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SPECIFICATIONS FOR MOISTURE CONTENT OF GCL TO PERFORM ELECTRICAL LEAK LOCATION SURVEYS

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Abstract: The authors investigate the moisture content of encapsulated geosynthetic clay liners (GCL) as it relates to the performance of an electrical leak location survey (ELL). ELLs are quickly becoming the standard practice for quality control of installed geomembranes for landfill applications and are now being used extensively in other industries such as mining. It has been documented that under hot, dry conditions a GCL can become desiccated during installation, losing conductivity and limiting reliability of an ELL. Once encapsulated, they are unable to wick moisture from the ground and thus cannot rehydrate. Design engineers often specify maximum moisture content due to slope stability issues but do not specify a minimum. The authors quantify the electrical conductivity of a GCL versus moisture content for various GCL manufacturers and the bounding lower limit moisture content for ensuring electrical conductance is examined. The intent of this paper is to give recommendations on the minimum moisture content of a GCL before it is encapsulated and to specify a water application rate and methodology during construction in order to keep the moisture content within the desired range.

Keywords: electrical leak detection, geocomposite clay liner (GCL), conductivity, measurement, quality control, geomembrane

INTRODUCTION

Electrical leak location (ELL) survey technology has experienced rapid evolution since its development in the early 1980s. The developers of the method performed the first commercial leak location survey in 1985. Since then, the capabilities of the method and relative low cost have brought it to the forefront of the geosynthetics world as the most state-of-the-art quality control method for installed geomembranes. Required by an increasing number of local and state control boards for new landfill expansions in the United States and now being applied to heap leach facilities in the mining industry worldwide, the demand for this service is spreading quickly, while detailed knowledge of the technology remains in the hands of a surprisingly few and standard methodology is severely lacking.

ELL surveys employ electricity to locate even very small holes in installed geomembranes, either exposed or covered with soil or water. With proper field conditions, the method can pinpoint leaks too small to perceive with an unaided eye. Only a small handful of companies provide this service, as substantial field experience is crucial to tackling the many problems that can arise in the field and successfully combining the science and the art of ELL. The first difficulty is that the method requires specialty equipment and software, which is largely not available commercially. This leads most pioneers of the field to fabricate their own equipment, none of which is standardized, and whose exact specifications are often carefully guarded. One debate that has risen in the past year between competing firms concerns the desiccation of encapsulated geosynthetic clay liners (GCL), purported by some to preclude an ELL survey while others tout limited statistics supporting this application (Darilek 2007).

GCLs are commonly used in place of compacted clay liners (CCL) for various reasons that are beyond the scope of this paper. When an ELL is prescribed in tandem with an encapsulated GCL, copper wires are often installed beneath the GCL to simulate a continuously conductive layer by connecting adjacent panels across the otherwise non-conductive panel overlaps. The survey then depends on the ability of the sheet of GCL to conduct electricity from the hole location to the ground of the power source. The authors' experience and a recently published article (Peggs 2007) concur that GCLs can desiccate in the field, with conductivity dropping below the critical level. When installed in direct contact with the ground, GCLs can easily wick moisture from the underlying ground, but when encapsulated they are sealed off not only from the moisture in the ground, but also the atmosphere itself.

In fact, design engineers take great care to ensure that GCLs are not hydrated in order to avoid slope instability. Manufacturing moisture content varies from 10 to 25% (dry weight basis), with 30% a commonly specified maximum. Construction specifications often (and properly) require that GCLs be handled so as to avoid any additional hydration, including provisions for covering stored GCL rolls and immediately installing the geomembrane over deployed GCL. There is rarely, however, any specified minimum moisture content or procedure to measure or limit dehydration. In arid climates, exposed to the sun and heat even for a few hours, GCLs can desiccate and thereby lose conductivity. Thus, if an ELL survey is to be used in conjunction with a GCL, specifications should address not only hydration but also dehydration.

