Destabilisation processes of soft rock at building sites

CAROLA BOENSCH[1]

[1] *Martin-Luther-University Halle-Wittenberg. (e-mail: carola.boensch@geo.uni-halle.de)*

Abstract: The varying solidness and the fast disintegration of overconsolidated claystones in man-made and natural outcrops are often an important geotechnical problem. These phenomena are part of a detailed investigation considering Triassic Roet claystones and Jurassic Opalinuston as examples from various locations in Germany. Changes in the clay mineralogy are insignificant during the fast disintegration process. Consequently there must be other reasons for the claystone to display a rapid disintegration. Suction tension in differently weathered claystones has an influence on the shear strength and the disintegration of claystone aggregates. In case of a similar mineralogical composition and chemistry of the pore fluid and at a certain saturation level, the suction tension increases with the degree of weathering. If the saturation level is low, the values of friction angle and cohesion are higher and high suction tensions are effective in the pore space. The suction tension is composed of two parts, a capillary one due to pore diameter distribution and an adsorptive one due to mineralogical and pore fluid chemical composition. High suction tensions decrease the tendency of disintegration of claystones. The adsorptive part of soil water tension obviously has a slight influence on the shear strength of the overconsolidated claystones of varying solidness.

Résumé: La résistance variable et la dégradation rapide des argiles surconsolidées dans les affleurements naturels ou artificiels posent souvent un important problème géotechnique. Ces phénomènes sont l'objet d'investigations détaillées prenant les argiles triassiques de Roet et les Opalinuston jurassiques comme exemple sur divers sites en Allemagne. Les modifications minéralogiques de l'argile sont insignifiantes pendant le processus de dégradation rapide. Il doit donc y avoir d'autres raisons à l'origine de cette dégradation. La tension de succion dans des argiles variablement altérées a une influence sur la résistance au cisaillement et la désagrégation des formations argileuses. La composition minéralogique et le chimisme des fluides interstitiels étant semblables, la tension de succion augmente avec le degré d'altération pour un niveau de saturation donné. Si le niveau de saturation est bas, les valeurs de l'angle de frottement et la cohésion sont élevées, et une tension d'aspiration élevée est présente dans l'espace interstitiel. La tension de succion se compose des deux éléments suivants: La capillarité liée à la distribution des diamètres des pores et l'adsorption due à la composition minéralogique et au chimisme du fluide interstitiel. Une tension de succion élevée réduit la tendance à la désagrégation des argiles. La composante adsorption de la tension de succion du sol a bien sûr une légère influence sur la résistance au cisaillement des argiles surconsolidées de diverses résistances.

Keywords: shear strength, weathering, clay, aggregate, weak rocks, laboratory studies

INTRODUCTION

The varying solidness and the fast disintegration of overconsolidated claystones can often be observed in man-made and natural outcrops. Detecting causal coherences for the solid-fluid-interaction has not been particularly successful until now. Therefore the behaviour of clays as building base materials often changes unexpectedly. So the bearing capacity of ground or the slope stability can change significantly during civil works. These phenomena are part of a detailed investigation considering Triassic Roet claystones and Jurassic Opalinuston from various locations in Germany. Water bound on clay minerals or included in the clayey sediment has a different influence on physico-mechanical behaviour of clays. Claystones with similar particle size and mineralogical distribution and almost equal diagenetic history from three weathering profiles – two in Roet and one in Opalinuston - were tested. The results of measurement of water reception, water retention potential, aggregate disintegration, Atterberg limits and specific surface as well as their relation to each other are in part surprisingly.

It is still not really clear what the reasons for these phenomena are. It could be that changes in the clay mineralogy or other possible reasons responsible for the rapid disintegration.

CLASSIFICATION OF WEATHERED CLAYSTONES

The examined claystones went through different states of weathering that can be classified as different types. There is a smooth transition from nearly unweathered type 1 to the replasticised type 4. The classification in well-defined weathering types is a necessary compromise, which is needed for practical reasons in the everyday civil engineering. The clay mineralogy presented in this paper was measured by X-Ray diffraction of the separated part < 2 µm.

Weathering types

The progressive weathering is related to a decrease of aggregate strength and an increase of the fine-grained part of the matrix. A distinction into four weathering types is used in this work, which is partly based on the weathering classes of Einsele & Wallrauch (1964) (see Figure 1).

