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Article title: Optimising the Performance of Bentonite in Geosynthetic Clay Liners

Year of publication: 2006

Citation: Wijeyesekera, D.C. (2006) 'Optimising the Performance of Bentonite in Geosynthetic Clay Liners' Proceedings of the AC&T, pp.124-129.

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OPTIMISING THE PERFORMANCE OF BENTONITE IN GEOSYNTHETIC CLAY LINERS

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Abstract: Geosynthetic clay liners (GCLs), developed over the last quarter century, are innovative composite matting comprising of bentonite with two covering geosynthetics. The three-layered (2:1) clay mineral montmorillonite forms the dominant (approximately 75-90% by weight) clay mineral in the bentonite that is used in its manufacture. Quantitative mineralogical analyses with an assessment of the adsorbed cation regime need to be normally carried out as part of performance appraisal. The mineralogical and geotechnical differences between the preferred sodium and the less effective calcium montmorillonite are presented in the paper. The liners with its encapsulated high active clay minerals depend on the water balance between the sealing element and the surrounding soil layers. Assessment of long term hydraulic conductivities and clay-leachate compatibility assessment is also deemed necessary and the derogatory factors affecting the performance of the bentonite in GCLs placed in difficult construction and hostile chemical environments are discussed. The performance specifications for GCLs are identified in this paper and the need to enhance its cation exchange capacity with polymer treatment coupled with the need for factory prehydration of the untreated sodium bentonite is emphasised.

1. Introduction

Clay is used popularly in barriers (Wijeyesekera et al, 2001) to minimise contaminant migration or in water proofing. The EU directives specify stringent regulations on the disposal of municipal, industrial and hazardous wastes. The EU recommends low permeability bentonite clay barriers, as a sealing material in landfill construction to ensure the protection of groundwater from pollutants. Such clay barriers can vary from thin bentonite liners (4.5 to 9 mm thick), to compacted/ natural clay liners (0.6 to 2 m thick).

Traditional compacted clay liners (CCLs) are becoming popularly replaced by geosynthetic clay liners (GCLs) in a variety of sealing applications (Daniel, 1999). Compacted clay liners may be unable to provide the required level of environmental protection from landfill contaminants under

certain hydro-geologic and geotechnical conditions.

GCLs are a composite of relatively thin layers of processed bentonite either bonded to a geomembrane or encapsulated between two sheets of geotextiles. Koerner and Wilson-fahmy, 1994 reported on the technical equivalency assessment of GCLs to CCLs. Some of the advantages of GCLs over CCLs are;

- Flexibility with a high failure strain,
- Uniform geoenvironment characteristics,
- Self healing properties,
- Resistance to freeze-thaw,
- Lower thickness for an equal fluid flux,
- Potential to maximise landfill volume,
- Higher quality control in manufacture,
- Rapidity and ease of installation, and
- Competitive costs.

2. Sodium and Calcium Bentonite

The quality and quantity of GCL infill affects its containment characteristics. Paper mill sludge, the residual material from paper making process has been an alternative used in the past (Quirroz et al, 2000). Although hydraulic conductivity is comparable to that of compacted clay, geotechnical properties such as water content, organic content, consistency limits, and consolidation parameters are only comparable with those of .peat. Bentonite is non-toxic plastic clay naturally occurring with alteration of volcanic ash with smectite (usually montmorillonite) as the dominant clay mineral. The dispersed particle size of bentonite being less than 2 microns, exhibits strong colloidal properties and it swells in volume several times when in contact with water. Its self-healing characteristic tolerates minor discontinuities in the material. This, and the associated thixotropic property makes bentonite a material with a wide range of temporary applications. However, in landfill containment applications, where bentonite mats are used, long term durability is vital. Montmorillonites are three layer minerals consisting of two tetrahedral layers sandwiched around a central octahedral layer. Oxide anions at the apices of the tetrahedral sub units are directed inward where they surround interior aluminium, iron and magnesium cations. Thereby they form the octahedral sub units of the octahedral layer. Bonding between the shared interior oxide anions and the cations in both the tetrahedral and octahedral layers, link the layers together and yields the unique sheet structure characteristic of clay minerals. Bentonites are classified according to their exchangeable interlayer cation; usually sodium or calcium, and at times magnesium may also be present. Hence,

sodium montmorillonite is the major constituent of sodium bentonite. A consequent and important characteristic is that they carry a net negative charge that is expressed as the number of deficient electrons / unit cell of ten oxygens with respect to charge neutrality. If there are no fixed cations between the sheets, the negative charge deficiency correlates directly with the cation exchange capacity (CEC) which is the measure of the number of positive cations in milliequivalents to neutralize 100g of clay. This slight excess negative charge on the sheets is counterbalanced by free moving (exchangeable) cations. Table 1 gives indicative geotechnical properties of natural sodium and calcium bentonites.

