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MATHEMATICAL MODELLING OF MOISTURE MOVEMENT IN GEOSYNTHETIC CLAY LINERS

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Abstract: Drying characteristic of clays has been revisited and a mathematical model to predict moisture change has been developed and is presented in this paper. The development of the mathematical model has allowed for the factors controlling the moisture movement within the clay for a range of temperature, relative humidity environments, and varying properties of clay composite. Strong correlations between aforesaid parameter and drying characteristics were observed and are discussed in detail. In addition, an argument is presented for the superiority of the drying-rate test in current laboratory procedures for determining the moisture retention in comparison with moisture extraction under 'on site' conditions.

1. Introduction:

Clay is popularly used in engineered contaminant barriers or as an essential component in most synthetic landfill liners to minimize contaminant migration or as waterstop in structural water proofing. Extrusion of a sodium bentonite clay layer, after controlled prehydration with cation (ions having a positive charge) exchange resisting polymer, has been developed as an innovative and environmentally reliable process in GCL production.

The factory prehydration to a fluid content of circa 40% ($\pm 2\%$) which is beyond the shrinkage limit of the clay gives the composite clay liner an integral nature to support its ease in transporting, field placement, and manhandling with a minimal loss ($< 0.1\%$) of the clay infill.

The research described in this paper is to further develop this product so that it can be used worldwide regardless of any hostile climatic conditions. To this end, the aims of the research are to research and develop an appropriate coating and/or admix to:

- a) Delay the premature swelling that can arise with undesirable rainfall prior to installation.
- b) Retard the movement of moisture from the clay liner in extreme thermal environments

2. Geosynthetic Clay Liners (GCLs)

GCLs are an innovative construction material that has been developed over the last two decades. These composite matting are comprised of relatively thin layer of processed bentonite either bonded to a geomembrane or encapsulated between two sheet of geotextiles. The primary differences between GCLs are the mineralogy and form of bentonite (e.g., sodium versus calcium, powder/granular versus prehydrated plasticine like core) used in the GCL, the type of geotextile (e.g., woven versus nonwoven) or the addition of a geomembrane, and the bonding methods. Figure 1 illustrates the typical manufactured GCL in an air dry granulated form and an innovated GCL that have been factory prehydrated to a moisture content beyond its

shrinkage limit and vacuum extruded. The distinct difference in particle size distribution of bentonite can be seen under a Scanning Electron Microscope (SEM). The laminated and dense structure exhibited in the factory prehydrated and vacuum extruded GCL is a desirable property that gives low hydraulic conductivity as well as minimizes the potential of polygonal desiccation cracking (Wijeyesekera 2003).

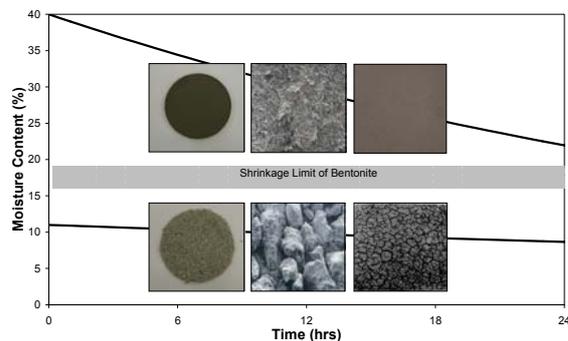


Fig. 1 Moisture Content of Manufactured GCL

3. Drying Mechanism of Clay

Drying has been defined as the removal of volatile substance (often water) by heat from a mixture that yields a solid product (Keey, 1978). In particular relevant to this study, Montmorillonite clay mineral have expanding type lattice structures which are known to withhold a large amount of water. This material behaviour during water elimination is controlled by the capillary water retained by the pores (pore water), by the bonded water at the surface of the raw material grains and by crystallization water (Dixon & Weed, 1989).

