Geosynthetics: Applications, Design and Construction, De Groot, Den Hoedt & Termaat (eds)
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Field permeability measurement of geosynthetic clay liners

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ABSTRACT: The time of test allowing to obtain the value of the GCLs saturated permeability is very long on laboratory: several weeks or months. This time makes difficult all field control procedure. It seems that a way of work would be the research of a methodology of short-term test allowing, non to provide the saturated coefficient of permeability, but rather to qualify the liner of the viewpoint of its sealing potential, from the alone exploitation of results obtained in the early time of test. So, tests may be performed in a short-term (a few days) or long-term (a few weeks or months). However, we propose, in this paper, a standard procedure for a short-term test (3 days) that can provide a good approximation of the permeability for the field quality control of GCLs. The paper describes a procedure for field permeability measurement using a sealed single or double ring infiltrometer. The test is applicable to every kind of GCLs. Permeability is determined from the rate of infiltration of liquid (typically water) versus time. The volume of liquid added to the ring (Mariotte's bottle) is the measure of the volume of liquid that infiltrates the GCL. The volume infiltrated during time intervals is converted to an incremental infiltration velocity. For GCLs with more or less constant thickness (needle-punched), permeability is calculated by Darcy's law. For GCLs with various thickness (stitch-bonded), which permeability cannot be calculated, we introduce permittivity coefficient.

1. INTRODUCTION AND TESTING STRATEGY

Traditionally, compliance evaluation of permeability for Geosynthetic Clay Liners (GCLs) was based solely on results of laboratory tests on small diameter (about 100 mm) specimens. Field testing represents a change, not only because it is more subject to interpretation but also because test duration are much longer and can impact construction schedules. The defects which can cause increases in the GCL permeability can be significantly reduced by a Construction Quality Assurance (CQA)/ Construction Quality Control (CQC) program during project development [7]. The CQA/CQC program will assure the owner and engineer that procedures are used during construction and that the GCL is installed in accordance with the plans and specifications. A well-conceived, strongly enforced CQA/CQC program is relied on to ensure that field permeability is less than specified value of permeability. Field testing should not be restricted to use in the design phase but may be warranted to ensure compliance. The introduction of field testing as part as compliance evaluation allows development of testing strategy and the following questions should be addressed: why, what type, when, where, and how many tests should be performed.

How many tests?

It is accepted in CQA/CQC that the frequency and locations of sampling should have a statistical basis (EPA 1984). Statistical procedures are available to determine the number of tests to achieve a given level in the results. So, the number of tests depends on the allowable error, the test group scatter, and the desired level of confidence that the mean does not exceed the test group mean [6].

where to test ?

The main criterion is to select an area representative of the GCL. Usually, tests are performed in the central area of roll , away from areas that may have defects. Preferred areas of testing are marginal zones (apparent abnormalities in thickness and mass/unit area), these will be one of highest permeability.

what permeability ?

Most regulations require to have a specified field permeability. However, permeability is not an intrinsic property which depends only on GCL type, but is dependent on a number of factors including: specimen preparation, initial water content, stress level, nature of permeant, and direction of flow. These factors should be accounted for when

