Effect of Initial Water Content and Dry Density on the Pore Structure and the Soil-Water Retention Curve of Compacted Clay

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Abstract. An experimental study was carried out to investigate the influence of the initial water content and dry density on the structure and the SWRC of compacted clay. The soil structure was studied by MIP. For the determination of the soil-water retention curve suction-controlled oedometer cells and a chilled mirror dew-point hygrometer were used. The paper describes the changes of pore structure due to different initial water contents and dry densities and its influence on the soil-water retention curve.

Keywords: soil-water retention curve, compaction, suction, mercury intrusion porosimetry.

1 Introduction

Compacted clays are used for hydraulic barriers in many geotechnical structures, e.g. in surface sealing systems of landfills or embankments built of slightly contaminated soils. For the determination of the seepage flow through compacted clay the soil-water retention curve (SWRC) and the unsaturated hydraulic conductivity are of particular interest. Both depend on the soil structure, which in turn is strongly influenced by the initial water content and the dry density.

First investigations on the influence of the compaction conditions on the microstructure of compacted clays were carried out by Lambe (1954) and Seed & Chan (1959). They showed that the pore size distribution depends strongly on the initial water content. As later described by Delage et al. (1996), the pore size distribution (PSD) of clays compacted dry of Proctor optimum takes a bimodal

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shape consisting of pores within the aggregates (intra-aggregate pores) and larger pores between the aggregates (inter-aggregate pores). If the soil is compacted wet of Proctor optimum, the distinction between intra- and inter-aggregate pores usually is not possible. Besides, several investigations (Romero et al. 1999, Sivakumar et al. 2006, Thom et al. 2007, Li & Zhang 2008) show that samples compacted at the same water content but different dry densities differ only in the larger inter-aggregate pores. Investigations of Monroy et al. (2010) demonstrate that the originally aggregated fabric of compacted clay can change into to a unimodal shape, if the soil is wetted. However, according to results of Romero et al. (2011) the aggregation created by compaction dry of Proctor optimum is a permanent feature of the compacted soil fabric.

As matric suction arises mainly from capillary forces, the SWRC of compacted fine-grained soils reflects the pore size distribution. Hence, the SWRC is strongly influenced by the initial water content (Vanapalli et al. 1999, Tinjum et al. 1997, Tarantino & Tombolato 2005, Romero et al. 2011) as well as by the initial dry density (Tinjum et al. 1997, Romero et al. 1999, Miller et al. 2002, Sun et al. 2006, Miao et al. 2006, Romero et al. 2011). However, due to different testing methods and procedures the different investigations cannot be compared to each other. Furthermore, only few investigations focussed on the influence of the initial water content as well as the initial dry density on the SWRC.

In this paper the influence of the initial water content and dry density on the SWRC and the pore size distribution of compacted clay is described. In comparison to previous investigations (Birle et al. 2008) the present study uses suction-controlled oedometer cells as well as a chilled-mirror dew-point hygrometer for experimental tests.

2 Material and Sample Preparation

For the experimental investigations, a Lias-clay powder used as a raw material in the production of bricks was chosen. According to DIN 18196, the Lias-clay powder utilized is a clay of medium plasticity with a water content at the liquid limit LL of 46.5 % and at the plastic limit PL of 19.5 %. The grain density ρ_s of the material determined by capillary pycnometer is 2.78 g/cm^3.

The samples were prepared as described by Birle et al. (2008): At first, the dry clay powder was wetted to a water content w of approximately 27 %, thoroughly mixed and crushed in a cutter, and then stored in an airtight container for at least 1 week to allow homogenization to occur. Thereafter, at a temperature of 50 C°, the water content of the material was decreased to roughly 14 % and the material was once more placed in an airtight container for at least 1 week to allow for homogenization. A few days before the test sample preparation this material was wetted to the desired water content and then again thoroughly mixed and crushed in a cutter. After homogenization over 24 h, the test samples were compacted statically to the desired dry density.

