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Compaction Behavior and Permeability of Clayey Soil in Scope of the Mineralogical Composition of the Clay Mineral

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ABSTRACT: Clayey soils play a major role in civil constructions. Clay can be used as base sealing in waste disposal sites, as sealing core in dams, but also can build up the construction ground in infrastructure projects. In all cases the soil-mechanical properties are important to consider. Soil-mechanical properties can vary according to mineral type and composition. Expansive and non-expansive clay minerals have different soil-mechanical behavior. But also, expansive soils of the same clay mineral type can pose different soil-mechanical properties depending on the diffusive Double Layer and hence on the type of ions surrounding the clay particles.
Mineral base sealing for waste disposal sites has gained a great significance in the last decade since there have been demands towards depositing increasingly huge amounts of waste on disposal sites. Such mineral sealing shows a complex behavior concerning the compactibility, permeability, and plasticity. Against this background, the influence of the diffusive Double Layer on the soil-mechanical properties is explained and the relationships of several parameters, especially with regard to compaction and permeability are presented in this paper. Significant aspects of the mentioned Properties are discussed and evaluated for three different soil types.
Keywords: Clayey soil, compaction of clayey soil, soil-mechanical properties, behavior of clayey soil, mineral base sealing, Proctor clay compaction.

I. INTRODUCTION

Due to the technical development of earthworks in the last few years and the need to deposit large amounts of waste materials, artificially compacted, cohesive soil has become increasingly important as sealing material. There are high quality requirements
- essentially the tightness - of the built-in material in the foreground. These requirements are mainly controlled by the compaction density achieved. However, since the dry density does not show a clear relationship with the permeability for the various cohesive soils, this control criterion is usually not sufficient for specifying e.g. the tightness. Expansive and non-expansive clay minerals have different soil-mechanical behavior. But also, expansive soils of the same clay mineral type can pose different soil-mechanical properties depending on the diffusive Double Layer and hence on the type of ions surrounding the clay particles (Figure 1).

Natural sealing materials were created under different geological, mineralogical and geological boundary conditions and therefore have different properties. Depending on the nature and composition of the material, the relationships and interactions between the material-specific properties, the influencing parameters induced by the compaction technology and the permeability can be very complex. Therefore, there is an urgent need to develop standardized compaction and control methods, which allow a comparison with regard to the quality requirements. This can only be achieved through a better knowledge of the relationships and interactions as well as through the theoretical understanding of the flow processes.

The present work tries to discuss and evaluate some aspects related to the compactibility and permeability of artificially compacted unconsolidated soil. For this evaluation three different soil types have been chosen for the laboratory testing. A Kaolinite (Oedinger Soil), an Illite mixed layer soil (Ratinger) and a Smectite-type soil (Eva).

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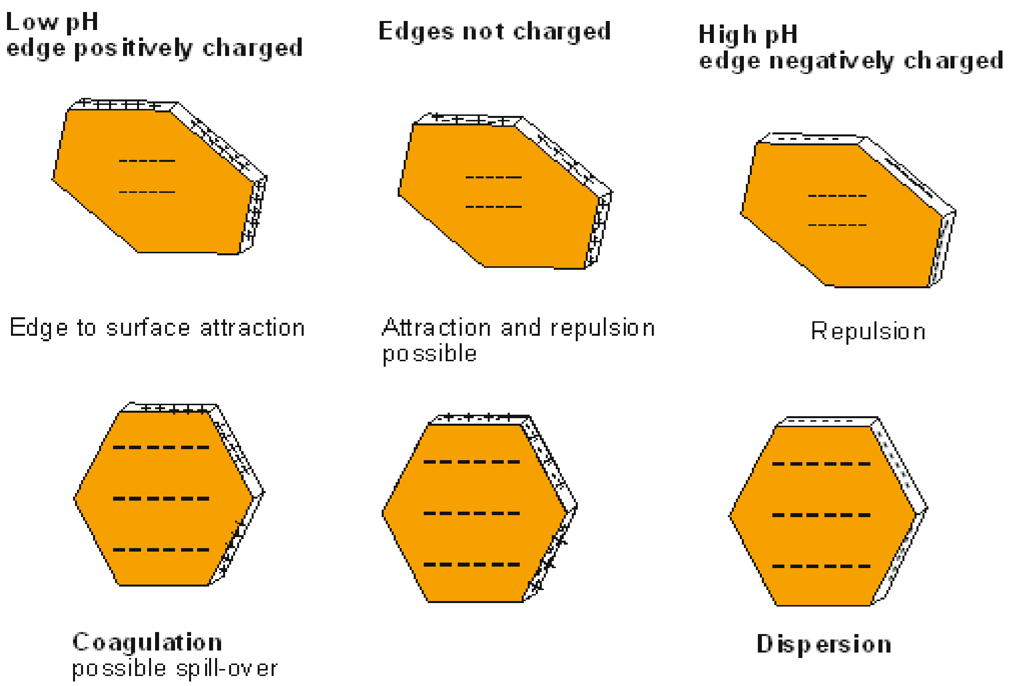

