GCL AND INCOMPATIBLE SOIL CASE HISTORY

The attached paper presents a 1997 case study from the western United States, where a standard geotextile-encased GCL (Bentomat ST) was specified as the sole liner for three wastewater treatment lagoons. The lagoons were 11 feet (3.4 m) deep, and both the subgrade and cover soils were coarse-grained (soil particles up to 6 inches, or 150 mm, in diameter).

At that time, plastic-laminated GCLs (such as Bentomat CL) had only recently been developed, and standard geotextile-encased GCLs (such as Bentomat ST) were still being specified in some pond applications. However, as demonstrated in the attached case study, a standard geotextile-encased GCL placed over a coarse-grained subgrade and subjected to high hydraulic heads is susceptible to "piping", or bentonite washout. Portions of the GCL in contact with large stones can undergo thinning or squeezing of hydrated bentonite into the gaps between the stones. When subjected to high hydraulic head, water can flow at high velocities through these thinned areas, potentially causing bentonite washout, and eventually leaving only geotextiles in contact with each other at these locations.

CETCO recommends that only plastic-laminated GCLs (Bentomat CL) or composite liners (standard GCL covered by a geomembrane) be used for high-head applications (greater than 1 foot). Additionally, the subgrade and cover soil recommendations in TR-402, GCL Installation Guidelines, should also be followed:

- Cover soils should range in size from fines to 1-inch (25-mm) minus.
- In applications where the GCL is the only barrier, subgrade soils should be at least 80 percent finer than the #60 sieve (0.25 mm). In other applications, subgrade soils should range between fines and 1-inch (25 mm).

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A GCL AND INCOMPATIBLE SOIL CASE HISTORY: A DESIGN PROBLEM

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and T.-Y. Soong, Eds., GII Publications
Philadelphia, PA USA 1998

ABSTRACT

A single GCL liner (by itself, without an associated geomembrane) was proposed for the containment of 3.4 m of water in three wastewater treatment lagoons using soils containing stones up to 150 mm diameter as subgrade and ballast materials. Despite the fact that calculations showed that it would be difficult to meet the maximum leakage regulation of 44 lphd, the engineer proceeded to install the liner. During full scale hydrotesting all three ponds showed identical excessive leakage rates. An overall leak location survey on the liners found many holes, some as large as 40 mm in diameter. Measurements of swell index and hydraulic conductivity on archive samples of GCL delivered to the site confirmed that the material met project and manufacturer's specifications. The same parameters measured on GCL samples exhumed from the site did not meet specifications. The site examination and testing program are reviewed to determine the nature and idiosyncrasies of the failure.

INTRODUCTION

The 1997 upgrading of a wastewater treatment plant in the western USA involved the construction of three new ponds – two 60 m x 150 m and one 30 m x 80 m. The designer preferred to use the rather coarse native soils and, therefore, felt that a single geosynthetic clay liner (GCL), covered by 450 mm of soil, would be preferable to a geomembrane for providing the required hydraulic barrier. The design depth of water was about 3.4 m and State regulations required a leakage rate of less than 150 mm drop in design water level over a 14-day full scale hydrostatic test, equivalent to about 44 lphd. This figure was "rounded-out" to 50 lphd by the engineer.

Project specifications required the use of a GCL with a hydraulic conductivity (ASTM D5084, no confining pressure defined) of 2×10^{-9} cm/s. The designer proposed to use a CETCO Bentomat ST GCL. Darcy's Law, as follows, was used for leakage rate calculations:

$$Q = kiA$$

where:

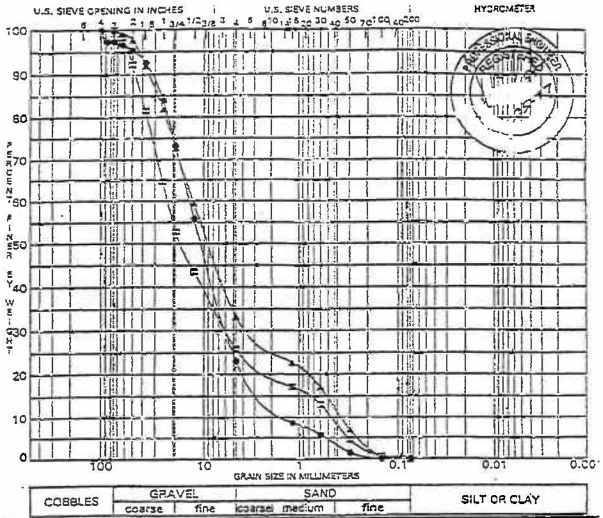
Q = leakage rate
k = hydraulic conductivity
i = hydraulic gradient $= (h + t)/t$
h = depth of liquid
t = liner thickness
A = liner area

The designer's initial calculations of leakage rates using CETCO's published hydraulic conductivity specification of 5×10^{-9} cm/s showed that the leakage rate would be 154 lphd at a depth of 3.4 m, far in excess of the specification. The engineers consulted CETCO to confirm that their calculations were correct. CETCO agreed. But, then the engineers found an older CETCO specification that listed an hydraulic conductivity specification of 1×10^{-9} cm/s, the use of which would provide a leakage rate of 31 lphd, within the allowable limits. The designer approached CETCO to request certification that the GCL would meet the lower hydraulic conductivity. CETCO refused. The designer asked what was the lowest hydraulic conductivity that might be expected in quality control testing. CETCO indicated about 1.4×10^{-9} cm/s, but that this should not be used for design purposes. This permeability would result in a leakage rate of 43 lphd, almost equivalent to the maximum allowable rate. Even at the project specification of 2×10^{-9} cm/s the leakage rate (62 lphd) through the GCL would exceed the allowable leak rate. The engineers, realizing that the groundwater level would be about 800 mm above the base of the pond, and adjusting the hydraulic head to 2.6 m, calculated a leakage rate of 48 lphd – below 50 lphd. On this basis the engineer decided to proceed with the GCL-only liner, against the advice of CETCO who were proposing the use of the CL product (incorporating a geomembrane) together with a nonwoven geotextile cushion layer to provide protection against the stony soil.

It was also noted that the engineer's calculations were made with a favorable GCL thickness of 10 mm, whereas CETCO's QC certificate thickness values were in the region of 6 or 7 mm.

The general contractor for the project, who was also installing the GCL, expressed serious concerns about the ability of the GCL to provide the required barrier function, but was assured by the engineer that all would work well. Installation proceeded. Despite the coarse granular soils, a smooth subgrade was prepared and the GCL deployed. A couple of small areas with inadequate needlepunching and geotextile mass were identified and covered with a second layer of GCL. The 450 mm soil cover, with a maximum specified particle size of 150 mm (gradation curve shown in Figure 1), was

placed. A system of concrete block support/weights and pipes for the aeration system was assembled on top of the soil.