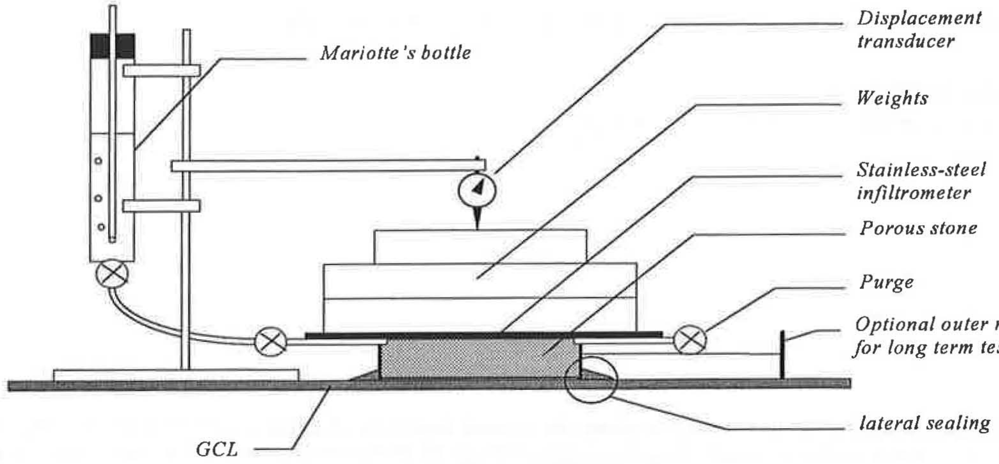

Figure 1: Apparatus for field measurement of GCL permeability

evaluating compliance. Specimen preparation is a factor when comparing tests performed on laboratory and field. So it is necessary that the tests must be performed under simulated site specific conditions and permeants for use in design or other performance related activities [6], and under non-destructive conditions.

2. APPARATUS AND TEST PROCEDURE

The apparatus is a 200 mm (8 in.) diameter sealed single or double ring infiltrometer with a constant hydraulic head. It allows to measure both infiltration and swelling kinetic under a given normal stress. The apparatus must be capable of maintaining a constant head of water on the tested GCL; for this purpose, Mariotte's bottle is used. Figure 1 shows different parts of infiltrometer designed in Geotechnical Laboratory of INSA Lyon (France). This test provides a value of permeability (or hydraulic conductivity) or permittivity for the GCLs tested under specific set of test conditions.

2.1. Test conditions

The following conditions are requested for the test:

- low hydraulic head during the saturation stage (< 1 cm);
- constant normal stress (σv) equivalent to design service stress (σ_{ELS});
- constant hydraulic head (Mariotte's bottle);
- Darcy's law validity for needle-punched GCLs; lower geotextile is assumed to be a drainage layer at the GCL/Structural fill interface. For stitch-bonded GCLs, because there are various thicknesses, evaluation of Darcy permeability can misleading. So it may be more significant to evaluate the quantity of water which would pass through the GCL under given head and vertical stress over a particular cross-sectional area: this is expressed as permittivity [3].

2.2. Methodology

The test requires an area of approximately 1 by 1 m (3 by 3 ft) nearly level; the procedure of testing method is the following:

- Impregnate the upper geotextile under the perimeter of the ring with bentonite paste. this avoids water losses resulting from a horizontal flow in upper geotextile;
- Place the porous stone on the GCL in the area limited by bentonite paste sealing;
- Place the stainless-steel infiltrometer;
- Make a bentonite paste sealing round the ring;
- For a long term test, place the outer ring and make a bentonite paste sealing round the outer ring; put a 5 cm water level (figure 2). This precaution avoids lost of water by parasite lateral flow from inner to outer ring; flow is virtually one-dimensional. For a short term test performed on initial dry material, impregnate the perimeter of infiltrometer with water to avoid immediate water edge lost during the fulling stage of infiltrometer and transient stage (figure 3).
- Connect the infiltrometer to Mariotte's bottle with Rilsan tube; a head of 50 mm of water is maintained on the GCL throughout the test.

- Apply a constant vertical stress corresponding to protective layer (σv equivalent to design service stress σ_{ELS});
- Place the displacement transducer needed for swelling control;
- Cover the ring with either a tarp or ply wood. The purpose of the cover is to minimize evaporation, temperature changes and rain-falls;
- Make a bentonite sealing round the testing area to minimize running under rainfalls wich can produce parasite swelling;

2.3. *Measurement*

It consists in determining and recording the volume of liquid that is added in the ring by measuring the change in elevation of liquid in the Mariotte tube during each time interval. Also, it is necessary to record temperature of the liquid within the ring and the swelling with a displacement transducer during the same time interval;

The appropriate schedule of readings is determined by the choice of short or long-term test. For short-term test, readings may be frequent, 15 min. for the first hour, 30 min. for the second, and 60 min. during the remainder of a period of at least 12 hours, or until after a relatively constant rate is obtained under a limited hydraulic head. For long-term test, after the same schedule than short-term test for the first day, reading intervals may be 24 hours.