Figure 1: Clay mineral structure depending on pH-value

Figure 2 shows the clay content versus the liquid limit of the three different clayey soils.

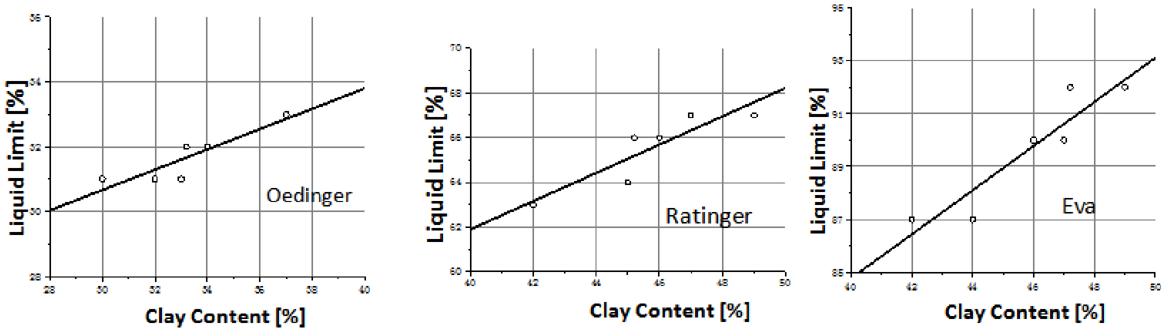

Figure 2: Correlation between the liquid limits and the clay contents of the three soils

Compaction

The compactibility and compression behavior of cohesive soils are usually investigated purely mechanically and explained theoretically. The underlying mechanical model of a honeycomb structure that collapses with increasing load and causes large reduction in volume, cannot explain many of the observed phenomena. Hence, it is important that clay mineralogy or colloquial chemistry should be included in the soil mechanical model analysis. Figure 1 shows the influence of the pH and hence the edge charge of the clay particles on the attraction/repulsion behavior and thus on the soil-mechanical properties.

FREUNDLICH (1935) tried to represent the various forces acting between the clay particles using a diagram. Figure 3 shows the Freundlich diagram with an additional extension, in which the action of external forces is shown (Azzam, 1989).

