

## THE STRUCTURE, PROPERTIES AND ANALYSIS OF BENTONITE IN GCLs

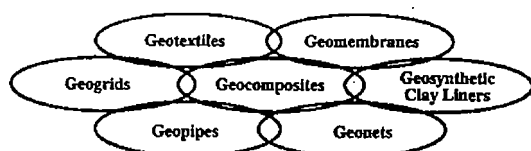
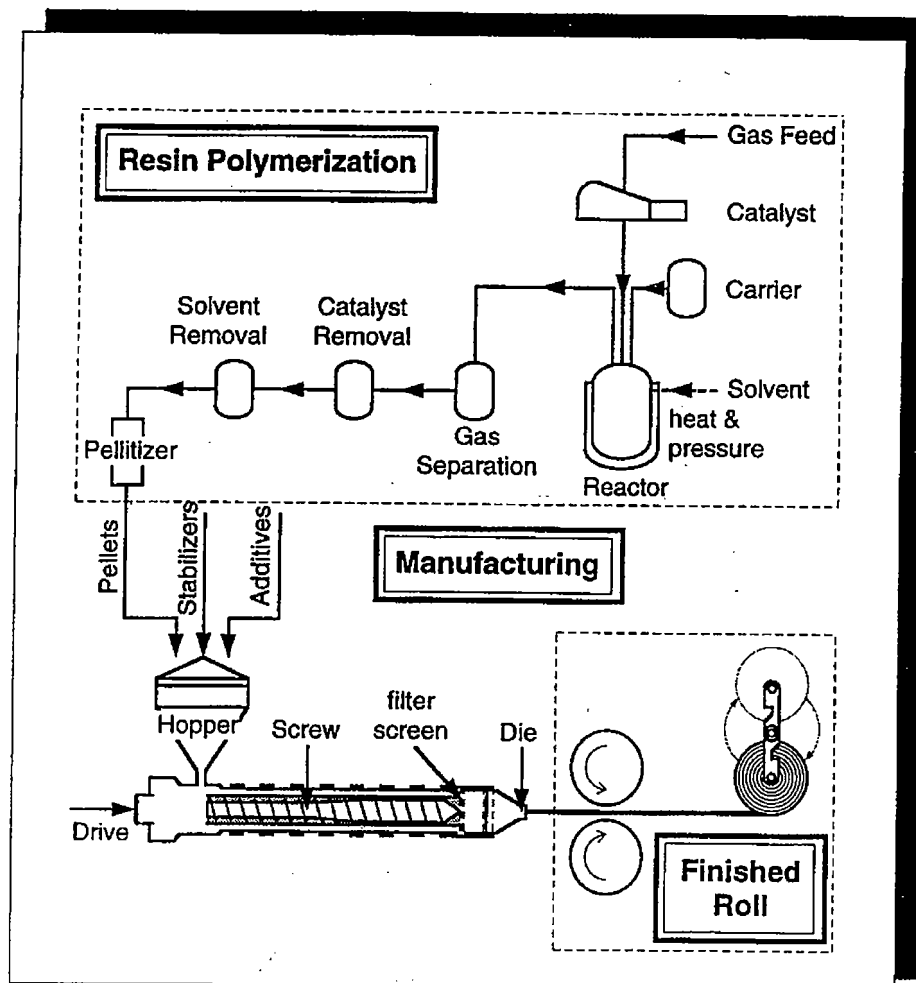
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This paper begins with an examination of the complex molecular structure of bentonite as a means to explain its unique chemical and physical properties. A discussion of bentonite mining and manufacturing processes is also provided. Then, the laboratory techniques for evaluating bentonite quality are described. Lastly, a series of index criteria and test methods are reviewed for specifying or inspecting the quality of the bentonite in a GCL.

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# **THE STRUCTURE, PROPERTIES, AND ANALYSIS OF BENTONITE IN GEOSYNTHETIC CLAY LINERS**

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## **ABSTRACT**

Bentonite is the most important yet least understood component of geosynthetic clay liners (GCLs). Anyone using GCLs must be aware of the physical and chemical properties of bentonite, because these properties exert significant influence on the performance of the GCL. Moreover, the user must have an awareness of the many analytical techniques for characterizing bentonite and must be able to provide a proper interpretation of bentonite test results.

This paper begins with an examination of the complex molecular structure of bentonite as a means to explain its unique chemical and physical properties. A discussion of bentonite mining and manufacturing processes is also provided. Then, the laboratory techniques for evaluating bentonite quality are described. Lastly, a series of index criteria and test methods are reviewed for specifying or inspecting the quality of the bentonite in a GCL.

## **INTRODUCTION**

Clay minerals have played a crucial role throughout the cultural and industrial development of mankind. For thousands of years, clays have been used for making pottery, brick, and other building materials. Man's use of expanding clays such as bentonite began later. Around 5000 B.C., prehistoric man used expanding clays for the cleaning (fulling) of animal skins and hides (Robertson, 1986). "Fullers earth," which is actually a low-grade sodium bentonite, later became an important commercial material for the cleaning and preparation of wool and woolen cloth (Odom, 1989). Sodium bentonite was also used by early Native Americans as a soap for cleaning cloth and blankets. Today, there are hundreds of uses for clay minerals, and bentonite clays in particular are used in a tremendous variety of products ranging from pet litters to pharmaceuticals to GCLs.