	Natural Calcium Bentonite	Natural Sodium Bentonite
Specific gravity	2.6 – 2.8	2.7 – 2.9
Liquid limit (%)	100-150	500-700
Plastic limit (%)	70-100	450-630
Plasticity index (%)	30 - 50	50 – 100
Activity	>1	>>1
Cation-exchange capacity (Methylene blue test data) (meq/100g)	28 - 45	36 – 42
Surface area (m ² /g)	60 -120	20 – 30
Fluid loss (ml)	< 24	<13
Free swell (ml/2g)	6 - 8	20 – 30
Hydraulic conductivity (water) (m/s)	6x10 ⁻¹¹	6x10 ⁻¹²
Hydraulic conductivity (1.5M CaCl ₂) (m/s)	6x10 ⁻¹⁰	9x10 ⁻¹¹

Table 1- Some geotechnical properties of sodium / calcium bentonites

The adsorbed sodium encourages a large amount of water to be adsorbed in the interlayer, inducing remarkable swelling properties, which is less prevalent with calcium or magnesium adsorption. Repeated hydration and drying, or freeze and thaw have little to no effect on the original swelling capacity. The following factors contribute to the swelling character of sodium bentonite (Wijeyesekera, 2003):

- Presence of sodium.
- Physical orientation of water molecules.
- Position of oxygen in the tetrahedral sheets.
- Surplus electrons on the clay surface.

Dry platelets of sodium bentonite are most commonly grouped together in a face to face arrangement, with exchangeable cations and small amounts of adsorbed ions in an interlayer region between each platelet. The thickness of the interlayer region is variable depending on the amount of water adsorbed between the platelets. The typical hydraulic conductivity for hydrated, dense sodium bentonite is around 1×10^{-11} m/s.

Bentonites generally occur in its more stable form as the calcium bentonites. Calcium bentonites have, by nature, a more coarsely aggregated internal structure providing a higher hydraulic conductivity than sodium bentonite (Table 1). GCL manufacturers would for reasons of cost, opt to use the calcium bentonite and have it activated with soda (sodium carbonate). However, tests show that sodium carbonate treated calcium bentonites have distinctly lower water holding capacity and a higher hydraulic conductivity (Dobras et al, 1993). Furthermore, calcium ions in leachate will readily replace the sodium in these treated bentonites. Any chemical change that peptises, disperses or expands the double layer will eliminate most of the free pore space and reduce hydraulic conductivity.

3. Chemical optimisation

The hydraulic conductivity at the same void ratio will increase due to a contraction of the double layer (Rowe et al, 1995) when;

- The pore water concentration is increased
- The cations are changed from monovalent to divalent or trivalent
- The dielectric constant is reduced
- The temperature is increased that results in a reduction in the dielectric constant.

Untreated sodium bentonite can degrade when exposed to certain chemicals during or after hydration. The ways in which this can happen are;

- The exposed aluminium oxide structural unit in the bentonite's octahedral layer can dissolve in concentrated acidic or alkaline solutions and as a consequence compromise its hydraulic barrier performance.
- The interlayer sodium in the untreated bentonite is readily exchanged by multivalent cations that attract the clay platelets together and consequently impair its swelling character.
- Adsorption of organic liquids can hinder the formation of the oriented water layers in the double layer, and cause shrinkage cracks and macro pores to develop increasing the hydraulic conductivity.
- High concentrations of ions such as calcium, magnesium, potassium, chloride and sulphate that may be present in a local ground water supply can have a potential impact to reduce swelling. The local water molecules will prefer to reorientate in such a way that they are not properly positioned to form strong bonds with the clay surface.

Thus, the bentonite in the GCL needs to be compatible with the leachate to be retained, lest they may be prone to chemically induced c axis contraction, double layer shrinkage and cracking. The performance of bentonite in GCLs can be optimised with the addition of linear polymer chains of the sodium polyacrylate and acrylonitrile type. 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 manufacturers mix such a polymer to aid resistance to contaminants and optimise performance. However, 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 segregation during a mechanical shake down associated with handling. This invariably leaves the bentonite in some parts of the mixture unprotected. The initial hydration of the air dry GCL will be a critical process to the attaching of the water-soluble polymer on to the bentonite surface. The process of factory prehydration with a liquid polymer is a better optimising technique in order to ensure an intimate mix and that the polymer reaches all the particles uniformly. Investigation (Wijeyesekera, 2003) carried out to ascertain the product quality between air dry granulated GCL (A) and a prehydrated extruded GCL (D) is given in table 2. A noteworthy observation is that despite 41.2 % prehydration moisture content, liner D had 32% more dry bentonite mass per unit area. The infill in liner A had a moisture content of 17.1% and was coarse grained (see Figure 1) with angular agglomerations (clusters of disordered clay platelets). The clay infill in Liner D was laminated and showed the consistency of plastic, pliable matting of uniform thickness.