2.4. *Calculations*

We saw previously that Darcy's law may be applied for needle-punched GCLs; however, for stitch-bonded GCLs, because of their various thickness, evaluation of Darcy's permeability can misleading. So it may be more significant to evaluate the quantity of water which would pass through the GCL under given head and vertical expressed by permittivity. Permittivity may also qualify other GCLs. For both methods, environmental and physical factors need to make some corrections on infiltration rate.

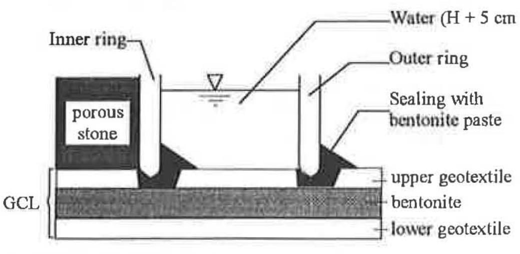

Figure 2: lateral sealing for long-term test

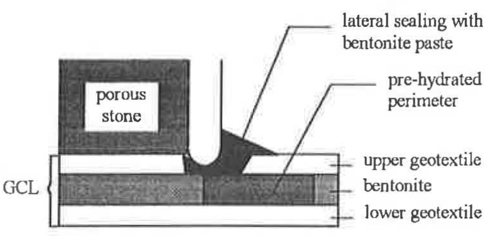

Figure 3: lateral sealing for short-term test on dry material

- Saturation stage

For initially dry samples, this stage can reach a few weeks. The results must be interpreted progressively. Figures 4 and 5 present two typical swelling and infiltration curves for long-term test on initially dry material under σv = 10 kPa (vertical stress).

For initially pre-hydrated samples, the effect of swelling is very limited and allows the measurement of permeability in short times. After a short time of settlement due to apparatus installation, a swelling stage begin but stabilised or increase very slowly. Figure 6 shows the difference of swelling curve for the same GCL with two initial conditions: nearly dry (bentonite moisture is 11 %) and pre-hydrated (30 minutes full immersion and two weeks isolated conservation). The comparison of infiltration curves for the early times of tests performed on initially dry and pre-hydrated GCL shows that the stabilisation of infiltration kinetic is more rapid for pre-hydrated samples (figure7).

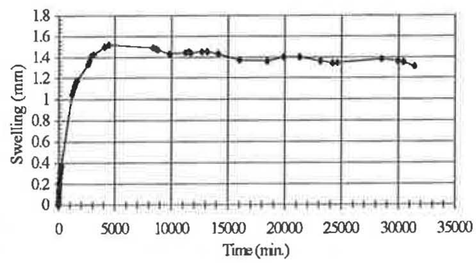

Figure 4: Typical swelling curve for a long-term test pre-hydrated GCL under 10 kPa vertical stress.

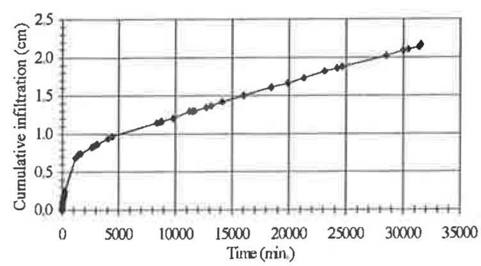

Figure 5: Typical infiltration curve for a long-term test pre-hydrated GCL under 10 kPa vertical stress.

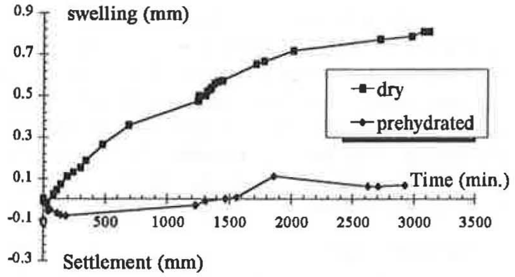

Figure 6: Comparison of Swelling curves of a pre-hydrated and a dry GCL for short-term test under 10 kPa vertical stress.

