SUSTAINABILITY STUDY OF THE APPLICATION OF GEOSYNTHETIC CLAY LINERS IN HOSTILE AND AGGRESSIVE ENVIRONMENTS

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Abstract: This paper discusses the sustainable performance of geosynthetic clay liners (GCLs) which are popularly specified as “leachate retaining” or as “water proofing” membranes in the geo-environmental construction industry. Geosynthetic clay liners (GCLs) are composite matting comprising of bentonite clay with two covering geosynthetics. These are innovative labour saving construction material, developed over the last three decades. The paper outlines the variety of Geosynthetic Clay Liners (GCLs) can be classified essentially into two distinctly different forms viz; (a) air dry (< 8% m/c) with granular or powdered bentonite or (b) bentonite cake factory prehydrated to a moisture content (~ 40% m/c) beyond its shrinkage limit and vacuum extruded as a clay cake to enhance its sustainable performance. The dominant mineral in bentonite clay is the three-layered (2:1) clay mineral montmorillonite. High quality bentonites need to be used in the GCL manufacture. Sodium montmorillonite has the desired characteristic of high swelling capacity, high cation exchange capacity and the consequently very low hydraulic conductivity, providing the basis for the hydraulic sealing medium in GCLs. These encapsulate the active montmorillonite clay minerals which depend on the water and chemical balance between the sealing element and the surrounding geo environment. Quantitative mineralogical analyses and an assessment of the adsorbed cation regime, diffusion coefficients and clay leachate compatibility must necessarily be an integral part of the site appraisal to ensure acceptable long term sustainability and performance. Factors influencing the desired performance of bentonite in the GCLs placed in difficult construction and hostile chemical environments are discussed in this paper. Accordingly, the performance specifications for GCLs are identified and the appropriateness of enhancing the cation exchange capacity with polymer treatment and the need for factory prehydration of the untreated sodium bentonite is emphasised. The advantage of factory prehydrating the polymer treated bentonite to fluid content beyond its shrinkage limit and subsequently factory processing it to develop laminated clay is to develop a GCL that has enviable sealing characteristics with a greater resistance to geochemical attack and cracking. Since clay liners are buried in the ground as base liners, capping layer or as structural water proofing membrane, they can easily avoid strict quality and performance monitoring being “out of sight, out of mind!”. It is very necessary that barrier design for leachate containment must necessarily be in accordance with legislative requirement Assessment of long term hydraulic conductivities and clay-leachate compatibility assessment is deemed necessary. The derogatory factors affecting the sustainable performance of the bentonite in GCLs placed in difficult construction and hostile chemical environments are discussed. Sustainability concepts incorporated in waste management practice must aim to achieve 100% recycling and fully implement the handling of solid waste in developing countries with relatively lower labour costs. These concepts are also applicable in land-filling the waste in developed nations, leading to sustainable landfills. This paper also presents laboratory scale information on the influence of aggressive tropical heat on the GCLs which cause them to shrink with the development of characteristic crack patterns reflecting the intrinsic structure of the clay agglomeration. It also presents a scientific physical - mathematical model to predict the hydration loss when used in tropical countries with an adverse thermal environment prior to the confinement of the clay liner. In particular, observations from isothermal drying of factory controlled pre-hydrated and extruded GCL over a wide range of temperatures (20°C to 40°C) and relative humidity (15% to 70% are presented as a part of the sustainability study.. The most commonly used kinetic drying models, i.e.; Page, Wang & Singh, Henderson & Pabis and Thin layer equation were investigated and it was seen that the Page model was more appropriate to simulate the equilibrium water contents of the clay mat for the range of temperatures and relative humidity studied. Critical study of the effective diffusion coefficient and exponential model parameter showed that the drying condition and type of polymer incorporated in the clay mat strongly influenced the drying kinetic and transport parameters.

Keywords: Bentonite, Cation Exchange Capacity, Geosynthetic Clay liner, Hostile Geo environment, Sustainability

INTRODUCTION

The urgent need for sustainable development in civil engineering has driven this research on the usage of Geosynthetic Clay Liners (GCLs) in the hostile and aggressive geo environments (chemical and climate). These are now being considered as an essential component in most synthetic landfill liners to minimize migration of contaminants or for water proofing structures. Wijeyesekera et al [1] outlined the design and performance of compacted clay liner / barrier (CCL) through a disused landfill site as a part of the construction of the then new Heathrow Express rail link. The GCLs which are only 6mm thick and factory manufactured are preferred over the traditional CCLs which are over 3m thick and laborious to construct. The effectiveness of this innovative material has led to the increasing usage in a variety of sealing applications, predominantly in hydraulic engineering, structural water proofing and groundwater protection. Presently, it is commonly being employed as a preferred alternative to CCLs in landfill cover systems or as bottom lining of waste containment facilities. All GCLs are factory-manufactured composite materials that consist of a thin layer of either calcium or sodium bentonite core, sandwiched between two geomembranes or geotextiles. There are mainly two forms of GCLs viz; (a) air dry (< 8% m/c) granular or powdered bentonite and (b) the factory pre-hydrated (~ 40% m/c) bentonite cake. This paper refers to the sustainable aspects in the performance of both of them.