The authors have developed a test method to measure the electrical conductivity of a GCL as a function of hydration or moisture content. Several samples of GCLs were obtained from various manufacturers and were tested for electrical conductivity at varying moisture contents. The threshold conductivity required for good ELL survey results was then applied to develop a relationship for the minimum conductivity and minimum moisture content of GCLs.

TEST METHOD

Five different samples of GCLs from two different manufacturers were obtained in one metre widths. The five products tested were Bentofix NWL (Sample AIE), Bentofix NWL-45 (Sample AMX), Bentofix NS (Sample AKS), Bentofix EC (Sample ALI) and Bentomat DN (Sample AMI). The initial target moisture contents were 30%, 25%, 20%, 15%, 10%, 5%, 1% and 0%. Moisture content determinations were obtained in general accordance with ASTM D2216-05 (2005) and D5993-99 (2004) to obtain water content by mass of the bentonite portion of the GCL.

Sample Preparation and Moisture Content Procedures

The one-metre wide samples of GCL were wetted before cutting them into 610 mm by 610 mm squares in order to avoid material loss from the edges of the sample. Once cut, the edges of the sample were sealed with tape. The samples were dried at 110 °C for 48 hours to obtain the dry weight. The weight of water necessary to achieve 30% moisture content was determined and added with a spray bottle to the GCL while enclosed in a plastic bag. The plastic bag was sealed after the addition of moisture and allowed to equilibrate for approximately four days. Each sample was tested for conductivity and immediately weighed to determine the actual moisture content of each sample at the time of the test. Each sample was then oven dried in order to decrease the moisture content down to the next moisture level target. Once partially dried and weighed, the samples were again sealed in a plastic bag and allowed to equilibrate for at least two days before performing another conductivity test. A bentonite thickness measurement in general accordance with ASTM D5199-01 (2001) was performed at each moisture content level to account for bentonite swelling. At the end of all of the conductivity tests the sample was oven dried for 24 hours and reweighed to check for material loss during the testing period.

Conductivity Method

The method used to measure the conductivity of a sample GCL is based on the Wenner four-electrode method (ASTM G57-06, 2006). The electrodes are set up equally spaced, with constant voltage applied to the outer electrodes. The inner two electrodes are connected to a voltmeter to measure the voltage between these two points and the current running through the outer leads is measured simultaneously. The most basic application of this method is to a sample prepared in a box. With the outer leads sufficiently far away the inner leads see a uniform electric field, the magnitude of which can be computed by

$$E = V/a$$

where a is the separation of the inner probes in metres, V is the measured voltage in volts across the inner leads, and E is the electric field in volts per metre. The current density can be computed by dividing the current measured through the outer leads by the cross sectional area of the box. Ohm's Law in vector form leads to the following formula for the conductivity

$$\sigma = (aI)/(AV)$$

where I is the current in amperes, A is the cross sectional area in square metres (m^2) and σ is the conductivity in amperes per volt-metre (ASTM G57-06, 2006). This simplest application will allow for comparison with the method developed here for a GCL sample. When this method is applied to soil in the field that has uniform properties to a depth larger than the spacing of the leads, and for some distance around the set up, the conductivity of the soil can be computed with the following formula

$$\sigma = I/(2\pi aV)$$

where I is the measured current, a is the electrode separation, V is the measured voltage and σ is the conductivity in amperes per volt-metre (ASTM G57-06, 2006). This formula assumes that the outer leads can be treated as point sources of electric fields derivable from a potential that solves the appropriate Poisson equation, and that the fields can propagate infinitely vertically and horizontally.

