Int. Agrophysics, 2004, 18, 317-323

INTERNATIONAL
Agrophysics
www.ipan.lublin.pl/int-agrophysics

Modification of mineral liner to improve its long-term stability**

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Received March 31, 2004; accepted June 2, 2004

A b s t r a c t. The discussion about the long term stability of mineral waste deposits excludes the effect of coupled processes in mechanics and hydraulics which can be summed up as follows: mechanical and dynamic energy inputs during compression result in higher soil homogenization and particle reorientation, positive pore water pressure values and consecutive normal shrinkage behaviour together with tensile crack formation.

Some alternatives are discussed and the consequences for a more impermeable mineral liner due to residual shrinkage behaviour, entrapped air and a very tortuous pore system are explained.

K e y w o r d s: capping, cracking, landfill, mineral liner, shrinkage

INTRODUCTION

The discussion about the necessary measures for the production of a long-term impermeable *ie* ecologically safe landfill capping has been led for more than 15 years in the most diverse fields of activity and under structural, scientific as well as economic criteria. Due to the physicochemical, biological and physical processes inside the dumped waste, waste deposits require both a bottom liner and a capping system. The main task of the bottom liner is to prevent ground water pollution with landfill leachates and to support the entire waste mass. So it should be impermeable to water, chemically resistant to the long-term leachate action, mechanically resistant and stable in time. The capping system should be, among other requirements, characterized by good conditions for plant vegetation and for methane oxidation (Stępniewski and Pawłowska, 1996; Stępniewski and Zygmunt, 2000; Stępniewski *et al*., 2002) in its upper part, by low or no permeability to water in its bottom part, and by stability in time.

The condition of impermeability of the sealing layer, both of the bottom liner and the capping system, can be fulfilled in the short time period by mineral clay layer and/or by commercially produced HDPE geomembranes. In the long-term scale, the geomembranes offer no solution as their persistence is limited to several decades of years. Due to this, in most of practical regulations (Brune, 1995) it is recommended to place a mineral sealing layer under the geomembrane. Thus, the only acceptable proposal seems to be mineral sealing built of clay materials which have persisted and will persist for thousands of years. There is, however, a problem connected with the prevention of crack formation of natural clay liners during their drying, likely to occur especially in the capping systems. As there are thousands of landfills to be either constructed or capped worldwide, the problem of preparation of sealing clay layers as the persisting component of the liners or capping is of primary importance.

It should be also kept in mind that changes in the water content in landfill sealing clay layer usually occur under mechanical load. The only exception is the preparation of uncovered sealing layer, when it should be protected from drying out. The static load is lower for the capping sealing layer as compared to the bottom liner. For instance, the overburden pressure for a 1m thick soil layer and 0.3 m drainage layer overlying the capping sealing layer according to German regulations (TASi, 1993) is slightly above 15 kPa, while in the bottom liner loaded with the waste layer (which can often be 20 m thick) it can exceed 100 kPa. The second factor affecting the water potential and the shrinkage

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**This work was supported by the Committee for Scientific Research Grant No. 1337/TO9/2001/20.

process, especially in the bottom liner, is the elevated temperature which can reach 70-90°C for long periods of time (Holzlöhner *et al*., 1995). The third factor affecting pore water potential and the eventual shrinkage process in the bottom liner is the osmotic potential resulting from the salinity of the landfill leachates, which, however, will not be considered in this paper.

The aim of the present paper is to analyze the possibility of constructing a permanent sealing layer of mineral materials and the conditions of their long-term stability.

ANALYSIS OF THE SHRINKAGE BEHAVIOUR OF CLAYS FOR MINERAL LINERS

General aspects

It is well-known that all materials, and especially clays (Graesle, 1999), during the dewatering process undergo shrinkage connected with cracking, especially if the substrate is not very rigid. In the dewatering process, the initial shrinkage range, *ie* the normal shrinkage, can be separated and distinguished from the residual shrinkage. The phenomenon of cracking during shrinkage process happens particularly if the substrate is homogenized and its moisture content is close to the maximum saturation point (Hartge and Horn, 1999). In agricultural soils, the phenomenon of residual or normal shrinkage, as well as the effect of predrying on shrinkage properties is described in detail, amongst others by Hartge (1965), Junkersfeld (1995), Junkersfeld and Horn (1997). The differentiation between the shrinkage behaviour of aggregated or homogenized materials clearly shows that a strong interaction between the shrinkage and soil strength does exist.

