GEOSYNTHETIC CLAY LINERS IN MINING APPLICATIONS

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ABSTRACT

Geosynthetic clay liners (GCLs) are gaining increased usage in mining applications, ranging from opencast reclamation to tailing lagoon lining to clean-up and restoration of old mine workings.

GCLs have traditionally been used as a replacement for compacted clay liners, mainly in landfill basal lining and capping, and in lagoon construction. In Europe, their use in mining applications is a more recent development, although one which is growing very rapidly.

Compared to landfill, mining projects tend to be few and far between, but they are often very large projects. In the past year GCLs have been used for tailing lagoon lining, for stream diversion, for attenuation and settlement lagoon construction in opencast mining, for capping of colliery spoil on old deep-mine sites, and in lining and capping of repositories for containment in-situ of contaminated material from previous workings, especially coking and gas works.

Recent projects include Minorco Lisheen in Ireland, and Aznalcóllar in Spain.

This paper discusses the origin and properties of sodium bentonite, and then goes on to develop its application in GCLs and lining systems.

INTRODUCTION

The CEN definition of a GCL is "A factory assembled structure of geosynthetic materials and low hydraulic conductivity clay materials (e.g. bentonite), in the form of a sheet, used in contact with soil and/or other materials in geotechnical and civil engineering applications".

The mining industry has been utilising geosynthetics for the past two decades, mainly for containment and reinforcement applications where regulatory or economic factors dictate. GCLs have generally been used as a replacement for compacted clay, or sometimes geomembranes.

Origin of bentonite

Sodium bentonite is a high swelling smectite clay mineral used mainly in the construction, environmental, foundry and oil well drilling industries. The name derives from Fort Benton, USA where the first commercial deposits were located. It is in this region, in the Black Hills area of South Dakota and the Big Horn Basin in Wyoming, that the most abundant reserves of high-grade natural sodium bentonite are found. These bentonites have a high montmorillonite content, typically 90%. They are mined using opencast techniques where the active pit overburden is used to fill up the previous opencast.

The bentonite here originated from volcanic activity about 100 million years ago in the Yellowstone Park, hundreds of miles to the East. At that time, much of the Western USA was covered by sea, upon which the ash landed and sank in a broad uniform layer. Later upheavals pushed these deposits to the surface and exposed them to weathering action. The ash particles were gradually modified from their original igneous structure to a soft, waxy claystone called bentonite. On excavation the bentonite is dried and milled to a granular or powder form.

Sodium bentonite is crystalline in nature and composed of flat, thin sheets or platelets, each having 3 layers, an alumina octahedron sandwiched between 2 silica tetrahedral. Through weathering some of the atoms in the platelets have been substituted by atoms of a lower valency, resulting in the sheets having large negative charges on their base planes, and smaller positive charges on their outer edges. The negative imbalance is partly compensated by exchangeable cations between adjacent platelets, these being sodium, calcium or magnesium depending on the predominant weathering agent associated with formation of the deposit.

One of the most important properties of bentonite is its swelling behaviour, and this characteristic is dependent on the type of cation present, i.e. sodium bentonite swells to about 15 times its dry bulk compared to 3 times for calcium bentonite.

Outside USA the vast majority of bentonite deposits are of the lower swelling calcium type, and in Europe it is common practice to treat calcium bentonite with soda ash to form a sodium activated calcium bentonite.

Properties

Due to its high montmorillonite content and interlayer sodium cations, Wyoming bentonite has a high swelling capacity and extremely low permeability and diffusion coefficients, making it an excellent barrier material.

The flake-shaped crystals have a large surface area, typically 800 m^2/g, and range in thickness from 0.2 to 2 microns. Hydraulically this is an important characteristic since the permeability of soils is inversely proportional to the square of the wetted surface area, and the very large surface area of bentonite combined with the low void ratio make it a very effective sealant.

When used in a GCL or as a grout, the minute bentonite platelets eliminate any path for fluid migration, resulting in extremely low permeabilities.

Another useful engineering property of sodium bentonite is its high plasticity index, approximately 500 compared to 20 for typical kaolinitic clay. A sodium bentonite seal thus remains flexible over a wide range of water contents and when subjected to localised deformation or settlement.

