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Shrinkage properties of three clay materials at different temperatures**

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A b s t r a c t. This experimental study was performed to obtain a relationship between moisture content and shrinkage potential at different temperatures of three soil materials (quaternary clay and granite loam from southern China and a basin silty loam from Germany). The soil materials were compacted by Proctor test at different water contents and the Proctor compaction curves were obtained. Shrinkage potential (change in bulk density) due to drying at 40 and 105°C was also determined.

K e y w o r d s: clay, loam, landfill capping, Proctor test, shrinkage potential

INTRODUCTION

Environmentally safe waste deposits require both a bottom liner and a capping system in order to exclude or at least minimize negative effects on the environment. The essential function of the bottom liner is to provide stability and to support the total waste mass as well as to prevent from the pollution of ground water with the landfill leachate. Thus, its basic characteristics should be impermeability to water, chemical resistance to long-term contact with the leachate, mechanical resistance and stability in time. The surface capping should be, among others, characterized by water impermeability in its bottom part, chemical resistance to the biogas action, and also long-term stability in time (Holzlöhner *et al*., 1995; Eggloffstein *et al*., 2000).

In practice the condition of impermeability to water and of long-term stability in time, necessary both for the liners and for the cappings, can be fulfilled by the construction of mineral sealing layers, by the use of plastic geomembranes, as well as by the combination of both. However, the real long-term stability can be assured solely by clays, which have persisted and will persist for thousands of years, as the stability of geomembranes is limited to several decades. However, clays are susceptible to shrinking and swelling processes, induced by changes in water content which can occur, especially in the landfill capping, during landfill maintenance. Shrinking causes the formation of vertical and horizontal cracks, which makes the sealing permeable. Thus, the way of preparation of the mineral sealing layer for long-term stability is very important as there are thousands of landfills worldwide which should be either linered or capped.

In order to elaborate an efficient technology of construction of such a stable sealing layer, a better recognition of shrinkage and cracking processes of clays is needed. It has been shown that cracking resulting from shrinkage processes occurs especially if the material is homogenized and close to its saturation point (Hartge and Horn, 1999). The shrinkage process has been divided into normal shrinkage phase and residual shrinking phase (*eg* Hartge, 1965; Junkersfeld, 1995; Junkersfeld and Horn, 1997). It has been shown by Albiker (cited in Horn *et al*., 2001) that if clay samples from a 7 ha landfill cover were subjected to compaction on the wet branch of the Proctor curve *ie* at moisture content above the optimum, they showed normal shrinkage properties, while compaction at water contents below the optimum resulted in residual shrinkage behaviour. Moreover, Bauer *et al*. (2001) have shown that the shrinkage potential of a kaolinite clay was much lower on the dry branch of the Proctor curve. Recently, it has been suggested by Horn and Stępniewski (2004) that compacting the soil on the dry branch of the Proctor curve, combined with recognition of hydraulic and mechanical interactions of the mineral substrate, offers a promising method of avoiding the crack formation.

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The aim of the present study was to obtain the Proctor compaction curves for three soil materials, likely to be used for mineral landfill sealing construction and to determine the relationship between their compaction water content and shrinkage potential due to drying at 40 and 105°C.

MATERIALS AND METHODS

Two soil materials from southern China: Plintic Acrisol (quaternary clay - Qc), Gleyic Acrisol (Granite loam – Gl), and Umbric Gleysol (silty loam – Sl) from Germany were used. The physical characteristics of the materials from China (Zhang *et al.*, 2001) and of the loam from Germany are presented in Table 1. The moisture content of air-dry materials from China was 2.3% by mass for the quaternary clay and 3.1% by mass for the granite loam. The silty loam from Germany brought to laboratory from field contained 16% of water and its air-dry water content was 2.9%.

The soil materials from China were sieved (through a 2 mm sieve) and only the particles <2 mm were used. The Proctor test was performed at five moisture contents for each clay material from China and at three water contents for the silty loam taken from Germany. The water contents (Table 2) were adjusted in order to obtain the Proctor optimum and the values by several per cent lower and higher than that. The Proctor test was performed using a standard manually-operated apparatus (mass – 4.8045 kg, cylinder volume – 0.897 dm^3). The compaction was performed in three layers with 25 strokes upon each layer. As a result the Proctor curves for each soil material were obtained.

In order to measure shrinkage potentials of the materials undisturbed cubes 20x20x20 mm were cut out of the cores after having them pushed out of the Proctor test cylinders. The cubes were triplicated for each drying temperature and for each water content during compaction. Thus for one water content six cubes were prepared of which three were dried at 40°C and the other three at 105°C for 24 h.