## **THE STRUCTURE OF SODIUM BENTONITE**

It is essential to understand the structure of sodium bentonite in order to understand how its unique physical and chemical properties influence the behavior of GCLs. This discussion

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also provides a basis for a more complete understanding of the various bentonite characterization tests described later.

The terms sodium bentonite and sodium montmorillonite are often confused. Sodium bentonite is the name for the *ore* removed from the ground during the mining process. Sodium montmorillonite is a mineral species of the smectite clay mineral group and is the primary constituent of the bentonite ore. In other words, while bentonite contains small amounts of nonfunctional ingredients such as feldspar, plagioclase, biotite, and quartz, its predominant component is montmorillonite (Elzea and Murray, 1990). In industry, montmorillonites are classified as sodium or calcium types, depending on which exchangeable cation is dominant. This is not a definitive method to classify montmorillonites, because the naturally occurring ratio of sodium to calcium and magnesium may form a continuous spectrum (Odom, 1987). The montmorillonites used in the GCLs produced in North America, however, are of the sodium type.

Montmorillonites are three-layer minerals consisting of two tetrahedral layers sandwiched around a central octahedral layer (Figure 1). Oxide *anions* at the apices of the tetrahedral subunits are directed inward where they surround interior aluminum, iron and magnesium *cations*, thereby forming the subunits of the octahedral layer. Bonding between the shared interior oxide anions and the cations in the tetrahedral and the octahedral layers, links the layers together and yields the unique sheet structure characteristic of clay minerals.

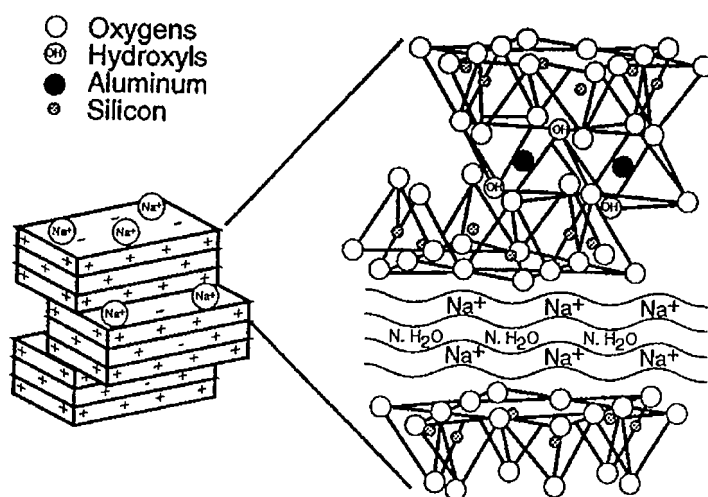


FIGURE 1. Schematic molecular structure of sodium montmorillonite, showing the absorbed water layers due to the presence of sodium in the interlayer region (various references).

The total negative charge contributed to the structure by the sum of all the oxide anions ( $O^{2-}$ ) somewhat in excess of the total positive charge contributed by the sum of all the structural cations ( $Si^{+4}$ ,  $Al^{+3}$ ,  $Fe^{+2}$ ,  $Fe^{+3}$ ,  $Mg^{+2}$ ), resulting in a slight overall negative charge to the surfaces of the clay sheets. This excess negative charge is counterbalanced by free-moving (exchangeable) cations which exist between them. The three layers in each sheet comprise

individual bentonite platelets which are typically 1 nm in thickness and 0.2-2 microns in length. Dry platelets of sodium montmorillonite are most commonly grouped together in a face-to-face arrangement, with exchangeable cations and small amounts of adsorbed water in an interlayer region between each platelet (Figure 2). The thickness of the interlayer region varies with the amount of water adsorbed between the platelets (Odom, 1986).



FIGURE 2. Scanning electron photomicrograph of montmorillonite, showing its platelet structure. Magnified 5,000 times.

The presence of sodium in the interlayer allows large amounts of water to be absorbed, resulting in the remarkable swelling properties of sodium bentonite. As will be discussed, the presence of sodium facilitates the almost unlimited adsorption of oriented layers of water molecules, a phenomenon which does not occur when calcium or magnesium are the dominant interlayer cations. Calcium and magnesium bentonites are consequently low-swelling in comparison to the sodium variety.

## THE PROPERTIES OF SODIUM BENTONITE

Physical Properties. Sodium bentonite is most widely known for its ability to swell. It can absorb nearly 5 times its weight in water and may occupy a volume 12 to 15 times its dry bulk at full saturation. The high water absorption capacity of bentonite also makes it very plastic and resistant to fracturing or cracking.