"Type 1" are claystones that have to be described according to the weathering classification to Einsele & Wallrauch (1964) as fresh jointed rock (W0). They have a firm consistency and are strongly overconsolidated. They don't contain a soft matrix quota.

Firm to semi-solid rock is classified in the weathering classes W1 to W2 under "Type 2". This material is predominantly overconsolidated but contains some soaked normally consolidated matrix quotas.

Inhomogeneous semi-solid rocks in the weathering classes W3 to W4 are summarised in "Type 3" clays. Stronger overconsolidated little chunks swim in a soft, normally consolidated matrix whose fraction increases proportionately with progressive weathering.

The weathering of "Type 4" clays is so advanced (W5) that the material is a homogeneous cohesive loose soil in a soft, sliceable and apparently normally consolidated state.

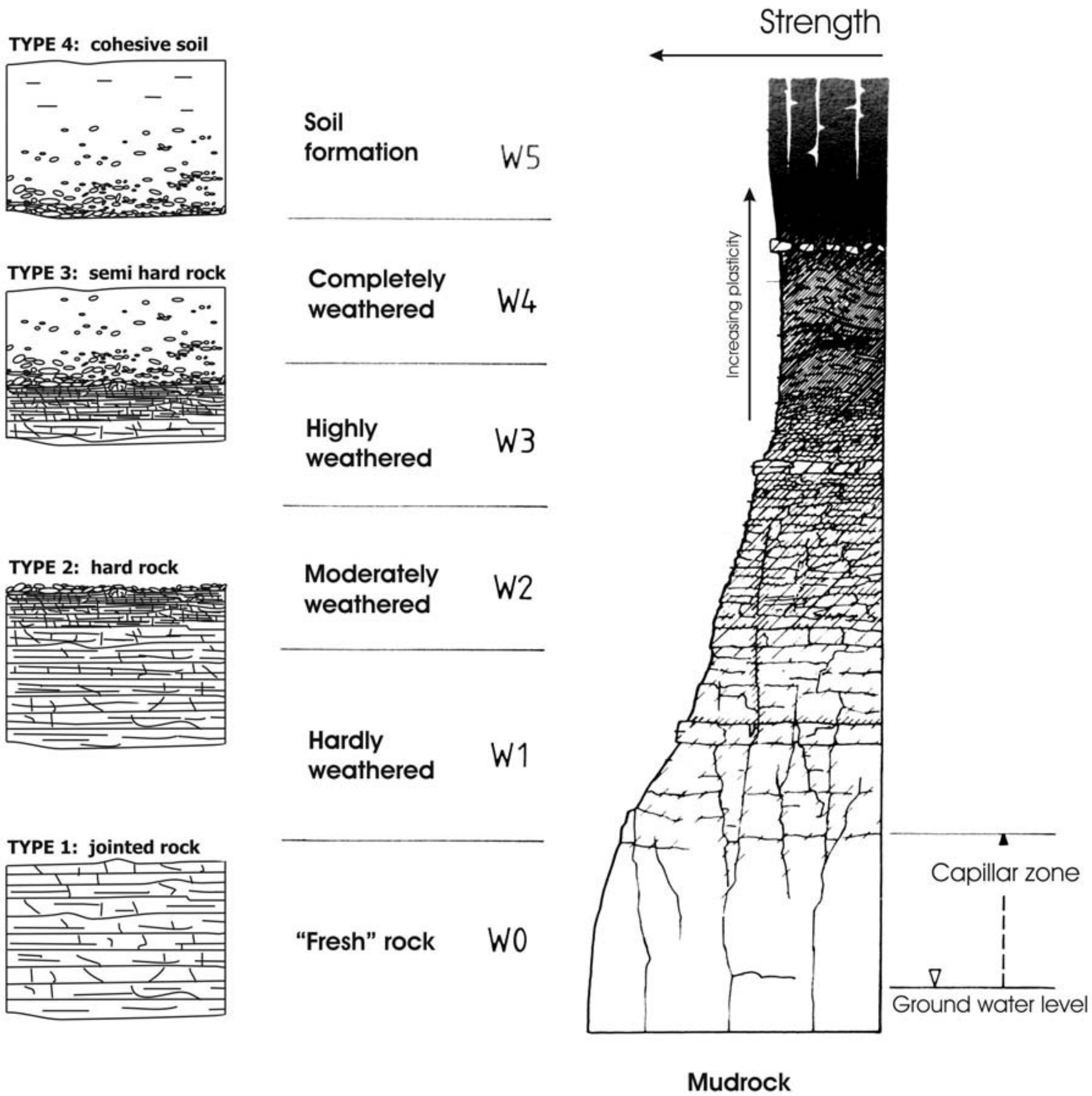

Figure 1. Weathering types of claystones (supplemented after Einsele & Wallrauch 1964).