Ultimate consideration is often given to the superficial physical design with less emphasis to both the ‘colloidal state’ and the ‘integral state’ of the bentonite core in the GCLs. Initial hydration of the bentonite in the GCLs with water is deemed ‘sine qua non’, very necessary during installation but, regretfully, it is not usually achieved. The pre-hydration in the field will occur naturally due to migration of water in the field from an underlying subgrade (as a result of capillary effects or vapor-phase diffusion) or can be intentionally done during the laying by spraying or inundating the GCLs. This however, does not fully satisfy the requirement of forming an integral clay liner due to the fluid-absorbing properties of bentonite (adversely effected by the presence of electrolytes particularly trivalent ions), crucial and sensitive issue to be considered in the methods of installation of the liners on sites [2],[3],[4],[5],[6],[7].

It is documented that a factory controlled prehydration with cation exchange resisting polymer added to an appropriate manufacture moisture condition is very desirable to combat the derogatory chemical attack in hostile and aggressive geochemical environments and thereby become an effective contaminant barrier [8],[9],[10],[11],[12]. Thus, satisfactory prehydration of GCLs prior to installation is always necessary [11],[13]. The consistency of the bentonite core must be preserved to ensure that the prehydrated GCL remains flexible at an appropriate moisture condition to facilitate the rolling process. This allows sufficient integral tensile strength and also that there will be reduced possibility of it drying and, consequently, developing brittle fractures when exposed to degenerating hostile thermo-environmental condition. The knowledge of the desorption isotherm, which portrays the moisture content distribution at a fixed temperature in the product and the water activity, is essential in the study of the effects of drying of the GCLs. The thermodynamic analysis of these isotherms makes it possible to determine the energies involved during the process which defines the drying of the prehydrated GCL. The variations in the moisture content observation during the isothermal drying of

GCLs and the feasibility in the application of physical modeling to the drying characteristic of the factory pre-hydrated GCL in a diverse climate condition was investigated and is presented in this paper and the results compared with the most commonly used kinetic drying models as cited in Sander et al [14]; Page, Wang and Singh, Henderson and Pabis and Thin layer equation. These models were used to fit experimental data using a non-linear regression analysis.

GEOSYNTHETIC CLAY LINERS

GCLs are a geo composite of relatively thin layers (~6mm) of processed bentonite, either bonded to a geomembrane or encapsulated between two sheets of geotextiles. Geomembranes are impervious polymeric sheet materials, whereas geotextiles are either in the form of woven or non-woven sheet material. Table 1 lists a summary of the more popular GCLs and their attributes. Stitch bonding and needle punching of GCLs to contain the granular / powdered bentonite provide additional internal resistance to shear but constitutes preferential flow channels for contaminant migration, particularly because of the lack of control of the uniformity in thickness. The sodium bentonite in Rawmat® is further factory treated with a liquid polymer, prehydrated and vacuum extruded to form a bentonite mat of uniform thickness. Though plastic based geomembranes offer also a degree of resistance to contaminants, such as hydrocarbons, their installation in a retro-fit application still demands complex on site welding procedures. These PVC liners also need fine sand cushions to enhance the puncture protection against accidental construction damage.

SUSTAINABILITY ASPECTS OF BENTONITE

The sustainable use of this innovative labour saving construction material has been in development over the last three decades. These have already been used and practiced in many sustainable civil engineering works. However, the quality and quantity of clay used affects the containment characteristics of the GCL. Some [15] have attempted to use paper mill sludge, the residual material from paper making process as an alternative to the hydraulic barrier material in landfill covers. Though required hydraulic conductivity can be achieved with paper sludge, it is only comparable to that of compacted clay. Additionally, its geotechnical properties such as water content, organic content, consistency limits and consolidation parameters are only comparable with that of peat. Table 2 provides a comparison of the geotechnical properties of both natural sodium and calcium bentonites, and how they differ from that of natural clays (London Clay).

Contrarily, the non-toxic plastic clay derived from the alteration of volcanic ash makes bentonite a suitable material in the geo-environmental construction industry. The dominant clay mineral type is smectite, and referred to usually as montmorillonite. Natural sodium bentonite is commercially packaged either in a fine powder form or as one of numerous sized granular distributions. However, the dispersed particle size of sodium bentonite is less than 2 microns. Bentonite presents strong colloidal properties and its volume increases several times when in contact with water, creating a gelatinous and viscous fluid. The special thixotropy property of bentonite makes it a valuable material for a wide range of uses and applications. Bentonite is sometimes known as “the clay of thousand uses”. It is popularly used for a wide variety of engineering purposes such as drilling mud in rotary piling and in the construction of diaphragm walls. These applications are temporary and do not necessarily require durability. Its self-healing characteristic accommodates and allows minor discontinuities in the material. For applications when bentonite mats are used for example in landfill containment and sealing underground reservoirs against intrusive contaminants, long term durability is vital. Bentonites are classified according to their exchangeable interlayer cation; usually sodium or calcium. At times magnesium ion can also be present. The presence of sodium causes a large amount of water to be adsorbed in the interlayer, resulting in characteristically unique and remarkable swelling properties. This does not occur with calcium or magnesium. Calcium bentonites therefore have lower swelling character. The high water absorption capacity of bentonite also makes it very plastic and resistant to fracturing or cracking. Repeated hydration and drying or freeze and thaw have little to no effect on the original swelling capacity. A layer of hydrated and dense sodium bentonite can have a typical hydraulic conductivity of around 1×10^{-11} m/s. The mineral Montmorillonite in bentonites is also known for its natural potential to ion exchange. Often the naturally occurring bentonites are the more stable calcium bentonites. Natural sodium bentonites are comparably rare. In order to utilise the better swelling properties of sodium bentonite, calcium bentonite for instance is activated with soda (sodium carbonate) and thus the primary calcium ions are replaced by sodium. On the other hand, any calcium ion in the leachate is likely to convert the sodium of the bentonite into calcium. Calcium bentonites have, by nature, a more coarsely aggregated internal structure providing a higher hydraulic conductivity than in sodium bentonite (Table 2). These have considerably lesser swelling properties and are less suitable for providing a tight seal (self-healing effect) in cases of perforation.