For a sample of GCL the assumption that fields, and current, can propagate vertically does not hold because the GCL is thin. Therefore, the outer probes create electric fields derivable from two dimensional solutions of Poisson's equation. If the probe spacing is a distance a, this potential has the form

$$\Phi(\mathbf{x}) = - \lambda \ln |\mathbf{x}| + \lambda \ln |\mathbf{x} - 3a\mathbf{i}|$$

where the parameter λ has an unknown value, in volts, that depends strongly on local properties of the outer leads. This parameter can be related to the measured current, thickness of bentonite, and the conductivity by application of Gauss' Law and Ohm's Law for electric fields, and must have the same value at both leads by continuity of current

$$I = \int \mathbf{j} \cdot d\mathbf{A} = \int \sigma \mathbf{E} \cdot d\mathbf{A} = 2\pi\lambda\sigma d$$

where d is the thickness of bentonite in metres. The potential difference on the inner leads in terms of the above potential field is

$$V = \lambda \ln 4$$

and equals the measured voltage. Using these expressions the following expression for conductivity in terms of measured quantities can be derived

$$\sigma = (I \ln 4)/(2\pi dV)$$

However, this formula assumes that the fields can propagate infinitely through the two dimensional surface. Initial measurements with a GCL sample of varying dimensions clearly indicate this assumption to be untenable. Therefore, the finite bounds of the sample must be accounted for. The salient property of the edges of a square GCL sample is that current cannot flow off the edge. In particular, this means that the electric field at an edge must be parallel with the edge. If there were only one edge and an electric field source charge inside the edge, a solution that matches the boundary condition of electric fields running parallel to the edge can be created by placing a 'phantom' charge of like sign and magnitude on the other side of the edge in the exact location an image would form if the edge were a mirror. The phantom charge is not physical, since it is outside the region of interest, but the fields it creates added to those created by the real source of fields on the other side match the required boundary conditions at the edge. Moreover, there is a line equidistant between two like charges in two dimensions that has no electric field penetration.

A sample GCL used for testing has more than one edge, and has two charges of opposite sign, since one is a current source and the other a sink, with one at each outer lead. Assume the sample is rectangular shaped with a length c and a width b, both in metres, and that the leads are placed along a line crossing the sample midway along its length, c, with a spacing a, in metres, between leads. Phantom charges must be placed outside this sample to match the boundary conditions at each edge. This requires, in principle, an infinite array of phantom charges. The location of the phantom charges correspond to all the images produced by the charges describing the outer leads if the edges of the sample were all mirrored surfaces. If the left outer charge is taken to be the origin, the right charge is located at $3a\mathbf{i}$, where $\mathbf{i}$ is the unit vector pointing from the left lead to the right lead. The location of these two charges and all the phantom charges can be described by the vectors

$$\mathbf{r}_{nm} = nb\mathbf{j} + mc\mathbf{i}$$

and

$$\mathbf{s}_{nm} = nb\mathbf{j} + (mc + 3a)\mathbf{i}$$

where $\mathbf{j}$ is the right-handed co-ordinate system unit vector that together with $\mathbf{i}$ spans the plane of the GCL sample. To describe the potential due to these charges, it is convenient to define the following functions

$$\varphi(\mathbf{x}, \mathbf{r}) = - \lambda \ln | \mathbf{x} - \mathbf{r} |$$

parameterized by a vector $\mathbf{r}$. These functions have the following properties

$$\varphi(2a\mathbf{i}, \mathbf{s}_{n,-m}) = \varphi(a\mathbf{i}, \mathbf{r}_{nm})$$
$$\varphi(a\mathbf{i}, \mathbf{s}_{n,-m}) = \varphi(2a\mathbf{i}, \mathbf{r}_{nm})$$