PROPERTY OBSERVED		GCL TYPE	
		A	D
Identifying characteristics of the GCL		Needle punched with grey granular bentonite	Laminated, prehydrated fine grey bentonite
Dimensions of roll L(m) x B(m)		4.9 x 1.1	5.0 x 1.0
Mass of roll (kg)		34.5	39.6
En masse Properties	Mass of GCL per unit area (g/m ²)	6107	7865
	Moisture content (%)	11.6	27.5
Infill bentonite clay properties	Mass of dry clay / unit area (g/m ²)	4067	5286
	Moisture content (%)	17.1	41.2
Thickness (mm)		5.1	5.1
Handling loss / m edge (g/m)	Horizontal laying	1.98	0
	On fixing vertically	54.1	0
	On cutting	19	0
Cation Exchange Capacity (meq/100g)		56	70
Free swell (ml/ 2g)		30	23

Table 2 – Product quality observations

The clay infill in Liner D was laminated, plastic and formed a pliable matting of uniform thickness. The laminated structure results from the vacuum extrusion process of the hydrated clay-polymer mix.

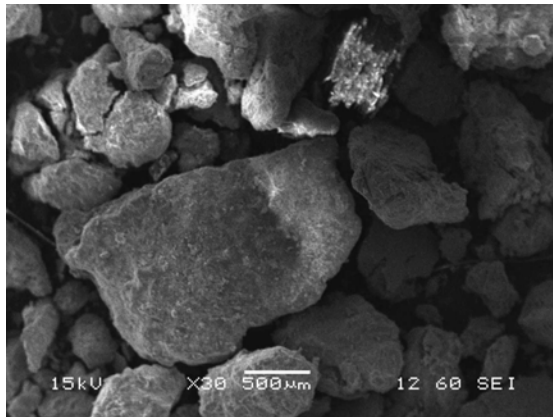


Figure 1 Electron micrograph of liner A infill

Of grave concern is the observation of the loss of dry bentonite that can occur with the handling of the granular GCLs (such as A) during installation (shake down on rolling out or attempting to hang the liners on a vertical surface). Estornell and Daniel (1992) reported the need for an additional geotextile filter to avoid bentonite loss with some GCLs in order to maintain a uniform distribution of the bentonite in the GCL. Prehydration and extrusion of the clay infill as in liner D prevents such losses. Figure 2 is a magnified view of a vertical section (edge on) of the central core of the bentonite in the prehydrated liner (D). Consistent evidence of the lamination and the dense structure are desirable properties that give the low hydraulic conductivity and minimises the potential for polygonal desiccation cracking. The lighter upturned features in the electron micrographs show the acrylation from uniform polymerization. Particular attention must also be given to the drying process that occurs when CCLs and GCLs are isolated from groundwater. When desiccation cracking occurs, it will result in

the liner having a much higher hydraulic conductivity than is desired. The first cracks resulting from dehydration in thin clay occur at water contents just above the plastic limit.

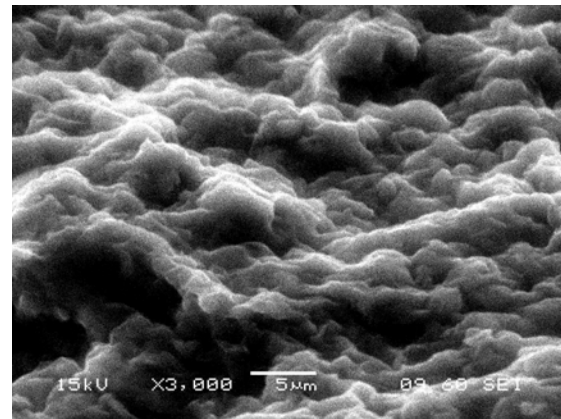


Figure 2 Electron micrograph of liner D infill

Cation exchange, being the ability of soils to retain cations is particularly significant to the behaviour of clay soils. CEC observations reported by the author (Wijeyesekera, 1993) show a decrease in CEC when the clay fill had been left in solutions of increasing cationic concentrations suggesting that a process of cation exchange takes place, reducing the CEC in the modified clay. The levels of Na^+ , K^+ , and NH_4^+ in MSW leachate are sufficiently high that they can effectively exchange some of the Ca^{++} and Mg^{++} present on natural clays through advection and diffusion.

4. Conclusions

The efficacy of contaminant barriers depend on the clay mineralogy, the manner of its placement and the construction placement history of the liner. The inappropriateness and geotechnical deficiencies in using granular / aggregated bentonite have been shown to produce non uniform swelling which promotes desiccation cracking.

GCLs hydraulic conductivity is sensitive to the type of permeant and the hydrating fluid and it is particularly significant 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, cannot facilitate hydrating “dry” GCLs to ensure continuity and uniform swell of the infill.

Bentonites treated with stabilizing agents and factory prehydrated seem to be a way forward to optimise clay infills with high CEC that lose only a 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. Air extraction during the extrusion helps to increase the density and saturation of the GCL.

The performance of bentonite in a 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 in its hydration stage. Through body polymerisation with a liquid polymer followed by vacuum air extraction and high-pressure die extrusion, can produce a clay with desirable clay barrier properties. The hydrated vacuum extruded clay has therefore fewer propensities to cation exchange with polyvalent metal ions as being protected by the liquid polymer as it retains its stable long chain structure.

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