In order to select the initial dry densities as well as the initial water contents for the experiments, a standard Proctor test (W=0.6 MN/m^3), a modified Proctor test (W=2.7 MN/m^3), as well as a partially modified Proctor test (W=1.0 MN/m^3) were carried out. The results of the Proctor tests are shown in Figure 1. On the basis of the Proctor curves the eight test points presented in Figure 1 were selected.

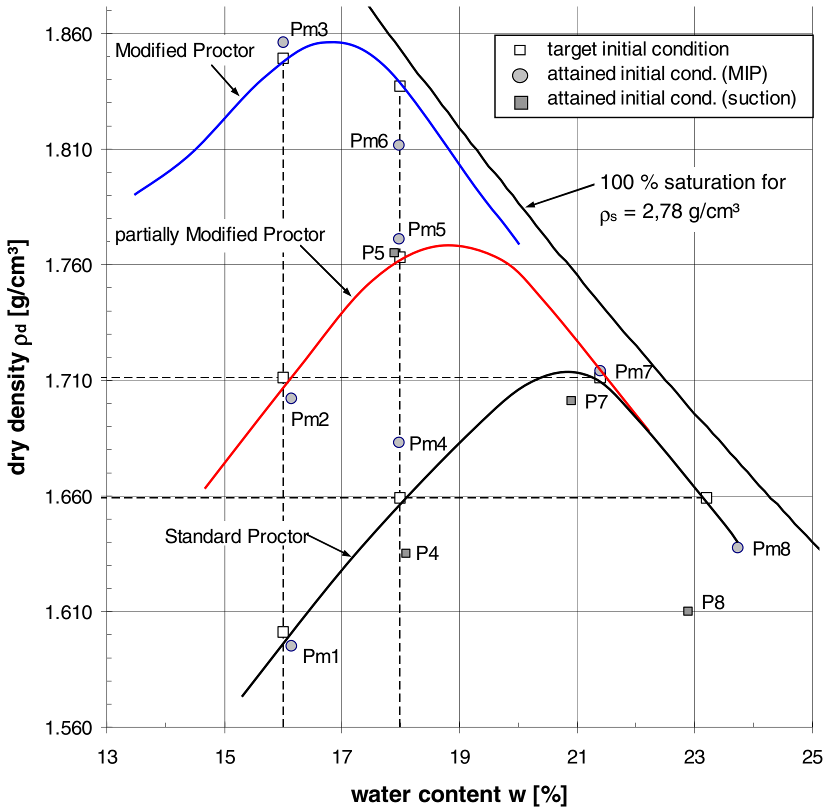

Fig. 1. Proctor tests and samples for the MIP and suction tests.

3 Equipment and Test Procedure

The PSD was determined by means of mercury intrusion porosimetry (MIP). To minimize the influence of the drying process on the soil structure, the freeze-drying technique was applied (Ahmed et al. 1974). Rapid freezing of the samples was achieved by immersing the samples in liquid nitrogen. After freezing the samples were placed immediately in the freeze-drying apparatus Alpha 1-4 and dried by sublimation. The mercury intrusion porosimetry was conducted in the Grimm 4.700 apparatus with a maximum mercury pressure of 207 MPa. An intrusion followed by an extrusion was performed.

The SWRCs were experimentally determined by means of suction-controlled oedometer cells and a chilled-mirror dew-point hygrometer (WP4 Dew-point PotentiaMeter). The experimental set-up of the oedometer cells is explained in detail by Birle (2011).