Interestingly, sodium bentonite can be hydrated and dried repeatedly without losing its original water absorption capacity (Grim, 1962). It can similarly be frozen and thawed repeatedly without losing this ability (Hewitt, 1994; Othman, et. al., 1994). Because the platelets are uniformly broad and flat, sodium bentonite has an exceptionally high surface area of 600 to

800 square meters per gram. Less than 10 grams of bentonite, if fully dispersed, could cover a football field. It is a combination of these physical properties that make sodium bentonite an excellent liner material. A layer of hydrated bentonite provides a dense, low porosity barrier to fluid flow that exhibits a typical hydraulic conductivity of  $1 \times 10^{-11}$  m/sec.

Electrochemical Properties. The structure of sodium bentonite gives it some important electrochemical properties. As previously discussed, bentonite platelets naturally possess an overall negative charge as a consequence of having more charge being contributed by the negatively charged oxide anions than is contributed by the positively charged cations. This unbalanced negative charge resides mainly in the oxide atoms found in the flat surfaces of the bentonite platelets. Nevertheless, at the edges of the platelets, where positively charged aluminum cations in the octahedral layer may be exposed without a full compliment of oxide anions, some localized positive charge (edge charge) occurs.

Hydration Properties. Despite an enormous amount of research in this area, the hydration process of sodium bentonite has not yet been definitively explained. Still, enough is known about this process to provide a general description of the principal mechanisms involved in water adsorption. A combination of four factors contribute to the swelling of sodium bentonite:

1. *The physical orientation of water molecules.* The water molecule is in a V-shaped arrangement of atomic nuclei, with the two hydrogen atoms forming an angle of 105 degrees with the oxygen atom. Because the oxygen atom has a denser electron cloud than the hydrogen atoms, the oxygen end is thus relatively negative and the hydrogen end is relatively positive. Thus, the water molecule constitutes a dipole, and this dipole is crucial in determining many of the remarkable properties of water.

Thus, when two water molecules approach each other, there is an electrostatic attraction between the negatively charged oxygen atom at the base of the 'V' in one water molecule and a positively charged hydrogen atom at one corner of the other. Although the force of this attraction, called *hydrogen bonding*, is only about 5-10% as strong as the normal covalent bonding between atoms in a molecule, it is considerably stronger than the weaker Van der Waal's force which holds uncharged molecules together in the liquid and solid states. The most important consequence of the hydrogen bonding is that it can impose an ordering effect (structure) on the molecules. This physical orientation of the water molecules facilitates their ordered adsorption onto the surface of the bentonite platelet.

2. *The position of oxygen in the tetrahedral sheets.* Viewed from the clay platelet surface, oxygen atoms within the tetrahedral sheets are arranged in a hexagonal pattern (Figure 3). Like matching pieces in a jigsaw puzzle, this pattern physically coincides with the pattern of the available hydrogen atoms in water molecules, and hydrogen bonding between the clay's oxygen and the water's hydrogen atoms is possible.

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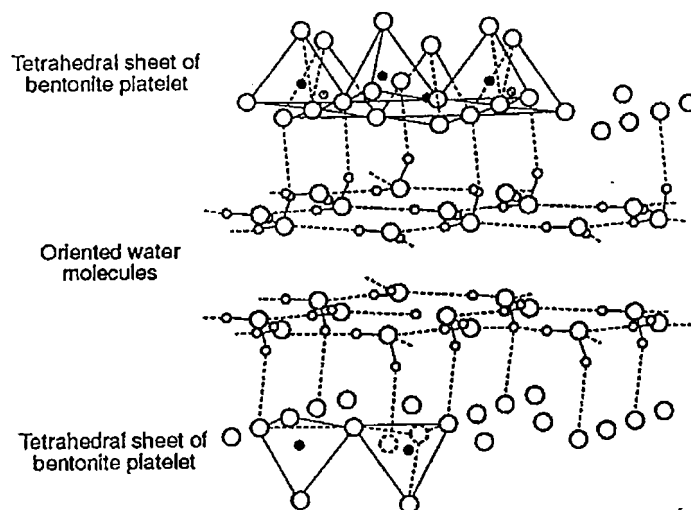


FIGURE 3. Configuration of the interlayer water system showing hydrogen bonding to the adjacent clay surfaces (Grim, 1968).

3. *Excess electrons on clay surface.* The isomorphic substitution of cations within the octahedral lattice results in the presence of excess electrons on the clay surface. These electrons enable the formation of hydrogen bonds of partially covalent character between the water molecules and the clay surface. The excess electrons therefore not only strengthen the clay-water bond but also facilitate the bonding of additional layers of water.

It is believed that these strong clay-water bonds alter the electron distribution of the first layer of water molecules and facilitate the formation of another water layer. Those bonds in the next layer allow the formation of a subsequent layer, to the extent that 3 or 4 similarly oriented water layers are formed. However, the kinetic nature of water causes the strength of the orienting forces to decrease with distance, and if enough free water is present, the additional layers of water molecules become increasingly less rigid as the distance from the clay surface increases (Grim, 1968).