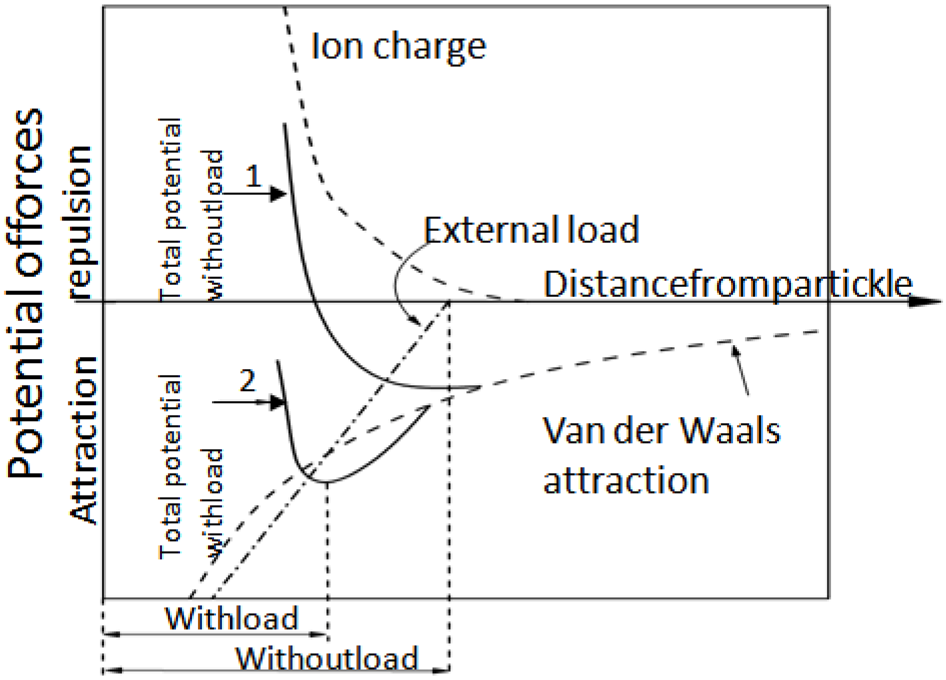

Figure 3: Schematic representation of the potential of forces and the distance between two clay particles considering external loads

The minimum of curve 1 corresponds to the distance of clay particles in a stable state. In order to change this state, the particles need additional energy. This is the case with a clay paste, for example. Should this minimum have a low potential level, a low energy input is sufficient to change the particle positions. This behavior is known as thixotropy.

If the clay is placed under an external force, a new minimum (curve 2) will occur. The clay particles strive for a new stable state with a smaller particle distance. This new condition causes an increase of the attraction forces and thus the cohesion.

The mechanical behavior of cohesive loose soil is determined by the existing force potential in the layer structure. This potential in turn depends on the hydration energy of the ions present. This determines the thickness of the Double Layer and thus also the distance between the particles. The compressive strength decreases according to a quadratic function with the increase of water content, as well as increases in accordance with a quadratic function with the increase of the degree of compaction, and increases linearly with the increase of confining pressure (LIU, H. B., et. al., 2016).

Figure 4 shows compression curves of different clay types. The void ratio depends not only on the applied load, but also on the cation occupancy. A sodium montmorillonite has more than twice the void ratio under the same stress condition as a calcium montmorillonite.

It can therefore be seen that an isomorphic exchange of ions or a change in the ion concentration results in a change in the soil mechanical properties. This aspect is extremely important for the long-term safety of pile landfills, which are equipped with a mineral base sealing. A change in the clay properties due to seepage water, for example, can have unforeseeable effects such as settlement, settlement differences, swelling, shrinking and changes in the permeability behavior.