Sodium bentonite is also natural and non-toxic. Its use in such applications as pharmaceuticals and cosmetics illustrate its non-toxic nature, and tend to give it impeccable environmental credentials.

History of bentonite use

On a historical basis, bentonite use in environmental applications began about 40 years ago with soil/bentonite or cement/bentonite cut-off walls. This technique is still in use today, and is often used to seal retrospectively around landfill sites or contaminated land beneath which a low permeability layer exists, and into which the cut-off wall can be keyed.

The cut-off trench, typically 600 mm wide, is excavated using a bentonite slurry comprising about 5% bentonite in water. In slurry form, bentonite is thixotropic. In other words, when the shearing action used to make the slurry is stopped, the slurry viscosity increases and a gel is formed. Thixotropy is due to the strong electrical charges on the base planes and edges of the platelets. On standing an internal structure forms, which matches positive and negative charges, and the platelets assume a "house of cards" structure. This structure is disrupted by additional mixing or pumping but will reform when pumping stops.

The slurry serves two main purposes. Firstly it interacts with the sides of the trench to form a tough low-permeability filter cake that binds the soil particles and limits fluid loss, and secondly, having a higher density than groundwater, it creates a positive hydrostatic head that stabilises the sides of the trench and prevents collapse.

It is possible to excavate very deep trenches using this technique, which is similar in many ways to the use of bentonite slurries in oil well drilling.

As soil is removed from the trench it is replaced with slurry, and for cement/bentonite cut-off walls, cement and sometimes blast-furnace slag and PFA are added in variable quantities, so that the slurry hardens to a specified permeability and set strength.

Next, in 1962 came Volclay Panels where a layer of bentonite is sandwiched between two sheets of biodegradable cardboard. These are nailed directly onto structures, which require waterproofing. Seams are formed by a simple dry overlap, and backfill is then placed. The cardboard biodegrades, leaving a thin bentonite gel, which provides the waterproofing. This is an active system in that the bentonite can migrate into, and seal off any cracks that appear in the concrete. Over the past thirty years, tens of millions of square metres of Volclay panels have been supplied for tanking structures beneath the water table, and for waterproofing tunnels.

In 1975 bentonite enriched soil, or BES arrived. This technique is still popular today, especially for landfill basal lining. Bentonite is mixed with soils, normally in the range of 5 - 10% by weight, to form a low-permeability layer, typically 1×10^{-10} ms^{-1}. The ideal host soil is well-graded sand with low voids, thus requiring a low addition rate of bentonite. The bentonite swells within the interstices of the sand or soil, plugging the net voids and lowering the permeability.

The effectiveness of a bentonite enriched soil liner depends on two factors. Firstly, prior to construction, the proper bentonite application rate and optimum moisture content must be determined. This involves a laboratory evaluation in which soil samples with various bentonite admixtures are tested for permeability. Secondly, the bentonite must be thoroughly incorporated into the site soils and uniformly distributed. There are two main methods of mixing bentonite and soil, rotovation in-situ using soil stabilisation equipment or high speed agricultural rotovators, or in a batching plant.

A controlled amount of bentonite is rotovated into the soil, normally to a depth of 100-300 mm, and the soil moisture content is adjusted to about 3% wet of optimum for compaction purposes. The mixture is then compacted to 90 or 95 %

maximum dry density with a vibrating roller. A more recent refinement to this technique is to rotovate the bentonite /soil in a pad, and then scrape the mix into a stockpile where samples can be tested for permeability QA before laying and compacting.

As engineering standards and quality control required in liner construction have become more stringent, plant mixing of BES has come to the fore. Advantages of plant mixing are in extra control and consistency.

Evolution of GCLs

More recently, it was realised that a thin layer of sodium bentonite may be similarly utilised as a liner or liner component. The original predecessor to the geosynthetic clay liner or GCL was a field-constructed liner called the Bento-Mat system, patented in 1981 in Canada. Installation of this liner system involved placement of a geotextile over a prepared sub-base, manual spreading of loose granular bentonite on the geotextile, placing an additional geotextile over the bentonite, and covering with soil. This system was successfully installed on several lagoons in Canada. At about the same time James Clem invented a prefabricated bentonite mat, still in use today, and now called Claymax.