With respect to the long-term stability of waste deposit liner systems such processes can counteract the requirements even if the requirements defined by law are fulfilled. In Germany, waste deposit capping or base liner systems are analyzed according to the German waste deposit construction law (TASi, 1993) which defines the mechanical and hydraulic conditions for mineral liners. However, Albiker (cited in Horn *et al*., 2001) was able to prove, for a 7 ha large mineral sealing, an interrelation between obtained Proctor density, hydraulic conductivity and, in addition, the corresponding shrinkage behaviour. Albiker proved that if the mineral sealing layer was compacted (as required) on the wet branch of the Proctor curve to the density values higher than the Proctor density, the hydraulic conductivity (m s^{-1}) was smaller than 5 10^{-10} m s^{-1}. However, if the shrinkage behaviour was analyzed at the same water content after having proctored the samples, he found out that samples wetter than the optimum for compaction showed normal shrinkage behaviour. Only at water content lower than the optimum the samples showed residual shrinkage properties.

Interaction of mechanical and shrinkage processes of mineral material

During the compaction process (Proctor test) soil samples will be exposed to a given mechanical energy applied (3 x 25 strokes) at varying water content. Thus, soil compaction under a given water content results not only in changed bulk density values but also in an increased homogenization by dynamic kneading (Horn, 1976). Bauer *et al*. (2001) showed that the shrinkage behaviour depends on the added dynamic energy and results in an additional shrinkage if the samples after compaction are subjected to further drying. They showed that, primarily, after exceeding the Proctor density and/or the corresponding moisture content any further addition of water results in an increased shrinkage potential. Thus, the difference between both curves reflects the material shrinkage potential defined as a percentage change in volume (Fig. 1).

Interaction between hydraulic and mechanical processes

The obtained rigidity of the compacted mineral liner system depends on the maximum drying during preparation and can be estimated for the given soil depth under various site conditions. Hartge and Horn (1977), Baumgartl *et al*. (1998) derived from tensiometer or water content measurements in soils under various land use systems in Germany the maximum pre-drying obtained under the driest site conditions. If we take into consideration that the effect of drying and of mechanical loading can be described and predicted by the effective stress equation of Bishop (1961), it is necessary to keep the rigidity of the compacted clay liner material according to this maximum expected drying stress *ie* negative pore water pressure.

In order to quantify the maximum mechanical soil strength, Casagrande first described the stress strain behaviour and the derivation of the pre-compression stress of soils. He found that, apart from normal compaction behaviour, soils are often overcompacted, which results in an internal soil strength called pre-compression stress. This concept was further developed by Horn (1981) for unsaturated soil conditions under various land use systems.

For coupled mechanical and hydraulic processes, Toll (1995) described a model which distinguished the mechanical and the shrinkage induced change in soil volume for a given hydraulic or mechanical preloading. To validate such a conceptual model, measurements with soil samples from a glacial till were carried out. If these samples are stressed with 30 kPa at a given pore water pressure of -6 kPa, there – after re-watered and re-dried stepwise again, it can be shown that until the pore water pressure value of -30 kPa is reached the soil samples show mainly residual shrinkage behaviour. Exceeding this value results in normal shrinkage as can be derived from the identical slope of the 2 curves (Fig. 2).