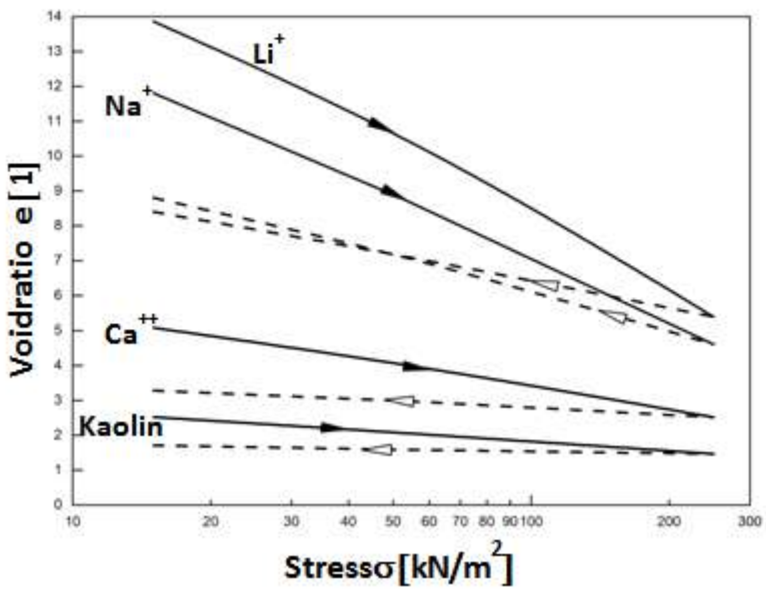

Figure 4: Void ratio versus compressive stress for different clay types

Influence on compactibility

The dry density is generally used to describe the degree of compaction under the action of a certain compaction energy. The resulted dry density varies for one and the same material depending on the water content. This relationship is represented by the Proctor curve (Fig. 5).

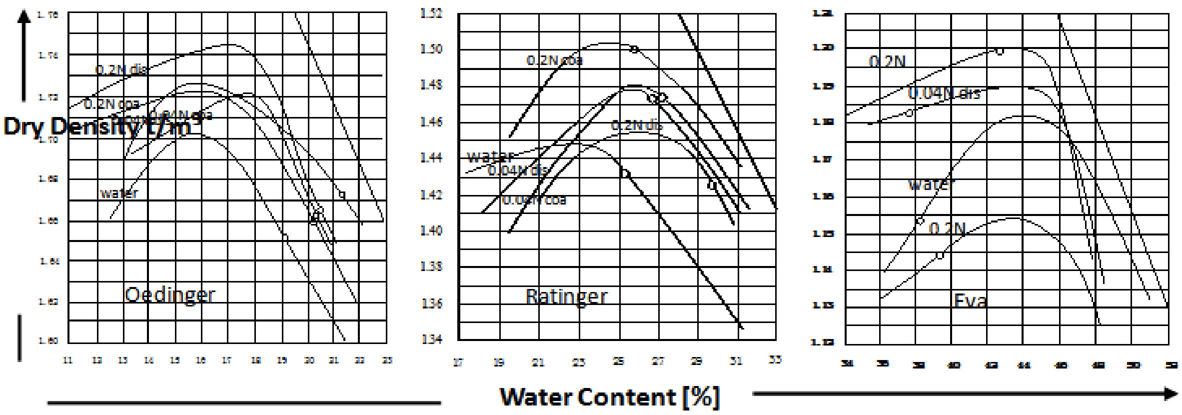

Figure 5: Dry density versus water content at compaction for the three tested soils

As can be seen from these curves, the water content at compaction has a considerable influence on the compressibility. This is due to the fact that the water has a lubricating effect and thus has a beneficial effect on the movement processes of the individual clay particles during compaction. If the water content exceeds a certain value, part of the energy applied is absorbed by the pore water in the form of excess pore water pressure and thus does not contribute to compaction. If the clay is compacted too dry, the compression energy is partly absorbed by friction. Therefore, the Proctor curve shows a maximum at which the lubricating effect and the friction allow optimal compaction. The parameter values belonging to this maximum (dry density and water content) are called Proctor parameters. The water content also determines the settling behavior of the cohesive soil. The maximum achieved with Proctor compaction is reflected in the settlement behavior. This is also influenced by the Diffusive Double Layer and hence the type of ions in it. water surrounding the clay particles which has considerable volume, leads

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to an increase in the water content and a decrease in the dry unit weight (SHAKIR et. al. 2019).

To explore the influence of the clay structure on the mechanical behavior coagulant (Calcium Chloride) and dispersant (Sodium Pyrophosphate) have been mixed with the soil. Figure 5 shows the Proctor-Curves of the three different soils mixed with pure water, with coagulant and with dispersant for comparison.

Figure 6 shows the relationship for the Proctor Density and Water Content from the additive chemicals for the tested soils (OK is Oedinger Kaolin, RT is Ratinger and E-70 is Eva). It can be seen that the maximum density at low water content is achieved for specimens that are mixed with Calcium Chloride. Where specimens mixed with Sodium pyrophosphate show the maximum water content and the lowest density.