The weathering scheme of Einsele & Wallrauch (1964) can be transferred to the scale of the Roet claystone aggregates (Bönsch & Lempp 2004). A break up of the individual aggregates takes place by a gradual weathering from the outside to inside, so that the outer, strongly broken up layer is formed with increased porosity while the degree of breaking is being reduced towards the centre (Figure 2). Gronemeyer *et al*. (1985) suggested this onion-skin principle for the classification of the weathering state of overconsolidated pelites. They have shown in electron microscope pictures that, as the weathering progresses, the fractional relaxation destroys the parallel stacking of clay minerals gradually from the margin toward the inside. Around the inner strongly overconsolidated core of the claystone aggregate there is a concentrically loose layer. With progressing weathering, this layer will be dispersed, the plastic matrix quota increases and the aggregate size decreases. Consequently there is a mixture of different sized aggregates and dispersed matrix. Therefore the behaviour of the overconsolidated claystone depends on the quotas of the individual fractions.

However, the disintegration behaviour of Opalinuston is different. The aggregates break up along the particle boundaries (see Figure 2). This difference between Roet claystones and Opalinuston is possibly induced by the very small content of mixed layer clay minerals in the Roet claystone. The gradual volume increase of the mixed layer clay particles due to osmotic swelling is sufficient to destroy the ordered clay particle scaffolding. Therefore the clay mineralogical composition determines the disintegration mechanism.

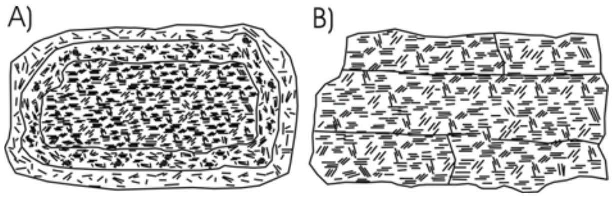

Figure 2. Disintegration mechanisms: A) Onion-skin like weathering of the Roet claystone aggregates. B) Aggregates break up along particle boundaries in Opalinuston.

Clay mineralogy

There is no significant change in the mineralogical composition during the weathering process. There may be differences in crystallinity. The Roet claystones consist of 87 to 89 per cent illite, 9 to 11 per cent kaolinite and a small quota, not determinable, of mixed layer clay mineral. The Opalinuston has an illite quota of 70 to 79 per cent. The rest of the clay minerals consist of kaolinite. Gypsum occurs finely distributed in the pore space or as a joint filling material in the two rocks. The coarser grains consist of quartz while feldspar could not be detected. Pyrite can be contained in the Opalinuston in less weathered areas.

Table 1. Clay mineralogy of two weathering profiles in a Roet claystone and Opalinuston.

	Roet claystone			**Opalinuston**	
Weathering Type	**illite**	**kaolinite**	**mixed layer**	**illite**	**kaolinite**
Type 1	87	10	3	75	25
Type 2	89	9	2	70	30
Type 3	87	11	2	73	27
Type 4	n.m.*	n.m.*	n.m.*	79	21

* n.m. equals not measured

MEASUREMENTS

Measurements of suction tension, tendency of disintegration and shear strength are considered in detail. Pressure membrane equipment was used for measuring the suction tension. The tendency of disintegration can be characterized by the decay during controlled drying-wetting cycles. The shear strength of the claystones was determined by direct shear tests.

Suction tension

Suction tension consists of capillary and adsorptive parts. The capillary part depends on the pore size distribution. The adsorptive part of suction tension is a function of the mineralogical composition of the solid part and the chemical composition of the pore fluid. There adsorptive tensions are about 50000 kN/m² (Schick 2004). Lu & Likos (2004) distinguish explicitly between the capillary regime of soil suction from 0 to 100 kN/m², the adsorbed water film regime between 100 and 10000 kN/m² and the tightly adsorbed regime at suction tensions from 10000 to 1000000 kN/m². Each of these segments of the soil suction curve is characterised by a change in slope at the transition points. Using pressure membrane equipment, the capillary part of suction and part of the suction due to the adsorbed water film can be determined for air pressures between 5 and 1500 kN/m². A special cellulose acetate membrane is used that is permeable by water but airtight.

