GEOSYNTHETIC CLAY LINER FOR SEASONAL THERMAL ENERGY STORES

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Abstract: In the usual application for geosynthetic clay liners (GCL), such as landfills or dams, the operating temperature is near ambient temperature. However, when utilized in a seasonal thermal energy store (TES) the GCL is exposed to water with temperatures ranging from 10 °C to 95 °C at pressures up to 10 m of water column. For the design of the envelope of a gravel- or soil-water TES with respect to the thickness of the liner, knowledge about the hydraulic conductivity as a function of the temperature and height of the (gravel-)water column is required. A maximum leakage rate must not be exceeded as the insulation has to be protected from getting wet.

According to the standards, testing is performed at 10 °C. Information about measurements at higher temperatures is sparse. A measurement device has been developed that enables the measurement of the hydraulic conductivity in the required temperature and pressure range.

A superposition of liquid water transport due to a gradient of absolute pressure according to Darcy's Law and of water vapour transport due to a vapour pressure gradient according to Stefan's Law could be observed. Above temperatures of 50 to 60 °C the vapour transport may even represent the dominating effect.

In contrast to polymer liners, a GCL is never 100% water-proof. Hence, a concept is considered that allows for a so-called controlled leakage: leakage water is drained behind the GCL and pumped back into the store. The secondary liner could be either polymer or GCL again. Outdoor experiments have been conducted in a research pit TES.

In this paper the experimental results obtained with the novel measurement device are presented. Recommendations for the use of GCL for high temperature applications such as TES or solar ponds are given.

Keywords: geosynthetic clay liner, clay liners, hydraulic conductivity, diffusion, measurement

INTRODUCTION

Seasonal storage of solar thermal energy or of waste heat from heat and power cogeneration plants will significantly contribute to substitute fossil fuels in future energy systems. More than 30 international research and pilot thermal energy stores (TES) have been realized within the last 30 years (see Ochs et al. 2007, Ochs et al. 2008).

Seasonal TES are either build as concrete or steel tank or as a pit TES. Pit TES, which are constructed without further static means by mounting insulation and a liner in a pit, are distinguished according to their storage medium in hot water, gravel-water or sand-\soil-water TES. So far most seasonal TES are sealed with stainless steel (VA) or with geomembranes (HDPE or fPP). Experience shows that, as a 100% water proof liner has to be guaranteed, high operation security can only be achieved by applying a double layer system with leakage detection. Examples are the gravel-water TES in Steinfurt (D) or in Eggenstein (D), both with vacuum detection.

Within the last 30 years there was some effort to construct cost-effective pit TES with compacted clay liner, such as in Ottrupgard (DK), Heller (2000) or Berlin (D), Voigt et al. (1988). However, until today no research project with compacted clay liner gave proof to be successful. The research store in Berlin showed severe leakage problems; the 1500 m³ hot-water TES in Ottrupgard is still in operation, however with leakage rates amounting up to 6 m³ per day, which corresponds to 150 % of the volume of the store per year, see Heller (2000b). Similar experiences were made with the hot water store in Hoerby (DK), [Duer 1993], which was sealed using bentonite concrete. It showed severe leakages due to cracks. Attempts to stop leakage remained without success, Wesenberg (1993). Experiences with GCL were also not satisfyingly in the case of the El Paso solar pond, Lu et al. (2004).

Hence, with regard to the lining of a TES there is still a cost reduction potential. As a cost-effective alternative to stainless steel liner or geomembranes, geosynthetic clay liner (GCL, bentonite liner) was suggested. The advantage would be a more cost effective and much faster installation of the liner compared to a welded geomembrane liner.

In the framework of the research project “Further Development of Pit Heat Store Technology” carried out at ITW, construction materials such as insulation materials and geomembranes were tested. Furthermore field tests on different concepts and designs of buried seasonal TES were conducted with the objective to reduce construction costs.

The objective of this work, which was part of the research project “Further Development of Pit Heat Storage Technology”, was to proof the feasibility of such a concept with a geosynthetic clay liner.

CONCEPT

When utilized in a seasonal TES the GCL is exposed to water with temperatures ranging from 10 °C to 95 °C with pressures up to 10 m of water column (head difference). These exposure conditions that are quite different from the usual application have to be considered, when developing a lining concept with GCL for a seasonal pit TES.

As a GCL is not 100 % water proof, in the case of the suggested concept the envelope of the TES is designed with a so-called controlled leakage. This is assured by a drainage layer made of geogrid, which is placed between an inner

GCL and a second outer liner. Storage water that permeates through the inner liner accumulates in a gravel drainage layer and is pumped back into the store, see fig. 1.