The potential resulting from all the sources can be expressed in terms of these as

$$\Phi(\mathbf{x}) = \sum (-1)^m [\varphi(\mathbf{x}, \mathbf{r}_{nm}) - \varphi(\mathbf{x}, \mathbf{s}_{n,-m})]$$

where the sum is over all integral values of n and m. The voltage across the inner leads is then

$$V = \Phi(a\mathbf{i}) - \Phi(2a\mathbf{i}) = \sum (-1)^m [\varphi(a\mathbf{i}, \mathbf{r}_{nm}) - \varphi(a\mathbf{i}, \mathbf{s}_{n,-m}) - \varphi(2a\mathbf{i}, \mathbf{r}_{nm}) + \varphi(2a\mathbf{i}, \mathbf{s}_{n,-m})]$$
$$= \sum (-1)^m [\varphi(a\mathbf{i}, \mathbf{r}_{nm}) - \varphi(2a\mathbf{i}, \mathbf{r}_{nm})]$$
$$= \lambda \sum (-1)^m \ln\{[(nb)^2 + (mc - 2a)^2] / [(nb)^2 + (mc - a)^2]\}$$

where the properties of the φ functions stated above were used in the third step. The placement of the phantom charges does not alter the earlier relation of the current, I, to the unknown parameter λ, conductivity, and thickness of bentonite, d, because no new charges have been placed within the Gaussian surface used to derive this relation

$$I = 2\pi\lambda\sigma d$$

These last two expressions combine to give

$$\sigma = (I/(2\pi dV)) \sum (-1)^m \ln\{[(nb)^2 + (mc - 2a)^2] / [(nb)^2 + (mc - a)^2]\}$$

The resistivity is equal to one over the above expression. The veracity of this expression was tested by performing four lead measurements with a probe spacing of 102 mm on different dimensions of GCL, with the largest measuring 610 mm by 610 mm, and the smallest 356 mm lengthwise and 51 millimetres wide. In order to do this, the terms in the above series were calculated to the sum of the absolute values of m and n being at most 9. By looking at the contributions of the higher terms, the series looks to converge to good results for the samples tested. It should be noted that for very narrow samples, with small b compared to a or c, more terms with higher values of n are generally needed. For three samples of dimensions 610 mm by 610 mm, 508 mm by 508 mm, and 508 mm by 406 mm the measured values of σ had discrepancies of half a percent or less. These samples were cut and measured within a short period of time, so the conductivity ought to have stayed the same since there was little time for the sample to lose significant moisture. This can be regarded as verifying that the above method and resulting formula for conductivity does accurately account for the geometry of the samples. The 356 mm by 51 mm sample was also measured. For this sample the accepted formula (ASTM G57-06, 2006) for a box shaped sample discussed at the beginning of this section should be valid, that is

$$\sigma = (aI)/(AV)$$

As well, the more general method derived above should be valid for this sample. The two formulas agree to within 0.4% at these dimensions. The result agrees with the measurements at larger dimensions to within expected instrument errors. This verifies that the general formula derived above works in good agreement with the method of ASTM G57-06 for a sample of this type. Since the general formula accounts for changes of the dimensions of the sample, that is, very flat and very wide, it is reasonable to conclude that it is an accurate measure of conductivity.

Conductivity Measurements

Each sample was tested for conductivity at each of the eight moisture content levels. Three different voltages of 10, 50 and 100 volts were applied to the samples using the modified Wenner four-electrode modified method previously described. The probe spacing was 102 mm, centred along one axis of the 610 mm by 610 mm samples. The lowest detectable current measurement was 0.1 µA.

TEST RESULTS

Conductivity versus moisture content curves were produced for each sample tested. Each sample exhibited curves with a strikingly similar shape though varying in magnitude, with the largest difference occurring between the products of the two different manufacturers. Samples AIE, AMX, and AMI experienced no significant material loss during the tests, but samples ALI and AKS lost 7.6 and 4.1% respectively of their bentonite granules due to the thinner geotextiles used for these products. The moisture contents of samples ALI and AKS were corrected by considering the loss of bentonite distributed over the time period where bentonite loss was noted. The three different voltages applied to each sample resulted in nearly identical measurements for conductivity.

No measurable conductivity could be obtained for any of the five samples once they were dried to one percent moisture content. As the moisture content of the samples increased beyond 20%, the conductivity increased tremendously. A table of conductivity values measured for sample AIE is presented as Table 1. A graph of conductivity versus moisture content up to 20 percent for the same sample is presented as Figure 1.