Table 1: Principal GCL Product types, adapted from [16]

Manufacturer	Description	Product type
Bentofix®	Activated sodium bentonite as primary ingredient and affixed by needle punching to a woven or nonwoven upper geotextile and a nonwoven lower geotextile.	Granular/powdered bentonite
Bentomat®	Sodium bentonite as primary ingredient and affixed by needle punching to a woven or nonwoven upper geotextile.	Granular/powdered bentonite
Claymax®	Sodium bentonite as primary ingredient mixed with water–soluble adhesive and bonded or stitch-bonded to a woven upper and lower geotextile.	Granular/powdered bentonite
Rawmat®	Natural sodium bentonite, factory pre-hydrated using liquid polymers, vacuum extruded to create a non-granular central core which is laminated between different woven or non-woven geotextiles or films relevant to the membrane application.	Bentonite cake
Gundseal®	Sodium bentonite as the primary ingredient mixed with an adhesive and bonded to a blend of high-density polyethylene and very low-density polyethylene.	Bentonite cake

Table 2: Comparison of some of the Geotechnical Properties of Sodium / Calcium Bentonites

Georechnical property	Natural London Clay [3]	Natural Calcium Bentonite	Sodium treated Calcium Bentonite	Natural Sodium Bentonite
Specific gravity	2.7	2.6 – 2.8		2.7 – 2.9
Liquid Limit (%)	70 - 75	100-150		500-700
Plastic Limit (%)	10 - 20	70-100		450-630
Plasticity Index (%)	10 - 40	30 - 50		50 - 100
Activity	0.4-0.9	>1		>>1
Cation Exchange Capacity (Methylene Blue Test Data) (meq/100g)	15 - 20	28 - 45	32 - 45	36 – 42
Surface area (m^2/g)		60 -120	60 - 120	20 – 30
Fluid loss (ml)		< 24	< 24	<13
Free swell (ml/2g)	6 - 10	6 - 8	15 - 24	20 - 30
Hydraulic conductivity with water (m/s)	10^{-11} to 10^{-9}	$6x10^{-11}$ [18]		$6x10^{-12}$ [18]
Hydraulic conductivity with 1.5M $CaCl_2$. (m/s)		$6x10^{-10}$ [18]		$9x10^{-11}$ [18]

Figure 1: Rapid self-healing character of Liner D - Rawmat HDB (high density bentonite)

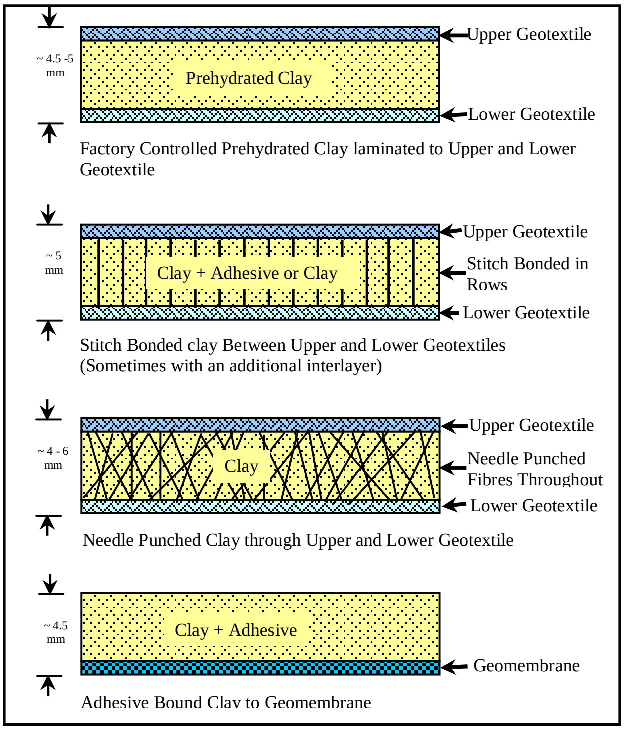

Figure 2: Make up of the different types of GCLs [1]