4. *The presence of sodium.* When enough clean water is available, sodium ions in the interlayer are the "engines" that drive the above reactions beyond the first 3-4 monolayers of water. The negative charge and hexagonal arrangement of oxygen atoms on the clay surface facilitate the formation of the first few oriented water layers. Thereafter, it is generally accepted that the presence of sodium ions produces osmotic pressure which draws water molecules into the interlayer, in an attempt to equalize the high concentration of ions between platelets with the low concentration of ions outside the platelets (Grim, 1968; van Olphen, 1977; Newman, 1987). Upon being drawn into the interlayer, these water molecules are subsequently organized and layered as already described. A high quality sodium bentonite will absorb 25-50 water layers (Grim, 1968).

## BENTONITE MINING AND MANUFACTURING

Mining. Sodium bentonite is a relatively rare mineral that is formed primarily through the aqueous deposition and weathering of volcanic ash. Most of the worldwide sodium bentonite supply lies within the United States, in Wyoming and Montana. Ash from ancient volcanic eruptions west of these rugged areas was deposited in layers into a great salt water sea that once covered this basin. Millions of years of weathering eventually transformed the crystalline structure of the sedimented ash into bentonite, and a series of geologic upheavals gradually pushed the bentonite towards the ground surface.

Before mining begins on a given claim, numerous exploratory borings are drilled to accurately identify the areal extent of the deposit and its overall variations in quality. This information is also used to develop a formal mining plan for the claim. Because bentonite is a naturally occurring material, its characteristics will vary geographically, and it is important to segregate the different types that lie within a claim. Analyses of bentonite samples obtained from the exploratory borings helps the bentonite supplier match the type of clay to its eventual end use. For example, a marginal (high calcium content) sodium bentonite would perform poorly in a GCL but would be an excellent material for pelletizing iron ore (taconite). These two bentonites would then be separately extracted as mining is initiated.

The exploration phase of the mining process also facilitates the development of a comprehensive reclamation plan. Prior to permitting, a thorough study of the local topography, watershed, soils, vegetation, and wildlife is performed. This information is used to direct later reclamation activities which attempt to restore the mined site to its original condition.

Bentonite is mined through a stripping process involving the concept of "continuous reclamation." A typical mining sequence involves the excavation of eight to ten individual pits in a progressive fashion. Each pit is approximately one to two acres in area and 5 to 10 m deep. The bentonite itself appears in beds that are 1 to 2 m feet thick. To extract the bentonite, it is first necessary to remove the topsoil and overburden. This is accomplished using standard earth moving equipment. The bentonite, typically gray in color, is easily distinguishable from the overburden and the subsoils. It is removed and placed into haul trucks which carry the "crude" clay to the processing plant.

As bentonite is removed from one pit, an adjacent pit is excavated. The overburden and topsoil from the adjacent pit are used as backfill for the first pit, so as to minimize the footprint of disturbed land and to allow reclamation activities to begin immediately after the bentonite is removed. The reclaimed pit is graded and seeded, and the mining and reclamation process continues in this fashion until the claim has been fully utilized.

Manufacturing. The bentonite manufacturing process is relatively straightforward. Bentonite removed from the ground is too wet (about 25 percent moisture) to be processed. Therefore, the crude clay is stockpiled at the plant to allow it to air-dry, and the stockpile is continuously turned over by bulldozers to help accelerate the drying process and to break up the clay into smaller particles. The exceptionally dry climate in northeastern Wyoming Basin makes this air-drying

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process feasible. Air-dried clay is then fed into the processing plant, where it is actively dried to a moisture content of 6-10 percent to make it more amenable to additional physical processing such as milling (for powdered bentonite), screening (for granular bentonite), or chemical treatment (for enhanced swelling or contaminant resistance).

The final manufacturing process is the packaging of the bentonite. GCL manufacturers will receive the bentonite either in bulk rail cars or in large sacks weighing 1,500 to 2,000 kg (3,300-4,400 lbs) each. The bentonite supplier provides manufacturing quality control (MQC) documentation for each shipment of bentonite delivered to the GCL manufacturer.

It should be recognized that bentonites can also be treated with polymers and other chemicals to improve their hydraulic properties. These ingredients are added in small quantities and will actually react with the bentonite as its hydrates to increase swell, maximize particle dispersion, increase contaminant resistance, or enhance water retention. One bentonite supplier has claimed to invent a physical and chemical processing system which significantly increases a bentonite's contaminant resistance, especially in high-calcium environments (CETCO, 1994).

## **BENTONITE CHARACTERIZATION**

There are many methods to evaluate the general quality of bentonite. Unfortunately, almost all of these methods were developed to assess a bentonite's performance in applications that are vastly different than GCLs. Before it is decided to utilize these tests for bentonite characterization in GCL projects, it is crucial to understand that they may possess severely limited relevance, applicability, and practicality. New standards are being developed in ASTM to specifically address bentonite quality in GCLs. Until the new standards become finalized, the specifier must recognize the many limitations of bentonite tests that have been borrowed from other industries and other bentonite applications.