Table 1. Conductivity Values of Sample AIE at varying moisture contents

Moisture Content (%, dry weight basis)	**Conductivity** (A/Vm)
0	N/A
1	N/A
6	0.0001
10	0.0006
15	0.0027
20	0.0093
25	0.0525
29	0.9458

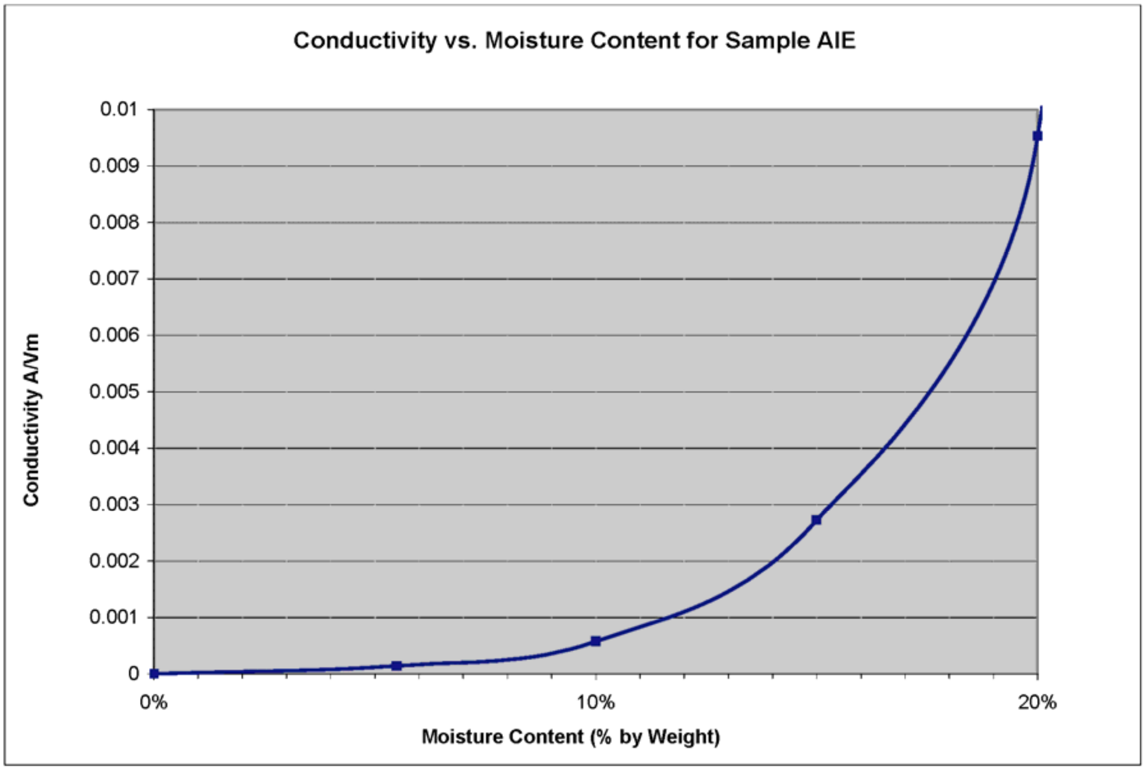

Figure 1. Graph of Conductivity versus moisture content up to 20 percent for Sample AIE

For comparison, values of conductivity measured for all five samples are presented in Table 2 at varying moisture contents. Actual moisture contents varied slightly between samples so the conductivity values presented are approximate.