In the late 1980s, Naue Fasertechnik developed the first needlepunched GCL in Germany (Bentofix), quickly followed by CETCO in USA (Bentomat).

Bentomat is a flexible high strength GCL that can be used for a wide variety of environmental containment applications. It is fabricated by distributing Volclay sodium bentonite in a uniform thickness between two or more geotextiles to give strength and low permeability. Needlepunching equipment pushes fibres from the carrier non-woven geotextile through the bentonite into the cover geotextile. The fibres encapsulate the granular bentonite, inhibiting migration of the clay in either the dry or hydrated state, and provide an inherent confining stress equivalent to 10 KPa, and the shear characteristics necessary for stability on steep slopes.

GCLs are wound onto rolls to facilitate handling, storage and installation, and as with other geosynthetic materials, are manufactured in a factory-controlled environment and tested for quality prior to delivery to the job site.

Applications

GCLs are generally used as an alternative to compacted clay liners (CCLs) in landfill liners and caps, secondary containment systems, lakes and wastewater lagoons, and canals and river bed linings. They are much easier to install than traditional CCLs, and have several performance advantages.

In the next section, we will look at some of these performance and design issues, including equivalence to compacted clay.

DESIGN AND PERFORMANCE ISSUES

In order to substitute a GCL for a CCL in a liner system we need to demonstrate equivalency, and that the GCL will function as intended. The following is a discussion of the main performance, design and construction issues.

Hydraulic performance

Since the purpose of a GCL is to function as a barrier to liquids, it must be demonstrated that the hydraulic performance of the GCL meets the equivalency requirements under the anticipated service conditions. The first step in determining hydraulic performance is to identify the service conditions to which the GCL will be exposed. This requires an understanding of the type of liner system to be constructed, the confining stresses and hydraulic heads present, and consideration of climatic factors such as freeze/thaw and desiccation/dehydration cycles. The potential for differential subgrade settlement may also be a concern.

Permeability or hydraulic conductivity has historically been used to measure the hydraulic performance of GCLs. Permittivity, defined as permeability divided by thickness, has been utililized to a much lesser extent. Recently, the American Society for Testing and Materials (ASTM) introduced test method ASTM D 5887 for measuring flux or leakage, defined as volume of GCL flow per unit area per unit time. Flux is a more appropriate means of measuring hydraulic performance since its value can be assessed directly from laboratory data, and it is not dependent on problems associated with measuring the thickness of the GCL and its clay component.

An important advantage of the flux test is that it provides results that can be compared directly to the performance requirements for a specific project. In Europe, for example, in landfill basal liners a GCL is commonly used as a substitute for a compacted clay liner 1 metre thick with a permeability of 1×10^{-9} ms^{-1}. The maximum head allowed is 1 metre. Darcy's law can be used to calculate the steady-state flux through the CCL as follows:

$Q =$ $k\,i\,A$,

where

Q	flux through the CCL, litres/ hectare/ day
k	hydraulic conductivity, 1×10^{-9} m/s^{-1}
i	hydraulic gradient, dimensionless = (hydraulic head + liner thickness) / liner thickness = (1.0 + 1.0) / 1.0 = 2.0
A	liner area, assume 1 hectare (10,000 m^2)

$Q =$ (1×10^{-9} m/s) (2.0) (10,000 m^2/ha) (1,000 l/m^3) (86,400 s/day) = 1728 litres/ha-day

The flux value calculated from the above equation may then be compared directly to the results of the GCL flux test. GCL flux values under the same confining stress and hydraulic head conditions have been determined to be approximately 1×10^{-9} $m^3/m^2/s$ or 864 litres/ha-day. Thus, it can be concluded, with respect to steady-state flux under these conditions, that the GCL provides acceptable hydraulic performance when proposed to replace a CCL. This simple flux comparison usually serves as the cornerstone for any GCL design or CCl equivalency demonstration.