Montmorillonite Content. Montmorillonite is the primary clay mineral, the "active ingredient," in sodium bentonite. In an apparent effort to specify bentonite "purity," engineers have required that the bentonite must contain a certain minimum fraction of montmorillonite (usually 80 or 90 percent). Although this is a logical endeavor, the montmorillonite percentage in a bentonite sample cannot be accurately determined. Many test methods have been proposed to evaluate montmorillonite content, but they are non-standardized and only semi-quantitative. Montmorillonite content testing not only creates difficulties in conclusively evaluating conformance but also provides no indication of GCL performance. Because montmorillonite content testing requirements persistently appear in GCL specifications and CQA plans, this subject merits further discussion to demonstrate why an accurate determination is not possible.

X-Ray Diffraction. X-ray diffraction (XRD) is a frequently specified method for determining montmorillonite content. When an X-ray beam impinges on the surfaces of a mineral lattice, the beam is scattered in a manner determined by the unique structure of the mineral. The constructive interference resulting from this scattered beam is known as diffraction. The diffracted beams are detected according to their diffraction angle and intensity. Characteristic patterns are charted as X-ray beams are diffracted from the basal surfaces of the

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mineral. From these patterns, the structure, and hence the species, of the clay mineral can be identified (Figure 4).

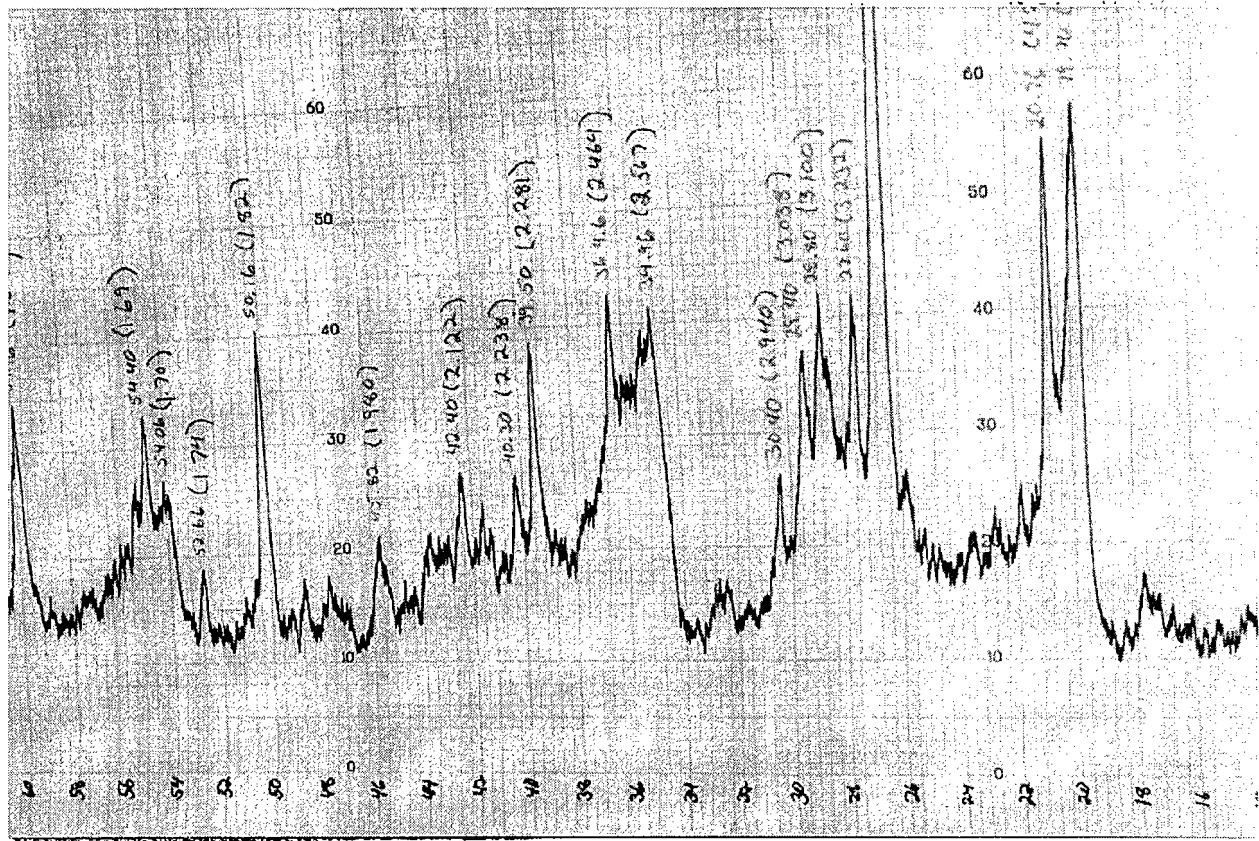


FIGURE 4. Example of an X-ray diffraction pattern characteristic of montmorillonite.