Pore water is the water which may move freely under hydrostatic pressure (Basma et al, 1994). Pore water system in a moist solid is represented by a two-pore system of joined capillaries of unequal diameter. When the pores are completely full, the body is totally sodden. As drying takes

place, as soon as any superficial moisture has been driven off, moisture begins to evaporate preferentially from the wider pores. The moisture level here then remains constant, whereas that in the narrower pore falls, since moisture from one limb to the other supplies the evaporation loss. The process continues as long as this capillary action can be sustained. After a certain 'critical condition' has been reached, both menisci begin to withdraw into the body. Moisture then evaporates from sites below the visible surface of the material.

3.1 Mathematical Modelling

Numerous models have been developed and studied for the prediction of the relationship between equilibrium solid moisture content, water vapour pressures, temperature. These models can be theoretical, semi-theoretical or empirical. The choice of a suitable model depends on a certain number of factors.

Following the literature, description isotherms are defined as the relationship between the equilibrium water content of a given material and the water activity or relative humidity at a certain temperature. In principle, Desorption isotherms are obtained by maintaining the sample at a given temperature, under a partial pressure of constant water vapour until thermodynamic equilibrium is reached. The Guggenheim-Anderson and de Boer (GAB) model is more appropriate and often used to describe the sorption isotherms of clay (Mihoubi et al, 2002). The general expression of this model is:

$$w = \frac{w_m C K A_w}{(1 - K A_w)(1 - K A_w + C K A_w)} \quad (1)$$

Where w is the material moisture content; A_w is the water activity; w_m , K and C are three constants to be determined.

4. Materials and Methods

Material used in the experimental measurements was a polymer treated and factory prehydrated bentonite (8.5 kg/m²). The experiments were performed in an environmental chamber with controllable temperature and relative humidity. A 5mm thick sample with a diameter of 50mm was placed on the sample holder and allowed to dry isothermally under preset conditions. The mass evolution of the sample with time was monitored using a digital balance linked to a computer facilitating regular data acquisition. Air temperature and relative humidity are measured by a thermo-hygrometer. The accuracy of measurement is as follows: 0.01g for mass, 0.1°C for temperature and 0.1% for the relative humidity. In order to model the drying kinetics, experimental conditions were arranged into two distinct sets. In the first set of runs, the temperature was fixed at 30°C and the influence of the air humidity changes on the drying rate was studied. In the second set, the relative humidity was set at 50% and the temperature was varied to study its influences.

5. Results and Discussion

The influence of drying air temperature and relative humidity on drying kinetic of clay are shown in Figs. 2 and 3. Since the initial moisture content varies a little; therefore the time dependent moisture content curves are presented in a normalized form.

The drying kinetic of the ‘constant-rate’ period (one wherein the rate remains almost constant while capillary action takes place) is visible; during this short equilibrating stage, the drying kinetic is independent of the air temperature under constant relative humidity condition. The transition of ‘falling rate’ period (the period wherein the

rate falls appreciably with reducing moisture content) is the onset of the critical drying stage, signaling the start of hindered drying. Increase air temperature results in steepest functional dependence $(X_t - X_{eq}) / (X_0 - X_{eq})$ (higher drying rates), reducing the drying time. The relative humidity of the drying air has a significant influence on the drying kinetic. At a relative humidity of 50%, bonding heat of water molecules at the surface of sample is weak and quite constant. The entropy of the water molecules is slightly lower than that of below or beyond this range. An increase in relative humidity from 50% to 70% increased the drying constant from 0.0181 to 0.076 at 30°C. On the other hand, it was also found that decrease in relative humidity from 50% to 30% of the 30°C drying air as well increased the drying constant from 0.0181 to 0.029.