Specimen Identification			Classification	MC%	LL	PL	PI	Cc	Cu
●	POND 3	0.0	WELL GRADED GRAVEL with SAND GW		NP	NP	NP	1.84	10.3
≡	POND 4	0.0	POORLY GRADED GRAVEL with SAND GP		NP	NP	NP	3.39	48.0
▲	POND 5	0.0	WELL GRADED GRAVEL with SAND GW		NP	NP	NP	2.06	34.4

Specimen Identification			D100	D60	D30	D10	%Gravel	%Sand	%Silt / %Clay
●	POND 3	0.0	100.00	13.83	5.939	1.3390	74.3	22.9	0.1
≡	POND 4	0.0	75.00	22.46	5.976	0.4684	74.2	25.8	0.0
▲	POND 5	0.0	75.00	12.70	3.107	0.3693	66.8	32.9	0.3

PROJECT Treatment Plant JOB NO. DATE 2/4/97

Figure 1. Gradation Curve

When the ponds were filled for hydrotesting, the water level was only at about 2.1 m when it was realized that leakage rates were far in excess of 50 lphd – they were estimated to be about 50,000 lphd. The same situation occurred in each of the three ponds. The contractor attributed the leakage to the soils, while the engineer faulted inadequate installation procedures. Each party brought in consultants. This paper is presented from the viewpoint of the contractor's consultant.

SITE INVESTIGATION

On arrival at the site one of the large ponds was as shown in Figure 2. The pipe systems were removed and the remaining water drained from the pond.

Figure 2. Overview of Pond

Four pits were noted in the corner of one pond from where the engineer had previously removed GCL samples. Figure 3 shows the subgrade exposed at two of these samples. It is not "smooth and free of all rocks, sharp stones, ...with no sudden, sharp, abrupt changes or breaks in grade" as required by the project specifications. Many of the larger stones are sharp and angular. Clearly, the GCL had been lying on the tops of the stones and bridging the gaps between stones. Therefore it had not been uniformly supported by the subgrade as required for the generation of a uniform confining pressure and maximum impermeability.

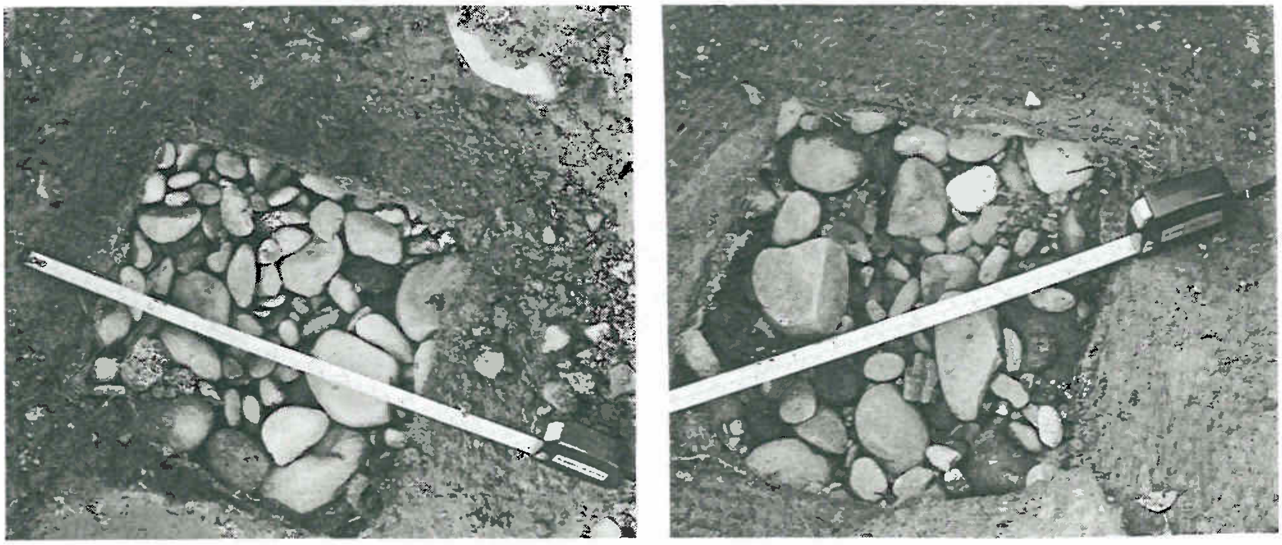


Figure 3. Soil surface under GCL

Figure 4 shows the bridging effect and thinning of the GCL over a rounded stone. In extreme cases the bentonite will all be squeezed sideways, or outwards, the geotextiles on each side of the GCL will make contact, and the liner will start leaking.

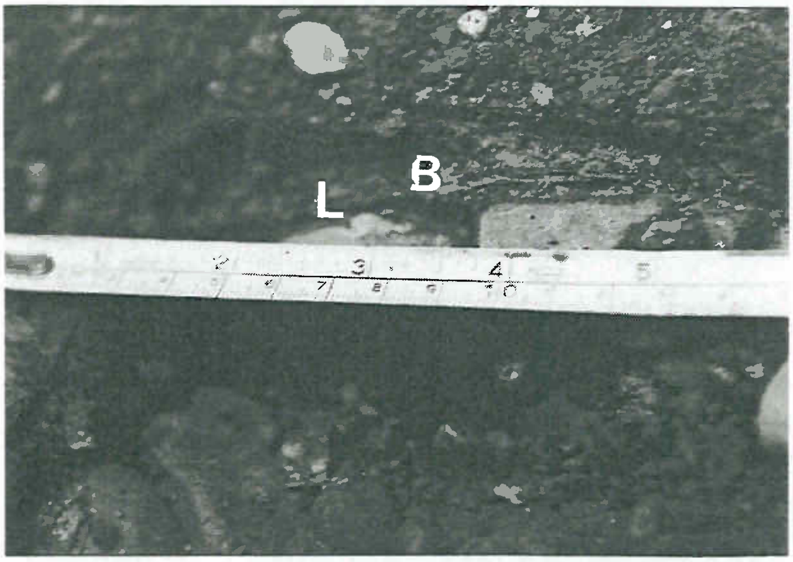


Figure 4. Thinning of GCL over stone on left, and bridging between stones.