The bulk density was obtained by measuring 4 horizontal and 4 vertical cube edges using an electronic slide calliper with the accuracy of 0.01 mm and by measuring the mass of the samples using a laboratory balance with accuracy of 0.01 g. The measurements were performed before and after the drying process. The shrinkage potential was expressed by increase of bulk density of the material due to drying.

RESULTS AND DISCUSSION

The results of the Proctor test are presented in Fig. 1. As it can be seen, the highest bulk density (1.75 Mg m^{-3}) value was obtained for the granite loam and the optimum water content was 0.17 kg kg^{-1}. Silty loam from Germany was characterized by the Proctor bulk density of 1.7 Mg m^{-3} occurring at water content of 0.185 kg kg^{-1} and by a high slope, especially of the right branch of the Proctor curve. The quaternary clay showed the lowest Proctor den- sity of about 1.57 Mg m^{-3} at moisture content of 0.2 kg kg^{-1} and a very low slope of the Proctor curve. These curves confirm the general rule that the heavier the texture of the material the higher the Proctor optimum water content for compaction and the lower the maximum bulk density obtained by application of the Proctor test.

T a b l e 1. Basic physical characteristics of the materials from China (Zhang *et al.*, 2001) and from Germany

Soil symbol (horizon)	Parent material (country)	Textural class (depth, cm)	Classification (WRB)	Grain size distributtion (%, dia in mm)				$C_{org.}$ (%)
				>2	2.0-0.05	0.05-0.002	<0.002	
Qc(Ap)	quaternary red clay (China)	Clay (0-15)	Phintic Acrisol	2.0	20.6	33.6	45.8	0.91
Gl(Ap)	granite (China)	Loam (0-15)	Gleyic Acrisol	21.0	50.7	30.5	18.8	0.52
Sl(C)	Basin silty loam (Germany)	Siltly loam (>200)	Umbric Gleysol	0	47.0	41.0	11.9	0

T a b l e 2. Water contents in the materials used for Proctor compaction test

Material	Water content (kg kg^{-1}) during Proctor test				
Qc	0.104	0.135	0.155	0.194	0.253
Gl	0.123	0.166	0.185	0.213	0.243
Sl	0.160	0.185	–	0.220	–

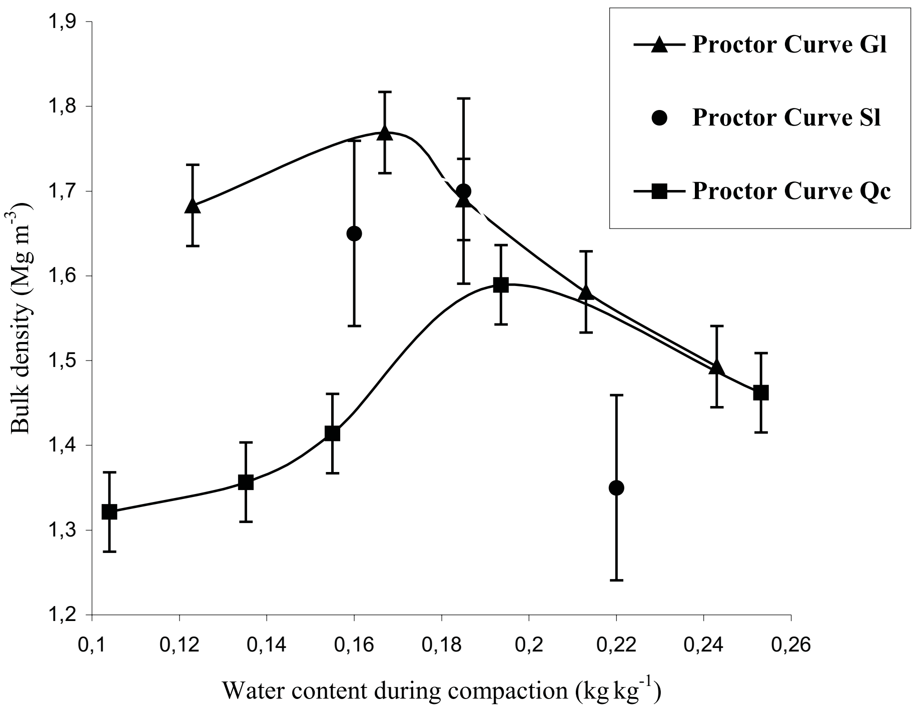

Fig. 1. The Proctor curves for the materials under study. Mean bulk density values with their standard deviations.