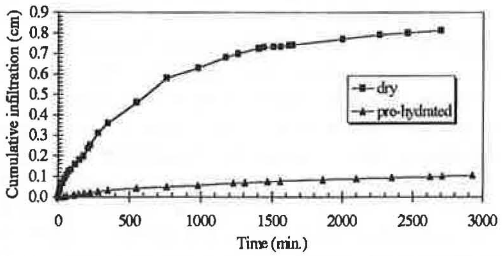

Figure 7: Comparison of infiltration curves of a pre-hydrated and a dry GCL for short-term testunder 10 kPa vertical stress.

- Correction due to swelling

Swelling exhibits high apparent infiltration rates which are not representative of water flow through the test zone. A significant portion of the water entering the GCL may be held by the bentonite due to swell. A corrected infiltration rate, corresponding to water actually flowing through the test area, can be calculated by subtracting the swelling rate from the measured infiltration rate. Swelling rate is equal to the rate of elevation change of the ring, which is measured by the displacement transducer [6]. Permeability is then calculated with the corrected infiltration value. To avoid measurement of swelling in field, which accuracy is not always good, construction of best-fit curves through data points under different set of test conditions should provide an adequate approximation of the field swelling rate.

- Permeability calculation

Only for needle punched GCLs, the Darcy's law is used [5]:

$$k = Rt.\frac{Q}{i \cdot A} = Rt.\frac{\Delta V / \Delta t}{\frac{Hw + Hf}{Hf} \cdot A} \qquad (1)$$

where k, permeability coefficient (m/s), ΔV inflow volume (corrected from swelling) recovered in time Δt, H_w constant hydraulic head (m), H_f, sample final thickness (m), A sample drained surface (m²). Rt, temperature correcting factor. If the temperature of the test specimen (assumed to be water temperature in most cases), is less than 15°C or greater than 25°C, the value of the permeability shall be determined with the equation 2 (ASTM D4491/D5084)[2]:

$$Rt = \mu_t / \mu_{20°C} \qquad (2)$$

During saturation and swelling stages, permeability is calculated for different values of time corresponding to a value of the hydraulic gradient. For each time, Hf is given by the following expression:

$$Hf = Hi - si + \Delta ht \qquad (3)$$

where Hi, is the initial thickness of GCL before installation of infiltrometer, in default, the value given by manufacturer; si, the instantaneous initial settlement after placing apparatus and weights; Δht, swelling or settlement read on the displacement transducer at time t.

Laboratory experimentation

Three commercial products were used in this study to cover the range of GCLs available: two needle-punched GCLs and a stitch-bonded one. For GCLs with powder or granular bentonite contained within needle-punched or stitch-bonded geotextiles, the problem with bentonite falling out from the edge of the material has been dealt by wetting GCL near the edge of the to-be-cut specimen using a plastic squirt bottle [2].

For long term test performed on initially dry GCL, measurement is continued until permeability stabilization (figure 8). Permeability decreasing is very slow and the ratio of initially high value to steady value is great for needle-punched GCL, more than 100.

Short-term tests have been performed on pre-hydrated same GCL. We notice that after only 1500 min. (about 1 day), permeability can be get with a very good approximation. Swelling effect is limited opposite flow infiltration, and permeability value

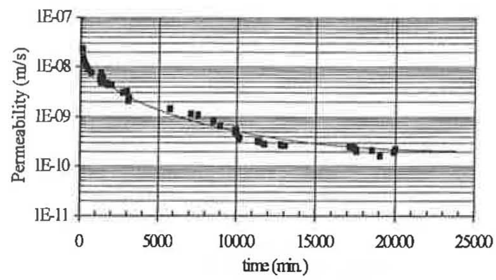

Figure 8: Evolution of permeability value versus time for long-term test performed on a needle-punched GCL initially dry under 10 kPa vertical stress.

Table 1. Results of the 7 laboratory short-term tests on pre-hydrated needle-punched GCLs under σv = 9.5 kPa.