Table 3: Product quality observations of four GCL rolls on delivery

CHARACTERISTIC PROPERTY OBSERVED		LINER			
		A	B	C	D
Identifying characteristics of the GCL		Needle punched with grey granular bentonite	Needle punched with cream granular bentonite	Needle punched with fine grained brown bentonite	Laminated with prehydrated fine grey bentonite
Dimensions of roll L(m) x B(m)		4.9 x 1.1	5.0 x 1.0	2.4 x 1.2	5.0 x 1.0
Mass of roll (kg)		34.5	27.5	13.4	39.6
En masse properties	Mass of GCL per unit area (g/m^2)	6107	5231	4670	7865
	Moisture content (%)	11.6	8.8	9.6	27.5
Infill bentonite clay properties	Mass of dry clay / unit area (g/m^2)	4067	4039	3443	5286
	Moisture content (%)	17.1	5.6	10.2	41.2
Thickness (mm)		5.1	7.35	5.29	5.1
Mass loss on handling / m edge (g/m)	On rolling out horizontally	1.98	3.83	1.31	0
	On fixing vertically	54.1	79.1	9.25	0
	On cutting	19	37.5	16.5	0
Cation Exchange Capacity (meq/100g)		56	66	65	70
Free swell (ml/ 2g)		30	25	24	23

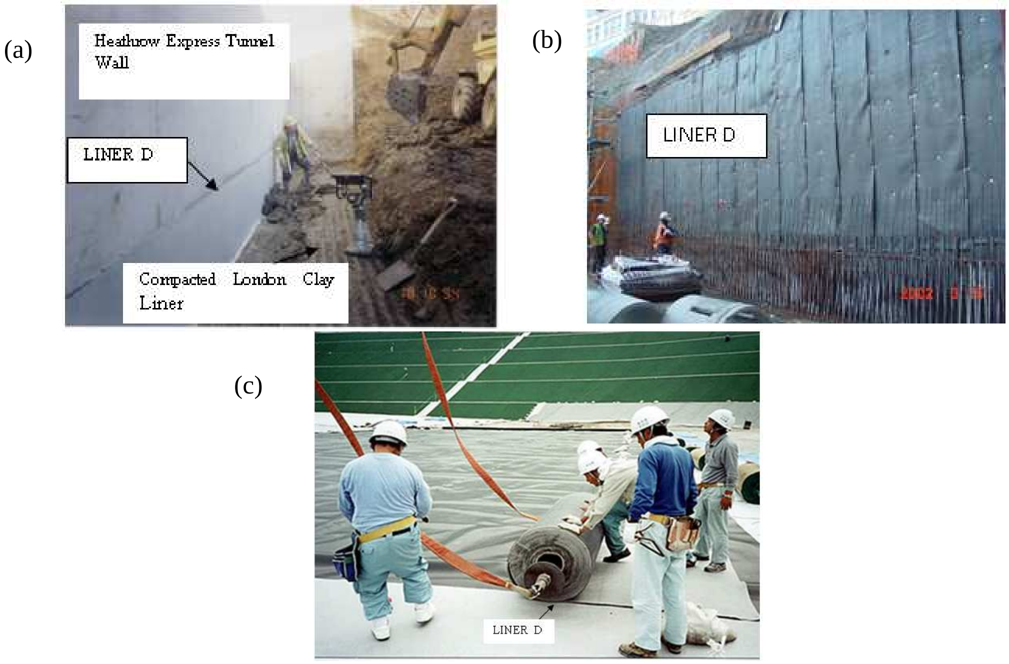

Figure 3: Various (vertical and horizontal) installation of liner D at (a) Heathrow tunnel (UK), (b) Britomart railway station (NZ) and (c) Kagashima Landfill site Japan

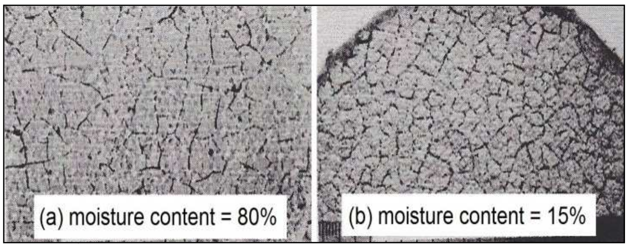

Figure 4: Desiccation cracks in Bentofix – x2000 at different moisture content [27]

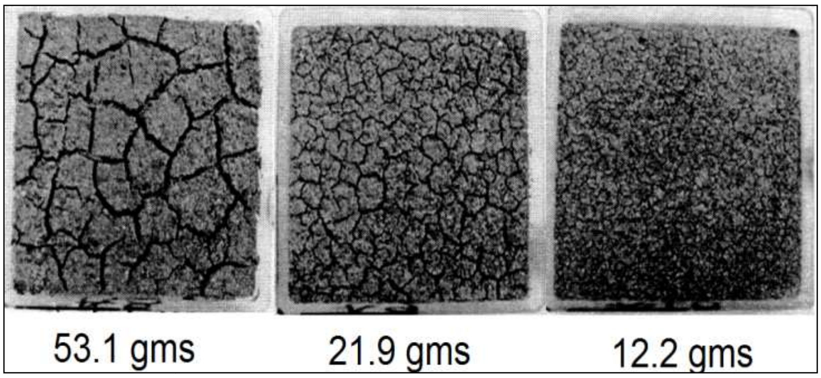

Figure 5: Desiccation crack patterns in liner A infill for different thickness – the effect of thinning out of the dry granular GCLs during handling or installation