Figure 5 shows the location of one of the engineer's samples removed at a seam, with a large adjacent stone resting on the GCL and with a smaller stone underneath it. There were many stones contacting the GCL that were larger than the maximum size of 25 mm recommended by CETCO, and other GCL manufacturers. The GCL was cut further away from the seam to reveal the powdered bentonite correctly placed in the seam overlap (Figure 6). The overlap was further exposed and a 600 mm length of bentonite powder scraped off the bottom GCL. This material was subsequently dried in an oven and found to weigh 200 g. With the material left on the GCL this would effectively meet the manufacturers requirements of 114 g of bentonite per 300 mm of seam. Thus, it could be assumed that the seams had been correctly made, so would not be responsible for the leakage.

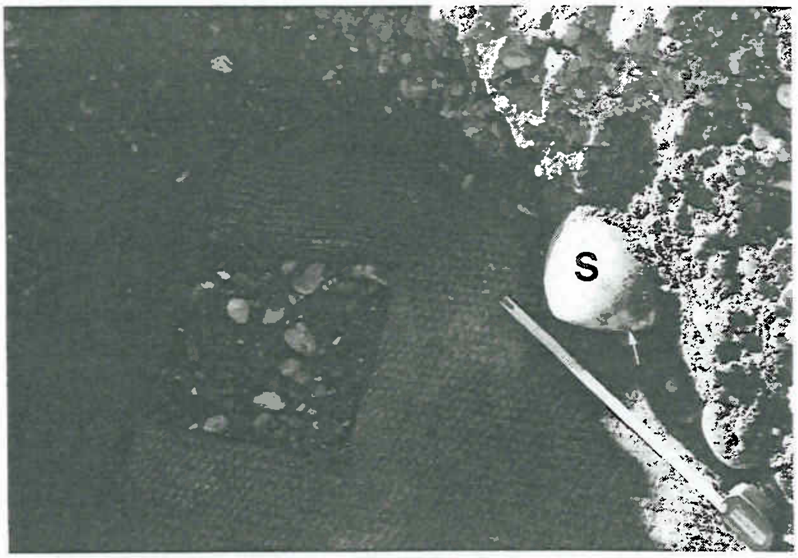


Figure 5. GCL seam. Note larger stone to right with smaller stone underneath it.

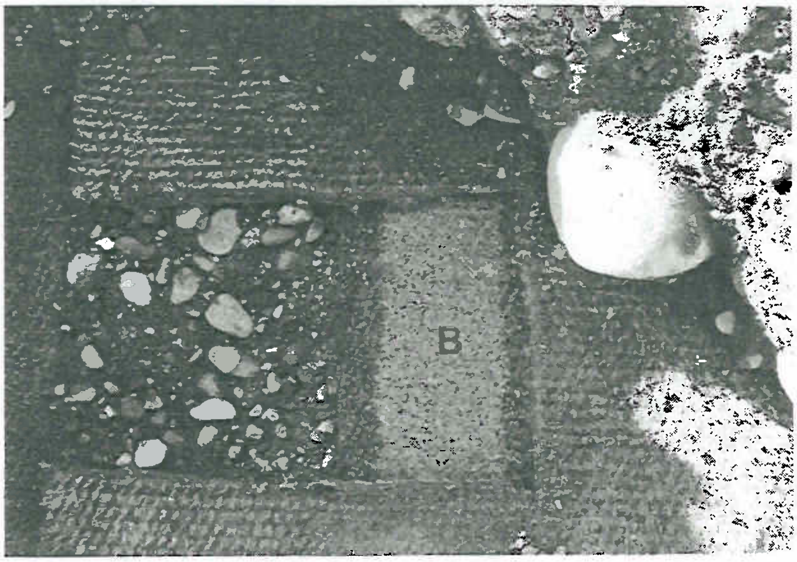


Figure 6. Powdered bentonite in seam overlap

Figure 7 shows several stones pushing upwards into the GCL. A large stone nearby, above the GCL was measured at about 200 mm long by 100 mm diameter. There were many areas where the GCL was deformed from stones both above and below the GCL. Strains in the region of 7 % were determined for some of the larger deformations. Such strain is not sufficient to cause failure of the GCL, but indicates that there might be sites where strains exceeding 15%, sufficient to cause failure, have occurred.

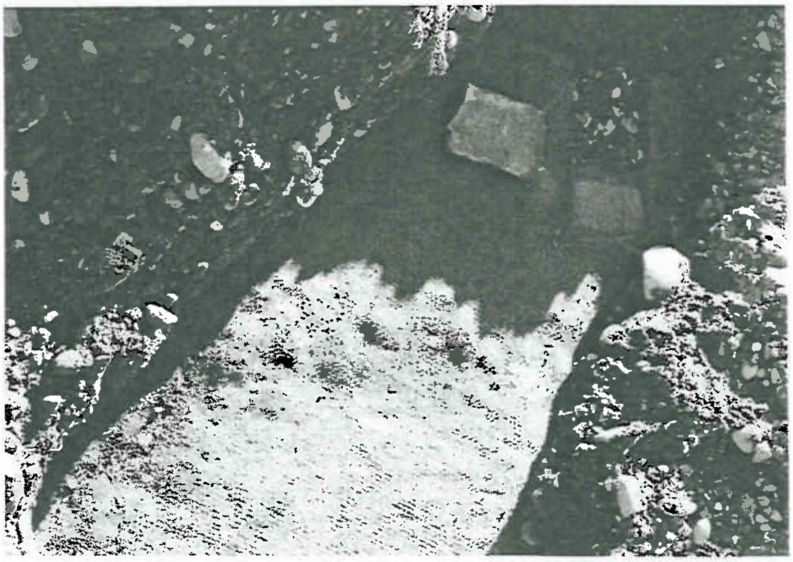


Figure 7. Profiles of stones under GCL

When a further sample of GCL was removed adjacent to one of the engineer's samples, there were again no fines between the stones (Figure 8) – the water had washed them all away. This was the condition almost everywhere that the subgrade was exposed. At one location (Figure 9) the dimensions of the stones and the gaps between them were measured, and were found to be:

- Triangular stone (a); 100 mm
- Gap between triangular stone (a) and stone to left (b); 25 mm
- Gap between stones (c) and (d); 50 mm