In the suction-controlled oedometer cells suction was applied using the axis-translation-technique. In this process the water pressure was kept constant at 300 kPa, while the air pressure was increased. The statically compacted samples had a height of 1 cm and a diameter of 7 cm. Starting from the state after compaction, the samples first were wetted to a minimum matric suction of approx. 10 kPa and then dried by increasing the matric suction step by step to a maximum value of 1350 kPa. The vertical net stress was kept constant at 30 kPa during the tests. Air bubbles that accumulated due to diffusion beneath the high air-entry ceramic disc were expelled by flushing the water line every 6 hours during the tests. The equalisation stages lasted about 3 to 7 days until no more water content changes were recorded. After dismounting the samples part of the sample was taken for measuring the suction in the high suction range using the chilled-mirror dew-point hygrometer. The other part of the sample was used for determining the water content. The principle of operation of the hygrometer is based on the thermodynamic relationship between relative humidity, temperature and total soil suction according to Kelvin's equation (Fredlund and Rahardjo 1993). By these means the total soil suction can be determined from the measurements of relative humidity and temperature above a soil sample.

After measuring the total suction in the chilled-mirror dew-point hygrometer the specimens were weighed and air-dried to the next desired water content. The next measurement was done after a homogenization phase of at least 24 h. After the last measurement the specimens were oven-dried and the final water content was determined. The maximum suction measured by the hygrometer WP4 Dew-point PotentiaMeter used was 60 MPa.

4 Results and Discussion

Fig. 2 and Fig. 3 show the results of the MIP for the samples Pm4, Pm5, Pm7 and Pm8. The samples Pm4 and Pm5 were compacted at the same water content dry of Proctor optimum, but at different initial dry densities. The sample Pm7 was compacted approximately at Proctor optimum, while Pm8 lies on the wet side of Proctor optimum.

The cumulative intrusion porosities of the samples Pm4 and Pm5 compacted dry of Proctor optimum, show typical bimodal shapes. By the construction of two tangents to the intrusion curve the intra-aggregate pores and the inter-aggregate pores can be distinguished. That way the inter-aggregate porosity of the sample Pm5 is much smaller than the inter-aggregate porosity of the sample Pm4. As the curve of the sample Pm5 is translated approximately parallel to the curve of the sample Pm4, it can be seen, that the higher compaction of the sample Pm5 leads mainly to a reduction of the pores with a size of 4 to 20 μm in contrast to the sample Pm4. Besides, the intra-aggregate porosity of the sample Pm5 is even a bit higher than that of the sample Pm4, as the sample Pm5 is denser and thus consists of more aggregates. This means that the compaction on the dry side of the Proctor optimum has nearly no influence on the intra-aggregate porosity and that a higher compaction results mainly in a reduction of the larger inter-aggregate pores.

With increasing water content the aggregates become softer and contribute to the deformation during compaction. Thereby the larger inter-aggregate pores diminish and the pore-size distribution takes on a more unimodal form. This can be seen especially for the cumulative porosity of sample Pm8 in Fig. 2, where a distinction between inter- and intra-aggregate pores is no longer possible.

Furthermore, the results of the MIP show that for small pore sizes (approx. < 0.1 μm) the shape of the cumulative intrusion porosity is similar for all samples and that they are only translated in a parallel manner.

A common way to distinguish between inter-aggregate and intra-aggregate pores is based on the analysis of the pore size density function (Romero et al. 2011). For the four samples the pore size density functions are given in Fig. 3. For the samples Pm4 and Pm5, which were compacted at the same water content but at different dry densities, the discriminating pore size between inter- and intra-aggregates can be assumed in the range of 0.5 to 1 μm. In comparison to the previous criterion based on the analysis of the cumulative intrusion curve this criterion gives a slightly higher discriminating pore size for the two samples.