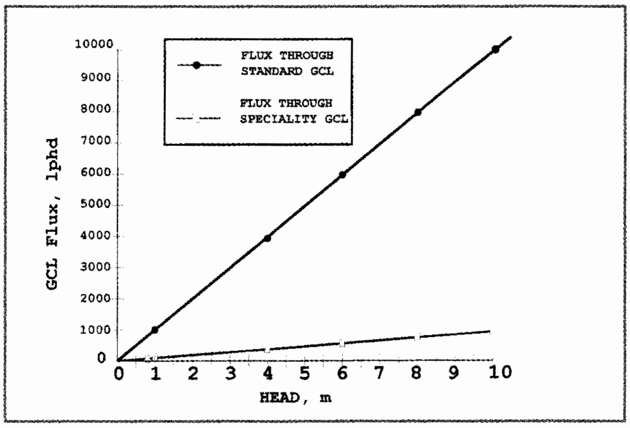

Figure 1. GCL flux as a function of head pressure. Flux testing was performed in a flexible wall permeameter under a constant confining stress of 35 Kpa (CETCO, 1996).

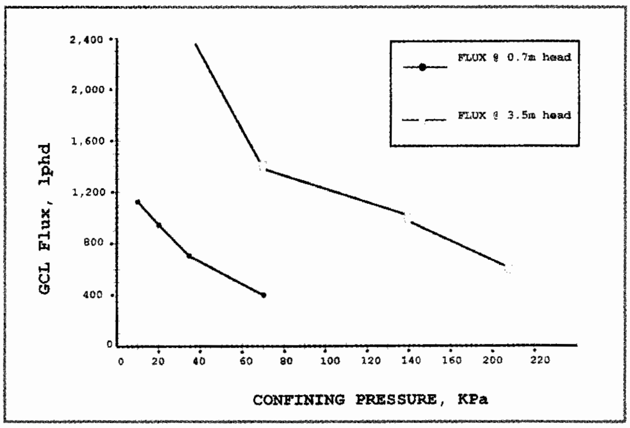

Figure 2. GCL flux as a function of confining pressure. Flux testing was performed in a flexible wall permeameter under head pressure of 0.7 m and 3.5 m (CETCO, 1996).

GCL flux curves can be derived from laboratory test data to model steady-state leakage under different confining stress and hydraulic head conditions. Figure 1 shows flux curves for GCLs subjected to a constant confining stress of 35 Kpa and hydraulic head pressures ranging from 3.5 to 97 Kpa, which corresponds to a range of hydraulic heads of 0.3 to 10 m. This curve would be useful for estimating the flux for a pond lining project in which the GCL is the only impermeable layer in the liner system. For example, if the average depth of a 3,000 m^2 pond is 3 m, Figure 1 predicts that the leakage rate from a standard GCL will be approximately 3,000 lphd or 900 litres/day. Therefore, in order for a constant water level to be maintained, there must be an average of 900 litres of water added on a daily basis. This analysis does not include loss of water through evaporation, which can range from 5-10 mm/day or more in certain climates. Evaporation nomographs can be used to estimate daily evaporative losses given data on temperature, wind speed, and relative humidity. Of these variables, wind speed has the greatest influence on evaporation.

Based on the data presented in Figure 1, it can be seen that GCL performance is maximised when the hydraulic head is relatively low. Although low-head conditions prevail in many GCL applications, high-head conditions may be encountered in ponds. In these conditions, an ordinary GCL may yield unacceptable leakage rates because the hydraulic gradient is so large. To address this problem, one manufacturer produces a speciality GCL whose flux is a magnitude lower than standard products currently available. This is accomplished through the use of a thin membrane laminated to one of the carrier geotextiles. The membrane helps to control the flux under high-head conditions and provides better performance for high-head applications. In a low-head design, however, the incremental performance improvement provided by this speciality GCL is less significant.

Figure 2 is a flux curve similar to Figure 1 except that hydraulic heads are held constant at 0.7 and 3.5 m, and the confining pressures range from 10 to 200 Kpa. The data shows that flux decreases with increasing confining stress and allows the designer to predict the actual flux expected from the liner system at a specific hydraulic head and confining pressure.