The water content or the saturation level is plotted against the logarithm of the tension in the pF curve. The permanent fading point corresponds to a pF value of 4.2 (1500 kN/m²). This is the maximum tension, which plant roots are able to exert in order to withdraw water from their substratum. The field capacity corresponds to a pF value of 1.8 (approx. 6 kN/m²). At lower suction tensions in partly saturated soil water cannot be held back against gravity in the pore space. The suction tension of a soil is zero if it is saturated completely. The difference between these two water contents of field capacity and permanent fading point is the utilizable field capacity, which represents the water available for plants. The steeper the suction tension curve, the higher the utilizable field capacity is.

The pore volume can be inferred from the water content contained by a sample under defined suction tensions. The pore volume determined in this way is not the total pore volume. It represents that part of pore volume that has a lower and an upper limit pore diameter (Schlichting, Blume & Stahr 1995). Under the assumption that all pores are equally big and spherical an equivalent pore diameter can be calculated. The calculation is carried out according to the formula:

$$d_p = 0.3 / p \qquad (1)$$

where d_p is the pore diameter in cm and p the suction tension in mbar.

The results in relation to the aggregate size distributions are represented in Figure 3. The curves of grain sizes and pore size distribution are not parallel, as occasionally described (e.g. Schick 2004), because, apart from the aggregate and particle size distribution, the order of the anisotropic clay particles and the type of the grain contacts, cements etc. also plays a role. The spatial order of the clay particles and the pore space geometry within single claystone aggregates change during the weathering process (Bönsch & Lempp 2003). So the change of the micropores according to weathering does not occur unconditionally simultaneously with the change of the macropore distribution as a result of mechanical aggregate disintegration.

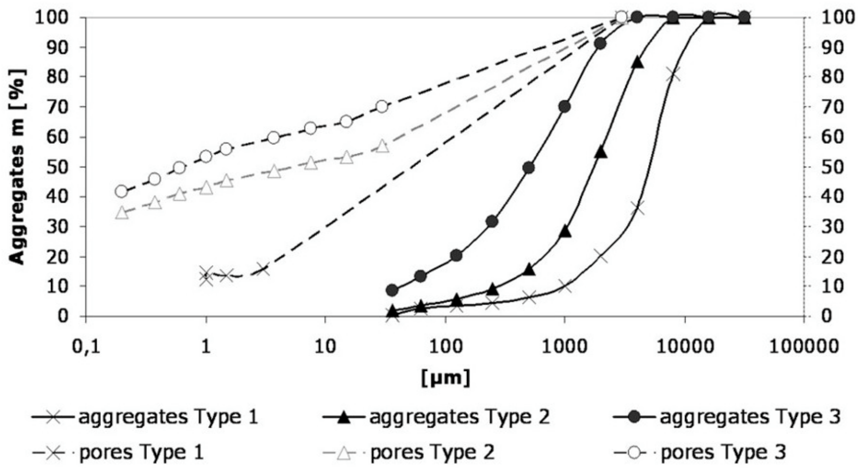

Figure 3. Pore diameter and aggregate distributions of differently weathered claystones.

The weathering degree or the associated differences in type and strength of the grain contacts, clay mineralogy etc. influence the suction tension at certain saturation levels to different extents (see Figure 4).