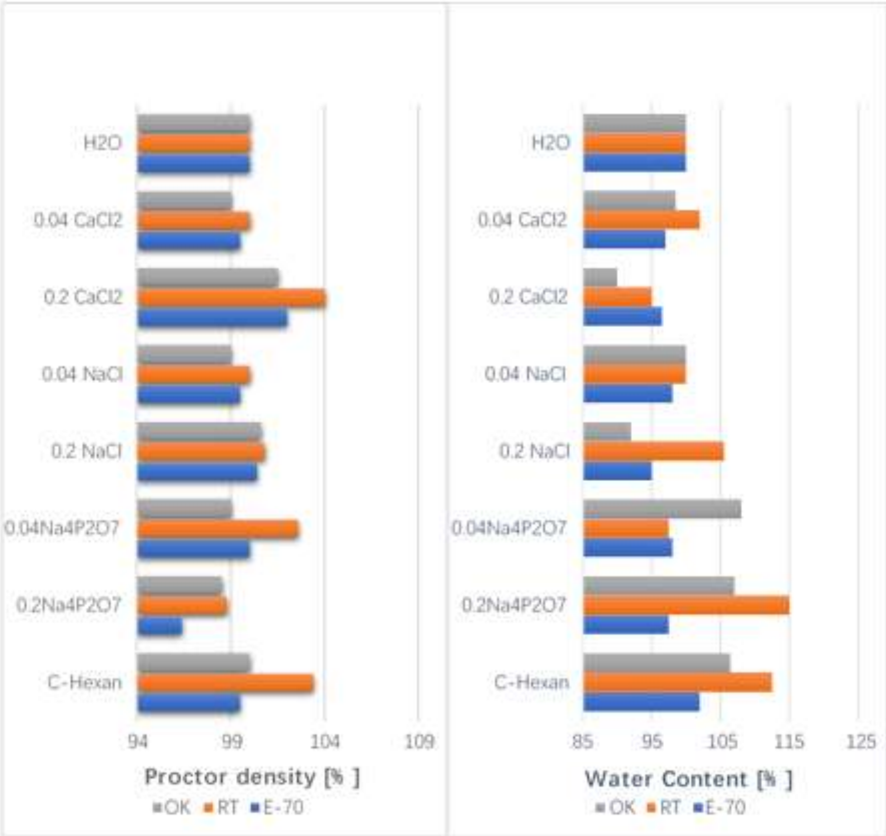

Figure 6: Proctor Density and Water Content for the tested soils depending on additives

The Proctor standard compaction is usually used as a comparison basis for the compaction that can be achieved on loose soil at construction site. Experience has shown that this compaction is economically, advantageous and sufficient for most earth-works applications. A stronger compaction can be achieved by using a considerably higher amount of energy.

In addition to the Proctor standard compaction, there is also the Proctor-modified compaction, which can be seen as the upper limit of economic compaction. The compression work is increased by four and a half times. The increase in compaction achieved is less than 20%. For more information on the Ratinger soil see also DÜLLMANN (1987).

Influence of the material parameters

Cohesive soils show a natural distribution of the material parameters. Depending on the geological formation conditions and the mineralogical composition, the soil-specific properties can vary within wide limits. This distribution is reflected in the compaction behavior

Since the liquid limit is a measure for the plasticity and hence for the cohesion, it shows a good correlation with the compaction. Figure 7 shows the influence of the liquid limit on the one hand on the optimal water content and on the other

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hand on the optimal dry density. According to KHALID et al., 2018 The higher the plasticity index, the smaller the dry density and the higher the optimum water content.
The dependency applies to the most clayey soils and allows an initial estimation of the achievable Proctor density at a certain optimal water content. The specified ranges are based on evaluations of results from various publications. A clear relationship between the achievable density and other index parameters could not be determined.