Shrinkage potential, expressed as the difference between the bulk density of the dry material and the bulk density from the Proctor test at a given water content during the compaction, is presented in Figs 2-4. In the case of the silty loam from Germany (Fig. 2) drying at the temperature of 40°C gave an increase in the bulk density by 0.38-0.45 Mg m^{-3}. Drying at 105°C increased shrinkage to the range of 0.42-0.50 Mg m^{-3}. The differentiation of the shrinkage potential within the considered water content range during compaction is very low. The shape and the course of the curves are similar to the classical model curves obtained for kaolin by Bauer *et al.* (2001), who found that the shrinkage potential for this mineral increased with water content during compaction.

The quaternary clay presented in Fig. 3 exhibits shrinkage due to drying at a temperature of 40°C in the range of 0.21-0.39 Mg m^{-3}. Drying at 105°C caused an increase in the bulk density by 0.26-55 Mg m^{-3}. The decreasing tendency on the wetter part of the curve is a typical behaviour compared to the materials in the pertinent literature (Bauer *et al.*, 2001; Wysocka *et al.*, 2004).

The granite loam (Fig. 4) is characterized by the shrinkage potential 0.29-0.50 at 40°C and 0.31-0.55 at 105°C. There was a distinct tendency of the increase of the shrinkage potential with water content during the compaction test.

Comparing the shrinkage potential for 40°C *ie* the temperature likely to occur in the landfill liners of the capping, for particular materials compacted at Proctor optimum moisture content it can be stated that it was not very differentiated as it ranged from 0.37 Mg m^{-3} for the quaternary clay to 0.40 Mg m^{-3} for the granite loam and silty loam.

Another form of presentation of shrinkage potential is percentage of the volume decrease of the material, which reflects better the possibility of crack formation. As it is shown in Fig. 5, converted for kaolin from the data of Bauer *et al.* (2001), the potential shrinkage of kaolin increases with water content during Proctor compaction from 0% at 0.02 kg kg^{-1} water content to about 9% at Proctor optimum water content (0.23 kg kg^{-1}) and to about 36.3% at water content of 0.55 kg kg^{-1}.

For our results the percentage of shrinkage at Proctor maximum density due to drying at 40°C was 19.1 % for the quaternary clay, 19% for the silty loam, and 18.6% for the granite loam. Thus, the granite loam – characterized by the highest Proctor bulk density and by the highest increase in the bulk density due to shrinkage (0.4 Mg m^{-3}) - was simultaneously characterized by the lowest percentage of shrinkage (18.6%).

For comparison with the volumetric shrinkage potential of kaolin presented in Fig. 5, an analogous graph of potential shrinkage for our granite loam is included as well. As it can

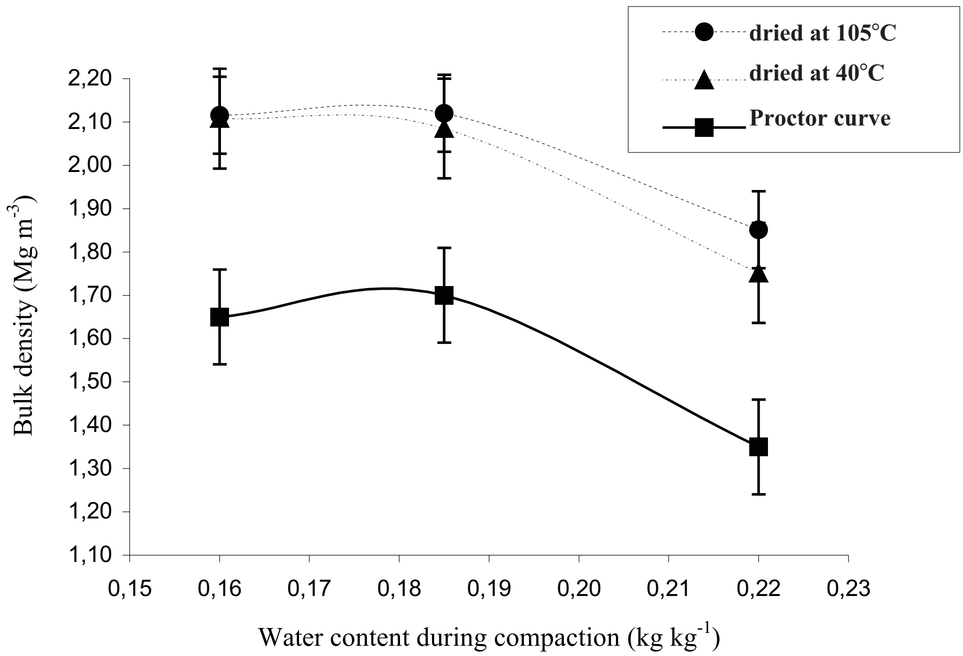

Fig. 2. The Proctor curve and the corresponding potential shrinkage curves (representing bulk densities) after drying at 40 and 105°C for the silty loam from Germany (Sl) versus water content during compaction test. Mean bulk density values with their standard deviations.