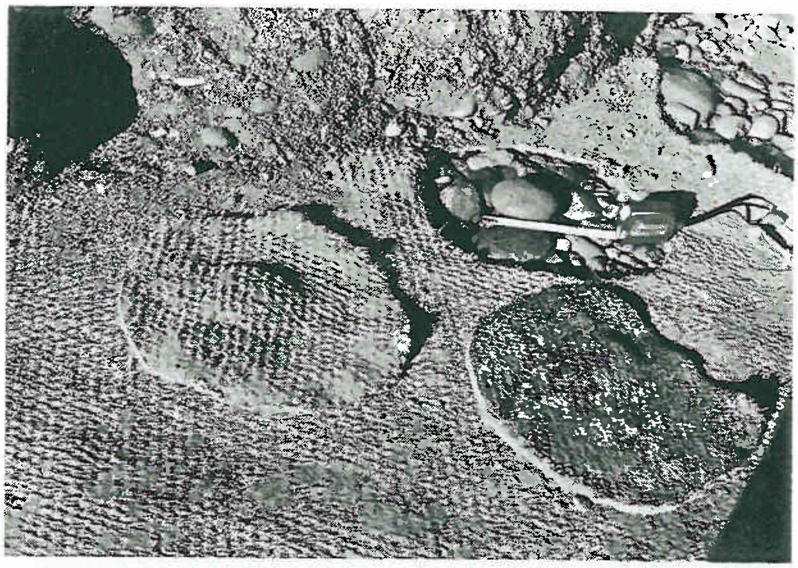


Figure 8. Subgrade at protruding stone

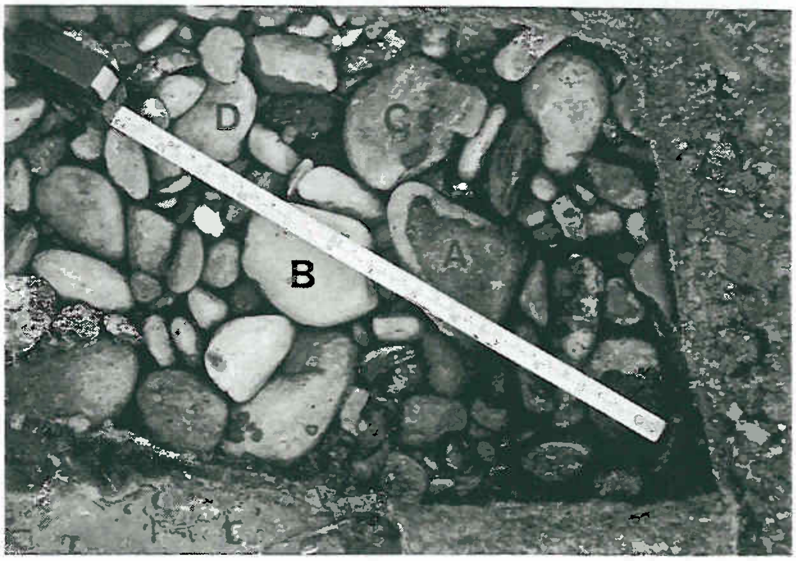


Figure 9. Stones in subgrade

A section of the GCL in one of the large ponds was exposed (Figure 10), to reveal several small holes in the upper geotextile. The GCL was removed, and exposed one large stone almost 100 mm long (Figure 11). Two of the holes were at the ends of one long edge of the stone. The largest hole was at the location of a 25 mm diameter rounded stone.

Figure 10. Small holes in GCL

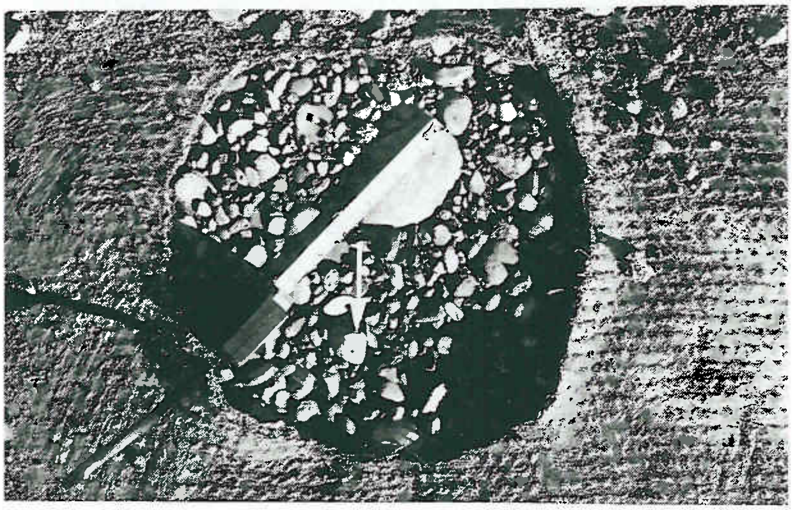


Figure 11. Round (arrowed) stone caused hole in Figure 10.

In another randomly exposed section of GCL two small holes were found, one being caused by a very small stone, about 10 mm long (Figure 12) that had been pressed into the geotextile by a much larger stone above it. When the GCL was pressed, bentonite was extruded through these holes. When the GCL was cut out, the subgrade appeared to be of reasonable quality (Figure 13), but there were still several stones with dimension of about 40 mm.