Table 4: Swell index and Cation Exchange Capacity observations for the clay in the liners

PROPERTY		CLAY INFILLS FROM LINER				Untreated Wyoming Bentonite
		A	B	C	D	
CEC of clay in: (meq/100g clay)	Deionised water	56	66	65	70	57
	Sea water	36	38	45	49	41
	Na^+ 2,500 ppm	56	60	64	68	56
	Na^+ 5,000 ppm	53	59	62	58	56
	Na^+ 10,000 ppm	43	47	51	57	46
	Na^+ 100,000 ppm	36	36	44	44	40
	Ca^{++} 10,000 ppm	38	40	42	64	42

The preferential water absorption characteristics of natural sodium bentonite is demonstrated in its potential to absorb nearly 5 times its weight in water for full saturation and thereby occupy a volume 12 to 15 times compared with that when it is dry built. The large hydration radius of the sodium ion is primarily responsible for the bentonite's sealing ability. Soda activation of calcium bentonite can also produce a swelling bentonite. However, tests show that sodium carbonate treated calcium bentonites have distinctly lower water holding capacity and a higher hydraulic conductivity [17]. Untreated sodium bentonite, on the other hand, can degrade when exposed to certain chemicals during or after hydration. In the case of the usage of GSLs in landfills, the bentonite in the GCL needs to be compatible with the leachate to be retained, lest they may be prone to chemically induced contraction (in the mineral's c – axis), double layer shrinkage and cracking. On the other hand, the performance of bentonite in GCLs can be increased with the addition of linear polymer chains of the sodium polyacrylate and acrylonitrile type. Adding dispersants such as lignite or sodium polysulphates to the bentonites can further prevent flocculation or gelling due to contaminating salts. This polymer attaches itself to the platelets by ion exchange and acts like a spring upon hydration, prying the stacked platelets apart like an accordion. Most air-dry bentonite GCL systems are mixed with polymers to aid resistance to contaminants and maintain performance. The specific gravity contrast between the bentonite (typically 2.5 to 2.7) and the polymer (typically 1.2 to 1.5) can promote undesirable non-uniformity in the dry mixing process of the powders. This causes a mechanical shake down associated with handling, invariably leaving the bentonite in some parts of the mixture unprotected. The initial hydration of the air dry GCL will be a crucial process to the attaching of the water-soluble polymer on to the bentonite surface. The process of factory prehydration with a liquid polymer is desirable to ensure an intimate mix and that the polymer reaches all the particles uniformly.

Geotextiles used to contain the bentonite are usually very robust and resistant to normal site activities, except in the instances when they are chosen to be relevant to a particular application. Heavy materials that attempt to puncture the layer normally have no damaging effect on the membrane. Any accidental cuts will self heal when the membrane is hydrated following correct installation, provided that bentonite material is not lost from the edges of the cut. Fig. 1 illustrates the prompt self-healing of the damage by a sharp blade through the bentonite cake of the factory prehydrated and vacuum extruded GCL (see liner D in Table 3). Its initial pre-hydration and denseness of the bentonite core at the point of manufacture facilitate the ready response. The geosynthetic component of the GCL is not critical to the long term performance of the bentonite in the GCL. Rowe [18] drew particular attention to leakage through holes in wrinkled geomembranes and GCLs. He also observed that there is no reason to believe holes will not occur at the location of wrinkles. He demonstrated that a leakage of about 2.3lphd can occur in a GCL with a hydraulic conductivity of 2 x 10^{-10} m/s, having only a single hole in a wrinkle 5m x 0.2m, when subjected to a "design" head of 0.3m.

BROAD CLASSIFICATION OF GCLS

There are a variety of GCL products now available worldwide. In regard to this, the diverse range of materials, the bentonite types and methods of manufacturing (adhesive bonding, stitch bonding or needle punching) is summarized in Fig. 2. The primary differences between them are: (a) The mineralogy and form of bentonite (i.e. sodium versus calcium, powder/granular versus factory controlled prehydrated and extruded mat) used in the core of GCL (b) The type of geotextile (i.e. woven versus nonwoven) or the addition of a geomembranes (c) The bonding methods (i.e. lamination, adhesive bonding, stitch bonding or needle punching) (d) The overlapping method (i.e. bentonite to bentonite bond versus bentonite to geotextile bond)

Factory controlled pre-hydrated GCL is made up of sodium bentonite clay. The clay is further polymeric hydrated and then vacuum extruded through a die and laminated with an upper and lower covering geotextile. The preparation and extrusion process of the GCL central core, i.e. bentonite allows for a high degree of manipulation. The authors are not aware nor were able to find information on any extruded bentonite GCL systems that has received any needling or other such mechanical attachments of the upper and lower geotextiles. The advantage of this is that the central core is not punctured by fibers. As a result, there is no possibility of fluid tracking due to the engineered bonding of upper and lower geotextiles. However, the internal shear strength can be low, resulting in potential slippage when used on excessively steep slopes. This limitation can be overcomes by an engineered solution. In the authors' opinion from a sustainable point of view, it is more important that GCLs can provide a long term barrier to contaminant rather than GCLs having great shear resistance, as a major proportion of the landfill covers require horizontally laid liners.