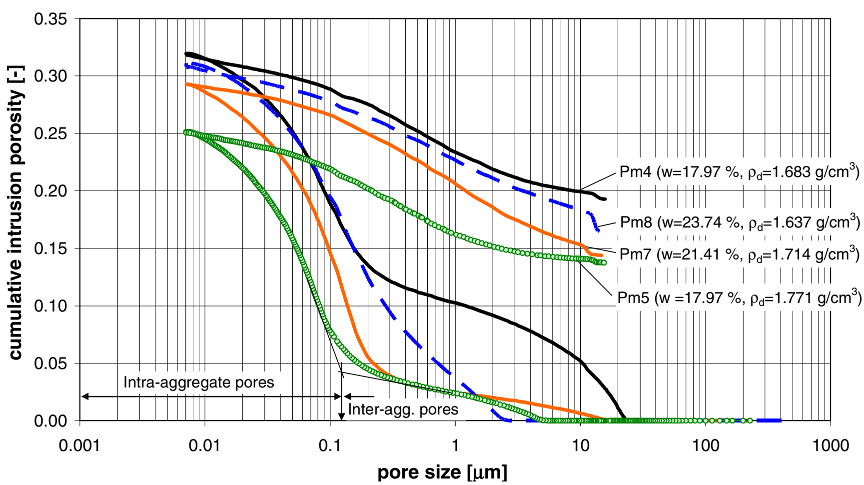

Fig. 2. Results of MIP for the samples Pm4, Pm5, Pm7 and Pm8 (intrusion and extrusion).

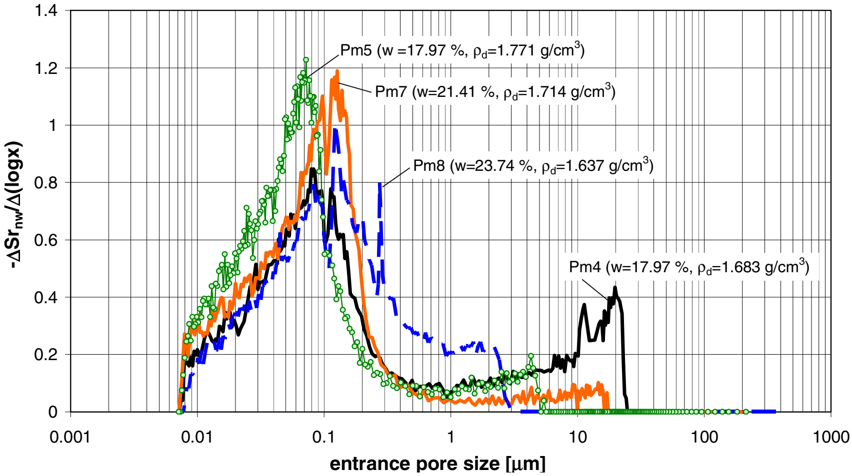

Fig. 3. Pore size density function of the samples Pm4, Pm5, Pm7 and Pm8.

Fig. 4 shows the retention curves of the samples P4, P5, P7 and P8 in terms of water content. The drying paths of the samples P4 and P5, which were compacted at the same initial water content, differ only in the low suction range at matric suctions smaller than 1500 kPa, while in the high suction range (> 1500 kPa) the drying paths are very similar. This agrees with the results of the MIP, that showed that the higher compaction of the sample Pm5 results only from the reduction of the larger inter-aggregate pores. Furthermore it can be seen that during the drying process, the curves P7 and P8 approach the curves P4 and P5 until they converge at a suction of 5.5 MPa. At suction values higher than 5.5 MPa the shape of all curves is very similar as already described by Birle et al. (2008).