Slope stability

GCLs are installed against soil layers and/or other geosynthetic products. For slopes greater than 4H:1V, use of a GCL requires a slope stability analysis. A GCL adds three interfaces to the stability analysis, and it is important that the interfacial friction characteristics between the GCL and the overlying and underlying layers are investigated, together with the internal friction angle of the GCL. Bentonite is an inherently weak material, and lubricates any interface with which it comes into contact.

The internal shear strength of fully hydrated, unreinforced GCLs translates into friction angles of 6 to 10 degrees, depending on the applied normal stress. Consequently, a fundamental GCL design guideline is to use an unreinforced GCL on slopes no steeper than 10H:1V or 6 degrees. Adherence to this guideline has resulted in the successful application of millions of square metres of unreinforced GCL.

When reinforced GCLs were introduced in the late 1980's, internal shear strength properties were increased significantly, allowing steep-slope applications. In needlepunched GCLs the fibres create a bond through the bentonite and provide high resistance to delamination. Laboratory research has shown confinement due to needlepunching to be in excess of 10 KPa in some needlepunched GCLs, with internal friction angles of over 50 degrees. This combined with field-scale testing and actual project experience has led to their use on a wide variety of steep-slope applications.

Chemical compatibility

Sodium bentonite, which is hydrated and permeated with relatively clean water, will be an effective barrier indefinitely. However, the interlayer sodium ions can be exchanged with other cations that may be present in the water during hydration or permeation. This can lead to decreased swell and an increase in permeability. This is the primary mechanism for chemical contamination of bentonite. Other chemicals such as organic molecules are far less likely to affect bentonite, and only do so in strong concentrations. Solid waste leachates generally do not cause compatibility problems, regardless of whether the GCL is prehydrated with clean water or with leachate. Experience with destructive chemicals has consistently shown that where we have good confinement, in excess of 35 Kpa, the hydraulic conductivity will still meet the design requirements, even after exchange reactions.

If there were doubt about chemical compatibility, we would recommend a three-tiered approach to testing on a site-specific basis. The first tier is a simple review of existing analytical data. If the data indicates the presence of potentially deleterious chemicals, then it is necessary to proceed to the second tier, where bentonite free swell and fluid loss tests are performed. If these test results are inconclusive or inconsistent, an extended permeability test is performed as the third tier of the compatibility analysis. A 30-day permeability test would be sufficient for evaluating a thin barrier such as a GCL.

If testing indicates a higher hydraulic conductivity than the design requires, then a GCL with contaminant resistant clay, or alternatively a composite laminate GCL should be considered.

Desiccation/rehydration cycles

Providing we have a minimum 300 mm of cover soils above the GCL, it is highly unlikely that the GCL will desiccate, especially in northern climates. If there is concern about desiccation, the depth of cover soils can be increased. In the event that desiccation does occur, research performed by various bodies has shown that the hydraulic performance of GCLs is unaffected.

Freeze/thaw cycles

Any shrinkage cracks that may occur during freezing are immediately closed off when the bentonite thaws and rehydration occurs. The high swelling pressures generated as sodium bentonite hydrates give the material a very useful self-healing characteristic.

Response to differential settlement

The high plasticity and swelling characteristics of sodium bentonite, combined with the reinforcement of the geotextiles enable GCLs to withstand strains of 10 to 15%, compared with less than 1% for CCLs.

Subgrade preparation

The surface upon which the GCL is placed should be firm and free of any large stones, sticks or other protrusions greater than about 15 mm in size. Additionally the subgrade should contain minimal voids.

Confinement

The minimum amount of confinement required depends on the application and type of GCL used. As a general rule, there needs to be 5-10 KPa to ensure adequate hydraulic performance at the overlapped seams. This corresponds to roughly 300-600 mm soil cover.

CASE STUDIES

Next, we will look at some recently completed projects involving GCLs. These include tailing lagoon liners, attenuation and settlement pond linings, stream diversions, colliery spoil caps and lining and capping of repositories for containment of contaminated material from earlier workings.

SUMMARY

Several million m^2 of GCL have been installed in mining applications, due to their ease of installation, cost effectiveness, overall performance and resistance to many physical and climatic issues that affect compacted clay liners.