GCL type	n° of test	Hydraulic gradient	Permeability at 2000 min. (m/s)
needle punched A	n°1	6	$4.7.10^{-10}$
needle punched A	n°2	6	$6.1.10^{-10}$
needle punched A	n°3	6	$6.0.10^{-10}$
needle punched A	n°4	6	$6.4.10^{-10}$
needle punched A	n°5	6	$8.0.10^{-10}$
needle punched B	n°1	6	$9.3.10^{-10}$
needle punched B	n°2	6	$8.0.10^{-10}$

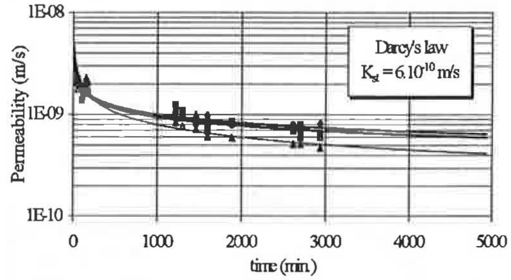

Figure 9: Evolution of permeability value versus time for 5 short-term tests performed on a needle-punched GCL (type A) initially pre-hydrated under σv = 9.5 kPa

doesn't decrease significantly after 2000 minutes (figure 9). Table 2 gives results of tests performed on two needle-punched GCL. Five tests were realized with the same experiment conditions of hydration, vertical stress (σv = 9.5 kPa) and hydraulic head stages (30 minutes of null head and then constant 5 cm head). The average permeability (K*) calculated by Darcy's law is 6.10^{-10} m/s after 2000 minutes, with a deviation of 1.10^{-10} m/s. Ratio of initially high value to steady value is low, about 10 (GCL type A).

- Permittivity calculation.

Permittivity may be used for all GCLs and systematically for stitch-bonded GCLs for which hydraulic gradient cannot be determined because of various thicknesses. As a reference value for quantitative description of GCLs sealing potential, permittivity allows independent comparisons of test results from laboratory and field tests [3]. Permittivity, ψ, is calculated as follows:

$$\psi = Rt.\frac{Q}{Hw \cdot A} = Rt.\frac{\Delta V/\Delta t}{Hw \cdot A} \quad (3)$$

where ψ, permittivity (s^{-1}), ΔV inflow volume (corrected from swelling) recovered in time Δt, H_w constant hydraulic head (m), A sample drained surface (m^2). Rt, temperature correcting factor determined using Eq.2.

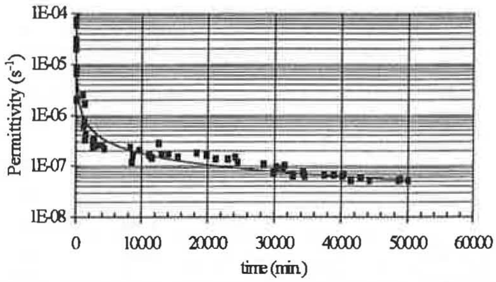

Figure 10: Evolution of permittivity value versus time for long-term test performed on a stitch bonded GCL initially dry (σv = 9.5 kPa)

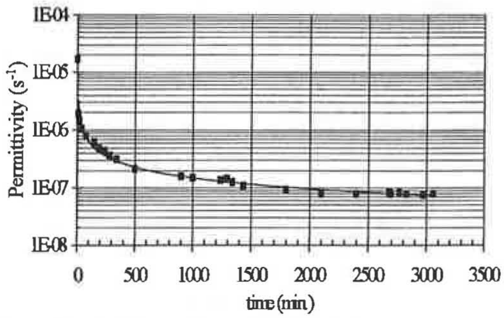

Figure 11: Evolution of permittivity value versus time for short-term test performed on a stitch bonded GCL initially pre-hydrated (σv = 9.5 kPa).

One long-term test was performed on a initially dry stitch-bonded GCL. Figure 10 shows permittivity evolution versus time for it, under σv = 9.5 kPa. Like for needle-punched GCLs, we notice that after 3000 min. (about 2 days) corresponding to short-term test, permittivity cannot be get with a very good approximation because swelling effect is still preponderant. Permittivity decreasing is very rapid in the first hours and slow after; ratio of initially high value to 2000 min. value is very great, more than 400, and to steady value (at 50000 min.), about 2000. These very great ratios may be explicated by initially flow through stitches.
One short-term test was also peformed and leads to the same observations than previously, for permeability measurement (Figure 11).