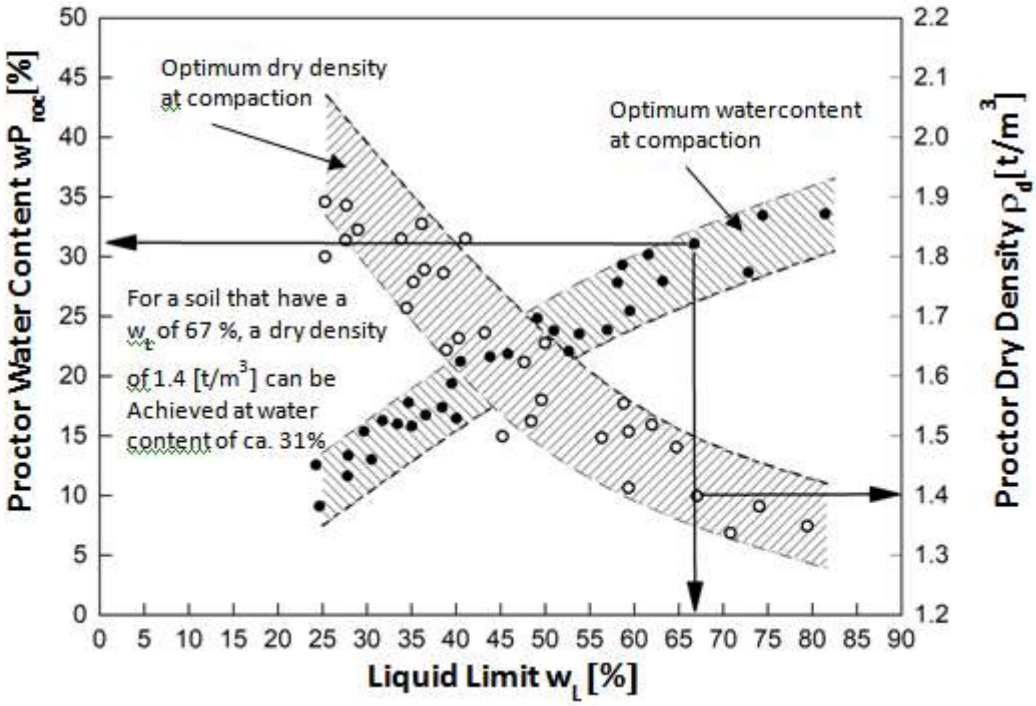

Figure 7: Dependence of the optimal dry density and the optimal installation water content on the flow limit for different clays (BJERRUM, 1952, supplemented by the authors).

Permeability of cohesive soil

The permeability of a soil is a property that is extremely important for many geotechnical construction projects. It represents a critical parameter, regardless of whether it is a question of stability problems in opencast mining, the economic functioning of an earth dam or groundwater protection in raised landfills. For this reason, research methods were developed at an early stage that aim to determine theoretical relationships and allow this parameter to be determined.
In contrast to non-cohesive soil, cohesive soils show a very complex behavior that has not yet been fully explained theoretically. The permeability of a porous material can be expressed theoretically:

$$K = Ds^2 \cdot \frac{9,82}{\nu} \cdot \frac{e^3}{1+e} \cdot C \qquad (1)$$

K = coefficient of permeability
Ds = effective grain diameter
V = kinematic viscosity (toughness) e = number of pores
C = factor

$$K = \frac{1}{R_O S^2} \cdot \frac{9,82}{\nu} \cdot \frac{e^3}{1+e} \qquad (2)$$

R = factor (depending on the pore shape and the quotient between the current length of the flow

path and the thickness of the material flowing through)
S = specific surface

In principle, both equations are identical, since the effective grain diameter Ds is functionally linked to the specific grain surface.

Experiments have shown that these equations accurately describe the permeability of saturated sand. However, they are not suitable for determining the permeability of cohesive soil. This is due to the fact that the influencing factors show complex relationships and the determined void ratio does not correspond to the effective one. When determining the influencing parameters, the adsorbed water or liquid is regarded as pore liquid and not as part of the clay particle. The distance between the clay particles and the amount of bound water to the surface depend on the hydration energy of the ions present. The first three bound water layers do not take part in the flow processes and behave like a solid. The distribution of the Double Layer determines, among other things, the amount of mobile liquid. This means that the size of the effective pore spaces is in fact much smaller than that determined.