Figure 12. Small stone that was pushed through the geotextile by a large stone

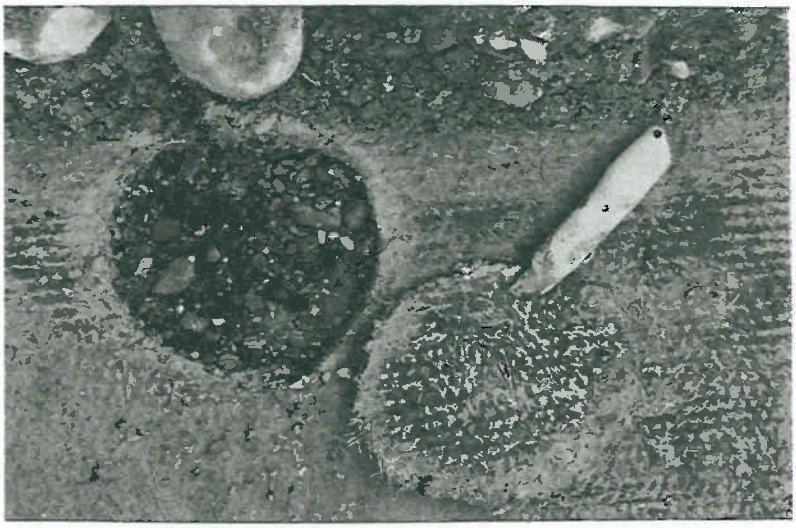


Figure 13. Subgrade at hole caused by small stones in Figure 12

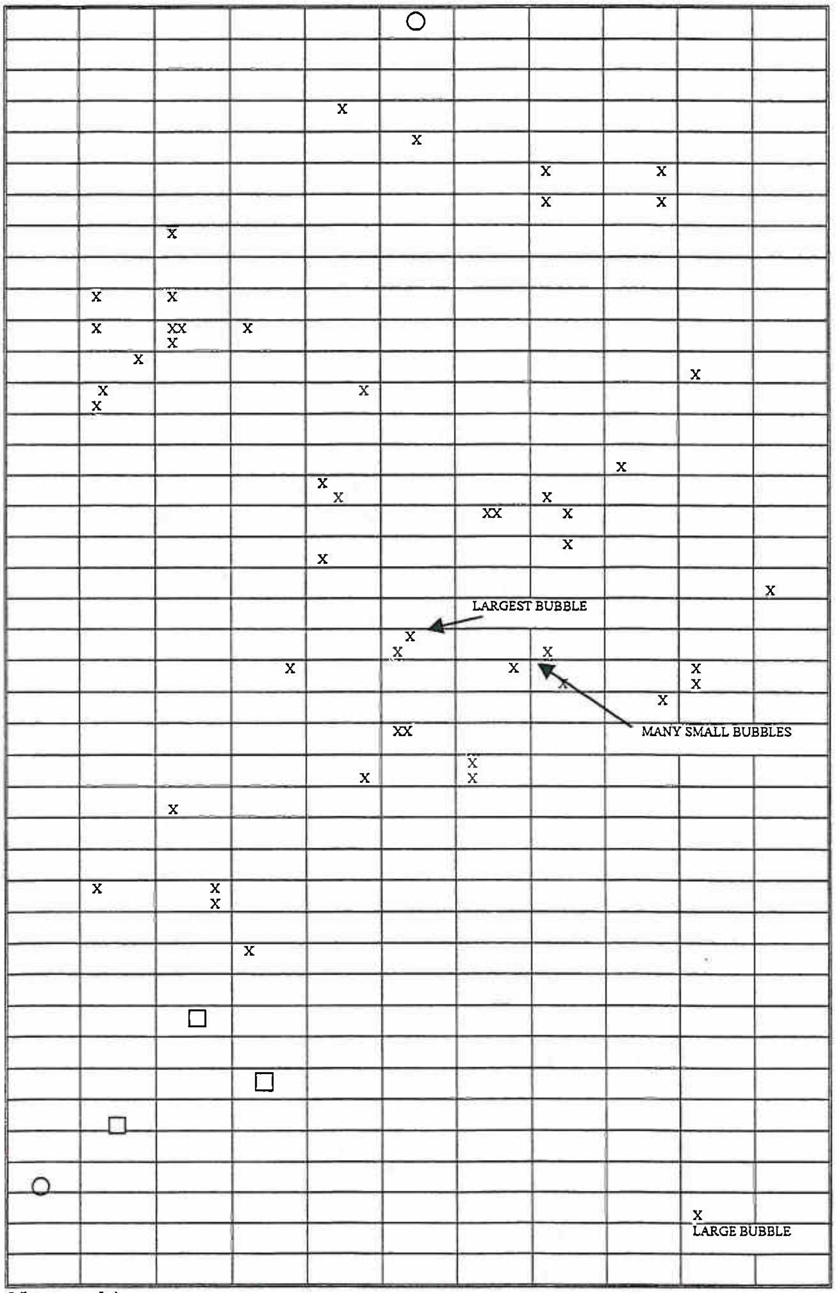
From these chance encounters with large stones and holes, it was clear that there would be many more holes in the geotextiles, and probably others completely through the GCL liners, in the three ponds.

At one stage in the investigation, water in a pit on the floor of the pond was seen to be welling upwards (Figure 14) through a GCL sample hole that had not been repaired. This suggested a method for performing a general leak survey.

Figure 14. Water rising through sample hole in GCL

The underdrain system of the pond was pumped almost dry and then allowed to refill. As filling proceeded, air under the liner was pressurized by the rising water and forced through the holes in the GCL. It then bubbled up through the cover soil (mud) and water as shown in Figure 15. These locations were flagged. In total 51 single and multiple leak indications were marked as shown schematically in Figure 16. Three of these locations appeared to be quite significant leaks, probably larger than the ones already uncovered. The same procedure was followed in the other large pond with very similar results.

Figure 15. Bubbles above holes in GCL



(Not to scale)
X = bubble locations, ○ = inlet pipe, □ = sample holes not patched

Figure 16. Schematic locations of leak indications.

The indicated leak location in the bottom right corner was carefully uncovered. A channel down to the GCL was dug through the cover soil around the marked location (Figure 17), and a pump was used to remove water draining into the channel. The cover soil was carefully removed from the channel in towards the marker and the hole. Figure 18 shows several large stones undisturbed from their original locations directly above the marked location when the water over the GCL was about 25 mm deep. The stones and soil were carefully removed, without damaging the GCL to reveal a hole almost 13 mm in diameter completely through the GCL, as shown in Figure 19.

Figure 17. Channel around leak indication (flagged).

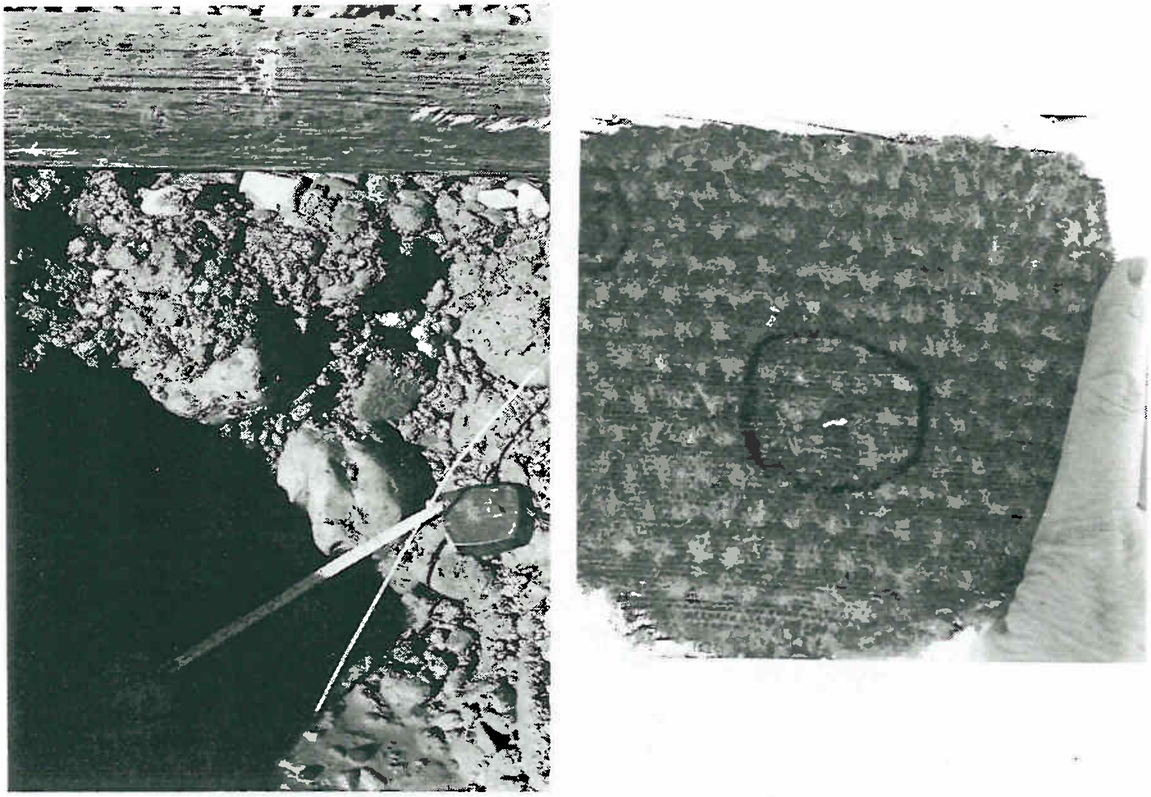


Figure 18. Large stones close to flagged leak.