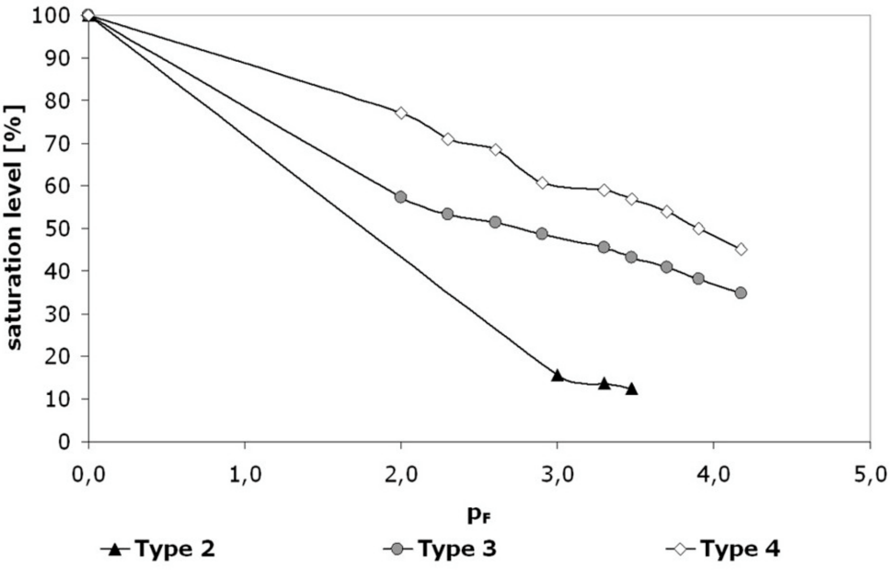

Figure 4. pF-curves of differently weathered claystones.

At the same saturation level of 0.5, the suction tensions increase with increasing weathering degree from pF lower then 2.4 in unweathered (Type 1) to pF about 4.0 in weathered (Type 4) Roet claystones (Figure 5). At a saturation degree of 0.95, the suction tension increases from pF of about 0.8 in the unweathered claystone (Type 1) to pF of 1.8 in weathered (Type 4) condition. In the case of Opalinuston the suction tension at a saturation degree of 0.5 ranges from pF 1.9 in the less weathered (Type 2) to pF 3.9 in weathered (Type 4) claystone. At a saturation degree of 0.95 there is an increase from pF 0.7 in the less weathered claystones (Type 2) to pF 1.0 in weathered (type 4) claystones. The suction tensions are almost independent of the weathering degree in the examined Roet claystones and the Opalinuston at very low saturation degrees. At saturation degree of 0.05 is the pF 4.4 for Roet claystones and between pF 4.1 and 4.4 for the Opalinuston (see Figure 5).

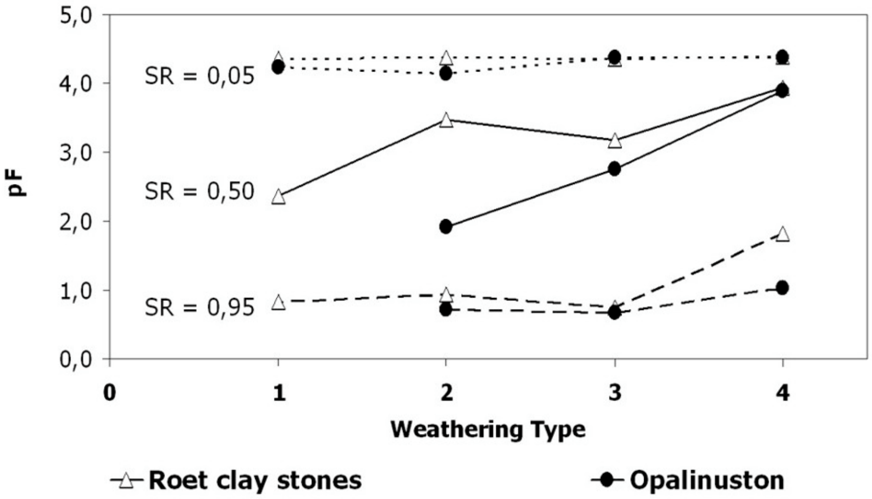

Figure 5. Suction tension at different saturation levels.

Water content-pF curves can be approximated by using a logarithmic regression of the following the form:

$$y = a + b \bullet \ln (x). \quad (2)$$

where the amount of the variable a represents approximately the saturation water content and the term $b \bullet \ln (x)$ describes the form of curve. More precisely, the flatter the curve, the smaller $b \bullet \ln (x)$ is. In the term $b \bullet \ln (x)$ is $-3 < b < 0$.

Normally the suction tension curves of more strongly weathered claystones are flatter because the aggregate disintegration reduces the coarse pores. The regression equations and some statistical parameters of the regression are given in Table 2. With the exception of Roet claystone Type 2 the variable a (i.e. the calculated saturation water content) increases from 8 to 30 per cent for Opalinuston and from 20 to 27 per cent for Roet claystones. These values correspond approximately with measured water contents at saturation. In this manner, it is difficult to compare the form of the pF curve of different weathered claystone using the water content (not the saturation level). Therefore in Figure 4 the saturation level is used in the pF curves of differently weathered Roet claystones for better comparison.