For this reason, cohesive soil has lower permeability than non-cohesive soils, although they have higher porosity. Also, a disperse structure in which the clay particles and thus the stratified water have a regular distribution, has a lower permeability than an irregularly coagulated structure of one and the same soil with the same porosity. This phenomenon has been investigated and shown by ZELLER & SCHNELLER, 1957. It is striking that the minimum permeability does not occur at wpr, but rather at w > wpr. This fact is known from many publications. Although the wet-built samples have the same void ratio as the dry ones, they have lower permeability. This indicates an even distribution of the pores and smaller mobile pore water quantities due to the wet compaction.

Soil water infiltration rate can also be used to monitor the soil compaction status because the soil compaction reduces the total porosity of the soil (SILVA et al. 2008).

In Figure 8 the permeability is shown as a function of the void ratio for different compacting water contents. For samples with the same water content, there is a linear relationship between log K and the void ratio. Samples compacted wet: show a lower slope of the straight line and thus also lower permeability than dry compacted samples with the same void ratio.

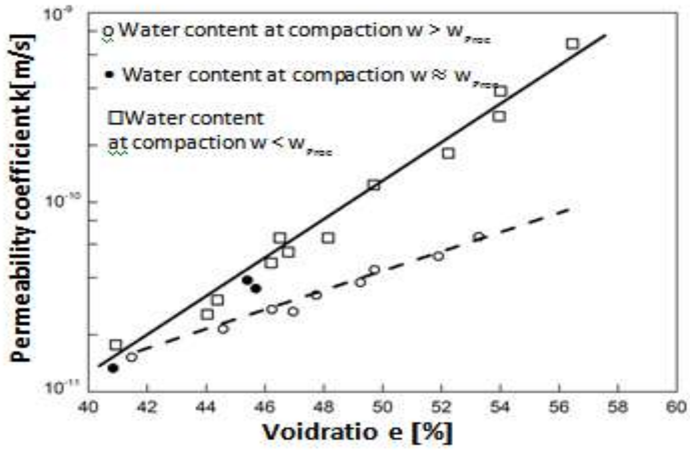

Figure 8: Dependence of permeability on the void ratio for samples with compaction water content w> wpr, w <wpr and w = wpr (ZELLER & SCHNELLER, 1957).

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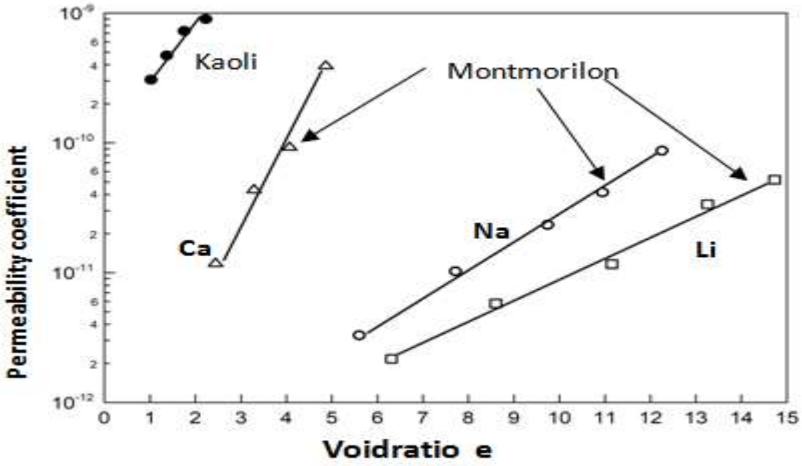

FIG: 9

There are further dependencies for different clay types. Figure 9 shows the influence of Figure 9: Dependence of the permeability on the void ratio for different types of clay (JIMENEZ SALAS et al., 1953).
cation occupancy on the void ratio and permeability. As can be seen from this figure, there is also a linear relationship between log K and e for individual clay types. The slope of the straight line shown depends on the hydration energy of the exchangeable cations. There is no global dependence of the permeability on the porosity. For example, the permeability of montmorillonite is lower than that of kaolinite, despite a higher porosity. The material composition therefore has a considerable influence on the permeability.
In order to be able to compare all the investigated clayey soils with regard to their permeability, the K-value is plotted versus the void ratio for all samples that are mixed with water and with additives. The results are shown in Figure 10.
It is striking to see that the clayey soil Eva shows the smallest permeability despite the high void ratio. However, the Ratinger shows similar permeability but at lower void ratios. The highest K-values are related to the Oedinger Kaolin (see also MICHAELS, 1954).