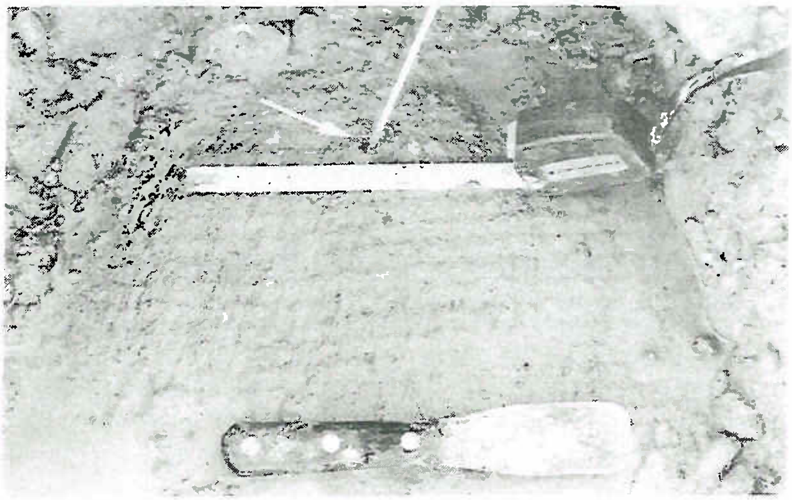


Figure 19. Hole (above tape) at location in Figures 17 and 18.

The most serious leak indication in the center of the pond was also uncovered. The sample removed from this location contained about 5 holes, the largest being about 40 mm in diameter. The stones above and below the GCL were about 50 to 75 mm in diameter. Figure 20 shows the holes in this sample after it had been dried and cleaned.

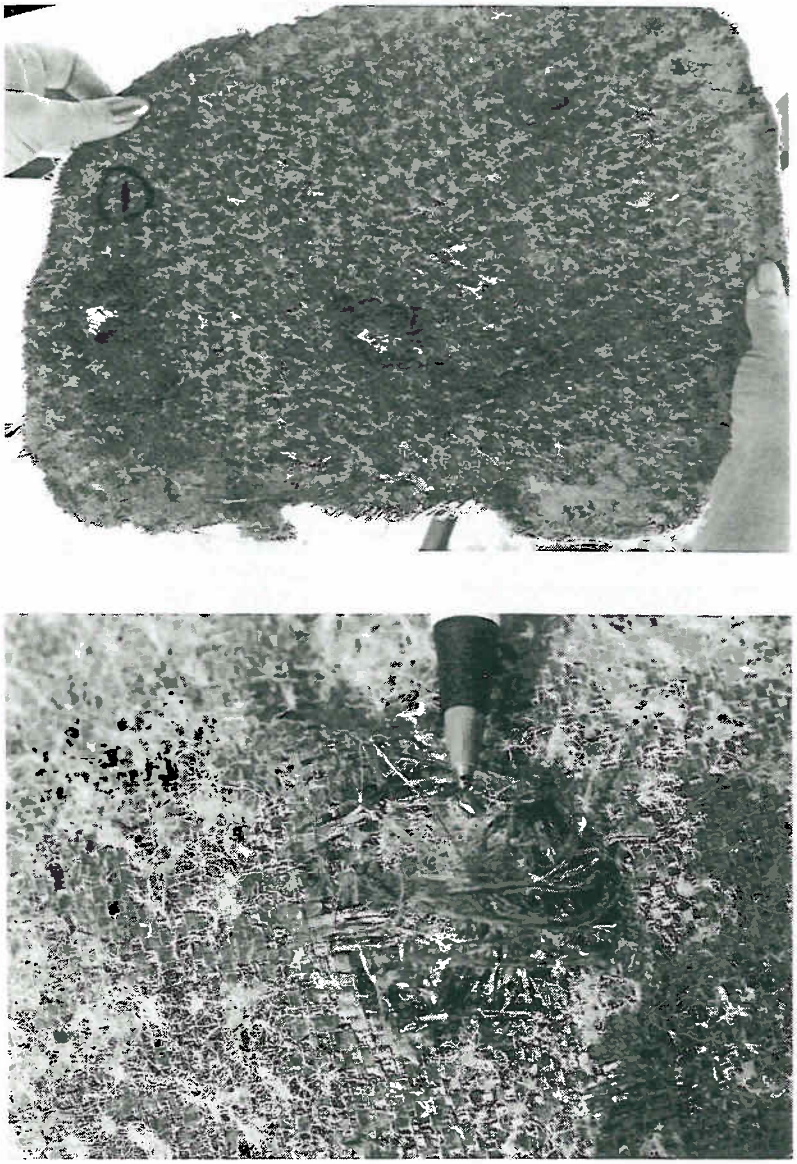


Figure 20. Holes in center pond sample.

LABORATORY TESTING

To determine whether the installed GCL met project specifications, archive samples of material from GCL rolls shipped to the site and installed were obtained from CETCO and subjected to conformance testing according to American Society for Testing and Materials (ASTM) standard test methods at the GeoSyntec Consultants Geomechanical and Environmental Laboratory in Atlanta, GA. Materials were not removed from the site for conformance testing since these types of natural and synthetic materials are subject to significant property changes during installation and service.

The tests performed on the archive samples were free swell on the bentonite in the GCL, and hydraulic conductivity on the GCL itself. Both of these tests assess the fundamental ability of the GCL to provide the required low hydraulic conductivity (permeability). The test results, compared to project specifications, are summarized in Table 1. All tests performed confirmed that this material met project specifications. They also show how hydraulic conductivity varies as a function of confining pressure.

Table 1. Conformance testing results on archive samples.