The concentration of a certain mineral in a clay sample can be *approximated* by comparing the intensities of the diffraction peaks to those observed for a “pure” standard specimen. Due to a variety of problems relating to interference, sample preparation, safety, and the uncertainty of various mathematical parameters, the accuracy of this evaluation is low (U.S. EPA, 1993; Moore and Reynolds, 1989). X-ray diffraction will indicate the presence of montmorillonite but cannot quantify its presence in a bentonite specimen more accurately than  $\pm 10$  percent. Furthermore, the cost of XRD equipment is high and its availability in geotechnical and environmental laboratories is limited. These factors place significant feasibility restrictions on the use of XRD for bentonite identification and analysis.

At least three other methods exist for estimating montmorillonite content. A *wet sieve analysis* or an *apparent colloid content* test may be used in an attempt to separate the colloidal montmorillonite from the other bentonite components. In a wet sieve test, a bentonite sample is ground into fine particles, dispersed, slurried, and passed through a 200 mesh (0.075 mm) or 325 mesh (0.045 mm) sieve, such that larger, non-montmorillonite components will be retained. The apparent colloid content test measures the weight fraction of a specific slurry that remains in suspension after 24 hours. The *methylene blue* test measures the cation exchange capacity (C.E.C.) of a bentonite. Positively charged methylene blue molecules attach to the negatively charged interlayer spaces within montmorillonite. The quantity of methylene blue absorbed by a bentonite sample is therefore a general indication of the montmorillonite content. The

methylene blue absorption (usually expressed in milliequivalents per 100 g) for a sample is compared to a standard of known quality in order to estimate its montmorillonite content. The obvious problem with this procedure is that it is not possible to quantify the montmorillonite content in the standard, thus making it impossible to do the same with the sample. Furthermore, even the C.E.C. of pure montmorillonite varies significantly in nature, rendering it impossible to establish a practical standard methylene blue value.

These tests are problematic also because of inaccuracies caused by incomplete sample dispersion and interference by the other components of the bentonite. Moreover, these methods can only confirm the presence of montmorillonite but cannot distinguish between the sodium and calcium species. Lastly, none of the tests provide an indication of the bentonite's ability to function as a barrier material. For all of these reasons, montmorillonite content tests should not be considered appropriate for use in GCL specifications or MQA/CQA plans.

Particle Size. GCLs contain bentonites that lie within a certain particle size gradation. The exact gradation itself is unimportant in terms of hydraulic performance, although a granular bentonite is preferred over powder for reasons of fugitive dust emissions and the potential for contaminating geomembrane seams and underlying drainage layers. Bentonite suppliers therefore provide GCL manufacturers with QC data on particle size.

Free Swell. In the free swell test, a certain quantity of bentonite (usually 2 g) is added in measured increments to a graduate cylinder filled to the 100 ml mark with water. Depending on the method used, the bentonite addition may be performed over several hours to allow the clay to fully hydrate. At a specific time after all of the bentonite has been added (usually 24 hours), the free swell value is recorded as the reading in cubic centimeters (cc) at the interface between the swelled clay and the clear water.

Almost every GCL specification contains a bentonite free swell requirement determined by the method known as "USP NF XVII." These letters stand for The United States Pharmacopeia and National Formulary, 17th Edition. The USP and NF is a compendia of analytical standards for drug formulation and dosage that is assembled and maintained by the U.S. Pharmacopeial Convention, Inc. (USPC). Is this test, borrowed from an entirely different industry, applicable to GCLs? Most experts agree that the free swell test can, to a certain extent, indicate the bentonite's ability to form a low-permeability barrier. However, a bentonite with a free swell of 36 cc/2g will not necessarily exhibit a lower permeability than a bentonite with a free swell of 26 cc/2g (Figure 5). In fact, just the opposite may be true, especially when the bentonite is exposed to contaminated solutions or tested under low confining stress.

The value of the free swell test is its ability to qualitatively distinguish between low-quality and high-quality sodium bentonites. A sample with a free swell of 18 cc/2g generally will yield permeability values acceptable for GCLs (approximately  $1 \times 10^{-9}$  cm/sec). A free swell value lower than 18, however, may result in a higher permeability than is typically acceptable. Most GCLs contain bentonite whose free swell is at least 24 cc/2g. Therefore, the free swell test is an adequate indicator of sodium bentonite quality but may not always be an adequate indicator of GCL performance.