3. FIELD EXPERIMENT

We have proceeded to the realization of four field tests on a needle-punched GCL for a cover-system construction Quality Assurance of a waste disposal. GCL had been pre-hydrated during one to two weeks by its upper face and without confinement. Each test was performed in short-term conditions with the following history:

Table 2. History of the four field tests

n° test	Duration of hydration (weeks)	Hydraulic head (cm)	σv (kPa)	Duration of head stage (min.)
F/ST/n°1	1	35	19.5	120
		45	18.5	180
		75	15.5	100
		100	13.0	200
F/ST/n°2	2	40	19.0	2200
F/ST/n°3	2	40	19.0	2200
F/ST/n°4	2	40	19.0	2200

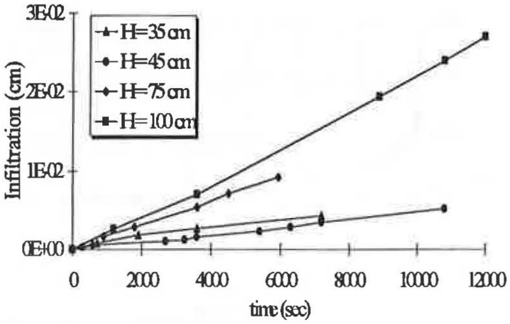

Figure 12: Test F/ST/n°1. Evolution of infiltration versus time for 4 hydraulic heads, 23 kPa initial vertical stress and after one-week free saturation stage.

The first test (F/ST/n°1) was performed with four hydraulic heads applied gradually, from 35 cm to 100 cm. Initial vertical stress was fixed to 23 kPa corresponding to upper soil layer. The vertical stress was not modified during test to equalize influence of hydraulic head increase.

Figure 12 shows evolution of cumulative infiltration for the different values of hydraulic head. The straight lines obtained allow the application of Darcy's law for each stage. The results of permeability calculation is given by Figure 13. Permeability decreases when head increases because vertical stress decreases in the same time. However, the permeability value is rapidly lower than 10^{-9} m/s, even in the early times (t < 1 h) of the first head stage (35 cm).

The permeability values, calculated at the end of each stage (about 600 minutes from test beginning), fluctuates between $2.5.10^{-10}$ m/s under Hw=100 cm and σv=13 kPa and 9.10^{-11}m/s under Hw=45 cm and σv=18.8 kPa. This difference is due to effective vertical stress applied on the test specimen which decreases with hydraulic head increasing.

The second serie of tests (F/ST/n°2 to F/ST/n°4) was

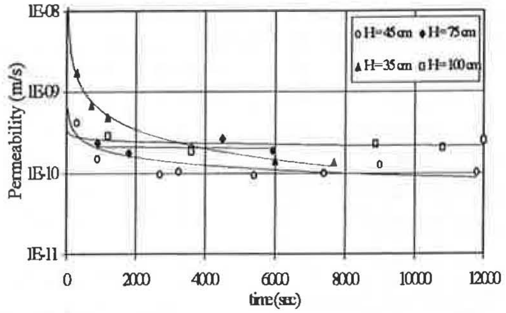

Figure 13: Test F/ST/n°1. Evolution of permeability versus time for 4 hydraulic heads, 19 kPa initial vertical stress and after one-week free saturation stage.

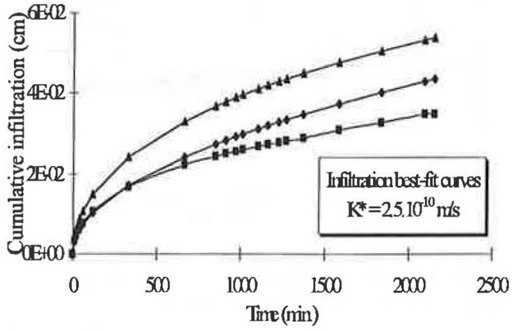

Figure 14: Evolution of cumulative infiltration versus time for 40 cm hydraulic head, 19 kPa vertical stress and after two-weeks free saturation stage (tests F/ST/n°2 to F/ST/n°4)