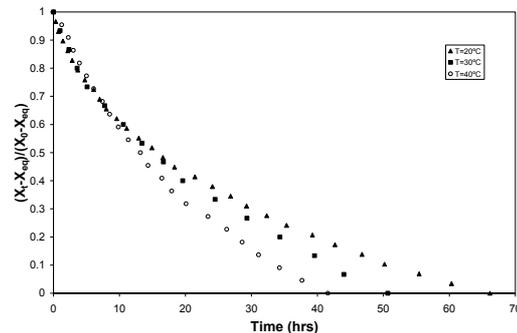


Fig. 2 The influence of temperature on drying kinetics at constant relative humidity (RH=50%)

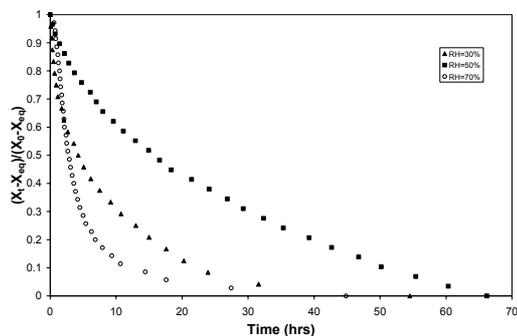


Fig. 3 The influence of relative humidity on drying kinetics at constant temperature (T=30°C)

Developing traditional models based on first principles is typically very time-consuming. An exponential model to describe the drying characteristic of GCLs has been adopted in this study. Water content at any time until equilibrium stage was reached during drying process can be represented as

$$w = W \cdot e^{-\alpha t} \quad (2)$$

where; w is the water content at any duration until equilibrium water content; W is the initial water content and x is the drying constant which is function of air temperature and relative humidity. The air temperature and relative humidity coefficient on the drying kinetic were presented in Fig. 4 and 5. As expected, temperature coefficient, β is increase linearly with rise in temperature; while the polynomial dependencies of the relative humidity coefficient, α is probably caused by the exponential temperature dependence of vapor pressure inside the samples.

The exponential model can be further developed by taking into account the drying constant and rewriting it in the form as;

$$X = (X_0 - X_{eq}) \cdot e^{\alpha(T)\beta(H)t} + X_{eq} \quad (3)$$

where; X – moisture content [kg_w/kg_{dm}]

X_0 – initial moisture content [kg_w/kg_{dm}]

X_{eq} – equilibrium moisture content

[kg_w/kg_{dm}]

$\alpha(T)$ – temperature function

$\beta(H)$ – humidity function

t – time [s]

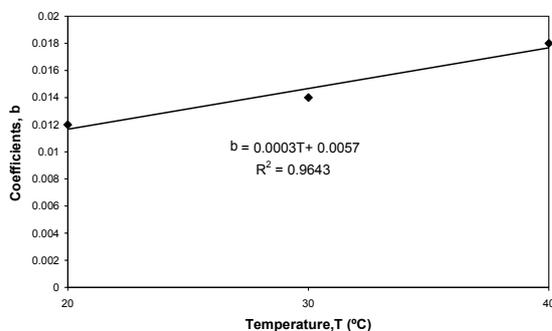


Fig. 4 The influence of drying condition on drying constant of parameter β

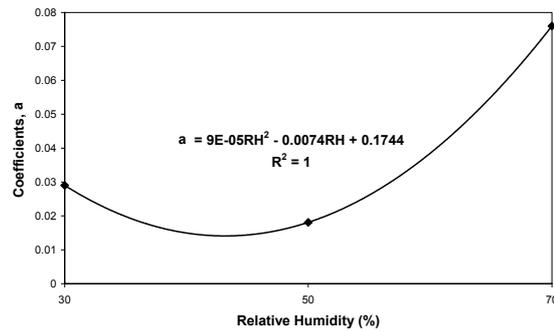


Fig. 5 The influence of drying condition on drying constant of parameter α

5. Conclusion

Achieving an understanding of the scientific basis to drying characteristic of GCLs was essential to improve long term prediction of the performances of the linear in thermal-environment and changing humidity condition. Literature searched helped to review that drying process as a remarkably predictable mechanism

In this study, we have determined experimentally the desorption isotherms of GCLs at different temperature and relative humidity conditions. Mathematical model of drying characteristic of GCL has been developed. The drying constant in the exponential model are the function of air temperature and relative humidity condition. The authors feel it is necessary as a matter of self assessment and criticism to point out that the laboratory simulation does not taken into account the air velocity which can be encounter at real site condition

6. References

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