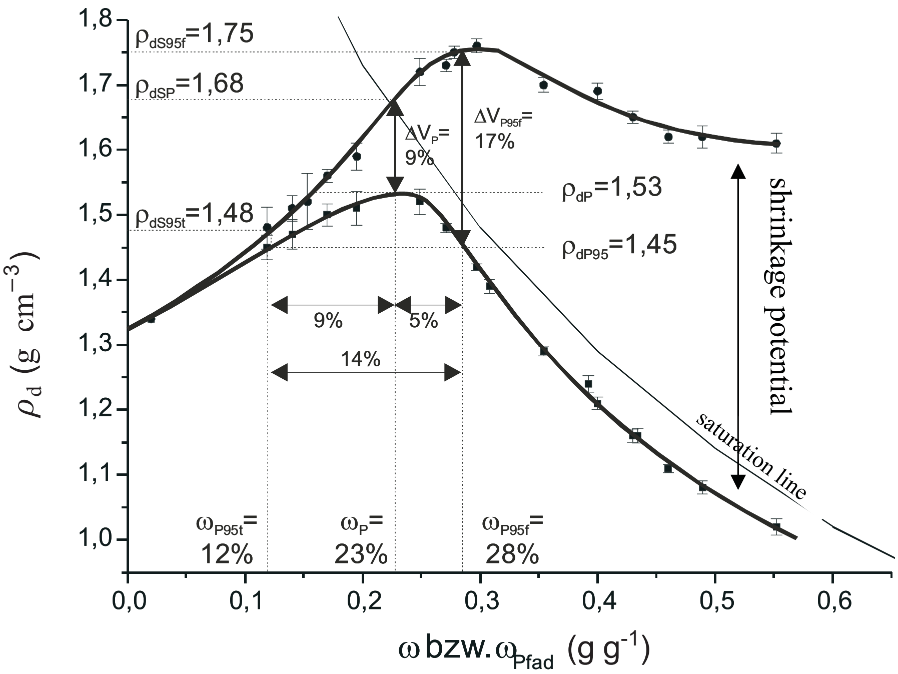

Fig. 1. Compaction curves (dry bulk density versus water content during Proctor test) in dependence on mechanical load, drying and compaction by meniscus forces, as well as by a definite rise in temperature (Bauer *et al.*, 2001). Explanations: ω bzw. ω_{Pfad} (g g^{-1}) - water content by mass (g g^{-1}) during the Proctor compaction test, ω_P - water content corresponding to the Proctor bulk density ρ_{dP}, ω_{P95t} - water content on the dry part of the Proctor curve corresponding to bulk density equal to 95% of the Proctor bulk density ρ_{dP95}, ω_{P95f} - water content on the wet part of the Proctor curve corresponding to bulk density equal to 95% of the Proctor density ρ_{dP95}, ρ_{dSP} - dry bulk density of the material compacted at Proctor optimum water content, ρ_{dS95t} - dry bulk density of the material compacted at water content corresponding to 95% of the Proctor bulk density on the dry branch of the compaction curve, ρ_{dS95f} - dry bulk density of the material compacted at water content corresponding to 95% of the Proctor bulk density on the wet branch of the compaction curve, ΔV_P - shrinkage due to drying expressed as % of the initial volume for the material compacted at Proctor optimum water content, ΔV_{P95f} - shrinkage due to drying expressed as % of the initial volume of the material compacted at water content on the wet branch of the compaction curve corresponding to 95% of the Proctor bulk density, ΔV_{P95f} - shrinkage due to drying expressed as % of the initial volume of the material compacted at water content on the wet branch of the compaction curve corresponding to bulk density equal to 95% of the Proctor bulk density.

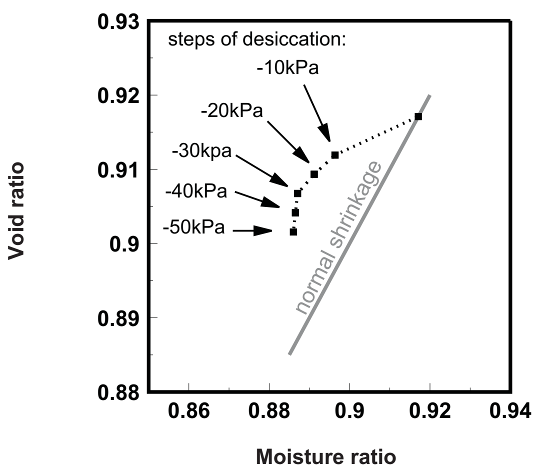

Fig. 2. Shrinkage behaviour of a glacial till soil at a given mechanical pre-stress of 30 kPa and consecutive drying.

Interaction between the mechanical and hydraulic processes always results in a mechanical and hydraulic stress dependent change in the hydraulic conductivity, as can be shown in Fig. 3.

If soils from glacial till are repeatedly dried and re-watered, they show an increase in the saturated hydraulic conductivity even at a smaller void ratio. The higher the mechanical stress during drying at a given temperature, the less pronounced the increase in the hydraulic conductivity.