Table 2. Regression of suction tension curves of each weathering type from two locations in Roet claystone and Opalinuston.

	Regression equation	Statistic parameters*
Opalinuston (Essingen)		
Weathering Type 1	y = 8.4 - 0.1 ln(x)	c_D = 0.9; c_C = 0.9; S = 0.1
Weathering Type 2	y = 22.1 - 2.4 ln(x)	c_D = 1.0; c_C = 1.0; S = 1.0
Weathering Type 3	y = 26.7 - 2.2 ln(x)	c_D = 0.9; c_C = 1.0; S = 1.5
Weathering Type 4	y = 29.8 - 1.9 ln(x)	c_D = 1.0; c_C = 1.0; S = 0.5
Roet claystones (Deuna)		
Weathering Type 1	y = 20.3 - 2.1 ln(x)	c_D = 1.0; c_C = 1.0; S = 0.8
Weathering Type 2	y = 42.4 - 2.9 ln(x)	c_D = 1.0; c_C = 1.0; S = 1.2
Weathering Type 3	y = 17.8 - 1.5 ln(x)	c_D = 1.0; c_C = 1.0; S = 0.5
Weathering Type 4	y = 26.9 - 1.8 ln(x)	c_D = 0.9; c_C = 0.9; S = 2.0

*c_D = coefficient of determination, c_C = coefficient of correlation, S = standard deviation.

The suction tension is almost independent of the weathering degree at very low saturation levels. It may be that the adsorptive water amount dominates the capillary water amount at these very low degrees of saturation. Due to the low mineralogical difference and similar specific surfaces the suction tensions are hardly different. The corresponding water tension increases at higher saturation degrees with the weathering degree; this effect is weakened again at water contents near the total saturation.

The results possibly subject to a systematic error since the measuring principle of the pressure membrane cell assumes a generally plane contact between sample and membrane which cannot, however, be ensured for rough claystone aggregates. An equilibrium water content that corresponds to the tension is possible to achieve after a appropriately long test time.

Tendency of disintegration

The claystones were dried carefully at 40° C and then sieved to determine the aggregate size distribution. They were then moistened, dried once more and sieved again. The drying/humidification changes were repeated five times and the disintegration of the claystone aggregates measured as a result of water content changes. The tendency of disintegration can be defined as the standardised difference between the Median of initial claystone aggregate distribution and the median after the fifth drying/wetting cycle:

$$Z = (D_{50/1} - D_{50/5}) / D_{50/1} \quad (3)$$

where is Z the tendency of disintegration, $D_{50/1}$ the initial median and $D_{50/5}$ the median of the aggregate distribution after the fifth drying/wetting cycle.

The large Z is so the higher is the tendency to disintegration. The tendency of further disintegration decreases with progressive weathering.

There were three weathering profiles investigated (see Table 3). Roet claystones of weathering Type 1 have a tendency of disintegration from 0.96 to 0.98, the tendency of disintegration of the nearly unweathered Opalinuston is a little bit lower. Z for Type 2 ranges from 0.84 to 0.93. For Type 3 Z ranges from 0.63 to 0.76 and for Type 4 ranges from 0.28 to 0.63 in Roet claystones. The Type 4 Opalinuston has still a higher tendency of disintegration.

Table 3. Amounts of Z of different weathered claystones from different locations in Germany.

Weathering Type:	**1**	**2**	**3**	**4**
Roet claystone (Deuna)	0.96	0.84	0.76	0.28
Roet claystone (Karsdorf)	0.98	0.93	0.73	0.63
Opalinuston (Essingen)	0.91	0.86	0.63	0.74

In Figure 6 the evolution of aggregate size median is shown, becoming smaller with every sieving cycle. After 4 to 5 drying-wetting cycles the median of the aggregate size distribution no longer shows a significant change. This median ranges from 150 to 750 µm in Roet claystones and from 200 to 700 µm in Opalinuston (Figure 6). Normally the median of the Type 1 claystones is bigger then that of the more weathered claystones.