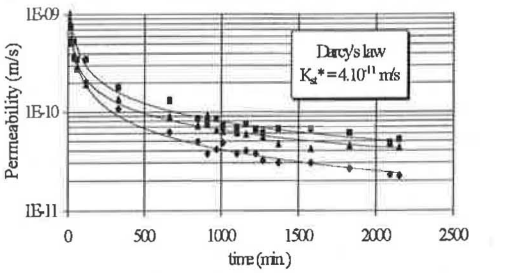

Figure 15: Evolution of permeability versus time for 40 cm hydraulic head, 23 kPa vertical stress and after one-week free saturation stage (tests F/ST/n°2 to F/ST/n°4).

performed with a different strategy: only one hydraulic head (40 cm) under a constant vertical stress (σ_{ELS} = 19 kPa). Infiltration kinetics for each of the three test are quiet similar (Figure 14) and the permeability calculation gives approximately the same values: 3 to 6.10^{-11} m/s. After 1000 min.(17 hours), each test gives a permeability lower than $1.0.10^{-10}$ m/s (Figure 15).

If we compare permeability value of the four tests at 600 min., we notice that it is the same than for test F/ST/n°1 with Hw=45cm, 9.10^{-11} m/s. All the tests are interpreted with Darcy's law but the estimation of hydraulic gradient is difficult because field measurement of GCL thickness is impossible because of non-destructive character of the tests. To avoid this problem, a reference sample is placed on the GCL already installed and follows the same hydration stage. This allows to know both initial thickness and water content of GCL at the begining of the test.

4. CONCLUSIONS AND RECOMMENDATIONS

This paper has the intention of contrasting to traditional testing program involved in CQA/CQC procedures [8] and proposing a new approach of field testing of GCLs including permeability / permittivity measurement. The method is available to control GCLs and the first tests performed in laboratory and field gave encouraging results. The self-sealing capability of GCLs can therefore be estimated with good accuracy. However, the reader is cautionned not to inappropriately extrapolate them. There were obtained under specific conditions of hydration, stress and hydraulic head history.

The advantage of the method is the ability to test large areas, control swelling, both rapidly (two days) with good accuracy and simple data interpretation. The test has not the objective to provide a saturated permeability according to Darcy's Law (only for needle punched GCLs), but rather to qualify the GCL of the tightness viewpoint in comparison with a specified value of permeability for design purposes.

Using this short-term test method, to determine field permeability along rigorous CQA/CQC program will assure the engineers, owners, regulatory agencies that the installed GGL provides an equivalent level of protection to that provided by other laboratory testing methods [6].

Based on the results of the study, the following conclusions are drawn:

· When a dry GCL is tested , water initially flows rapidly, bentonite quickly expands and permeability decreases while bentonite absorbs water and swells. The long term-test gives a steady value of permeability after a very long transient stage (several weeks). The initially high value of permeability of the initial dry GCLs may not be representative of true field conditions because the overlying cover soils would adsorb some of the incoming rainfall and cause a more gradual wetting of the GCL [1][2][6]. So the significance of high initial permeability should be considered on a project-specific basis [1].

· For short-term tests performed on initial pre-hydrated GCLs, edge parasite flow are not significant after two days, increment of water content at external circumference of ring is not significant (less than 5 %). Initially value of permeability or permittivity is early low and stabilized rapidly. Interpretation of data is very simple and rapid. We specified previously the need to know some basic physical parameters of GCLs before test beginning (water content and thickness) for permeability calculation according Darcy's law. A simple reference sample (200 mm diameter) can give the necessary informations if it is sampled on the same roll, placed in the same hydration conditions and under the same initial vertical stress. Settlement and swelling of reference sample are then followed simultaneously with the test.

These tests should be performed under a full range of possible field conditions and apparent abnormalities: desiccated specimen, low and/or heterogeneous mass/unit area, damaged specimen (punched or torn). We have been conceived a specific apparatus to appreciate permittivity of butt joints. It consists of a rigid rectangular PVC plate on which one can be applied a specified vertical stress.

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