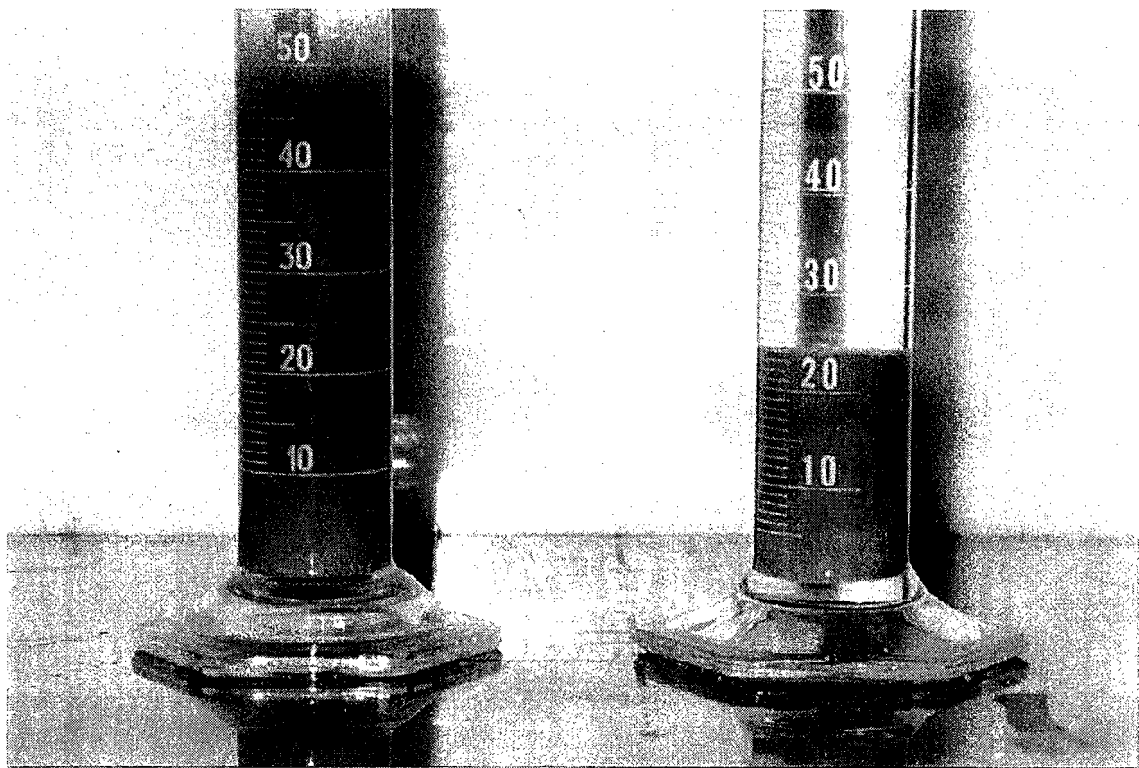


FIGURE 5. The swell value of the bentonite on the left is 45 ml/2g, while that on the right is 25 ml/2g. Both bentonites, however, are likely to exhibit similar permeabilities.

GRI GCL-1 (Swell Test). To more directly assess GCL field conformance, GRI developed a different type of swell. The test described in GRI GCL-1 involves the removal of 100 grams of bentonite from a GCL sample and placement of the bentonite within a rigid cylinder equipped with a cover plate and dial gauge for measuring swell. The entire apparatus is placed in a pan of water, and the bentonite swell is recorded from the dial indicator after 24 hours. This test has seen little use because it is much more difficult to execute and reproduce than the free swell test and because its results are very product-specific.

Moisture Content. Most GCL manufacturers provide data for bentonite moisture content, although care should be taken to recognize that the moisture content of the bentonite supplied by the bentonite manufacturer may differ from the moisture content of the finished GCL. Regardless of these differences, bentonite moisture content is important to qualify the bentonite mass per unit area in the finished product. Each GCL manufacturer may have their own internal requirements for moisture content as it pertains to handling and production issues. For the end user, however, moisture content itself is not a relevant parameter and is not an indicator of bentonite performance.

pH. Bentonite can be tested for pH. The pH of a standard suspension of sodium bentonite usually ranges from 8.5 to 10.5, whereas the pH of a calcium bentonite suspension will usually be lower than 8.5. However, the relationship between the pH of a bentonite suspension and the performance of a bentonite-based GCL is not completely understood, except that it is a general indicator of the type of exchangeable cation present in the bentonite.

Plate Water Absorption. As with most of the tests previously described, the plate water absorption (PWA) test standardized as ASTM E-946 was originally developed for an application other than GCLs. Taconite is a hard, iron-bearing mineral that can be processed to yield iron ore. Bentonite is used in the taconite industry for pelletization of the iron ore and provides the added benefit of removing excess water from the ore to increase the strength of the pellets. The PWA test crudely simulates this water-removal ability by allowing a measured bentonite sample to absorb water from a large porous plate or stone. Two grams of bentonite are evenly placed on a filter paper, which is placed on the porous plate. The plate sits within a shallow pan, and water is added to the pan to a level near the top of the plate. The increase in bentonite weight due to water uptake is measured after 18 hours.

Like the free swell test, the PWA test can make a general distinction between low- and high-quality sodium bentonites but cannot be relied upon as an accurate indicator of the hydraulic performance of the bentonite. The PWA indirectly assesses bentonite quality, as only a high-quality sodium bentonite can absorb large amounts of water (weight increases range from 700-1000 percent). Unfortunately, PWA test results may be affected by variables such as the thickness of the bentonite layer, the presence of additives, water level, ambient humidity, bentonite grain size, and initial moisture content. These variables have been found to cause reproducibility problems, and because relatively few independent laboratories perform it, the PWA test is not particularly well-suited for routinely assessing GCL quality. The free swell test is a much simpler means to assess the water absorption properties of the bentonite.