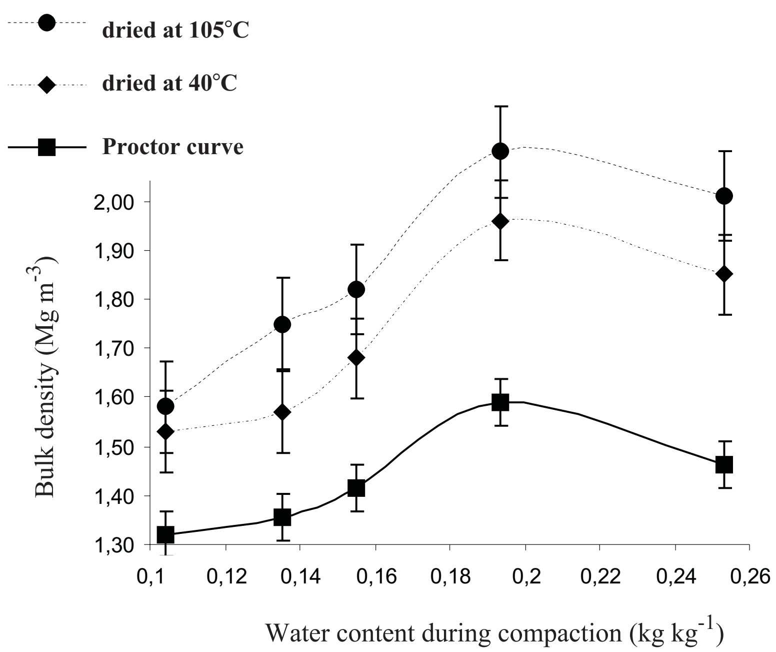

Fig. 3. The Proctor curve and the corresponding potential shrinkage curves (representing bulk densities) after drying at 40 and 105°C for the quaternary clay (Qc) versus water content during compaction test. Mean bulk density values with their standard deviations.

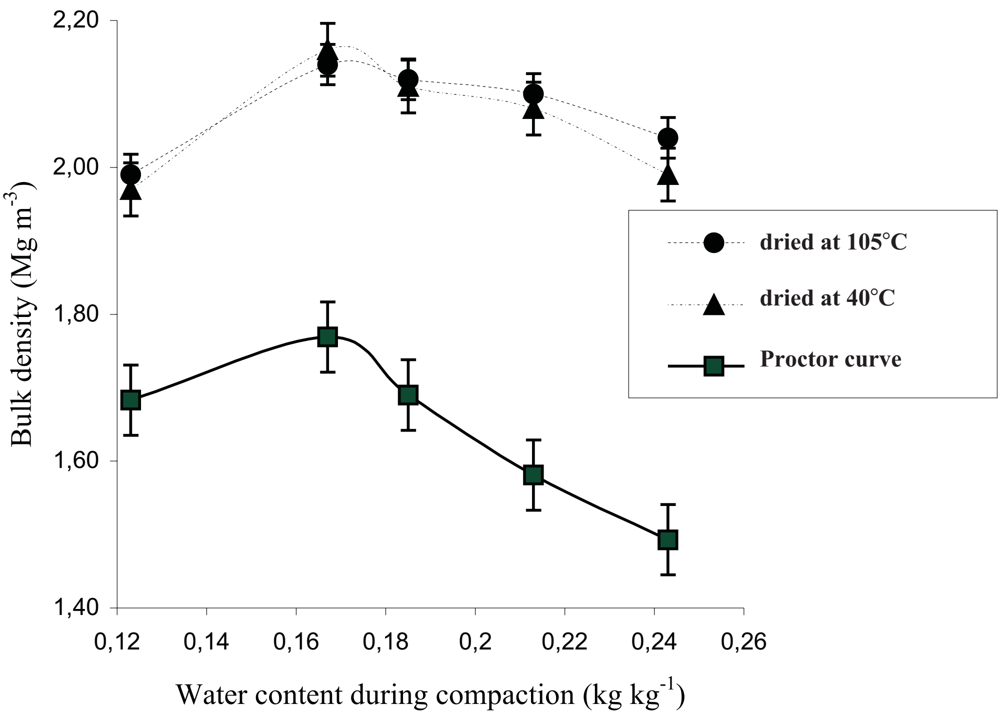

Fig. 4. The Proctor curve and the corresponding potential shrinkage curves (representing bulk densities) after drying at 40 and 105°C for the granite loam (Gl) versus water content during compaction test. Mean bulk density values with their standard deviations.