Parameter	Test Method	Sample	Result	Project Specification
Free Swell	ASTM D5890	1	33 ml	>20 ml
Free Swell	ASTM D5890	2	33 ml	>20 ml
Hydraulic Conductivity	ASTM D5084	1	1.4×10^{-9} cm/s at 35 kPa	$<2 \times 10^{-9}$ cm/s
Hydraulic Conductivity	ASTM D5084	2	1.2×10^{-9} cm/s at 35 kPa	$<2 \times 10^{-9}$ cm/s
Hydraulic Conductivity	ASTM D5084	2	8.7×10^{-10} cm/s at 70 kPa	

Two separate consultants for the engineer removed samples of GCL from both the floors and anchor trenches of the installed liner for conformance testing, with the results shown in Table 2.

Table 2. Test results on actual liner samples.

Consultant	Sample Location/Description	Hydraulic Conductivity (cm/s)	Free Swell (ml)
1	Anchor trench (each pond)	-	15, 19, 15
1	Bottom 1 indentation 25% indentations 100% indentations	 4.1×10^{-9} 6.1×10^{-7} 3.5×10^{-8}	 10.5 6.0 6.5
2	Bottom "coarse" dimples "medium" dimples "no" dimples	 2.45×10^{-6} 2.99×10^{-6} 5.10×10^{-7}	 6.5 6.5 6.5

Not surprisingly, none of these test results meet project specifications. However, it is interesting to note that the free swell value is much higher at the top of the slopes than on the floor under the water. Hydraulic conductivity does not seem to be a function of the amount of dimpling or indentation. These results will be discussed later.

QUALITY CONTROL DOCUMENTS

All quality control (QC) and quality assurance documents for the bentonite, geotextiles, and manufactured GCL were reviewed. They show that the GCL shipped to the site met all project specifications except marginally for 13 of the 132 rolls that had representative grab strengths of 530 N compared to the project specification of 535 N. However, CETCO's specification is a minimum value of 400 N as was presented to the engineer with the Bid Submittal package.

The QC test certificates for two rolls showed hydraulic conductivity values of 3.6×10^{-9} cm/s and 2.2×10^{-9} cm/s. Both exceed the project specification of 2.0×10^{-9} cm/s, but both are well within the CETCO specification of 5×10^{-9} cm/s. The former specimen is considered acceptable since the test result is the average of the three last values measured on the same specimen as a function of time; the last value reported was 1.89×10^{-9} cm/s. The latter must have been considered acceptable by the Engineer (also performing the CQA function), otherwise the rolls it represents would have been rejected. However, this specific roll represents only four rolls delivered to the site, the closest numbered roll being 109 rolls away. The 132 rolls delivered to the site were from a series of about 1000 rolls. Additional, but independent, QC tests performed by Atlanta Testing & Engineering, on a different series of 5 rolls (including one within the range of these last four rolls) representing the full range of product delivered to the site, show (Table 3) total conformance with the project specifications. Hydraulic conductivity values were all less than 1.6×10^{-9} cm/s. This, perhaps, provided the basis for the Engineer's acceptance of the last four rolls.

Table 3. Independent MQA Test Results

Sample #	Confining pressure (kPa)	Hydraulic conductivity (cm/sec)*	Final thickness of Bentonite layer (mm)
1	35	1.5×10^{-9}	3.6
2	35	1.6×10^{-9}	4.2
3	35	1.4×10^{-9}	4.6
4	35	$1.5. \times 10^{-9}$	5.0
5	35	1.3×10^{-9}	5.3

* Hydraulic conductivity based on final thickness of bentonite layer

DISCUSSION

The principle on which a GCL achieves its low hydraulic conductivity and generates its barrier function is that the bentonite must be effectively and uniformly

confined to prevent it swelling as it hydrates. Without adequate and uniform confining pressures a low hydraulic conductivity will not be achieved. Clearly, if bentonite is displaced sideways from a point (such as between two stones), thereby reducing its thickness or allowing the geotextile surface layers to contact each other, the impermeability function will be lost.

The GCL installed in the project is a high quality conventional GCL capable of providing all the functions required of typical GCLs. However, the capability of the GCL to perform within the required leakage specification while containing 3.4 m of water with 450 mm of soil ballast is questionable. Typically, for "good" containment, the maximum depth of water for a single GCL liner would be about 1.5m. Depths of 3m or more have been contained, but with higher leakage rates than normally acceptable for a barrier function. Typically, increasingly finer cover (and subgrade) soils are required as depth increases.

Figure 21 shows the hydraulic conductivity of a Bentomat GCL as a function of confining pressure. Assuming that the 450 mm thick cover soil has a density of 1.9 Mg/m^3, thereby generating a confining pressure of 5.8 kPa (0.83 psi), Figure 20 shows the hydraulic conductivity of the GCL to be approximately 4.0 x 10^{-9} cm/s. The leakage rate through such a GCL (thickness 6 mm) with 3.4 m of hydrostatic head will be 193 lphd. This is far higher than the typical 2 lphd usually specified for primary lining systems that incorporate geomembranes, and far higher than the allowable leakage rate.

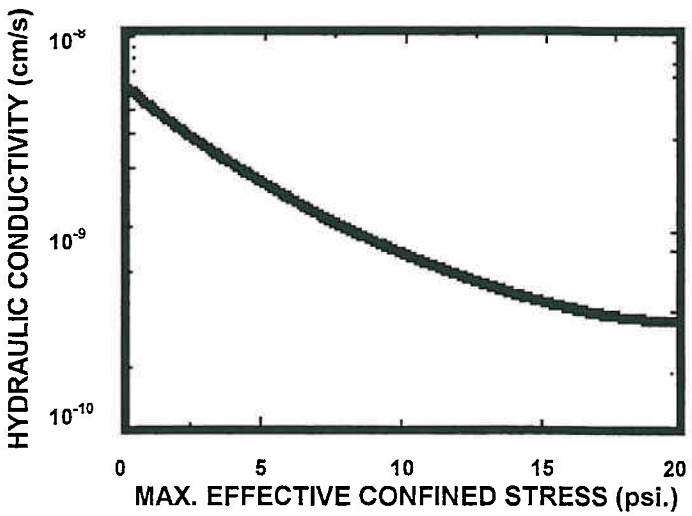


Figure 21. Hydraulic conductivity as a function of confining pressure

In all their calculations the engineers simply used the hydraulic conductivity value of 5 x 10^{-9} cm/s or (1x10^{-9} cm/s) specified by CETCO, without any consideration of the actual on-site confining pressure. CETCO's specified value is based on a confining pressure of 35 kPa, much higher than generated by 450 mm of soil cover. Based on the aforementioned cover soil density assumptions, a 35 kPa confining pressure would require a minimum soil depth of about 2m , far in excess of the 450 mm used. Thus, the engineers should have used a more realistic hydraulic conductivity value in their calculations.