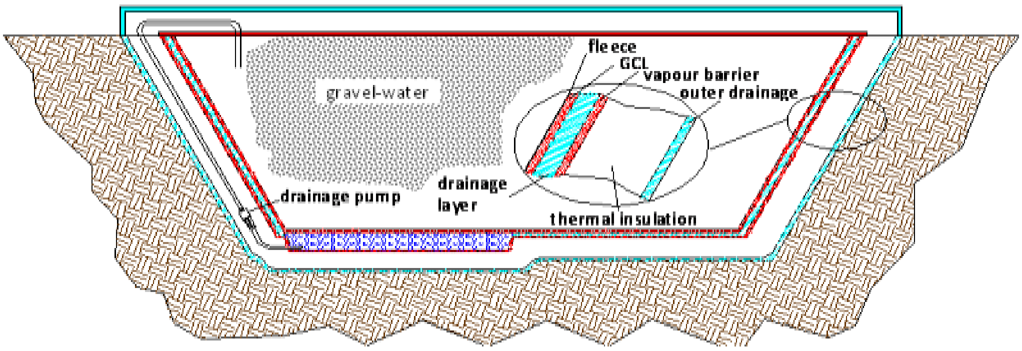

Figure 1. Concept for lining of pit thermal energy store with controlled leakage (source: PKi, modified)

In the first phase of the project it was suggested to build the second liner again with GCL. However, as will be shown later such a concept consisting of two layers of GCL does not work due to water vapour diffusion: the insulation is not protected from getting wet. Instead, the second outer liner could be realized using a vapour barrier. It is not required to weld the outer liner. By placing a series of vapour barriers with sufficient overlapping areas a water proof installation could be realized. As no seaming is required, installation is much easier and less expensive. The outer liner must be embedded into the drainage of the bottom.

The sealing effect of bentonite originates from the expansion of the moistened bentonite, while it is compacted under pressure. In order to ensure that bentonite is not washed out, rip-rap is required. Hence, the suggested concept is only applicable for a gravel-water or sand/soil-water pit TES but not for a hot water TES.

THEORETICAL DESCRIPTION OF THE WATER AND WATER VAPOUR TRANSPORT

Darcy's Law

The definition of the hydraulic conductivity is based on Darcy's Law, the proportional relationship between the flow rate Q through a porous medium with the area A and the pressure drop over a given distance. The measurement device and method are described in ASTM D 5887or DIN 18130, respectively.

$$k_f = \frac{Q \cdot H_w}{A \cdot d}$$

The ratio of the head difference H_w and the thickness of the porous medium d is hydraulic gradient

$$i = \frac{H_w}{d}$$

The expression of the flux (= Dary velocity) v_D is

$$v_D = \frac{Q}{A}$$

with the area A and the infiltration rate Q at steady state.

Hence, the Darcy velocity v_D can be expressed as the product of hydraulic conductivity k_f and hydraulic gradient i as

$$v_D = k_f \cdot i$$

With the permittivity Ψ products with different thickness d can be compared.

$$\Psi = \frac{k_f}{d}$$

The permeability k is the product of the hydraulic conductivity and the dynamic viscosity η of the fluid (i.e. water).

$$k = k_f \cdot \eta$$

According to the theory the temperature dependence of the hydraulic conductivity k_f is already considered with the temperature dependence of the dynamic viscosity η. The dynamic viscosity of water can be approximated by a fourth order polynomial of the absolute temperature T / [K], Bednard (2002) as follows:

$$\eta(T) = +0.465625 - 0.00538585 \cdot T + 2.34689 \cdot 10^{-5} \cdot T^2 - 4.55704 \cdot 10^{-8} \cdot T^3 + 3.32314 \cdot 10^{-11} \cdot T^4$$

Permeation and Diffusion

In presence of a vapour pressure gradient $\Delta pv/d$, e.g. due to a temperature gradient, the liquid water transport according to Darcy's Law can be superposed by water vapour transport. The water vapour transport due to diffusion can be described according to the Fickian Law. The water vapour transmission (WVT) is a function of the partial pressure drop Δp_v over the porous medium with the thickness d.

$$WVT = \frac{\delta_a}{\mu} \cdot \frac{\Delta p_v}{d}$$

The water vapour resistance factor μ is used as the proportional factor. The water vapour resistance factor is related to the permeability of water vapour in air. It accounts for the additional distance (extra path length) one vapour molecule has to cover in relation to the thickness of the material, see Figure 2.