If we apply the conceptual model of Toll (1995) for our findings, we can derive a more profound model as an explanation for the *in situ* cracking and shrinkage processes (Fig. 4).

Assuming that the normal and residual shrinkage curve, as well as the primary and reloading curve, have the same pattern, we can obtain a reduction in the void ratio either by mechanical stress or by more negative pore water pressure application. In the same way also acts the temperature which in itself also decreases the pore water pressure due to

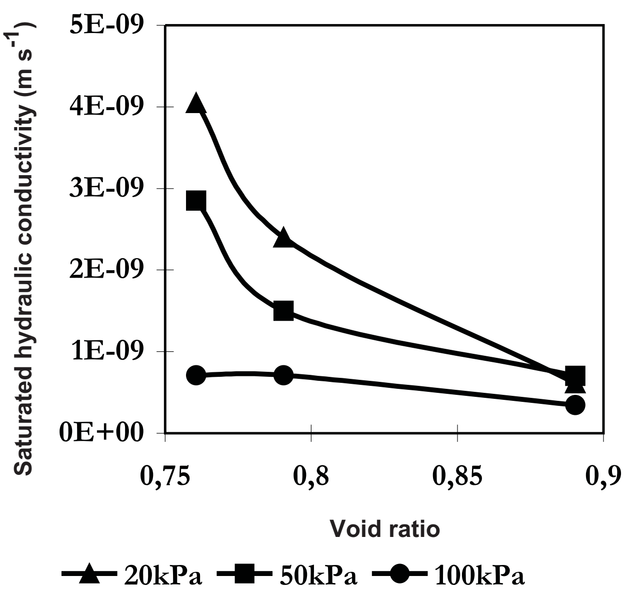

Fig. 3. Saturated hydraulic conductivity as a function of mechanical stress applied and the number of wetting and drying cycles for the same glacial till.

evaporation at the soil surface. In principle these processes will result in a more pronounced shrinkage.

Thus, if mechanically pre-stressed soil samples are further on dried at *eg* 40°C, which is equivalent to a pore water pressure of approx. -15 MPa, before installing in the mineral capping system, then these samples show no further shrinkage or volume change behaviour until they have reached this maximum pre-stress value.

Requirements with respect to substrates to be used for liner construction

Hydrologic requirements comprise a desired hydraulic permeability value. The sealing layer should serve as an impermeable barrier. So, in an ideal case, it should have no water permeability, but in recommendations required in different countries the value of hydraulic conductivity varies from 10^{-8} m s^{-1} in Italy through 10^{-9} m s^{-1} in Austria, Switzerland, Great Britain, and USA to 5 10^{-10} m s^{-1} in Germany and to 10^{-10} m s^{-1} in Denmark (Brune, 1995). The thickness of the mineral layer is different in different countries.

A POSSIBILITY OF WATER CONTENT MODIFICATION DURING PREPARATION OF THE MINERAL LINER UNDER *IN SITU* CONDITIONS

Irrespective of the required thickness of the mineral layer, the serious problem in practical preparation of the compacted sealing clay layer is the possibility of maintaining the water content in the substrate at a level suitable for performing the compaction process without further homogenization and without increased normal shrinkage behaviour due to positive pore water pressure. One such possibility is offered by the amendment of the clay substrate with CaO which absorbs free water from the soil and reduces its content both directly (1 kg CaO absorbs 0.32 kg water during transformation to $Ca(OH)_2$) and indirectly - due to temperature rise (exothermic reaction of CaO with water) and induced increase in the evaporation rate.

Application of CaO to the clay substrate raises the question to what extent this affects the properties of the substrate as it is connected at least with an increase of pH and of the Ca^{2+} ion content in the clay substrate. This question was studied by Junge and Horn (2001) who applied calcium oxide to a sedimentation clay material containing 41% of clay fraction.

Liming the soil not only influences the moisture content of the material but also the pattern of the Proctor curve. The amendment of 20 or 24 kg CaO m^{-3} resulted in a shift of the Proctor curves to the right. Thus, the mineral material became more rigid and during its compaction it remained in a residual shrinkage behaviour without any further dynamic shearing and homogenization.