Laboratory investigation [1] carried out to ascertain the product quality on the delivery of four different types of GCLs (viz, A, B, C and D) is presented in Table 3. An observation of particular note is the range of the dry mass of bentonite infill per unit area (4.7 to 7.9 kg/m^2). Despite the 41.2 % prehydration moisture content, liner D had 32% more dry bentonite mass per unit area than that in other liners A, B and C. The infill in liner A was coarse grained with angular agglomerations (clusters of disordered clay platelets) though it had a moisture content of 17.1%. The cluster size distribution of the fill in liner B was more graded and the infill in liner C was a very fine-grained powder. The clay infill in liner D was laminated and showed the consistency of plastic, pliable matting of uniform thickness. The laminated structure of liner D is a result of the vacuum extrusion process of the hydrated clay- polymer mix and has fewer propensities to cation exchange with polyvalent cations. A matter of grave concern is the observed loss of dry bentonite that can occur with the granular GCLs A, B and C during installation (shake down on rolling out or attempting to hang the liners on a vertical surface). Figures 3 show installation practice on sites in United Kingdom [20], New Zealand [21] and Japan [22] where liner D has been used successfully and have resulted in no shake out or loss of the infilled bentonite during installation. Estornell and Daniel [23] reported the need for an additional geotextile filter to avoid bentonite loss for some GCLs, and Rowe [19] reiterated the care to be adopted in the construction procedures to maintain a uniform distribution of the bentonite in the GCL. Geoenvironmental engineers must recognise the potential for physical or thermal induced bentonite movement which varies from one GCL to another and that there is no bentonite loss with factory pre-hydrated GCLs of the type of liner D (Table 3).

FRACTURE PATTERNS ON DRYING

Particular attention must also be paid to the drying process, especially in hostile and aggressive tropical environments, as fracture or cracking might occur on GCLs due to isolation from groundwater. There is potential for the clay in the liner to crack with desiccation. The risk of cracking is greatest for highly active clays (bentonites) under conditions of low confining stress. When cracking occurs it will obviously result in a liner having much higher hydraulic conductivity than is desired. The first cracks resulting from dehydration in thin, clay occur at a water content above the plastic limit and at the transition from a single axial (purely vertical) to a triple axial (vertical and horizontal) shrinkage. Bentonites are susceptible to cracking when the natural water content drops below 80-90% with no load. Fig. 4 [24] shows the influence of the water content on the crack patterns formed in the granular infill. The significance of the thickness (mass/ unit area) on the crack patterns formed was investigated. Different mass / unit area of the liner A infill was saturated with deionised water and allowed to desiccate. The intensity of cracking was clearly observed to be dependent on the thickness and this is illustrated in Fig. 5. The authors observed from similar tests carried out on prehydrated and laminated liner D that this type of liner did not show any surface polygonal crack patterns. This is a consequence from the vacuum extrusion process that produces a laminated macro structure with a highly oriented clay microstructure. Egloffstein [2] reported through comprehensive tests that it will take a few weeks for the structure healing process to take effect in the needle punched bentonite liner after dehydration and ion exchange from different landfills.

Reuter and Markwardt [25] report that the needle punched / stitch bonded method of manufacture of GCL has a distinct influence on the structure of the desiccation cracking. The needle punched product showed a relatively even distribution of more fine cracks whilst the stitch bonded product had fewer but larger cracks which with an xray investigation showed a “ladder” type crack structure with the sewing thread. Vangpaisal et al [24] observed that with desiccation, a Bentofix x2000 GCL, led to the formation of desiccation cracks within the bentonite component. This implied that such GCLs in cover systems must be properly protected from desiccation to reduce the strong possibility for the gas to escape with the desiccation of the GCL. They also observed that the presence of the needle punched fibres helped in the development of uniform desiccation cracks. It is probably possible that these desiccated cracks will close during rehydration. However, although the self-healing capacity of sodium bentonite in the GCLs can be high, both experimental and field evidence published [26, 27] show that self - healing can be impeded if it is coupled with ion exchange.

CATION EXCHANGE CAPACITY (CEC)

Cation exchange is a fundamental electrochemical soil property and is mainly significant to the behaviour of clay soils [2],[28],[29],[30]. CEC is the ability of soils to retain cations. Cations due to their positive charge are attracted to the negatively charged portion on the soil surface . Sites for cation exchange include both the mineral and organic fractions of the soil. The CEC observations (Table 4) on all the samples apart from the liner C fill show a decrease in CEC when the clay fill had been left in solutions of increasing cationic concentrations. This suggests that a process of cation exchange takes place, reducing the CEC in the modified clay. The levels of Na^+, K^+, and $NH4^+$ in municipal solid waste (MSW) leachate are sufficiently high that they can effectively exchange some of the Ca^{++} and Mg^{++} present on natural clays during advection and diffusion. CEC is adopted as a good performance indicator of GCLs and that a high CEC is desirable [1]. Fluid Loss test, adapted from the American Petroleum Institute’s testing manual for drilling muds, is meant to measure the efficiency of a clay suspension (drilling mud). Fluid loss test results [31] also show the sensitivity of CEC to the chemistry of the fluid.