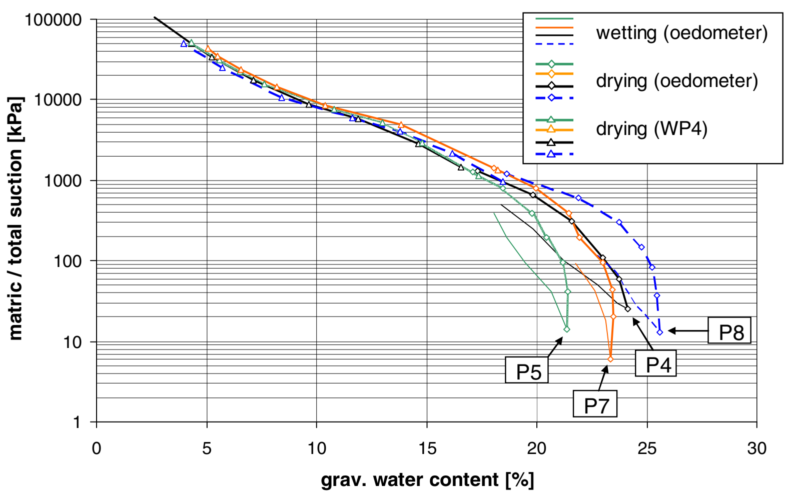

Fig. 4. SWRCs in terms of water content for the samples Pm4, Pm5, Pm7 and Pm8.

The SWRCs in terms of degree of saturation are presented in Fig. 5. Due to the higher dry density of the sample P5 its air entry value is much higher than that of the sample P4. Besides, in the high suction range the higher density of P5 results in higher suction at same degree of saturation in comparison to the sample P4.

Despite the low density of the sample P8, its air-entry value is much higher than that of the dry compacted sample P4. According to the results of the MIP this is caused by the smaller inter-aggregate porosity of the sample P8. In the high suction range the retention curves of the samples P4 und P8 are very similar, although the initial dry density of P4 was higher than that of P8. However, during the drying process the sample P8 exhibited a larger shrinkage than that of P4. Due to compaction at Proctor optimum the sample P7 has a small inter-aggregate porosity and hence a high air-entry value similar to that of the sample P5.

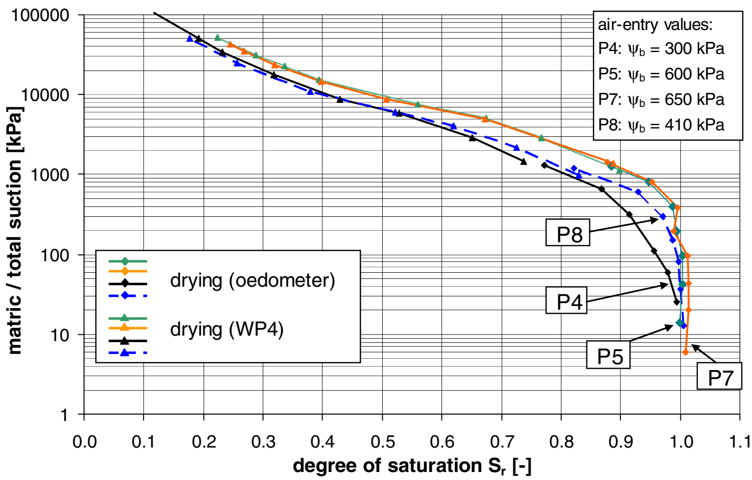

Fig. 5. SWRCs in terms of degree of saturation for the samples Pm4, Pm5, Pm7 and Pm8.

5 Conclusions

An experimental study was carried out to investigate the influence of the initial water content and dry density on the structure and the SWRC of a compacted clay. The soil structure was investigated by means of MIP. For the determination of the SWRC suction-controlled oedometer cells and a chilled mirror dew-point hygrometer were used. The following results, which agree with several publications cited above, were obtained:

- The SWRC in terms of gravimetric water content is independent of the initial dry density in the high suction range (> 1500 kPa). This is supported by the results of the MIP, which show that only the inter-aggregate porosity changes if the dry density increases at constant water content.
- At suction pressures higher than 5.5 MPa the SWRC is even independent of the initial water content. Correspondingly, the results of the MIP gave very similar results for all samples at small pore sizes (< 0.1 μm).

- For the SWRC in terms of degree of saturation it can be stated, that the air-entry value increases, if the dry density increases at constant water content or if the water content increases at constant dry density. Both effects are linked to a reduction of the inter-aggregate pores.

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