Table 2. Conductivity Values at varying moisture contents for all samples

Sample	**Conductivity at ~5% Moisture Content** (A/Vm)	**Conductivity at ~10% Moisture Content** (A/Vm)	**Conductivity at ~20% Moisture Content** (A/Vm)	**Conductivity at ~30% Moisture Content** (A/Vm)
AIE	0.0001	0.0005	0.0093	0.9458
AMX	0.0003	0.0033	0.0080	0.051
AKS	0.0002	0.0028	0.0639	0.1783
ALI	0.0003	0.0021	0.0162	0.0961
AMI	0.00005	0.00006	0.0001	0.0057

MINIMUM MOISTURE CONTENT CALCULATIONS

The required moisture content is obtained by considering the survey set up and leak location equipment to obtain the minimum conductivity required to perform the survey. The curve of measured conductivity versus moisture content is then used to specify a minimum moisture content.

Determinations of Minimum Conductivity

Two types of electrical leak location surveys are performed on geomembranes. The water puddle method (ASTM D7002-03, 2003) is performed on exposed geomembranes and the dipole method (ASTM D7007-03, 2003) is performed on geomembranes covered with earth or water. Each method requires a different DC voltage applied to the lining system. The water puddle method typically operates at 27 volts, while the dipole method for water cover operates at up to 100 volts and the dipole method for soil cover requires up to 500 volts. Since the water puddle method operates at the lowest voltage, it can be considered the worst case scenario in terms of driving current through the GCL. Therefore, the minimum conductivity required to perform a water puddle survey should correspond to the minimum moisture content required for an encapsulated GCL.

The minimum conductivity required for a dipole survey need also be explored, but it does not yield as simple a solution as for the water puddle method. A mathematical method beyond the scope of this paper must be developed along with field validation. This will be the subject of future research by the authors.

Lowest Detectable Current

The sensitivity of the current detectors fabricated by various leak location contractors are adjusted with varying site conditions. Typical ranges of current for a water puddle survey range from 0.5 mA to greater than 1 mA for a single geomembrane on subgrade. The detectors are engineered to produce a signal when the scale of a given operating range has reached 100%. The specific sensitivity is operator selected. To find the lowest current that will signal a hole location, one water puddle current detector was set to its highest sensitivity setting and the inline current was measured while it probed a hole location in a lining system. The current required to reach 100% signal strength was 0.1 mA on the equipment's highest sensitivity setting. This setting would typically be much higher than the required sensitivity (0.5 to 1 mA), and is often set lower in order to filter out background noise occurring in the survey area. This sensitivity is comparable to other leak location equipment known to the authors.

Ammeters measure current by measuring the voltage drop across a known resistance. For measurements of very low current, a higher resistance is required to read the small values of current. Adding resistance to the circuit naturally affects the overall current capacity. There is therefore some lower bound for current measurements, which can vary between leak location equipment manufacturers. This limit depends to a great extent on the quality of the instruments, with higher sensitivity equipment being more prone to damage in the field.

Calculating Minimum Conductivity

Assume a hole of radius r_1 in metres and a ground wire with radius r_2, separated by a length of GCL c in metres. Assuming the GCL is large, boundaries can be ignored and the potential is approximately

$$\Phi(\mathbf{x}) = -\lambda \ln |\mathbf{x}| + \lambda \ln |\mathbf{x} - c\mathbf{i}|$$

where the hole and ground wire are being treated as a source and a sink with unknown charge λ. It should also be noted that the hole is being regarded as a perfect conductor with radius r_1. To what extent this matches real conditions is debatable.

The voltage across the hole to ground can be expressed approximately as

$$V = \lambda \ln [c^2/(r_1 r_2)]$$

where approximation leads to insignificant deviation as long as c is much bigger than the radii. The current can be expressed in terms of the conductivity, thickness of bentonite d, and the charge using Gauss' Law and Ohm's Law, just as was done in an earlier section

$$I = 2\pi\lambda\sigma d$$

These two expressions can be combined, eliminating the unknown charge, to yield a formula for the minimum conductivity in terms of the minimum detectable current, the minimum radius of the hole, the radius of the ground wire, the distance between the hole and ground, and the thickness of bentonite

$$\sigma = \{I \ln [c^2/(r_1 r_2)]\}/(2\pi d V)$$

This formula is meant to be a conservative approximation of actual conditions.