HOSTILE TROPICAL ENVIRONMENT

The laboratory scale information on the influence of aggressive tropical heat on the GCLs is presented in this paper using scientific physical - mathematical models adopted to predict the hydration loss when GCLs are used in different geothermal environments, particularly in tropical countries with an adverse thermal environment prior to the field confinement of the clay liner. The variations during the isothermal drying of GCLs are critically observed. It is also crucial that the consistency of the clay is preserved to ensure that the mat remains flexible with no possibility of it developing brittle fractures in a hostile thermal environment. In order to fully understand the influence of drying characteristic of the clay mat in different thermal environment, it is essential and necessary to propose some descriptive and predictive mathematical models which include the evaluation of the key process drying parameters. An environmental chamber with controllable temperature and relative humidity was used on a 5mm thick, 100mm diameter factory prehydrated sample, which was placed on a sample petri dish and allowed to dry isothermally under preset conditions. The mass evolution from the sample with time was monitored using a digital balance linked to a computer facilitating regular data acquisition. Air temperature and relative humidity were measured using a thermo-hygrometer. The accuracy of measurements was as follows: 0.01g for mass, 0.1ºC for temperature and 0.1% for the relative humidity. The experimental data were correlated with the following different mathematical models in order to establish the most appropriate equation out of the applied models for the experimental data, a non-linear least squares regression analysis was used to fit the experimental data.

[1] Wang & Singh

$$X = (X_0 - X_{eq})(1 + at + bt^2) + X_{eq} \quad (1)$$

[2] Henderson & Pabis

$$X = (X_0 - X_{eq}).\beta e^{-k.t} + X_{eq} \quad (2)$$

[3] Thin layer equation

$$X = (X_0 - X_{eq}).e^{-k.t} + X_{eq} \quad (3)$$

[4] Page

$$X = (X_0 - X_{eq}).e^{-k.t^n} + X_{eq} \quad (4)$$

A SigmaPlot® graphing software from SYSTAT was used for this purpose. The quality of the fitting was evaluated by calculating the mean relative percent error (*P*), standard error (*SE*) and the coefficient of correlation (R^2) between the experimental (y_{exp}) and predicted data (y_{cal}). These are defined by the following expressions:

$$P = \frac{100}{N}\sum_{j=1}^{N}\left|\frac{y_{jcal} - y_{j\exp}}{y_{j\exp}}\right| \quad (5)$$

$$SE = \sqrt{\sum_{j=1}^{N}\frac{\left(y_{jcal} - y_{j\exp}\right)^2}{N - n_p}} \quad (6)$$

$$R^2 = \frac{S_t - SSE}{S_t} \quad (7)$$

where,

$$S_t = \sqrt{\frac{\sum_{j=1}^{N}\left(\bar{y} - y_j\right)^2}{n-1}} \quad (8)$$

$$\bar{y} = \frac{\sum_{j=1}^{N} y_j}{N} \quad (9)$$

$$SSE = \sum_{j=1}^{N}\left(y_{jcal} - y_{j\exp}\right)^2 \quad (10)$$

Experimental data for sample obtained from the tropical environment condition (temperature = 30°C and relative humidity = 50%) was chosen and the observed outputs for this condition are presented in Table 5. From an overall view point, the Page model gave the most desirable *%P*, *SE* and R^2 values compared to the other models. The highest coefficient of correlation R^2 value (0.9998) as well as the lowest *%P* (0.3452) and *SE* (0.0884) value made this model the most appropriate regression model. The drying constants *k* and *n* in the Page equation are essentially functions of transport properties. Fig. 6 and Fig. 7 show the influence of the thermal environmental conditions on these two parameters.

Table 5: Statistical parameters and comparison criteria for different kinetic model

	Model			
	I	**II**	**III**	**IV**
SSR	38092.14	38316.26	38316.26	38377.14
SSE	291.73	67.62	67.62	6.73
S_t	38383.88			
(%P)	2.0541	0.8806	0.8806	0.3452
SE	0.5821	0.2802	0.2801	0.0884
R^2	0.9924	0.9982	0.9982	0.9998