If we further take into consideration that according to the stoichiometric reactions of CaO to $Ca(OH)_2$, 20 kg m^{-3} CaO results in a 0.4% water reduction due to chemical reactions, while the observed 5% water loss during this treatment is primarily due to exothermic reaction of the CaO in the amended material. However, it has to be considered that the application of CaO follows an optimum curve, because with increasing CaO (more than 30 kg m^{-3}) the maximum Proctor density values increase again but at much smaller water contents, due to a complete cementation which is equivalent with the formation of coarse pseudogravels.

For the smaller CaO application rates, the Proctor density is reduced with liming, but mineral liner systems prepared in this way have still saturated hydraulic conductivity values smaller than the required ones. Thus, the prepared mineral liner can be characterized as rigid which only shows residual shrinkage behaviour.

In order to underline this positive effect of compressing the mineral material at water content levels smaller than the optimum, Junge and Horn (2001) also measured the Mohr Coulomb failure line as a function of the stress and shear kneading of clay samples for the wet and the dry part of the Proctor curve. They could prove that, if the samples were sheared at an excessively high water content, the shear strength dropped substantially below the 'normal' failure line. Thus, the internal soil strength as well as the derived tensile strength of the material was reduced and would result in a more pronounced shrinkage.

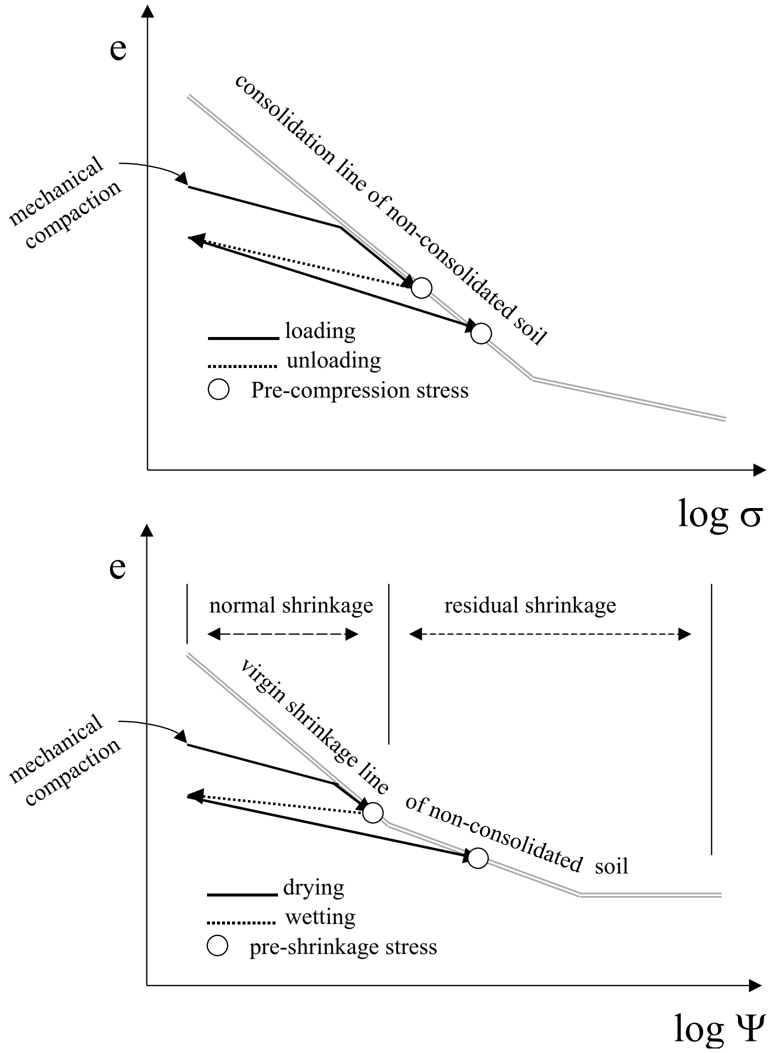

Fig. 4. Shrinkage and stress strain behaviour of soil samples (conceptual model according to Toll (1995)). Explanations: e - void ratio, σ - mechanical stress, Ψ - matric water potential.