Enslin-Neff Test. This bentonite quality assurance test is similar in concept to the PWA test, except that water is absorbed through an apparatus consisting of a glass filter and capillary tube instead of an immersed porous plate. The Enslin-Neff test is standardized in Europe (DIN E18132) but is not used in the U.S. bentonite and GCL industries. This test is believed to be fairly reproducible but is still susceptible to many of those problems already attributed to the PWA test.

Fluid Loss. API's fluid loss (also called filtrate loss) test evaluates the ability of a clay slurry to form a low-permeability filter cake similar to that which coats the sidewalls of an exploratory borehole. To evaluate filter cake formation, the API procedure requires that a 6% slurry aged for 16 hours be poured into a special container (Figure 6) which is then pressurized to 690 kPa (100 psi). As filtrate drains from the container, a cake forms, and the flow of filtrate diminishes. The volume of filtrate collected from the container is measured over a specific time interval. The higher the fluid loss value, the less effective (and more permeable) the filter cake. Therefore, low-fluid loss clays are typically preferred for drilling applications.

Can this test be used for evaluating bentonite in GCL applications? There are obvious physical differences between a thin, pressure-induced filter cake and a thick bentonite layer found in GCLs. However, the fluid loss test is the only existing bentonite quality test that relatively rapidly evaluates the ability of a bentonite sample to function as a hydraulic barrier. Furthermore, most comparative data indicates a consistent relationship between low permeability and low fluid loss, to the extent that fluid loss is a justifiable bentonite testing

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parameter. The API requires a drilling fluid to exhibit a maximum fluid loss of 15 ml, and this value appears to be acceptable for the GCL industry as well.

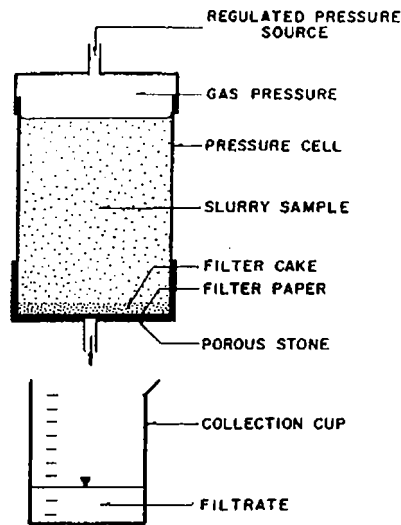


FIGURE 6. Schematic of the API filtrate loss test apparatus (Alther, et. al, 1985).

**Permeability Testing.** Unlike other tests, the permeability test provides a direct indication of bentonite performance. GCL specifications list either ASTM D 5084 or GRI-GCL-2 as the appropriate test method (ASTM is currently drafting a new standard specifically for GCLs). These two methods are largely the same, with the exception that the GRI method includes guidance on GCL sample preparation. An experienced technician in a qualified geotechnical laboratory can use either test method successfully. Permeability test results are reproducible, provided that all relevant specimen preparation procedures and test conditions are clearly specified.

Although it may be a good performance indicator, permeability testing has several disadvantages. Test results are thickness-dependent, but the thickness of a GCL's bentonite component may be difficult to determine. This obstacle can be overcome by utilizing permittivity (flux) as a hydraulic performance criterion. Also, the permeability test is not suitable for geomembrane-backed GCLs, because the laboratory hydraulic performance of these products is controlled by the geomembrane. The most significant disadvantage of the permeability test is the time required to prepare, saturate, and permeate the specimen until steady-state conditions are achieved. The test requires two or more weeks, creating a potential problem if permeability is used as a QA/QC criterion for specimens taken at the manufacturing plant immediately prior to shipment or at the job site prior to installation. In other words, permeability testing cannot provide "real time" bentonite evaluation data.

## CONCLUSIONS

Bentonite is a naturally occurring material that may be unfamiliar to many designers and engineers. As a raw material in a geosynthetic product, bentonite needs to be regularly tested to ensure that it will provide adequate GCL performance. Unfortunately, despite relatively simple

mining and manufacturing processes, bentonite's complex structure and unique chemical/physical properties render it difficult to evaluate. Added to this problem is the fact that the GCL industry is quite young compared to the plastic geomembrane industry. As the GCL industry matures, more appropriate bentonite identification methods and quality control tests will evolve. However, caution must be exercised if it is decided to utilize bentonite tests derived from other industries and other bentonite applications.

We have seen in this discussion that most bentonite tests now used for GCLs originated from vastly different industrial applications. Free swell and fluid loss are the only two tests that provide an adequate indication of GCL performance. Another benefit of these two tests is that they can be performed using leachate instead of water, to assess the chemical compatibility of the bentonite. A significant difference in results between the tests performed with water and with leachate would indicate potential compatibility problems. These issues, of course, would be explored in the design phase of the project.

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