Equipment Requirements

The required conductivity of the GCL is highly dependent on the capabilities of the leak location equipment. A typical multimeter can measure several microamperes; however it is the high end of a specified range that is considered the minimum to conduct a survey in order to be sensitive to variations in background noise. Using the previously described formula, the minimum conductivity for Sample AIE was determined for several realistic water puddle set ups. It was assumed that the current would travel through 46 metres of GCL before grounding to a 16-gauge wire. The radius of the hole is per ASTM D 7002 (2003), measuring 0.5 mm. Several values for equipment sensitivity and applied voltage were used to specify a minimum conductivity. The applied voltage refers to the voltage source used to conduct the survey. A voltage of no more than 27 volts is always used for single-lined systems, but up to 81 volts has been used for encapsulated GCLs. A higher voltage would result in excessive risk for the water puddle equipment operator, since he/she is in direct contact with the flow of current. The curve of conductivity versus moisture content of Sample AIE presented as Figure 2 is used to find the required moisture content to achieve the minimum conductivity calculated.

Table 3. Equipment and Moisture Content Specifications

Applied Voltage	**High End of Range** (μA)	**Minimum M.C.** (%)
27	100	16.5
27	50	14.0

27	25	11.5
27	10	9.5
81	100	12.5
81	50	10.5
81	25	8.5
81	10	~3

RECOMMENDATIONS

For projects employing an encapsulated GCL, quality control measures must occur both in the planning phase and during construction. Due to the variance in conductivity with moisture content between samples of different manufacturers, the leak location contractor should request a sample of the specified GCL well in advance of construction. Conductivity measurements with varying moisture contents should be performed to produce a curve similar to those presented in this paper. The leak location contractor can then advise the geosynthetics contractor the minimum moisture content required to perform the work with his proprietary equipment.

When GCL conductivity testing is not performed in advance, the geosynthetics contractor should be obligated by the specifications to maintain or increase the moisture content of the GCL to near the maximum allowable. This will not only maximize the sensitivity of the survey, but also avoid the litigious situation of not being able to perform one or having a survey with false negative results (that is, a false reading of a defect-free liner system). To test for moisture content of the GCL in the field, the contractor can place a sample of GCL in the vicinity of the construction area at the same time that the first GCL roll is deployed. Before covering the GCL by the primary membrane at the end of the day, the sample can be tested for moisture content in accordance with ASTM D2216-05 (2005) and D5993-99 (2004). If field testing for moisture content is not performed, which could understandably delay placement of the overlying geomembrane, the contractor can strategically add moisture at a rate that will not exceed the maximum specified. For example, if the maximum allowable moisture content per design specifications is 30% and the GCL is manufactured with a maximum moisture content of 12%, the contractor can add water equating to a 12% moisture content and still stay below the maximum allowable by 20%. This method assures that the GCL contains at least 12 but not more than 24 percent moisture content. It should be noted that GCLs are generally considered to be relatively dry at less than 35% moisture content and shear strengths are generally not reduced until moisture contents exceed 40 to 50% (Erickson, 2002).

In applying water to a GCL, a labourer or two watering by hand ahead of the primary geomembrane placement would suffice. The GCL mass per unit area is reported in every GCL product specification. To calculate the volume of water per unit area necessary to add a specific moisture content, the following formula can be used.

Litres of water added per square metre = (Target Moisture content/100) x (Mass per Area (kg/m^2))

CONCLUSIONS

Control of moisture content in an encapsulated GCL is a necessary step to ensure the performance of a geoelectric leak location survey. With the success of a geoelectric leak location survey hinging on a relatively minor construction specification, the further development and application of methods such as those presented in this paper are a necessary next step in the evolution of electrical leak location quality control methods.

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