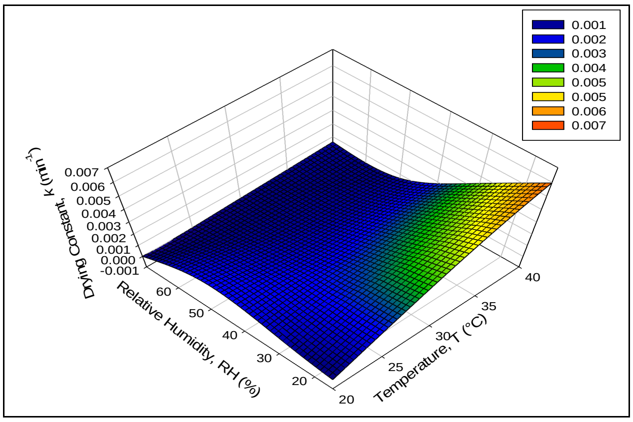

Figure 6: Influence of Thermal Environment Condition on the Drying Constant *k*

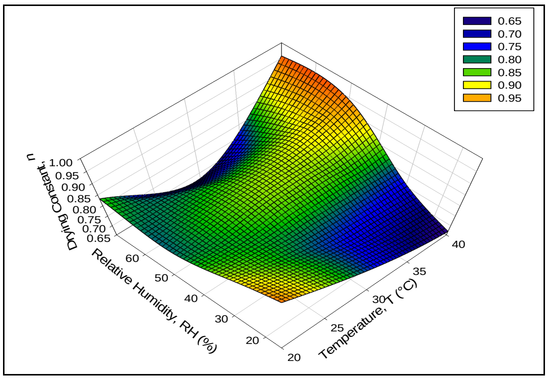

Figure 7: Influence of Thermal Environment Condition on the Drying Constant *n*

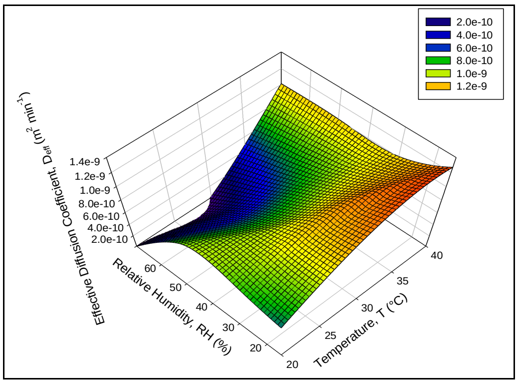

Figure 8: Influence of Thermal Environment Condition on the Effective Diffusion Coefficient, D_{eff}

For a given temperature, an increase in the relative humidity causes a reduction of parameter *k*. This phenomenon is more pronounced in the higher temperature range. Conversely, the sensitivity of parameter *k* to temperature apparently reveals that at a lower relative humidity range. An increase in temperature led to an increase in the parameter *k*. Parameter *n* on the thermal environment was noted to be independent as also reported by Sander et al. [14] for thin plates of illite and montmorillonite clay. Sander concluded that the parameter *n* is independent of the drying condition. Table 5 gives the values of the parameters that define the quality of the fitting.

It is assumed that the internal diffusion prevails as a mechanism of matter transfer. Equation (5) can be approximated to a linear form, which is convenient for determining effective diffusion coefficient, in the manner show in Equation (6). According to Geankoplis [32], the solution to the diffusion equation for thin plate shaped material drying from one surface is:

$$\psi = \frac{X - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2} \cdot e^{\left(\frac{-\pi^2 \cdot D_{eff} \cdot t}{L^2}\right)} \qquad (5)$$

$$\ln\psi = \ln\frac{8}{\pi^2} - \frac{\pi^2 \cdot D_{eff}}{L^2} \cdot t \qquad (6)$$

From a study of dimensionless moisture content on drying time in a semi-log graph, straight lines are obtained from which the slope, the effective diffusion coefficient is calculated and presented in Fig. 8. It is evident that the effective diffusion coefficient is dependent on the drying temperature. The higher temperature gives a higher value for the effective diffusion coefficient. Contrarily, an increase in the relative humidity level results in a reduction in the effective diffusion coefficient. This observation is further supported by the evidence from the drying kinetic model as shown in Figure 5. The drying kinetics increase with the air temperature due to an increase in the convective heat flux transport brought about by the air to the sample. The acceleration of the internal moisture migration, results in an increase of the effective diffusion coefficient value. Conversely, an increase in the relative humidity causes a reduction of the isenthalpic flux. The critical moisture content corresponding to the drying regime change varies in the same way. The equilibrium moisture content increases naturally with an increase in the relative humidity level.

CONCLUSION

GCLs are an important development in construction materials used in civil engineering works. These are meant to provide a clean and safe environment for everyone. The factors affecting the performance of bentonites in GCLs have been critically presented and also suggestions were made for further quality control. Attention has been drawn to the sensitivity of GCLs hydraulic conductivity to the type of permeant and the hydrating fluid. Concern has been raised about the inappropriateness and probable geotechnical deficiencies in adopting granular / aggregated bentonite GCLs. Granular bentonite is prone to produce non uniform swelling which then can promote cracking with shrinkage or ion exchange.

It is particularly necessary to appreciate the reaction of a GCL with the chemical make up of the local groundwater or the leachate. Consequently, site conditions with changeable water quality, does not facilitate the hydration of "dry" GCLs to ensure a continuous and uniform swell of the infill. Furthermore, study of the clay's interaction with just deionised water as that recommended in standard testing can fail to recognise any of its peculiar behaviour in chemically hostile environments. Bentonites treated with stabilizing agents and factory prehydrated seems to be a way forward to obtain clay infills of high CEC that lose only minimal amount of its CEC under hostile chemical environments. Factory prehydration avoids the difficulties of on site hydration of dry GCLs, which can endanger the efficiency of such initially dry liners. The performance of bentonite in GCL to resist chemical attack from hostile environments has been successfully enhanced by the addition of polymer chains. However, if the polymer is added only in a dry state, it can readily be lost during the GCL manufacture and during its hydration stage.

For the study of the drying characteristic of the factory controlled pre-hydrated and extruded GCL in tropical environment, the kinetic of isothermal convection drying were also investigated. High correlation between Page model and experimental data justifies the applied mathematical model for describing the drying kinetic in isothermal condition. The influence of temperature and relative humidity level on the transport properties such as drying constant, drying rate, effective diffusion coefficient and exponential model parameter were estimated.

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