eesti jõed, on erosioonilised ja viirsavi tugevuse vähenemine orgude nõlvadel on ajas paratamatu. Käesoleva doktoritöö uuringud näitavad, et savi tugevus nõlvas on kohati kahanenud kriitilise seisundi tugevuseni. Maalihkeohtlikud on nõlvad, mille kallak on pool kriitilise seisundi sisehõõrdenurgast.

Poolkoks, must erineva terasuurusega poorne materjal, tekib utmisprotsessides ja sisaldab tüüpiliselt kuni 10% ulatuses orgaanilisi jääke (Sedman *et al.*, 2012). Eestis on poolkoksi aastate jooksul ladestatud Kohtla-Järvel ja Kiviõlis paiknevatesse ladestutesse, mida ladestamistehnoloogia tõttu iseloomustab suur heterogeensus. Eraldatud on kolm struktuuritüüpi: peeneteraline kildalaadne, jämedateraline konglomeraadilaadne ja sorteerimata poolkoks (Sedman *et al.*, 2012).

Ladestatud poolkoksi iseloomustab suur poorsus ning ebatavaliselt kõrge voolavuspiir vaatamata sellele, et poolkoksil puuduvad peale Atterbergi piiride igasugused savipinnastele iseloomulikud plastsed omadused. Voolavuspiiri väärtust kontrollib orgaaniliste jääkide sisaldus ning ka poolkoksi ladestusjärgne suur poorsus on osaliselt põhjustatud suurest orgaaniliste jääkide sisaldusest. Samas näitavad algse struktuuriga ja purustatud proovide poorsustegurite erinevused, et algpoorsuse kujundamist on mõjutanud ladestamise ajal pooriruumis toimunud kiire uudismineraalide kristalliseerumine – peale proovi purustamist ladestamisjärgse poorsusega materjali enam taastada ei õnnestu.

Uudismineralisatsiooni protsessid, mis poolkoksis tsementatsioonilisi sidemeid moodustavad, on ettringiidi ja sekundaarse kaltsiidi tekkimine (Mõtlep *et al.*, 2007). Uudismineraalid kristalliseeruvad poolkoksi pooriruumis osakesi siduvate võrgustikena, andes poolkoksile, vaatamata selle suurele poorsusele, ka suure tugevuse (Sedman *et al.*, 2012a). Kuna uudismineraalid täidavad osaliselt pooriruumi, siis väheneb ka poolkoksi veejuhtivus tingimusel, et uudismineralisatsioon ei põhjusta poolkoksi struktuuri purunemist (Sedman *et al.*, 2012a).

Ettringiit on kvaasistabiilne mineraal, mis laguneb, kui pH langeb alla 10,7 (Myneni *et al.*, 1998) või kui temperatuur tõuseb üle 70 ºC (Pourchez *et al.,* 2006). Seetõttu on tsementatsioon poolkoksimägedel kuni 0,5 m paksuses pinnakihis (Talviste *et al.*, 2008) ja põlengu- või kuumenemiskollete ümbruses

(Talviste, 2012) hävinud. Lisaks algab ettringiidikristallide mehhaaniline purunemine kohe peale lasuvate poolkoksikihtide ladestamist. Seetõttu on ettringiitse tsementatsiooni säilimine poolkoksi ladestu geotehnilise stabiilsuse ja väikese veejuhtivuse tagamiseks äärmiselt oluline. Tsementatsiooni pika-ajalisuse tagamiseks on alates 2005. a poolkoksi kohe peale ladestamist tihendatud. See tagab väiksema algse poorsuse ning seeläbi ühelt poolt parema mehaanilise kindluse (vähenenud deformatsioonide kaudu koormamisel); teiselt poolt parema geokeemilise ja temperatuurikindluse (vähenenud vee- ja õhujuhtivuse kaudu). Doktoriuuringute raames läbi viidud eksperimendid poolkoksi poorsuse vähendamiseks põlevkivituha lisamisega näitasid, et pooriruum sulgus juba üle 20% tuhasisalduse juures ning hilinenud ettringiidi tekkimine põhjustas proovide paisumise ja pragunemise (Sedman *et al.*, 2012a).

Must tuhk, teine õlitööstuse jääk, tekib uuemates utmistehnoloogiates ning võrreldes poolkoksiga kõrgematel temperatuuridel (Talviste *et al.*, 2013). Must tuhk sarnaneb oma lõimise poolest rohkem põlevkivituha kui poolkoksiga. Tumeda värvuse annab kuni paariprotsendine orgaanilise aine jääk tuhas. Musta tuhka ei ole seni eraldi ladestatud, kuid kuna selle tuha mahud pidevalt kasvavad, siis on alanud uuringud optimaalse ladestamise meetodi leidmiseks. Väikse orgaanilise jäägi sisalduse tõttu on musta tuha algpoorsus *ca* kaks korda väiksem kui poolkoksil ning sõltub oluliselt vee hulgast. Uuringud näitavad, et musta tuha tsementeerumine ei põhine ainult ettringiidi tekkel (Talviste *et al.*, 2013) ja see on ilmselt põhjuseks, miks musta tuha proovikeha ei paisu ega pragune. Vastupidi, senised uuringud näitavad poorsuse vähenemist, mis saab üldise proovi ruumala säilimisel toimuda tsementeeriva materjali pooriruumi settimise arvel. Seniste uuringute järgi sõltub musta tuha tsementeerumisel saavutatav maksimaalne survetugevus sarnase lõimisega proovide puhul algsest tihedusest. Edasised uuringud peavad selgitama musta tuhka tsementeeriva faasi paiknemise pooriruumis ja kontrollima lõpptugevuse reguleerimise võimalusi proovi algtiheduse kaudu.

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PUBLICATIONS

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