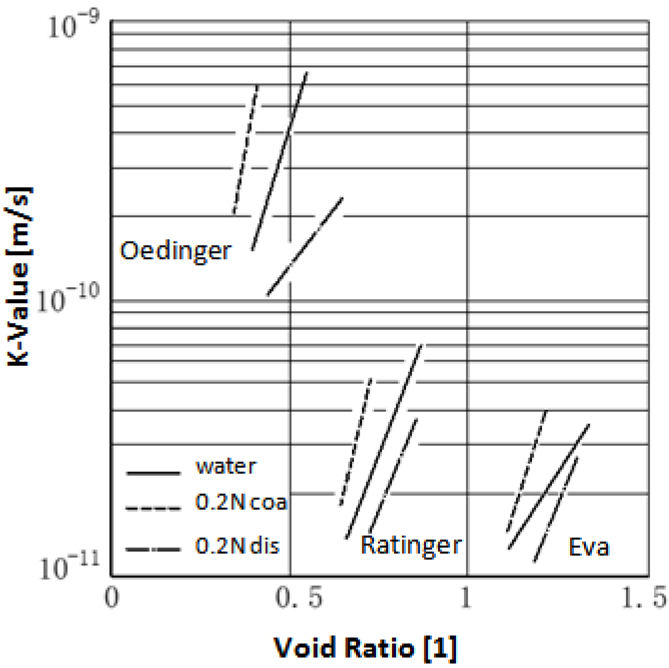

Figure 10: Permeability Coefficient versus Void Ratio for the investigated clayey soils

II. SUMMARY AND OUTLOOK

The dependencies and interactions of material-specific soil-mechanical parameters that are related to the compaction behavior as well as to permeability of cohesive soils are complex and vary greatly for the different types of clay. These dependencies and interactions can be briefly summarized as follows:

- The compaction water content influences the permeability independent of the dry density. Structure-related, fine distributed pore spaces, as occur during wet compaction, cause the proportion of mobile liquid in the pores to decrease. The bound water that envelops the particles does not take part in the flow processes and behaves like a solid. Therefore, the effective porosity is reduced. In contrast, clays with a structure in which the particles are coagulated to form small structural elements (domains) or even to higher-level groups of elements (clusters) have higher permeability than a disperse structure. The aggregates are inherently dense, the clays behave like a granular material in terms of permeability. As a result, the relatively large intermediate zone allows water to flow freely. This model position only applies in connection with the process of advection, in which no additional ion concentration differences exist and an extra offer of exchangeable cations in the solution is missing.

- The cations present and their hydration capacity and charge not only influence the compressibility, but also the permeability regardless of the porosity. This is due to the fact that different cations have different water-binding capacities. An additional ion concentration gradient causes diffusion that superimposes the advection at very low permeability. A supply of exchangeable cations in the solution can lead to an isomorphic exchange of the existing cations taking place, whereby the particle distances and also the physical properties of the unconsolidated soil are changed considerably.

- Another aspect is that the permeant polarity also influences the permeability. It can therefore vary greatly for different liquids.

This complex and comprehensive behavior of clays with regard to permeability is not relevant in sealing bodies for which only pure water can be used as a permeant and the soil mechanical behavior is generally known prior to compaction. It is different with landfill base sealings, through which fluids of different compositions flow. Seepage waters not only offer a variety of exchangeable cations, but also have different polar moments depending on the chemical ingredients available.

The interaction of all influencing factors can cause unforeseeable changes in the behavior of the clays. Both the physical properties of the soil, such as the plasticity and the permeability can be changed to the extent that a perfect seal is no longer guaranteed.

III. ACKNOWLEDGEMENT

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