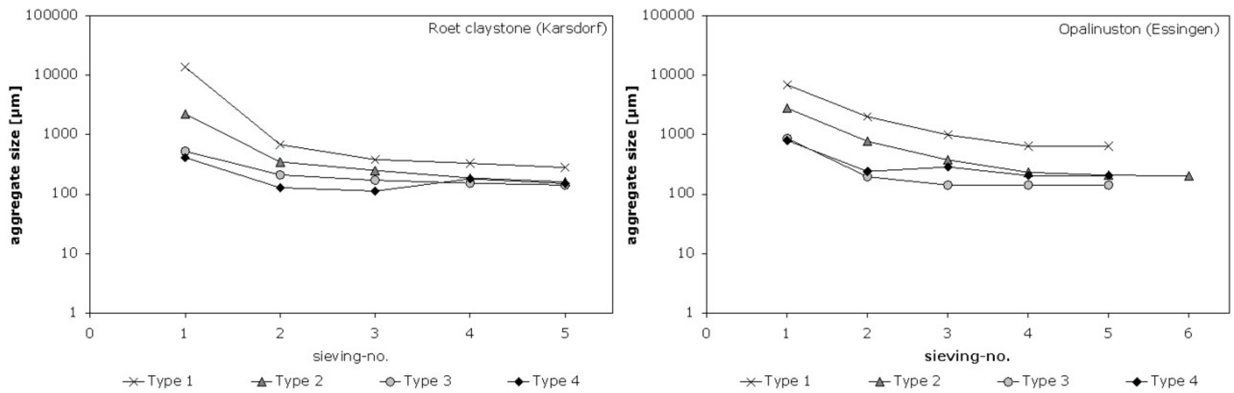

Figure 6. Changes of the median of aggregate size distribution during cyclic wetting-drying (Roet claystone from Karsdorf and Opalinuston from Essingen as an example).

Shear strength

The shear strength was measured by direct shear tests under different conditions. Some samples were nearly dry; others had natural water contents or were saturated. The test of a claystone Type 1 was impossible with the available conventional shear apparatus. In spite of the small sample dimension in direct shear tests using a normal soil mechanical shear box the shear strength of the Roet claystones is of a similar dimension like the results of the big sample shear tests by Sommer, Meyer-Kraul & Prinz (1989). At natural water content the friction angle of Roet claystone ranges from 22 to 32 ° and the cohesion ranges from 31 to 39 kN/m² (Table 4). The shear strength parameters of Opalinuston are of a similar dimension. At natural water content the friction angle ranges from 21 to 34 ° and the cohesion ranges from 21 to 65 kN/m². The shear strength is influenced by the suction tension conditions prevailing in the partly saturated claystone.

Both the friction angle and the cohesion are reduced by a higher saturation degree independently of the weathering degree (Bönsch & Lempp 2005). A change of the water content has an effect on the strength of the claystone aggregates since the quality of the cohesion of the fine-grained particles inside aggregates is influenced. The changes of the friction angle and cohesion according to changes in water content are larger at lower saturation degrees as compared for higher saturation level (Figure 7). Thus the shear strength changes moderately due to water content while suction ranges from 0 to 10000 kN/m². When suction tension achieves values of the adsorbed water component then the strength increases strongly.

Table 4. Shear strength parameters of the claystones at natural water content.

	Roet claystone	Opalinuston
φ [°]	22-32	21-34
c [kN/m²]	31-39	21-65
w [%]	9-28	8-19

A higher suction tension in the pore space increases the strength. The higher the friction angles and cohesion are, so the lower the saturation degree in the shear test. This effect is independent of the degree of weathering. Normally the highest suction tensions are in dry, low weathered claystones. If strong weathered claystones have a very small water content then their shear strength is very high. The plasticized fine grained matrix behaves like a normal clay with high "dry strength".

Depending on water content and tension level, a measurable scaling down of the claystone aggregates in direct shear test takes place, which is based on a crushing of the aggregates by the vertical stress and a grinding in the shear joint. In tests with water covering, the aggregate disintegration tendency according to the weathering degree also plays a role.