DESIGN OF A CAPPING SYSTEM WITH THE CONSIDERATION OF MECHANICAL AND HYDRAULIC PROCESSES

The concept presented above has been realized during the capping of a 14 ha landfill in Haferteich, in the northern part of Germany. The liner constructed there is based on the concept of impermeability of clay layers and on capillary barrier as a sealing layer. Its construction is presented in Fig. 5.

As main criteria for the maintenance of the permeability properties, the following items should be considered when designing a capping system:

•shrinkage potential of the mineral substrate,

•water storage as a buffer for the maintenance of the swelling condition of the mineral layer,

•lateral drainage of infiltrating water (along slopes) in combination with the use of the system of capillary barriers,

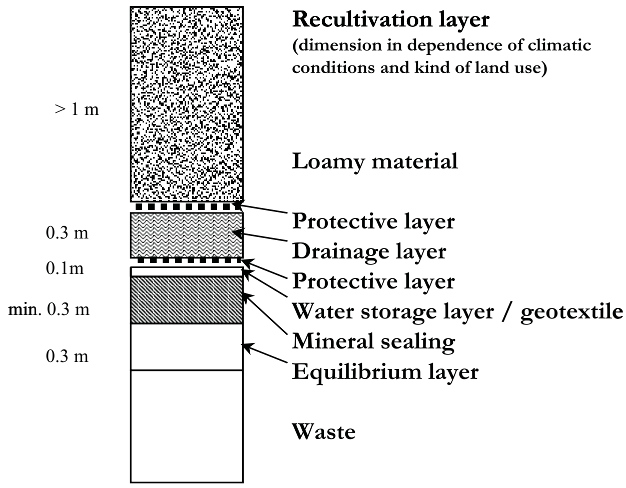

Fig. 5. A schematic of the pore barrier as an unpermeable layer in the landfill capping.

•calculation of adequate dimensions of the recultivation layer with respect to plant available water,

•stability against land sliding caused by water logging layers in slopes.

The core of the sealing, which consists of a mineral substrate, is underlain by a fine-sand equilibration layer and overlaid by a mainly fine-sand water storage layer. The clay material of the mineral layer was amended with 20 kg CaO m^{-3} and compacted to 95% of Proctor density at moisture content 5% lower than the Proctor optimum. Both the overlying and the underlying layers prevent the immediate diffusive and convective water loss. With depth, these layers serve as a water storage layer, which is re-saturated by condensation of water. The water storage layer above the seal reduces the drying caused by diffusive processes and guarantees a mean swelling situation.

The drainage of percolating water is achieved by a gravel layer which is secured by a thin geomembrane on both sides. The above recultivation layer acts as water storage for plant growth. It should be dimensioned by using different kinds of textures (*eg* sandy loam in the lower parts) to minimise root growth (lack of oxygen at high degrees of water saturation reduces root growth).

CONCLUSIONS

1. The context discussed makes it clear that the usage of clay minerals for sealing purposes eliminates cracking in the long term, when the water content or water potential, respectively, at the time of construction is smaller than any later intensity of drying. In Germany, this value can be derived using data analysis based on data sets of field sites spread over various regions. Based on the effective stress equation which relates the mechanical and hydraulic stress components, the soils can be considered pre-stressed in the mechanical sense by desiccation. By including this information, further crack formation and increase of the hydraulic permeability can be avoided.

2. By combination of a mechanical/hydraulical pre-stressed mineral seal with a soil water storage system, a drainage layer and elements of a capillary barrier including a root growth stopper within the recultivated layer, the safe long-term stability of the capping system can be based on these components. Depending on the situation, the possibility exists to even emphasize one or the other component.

3. When these soil physical facts are taken into consideration, neither irreversible normal shrinkage nor cracking will occur. A long-term secure sealing system can be created, being also adapted to different kinds of climatic conditions. Furthermore, a stable capping system can be created by an optimized combination of specific substrates and layers.

4. Based on these considerations, an effective seal can be formed over long periods. Consequently, the cycle of attempts to find alternative sealing systems can be stopped using the common knowledge about the physics of mechanical and hydraulic pre-consolidation, pore stability and pore function, flow laws and plant growth. As a consequence, the intensity and pattern of cracking of mineral substrates is not bound to a specific material but, rather, to the technique of its emplacement. The use of geomembranes of HDPE or of other organic components is not necessarily an alternative for sealing systems, because the same physical processes and problems will take place.

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