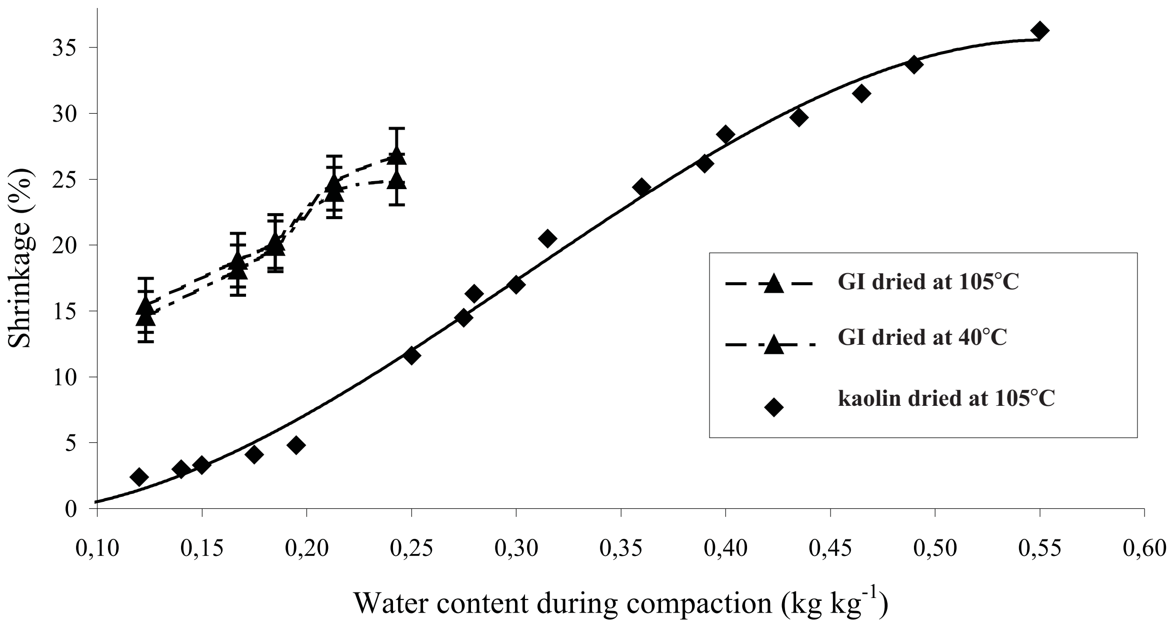

Fig. 5. Comparison of the kaolin potential shrinkage curve at 105°C expressed as percentage of volume change (calculated by us on the basis of the results of Bauer *et al*., 2001) with analogous curves obtained by us for the granite loam at 40 and 105°C.

be seen, the shrinkage potential of the granite loam increased with water content from 15 to 25% for the examined water content range of 0.12-0.25 kg kg^{-1}. The curves for drying at 40 and 105°C were differentiated within 3% and were above the kaolin shrinkage curve. In general, the shrinkage potential of the granite loam was 15% higher compared to that of kaolin at the same water content.

The general conclusion of this study is that in order to reduce the shrinkage potential the compaction should be performed at water content lower than the Proctor optimum. This is a support for the idea expressed in previous papers (Bauer *et al*., 2001; Horn and Stępniewski, 2004; Wysocka *et al.*, 2004).

CONCLUSIONS

1. The highest Proctor bulk density (1.75 Mg m^{-3}) was obtained for the granite loam and the lowest (about 1.57 Mg m^{-3}) – for the quaternary clay.

2. The Proctor optimum water content was the highest for the quaternary clay (0.2 kg kg^{-1}) and the lowest – for the granite loam (0.17 kg kg^{-1}).

3. The shrinkage potential at Proctor optimum water content for 40°C was within 0.37-0.40 Mg m^{-3} or 18.6-19.1% of the volume.

4. Shrinkage potential increased with water content during compaction and with drying temperature; the temperature effect being the highest for the quaternary clay and the lowest for the granite loam.

5. The results obtained confirm that compaction of clay material for landfill liner construction should be performed at water content lower than the optimum for the Proctor compaction test.

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