It is clear, even without consideration of the nature of the soils, that it would be very doubtful that the State's maximum leakage rate specifications could be met with the use of a GCL-only liner. And, from the Engineer's consultants' testing, it appears that hydraulic conductivity values while the GCL is in service (in this specific project) could be even lower than expected. If one assumes an average hydraulic conductivity value of 3.5 x 10^{-8} cm/s (from the data reported), the calculated leakage rate through a GCL with a thickness of 6 mm under 2.1 m of water (the conditions during the hydrotest) would only be about 11,300 lphd. This alone would not explain the estimated leakage rate of 50,000 lphd estimated by the Engineer as being the leakage rate during the hydrotest. However, the observed holes could clearly explain the much higher leakage rate.

As evidenced by the site examination, compounding these basic calculated seepage rates through the liner were the large stones in the subgrade and cover soils that caused the liner to be punctured or abraded, caused bentonite to be squeezed sideways, and that provided areas of no applied confining pressure where the GCL bridged gaps between large stones. The Project Specifications allowed stones up to 150 mm in diameter. This is contrary to CETCO's Specification Guidelines for Bentomat GCL's (TR-403) dated December 1994, that clearly state (Section 3.3A) the subgrade shall not contain sharp rocks larger than 50 mm (2 in.) CETCO document TR-405 (1995) "General Installation Guidelines" further states that the surface shall be free of sharp rocks larger than 25 mm (1 in.) in diameter. Obviously, the acceptable rock size was decreased with experience. In the majority of those areas from which GCL samples were removed the subgrade did not meet these sharp rock size requirements. However, it was understood from the Contractor, and confirmed by videotape that the subgrade was rolled to be visually quite smooth prior to deployment of the GCL, and that all protruding stones were pressed into the surface or removed.

Section 3.3B of CETCO document TR 403 also states:

- Subgrade surfaces consisting of granular soils or gravel may not be acceptable due to their large void fraction. Subgrade soils should possess a particle size distribution such that at least 80 PERCENT OF THE SOIL IS FINER THAN 0.2 mm (#60 SIEVE)

Gradation curves (Figure 1) for the soil from each of the three ponds show that the subgrade soils did not meet this requirement. Only about 10%, rather than 80%, of the soil would pass a US #60 sieve. Hence the subsequent loss of this small amount of fine material in the subgrade which, at the time of preparation would just be forming a bridging surface layer above the stones. Subsequent settlement and relative movement of the subgrade stones during continuing construction and filling of the pond would cause erosion and loss of the fines with consequent lack of support for the GCL. In addition to the consequent lack of confining pressure on the GCL are areas where coincident stone impingement below and above the GCL causes sideways dispersion of the bentonite, contact of the two geotextiles, and even puncturing of the geotextiles. At such locations, once water flow through the GCL commenced, bentonite would have been washed out of the GCL, fines in the subgrade would have been eroded, and the leakage rate would accelerate.

Movement of fines is also probably responsible for the poor hydraulic conductivity and free swell performance of samples removed from the liner. The Apparent Opening Sizes of the geotextiles used in the GCL are 0.452 mm (woven) and 0.20 to 0.25 mm (nonwoven). In comparison, 8% of the site soils has a particle size less than 0.40 mm. Thus, the soils can penetrate through the geotextiles into the bentonite. Such contamination will cause a reduction in free swell and hydraulic conductivity values. The samples that have been underwater would be more susceptible to this degradation process than those from higher up the slopes that have not been exposed to the installation traffic and the flushing action of the water.

Another potential cause of reduced hydraulic conductivity of a GCL is a cation exchange process in which calcium cations from the cover and/or substrate soils, or in the contained liquid, replace the sodium cations in the bentonite. This change in microstructure results in a decrease in hydraulic conductivity. However, this process occurs relatively slowly and would not have occurred by the time of the hydrotest. Cation exchange does not typically occur in treatment plant wastewaters, nor was there any reason to suspect the surrounding soils. In any case, the presence of holes in the GCL was a far more serious problem than cation exchange would ever be.

SUMMARY

In summary, the cause of the leakage was quite apparent. The single GCL design essentially could not generate the required impermeability to meet the maximum leakage requirements of the State. The use of subgrade and cover soils with stones exceeding 25 mm in diameter, against the recommendations of the manufacturer, resulted in abrasion holes and punctures in the GCL and extensive areas of lack of adequate applied confining pressure. Also, the subgrade soils have contained inadequate proportions of fines to provide proper continuing support for the GCL.

In addition to performing the design function for the project, the Engineer also provided the on-site construction quality assurance (CQA) function. The function of CQA is to ensure that what was designed is built, whether or not the design is technically adequate. And who better than the designer to ensure that his/her design is actually built? Thus, the GCL delivered to and installed at the site, and the soils used below and above the GCL, despite concerns expressed, were those required and approved by the designer. Thus the final stamp of approval of the completed installation, prior to hydrotesting, was also provided by the designer in his function as CQA consultant.

The ultimate responsibility for the proper functioning of an installation is with the designer, particularly when the designer also acts as CQA consultant. The contractor simply prepares the ground and installs the specified GCL as required, and bears no responsibility for the design or suitability/unsuitability of the different materials, other than to point out when he/she considers there to be a problem.

OUTCOME

The contractor was required to install a polypropylene geomembrane in each pond, at his own expense in order to provide liners with the required barrier function. The contractor filed a claim against the owner and the engineer. The case was eventually settled out of court.

CONCLUSIONS

The following represents a set of "lessons learned' from this particular case history:

- A GCL liner requires adequate uniform confining pressure to provide adequate barrier performance characteristics.
- Soils with stones larger than 25 mm (up to 150 mm diameter) and a low percentage of fines can result in the generation of holes up to 40 mm in diameter in a GCL.
- GCL samples exhumed from an installation should never be used for conformance testing without allowing for major changes that could occur during installation and operation.
- If fine soils can penetrate the geotextiles, the hydraulic conductivity of a GCL may be lower than presumed.
- Listen to those who have more experience than you do and don't push the limits too far.

- For projects incorporating geosynthetics engage the services of an engineer with adequate proven experience in geosynthetics.

- Above all, be practical in performing a failure analysis. It is unlikely that such a large area of inferior product would have been delivered to the site and would have affected all three ponds similarly. The rolls delivered to site were not numbered sequentially, so if those delivered to the site had been inferior there would have been many other sites reporting the same problem. The manufacturer would have then accepted responsibility. The problem had to be more local and common to all three ponds.

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