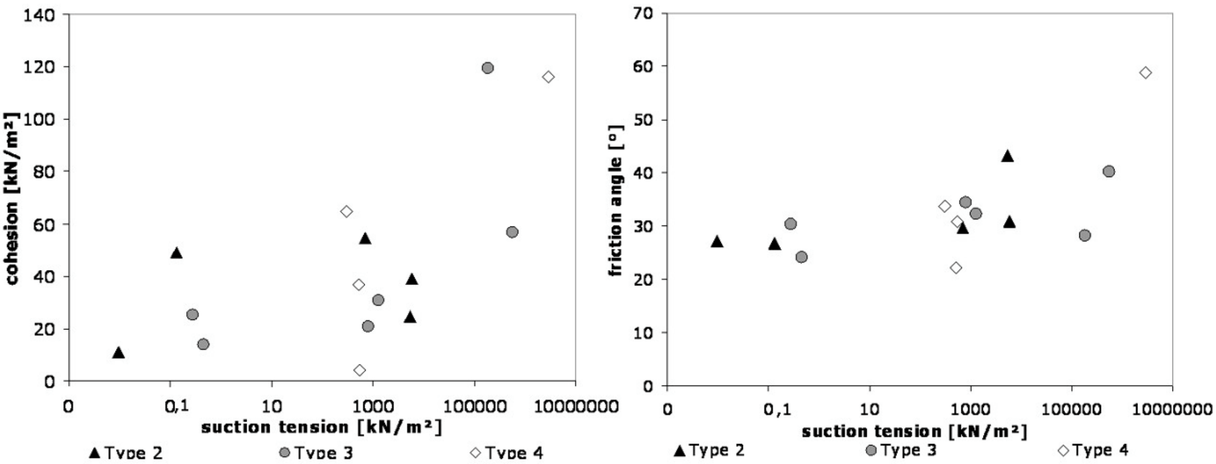

Figure 7. Shear strength parameters cohesion and friction angle against suction tension.

CONCLUSIONS

Changes in the clay mineralogy are insignificant during the fast disintegration process. The suction tension in differently weathered claystones has an influence on the shear strength and the disintegration of claystone aggregates. In the case of a similar mineralogical composition and chemical composition of the pore fluid and at a certain saturation level, the suction tension increases with the degree of weathering. If the saturation level is low, the values of friction angle and cohesion are higher and high suction tensions are effective in the pore space. High suction tensions decrease the tendency of disintegration of claystones. The absolute value of suction tension is not the only decisive factor for material strength. The influence of the amount of the suction tension change that is passed through during a desiccation or re-humidification process is more significant. If the utilizable field capacity is high, enough pores of a greater diameter are available to transport water during water adsorption of the dried out claystone to inside sufficiently quickly. The suction tension reduces itself relatively evenly. The utilizable field capacity is low; however, the water permeability is normally also lower. The water adsorption to the aggregates then is irregularly. This leads to tension differences if the suction tension partly was reduced by saturation and is partly still existing in neighbouring pores. This tension difference can be orders of magnitude above the rock strength, leading to an internal deformation distortion of the structure that causes "blowing-up" of the aggregates.

The different amounts of the utilizable field capacity could be interpreted as a measure of the effectiveness of the water transport in the pore space. At the same water tension change a larger quantity of water is transported in the more strongly weathered claystones. In the less weathered claystones, less water can be transported because a part of the energy is consumed to break the grain contacts.

The adsorptive part of soil water tension has a slight influence on the shear strength. Because of the onion-skin like weathering of the Roet claystones, the specific surface decreases with progressive weathering. Therefore changes in the absolute value of the adsorptive part of suction tension have to be expected. These apparently are not reflected in the shear strength. It is conceivable that the adsorptive suction is activated only if the dehydration is appropriately high. However, under natural conditions, such a strong dehydration is not reached in the near surface area because higher temperatures are required for the removal of adsorptively bound water. As far as the rock behaviour is concerned, it is more important to know whether the clayey parts of the matrix or the solid aggregates are dominating. Aggregates with smaller than 100 μm diameter behave like a silty or clayey soil.

The different disintegration mechanisms of Roet claystones and Opalinuston influence at the most the rock strength indirectly by matrix quota that results from the disintegration. In spite of their different disintegration mechanisms the

Roet claystones and the Opalinuston with comparable weathering degree and saturation levels have similar shear strength.

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Corresponding author: Mrs Carola Boensch, Martin-Luther-University Halle-Wittenberg, Von-Seckendorff-Platz 3, Halle, Saxony-Anhalt, 06120, Germany. Tel: +49 345 5526157. Email: carola.boensch@geo.uni-halle.de.

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