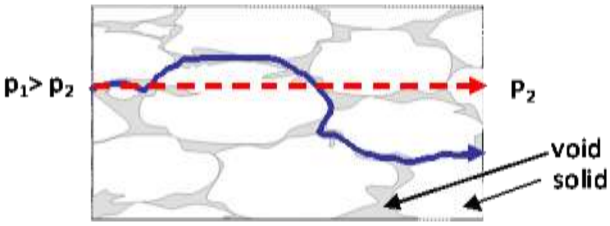

Figure 2. Water vapour diffusion through a porous medium, water vapour resistance as extra path length

The permeability of water vapour in air δ_a is a function of the diffusion coefficient D_v the absolute temperature T and the gas constant of water vapour $R_v = 461.5\,\text{J/(kg K)}$

$$\delta_a = \frac{D_v}{R_v \cdot T}$$

In the literature several approaches for the calculation of the diffusion coefficient may be found [Krischer (1992), Schirmer (1938), Vos (in De Vries, 1966) or DIN 52615]. The correlation used in this work is taken from the VDI Heat Atlas (2002)

$$D_v = \frac{2.252}{p} \cdot \left(\frac{T}{273}\right)^{1.81}$$

with the absolute pressure p/[bar] and the absolute temperature T/[K]. The partial pressure is the product of the relative humidity ϕ and the saturation vapour pressure p_s

$$p_v = \phi \cdot p_s(\vartheta)$$

The saturation vapour pressure increases exponentially with temperature ϑ and my be calculated using the empiric correlation according to Magnus, in Sonntag et al. (1982)

$$p_s = 10.5 \cdot \exp\left(\frac{17.269 \cdot \vartheta}{237.3 + \vartheta}\right)$$

For unidirectional diffusion the Fickian law does not apply. Unidirectional diffusion, which was discovered by Stefan (see Krischer 1992) must be considered if convection is non-negligible i.e. for high vapour concentration. The evaporated liquid displaces air resulting in a movement of air away from the surface of the liquid. In this case the water vapour transmission may be calculated as

$$WVT = \frac{\delta_a}{\mu} \cdot f \cdot \frac{\Delta p_v}{\Delta x}$$

For temperatures above 40 °C the mass flow factor

$$f = \frac{p}{p - p_{v,m}} = \frac{p}{p_a}$$

exceeds 1.1. Hence, negligence would result in unacceptable high errors.

MEASUREMENT OF WATER AND WATER VAPOUR TRANSPORT

Experimental Setup

In the literature, information about measurements of the hydraulic conductivity at higher temperatures is sparse. According to the standards (ASTM D 5887 or DIN 18130), testing is conducted at 10 °C. Hence, the suggested test procedure and measurement device are not suitable for this investigation.

For the temperature dependent measurements a novel measurement device was developed. It is a further development of the device presented by ZSW, West (2000). The design accounts for the special conditions GCL are exposed to when installed in seasonal TES. The measurement device (Figure 3) allows for continuous gravimetric measurement of the permeation rate at steady state for varying temperatures and hydraulic gradients. The temperature can be controlled in a range from 10 °C to 95 °C using an external thermostat.

Furhermore, different degrees of compaction are considered, as the load on the GCL has influence on the hydraulic conductivity. The height of the gravel cover can be changed in a range from 1 m to 75 m with the help of a pneumatic pressure cylinder (1 to 10 bar). The head difference (height of the water column) can be independently adjusted to up to 30 m by changing the pressure in the pressure vessel (1 to 4 bar).

The specimen is mounted without further sealant between two flanges. The bottom flange is perforated. As suggested by Fox (2000), a 1200 g protective fleece is placed onto the specimen in order to distribute the load of the gravel cover. Additionally, underneath a fleece covered geogrid distributes the load on the perforated flange. With this set-up the specimen is mounted in the measurement device similar to the way it would be installed as liner in a pit TES.

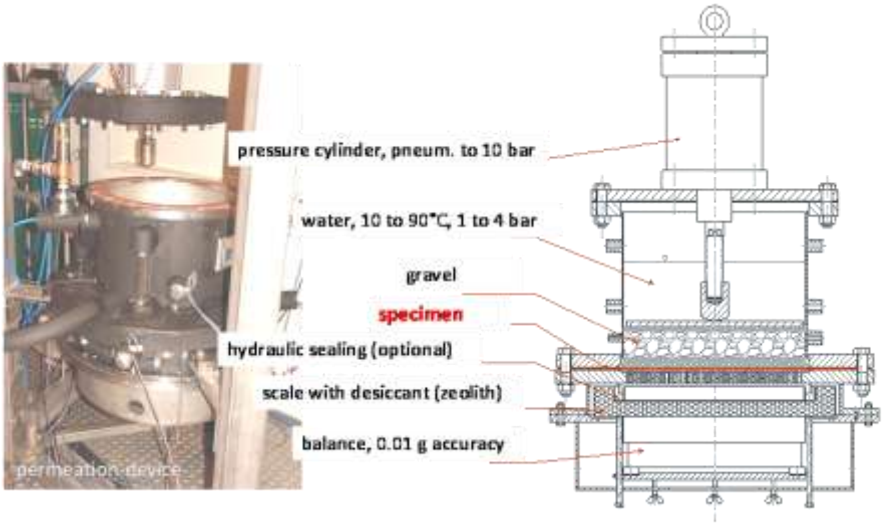

Figure 3. Photo and sketch of the permeation measurement device

The permeating water is collected in a scale, which is insulated at the sides and at the bottom in order to minimize the temperature gradient in the measurement chamber and to protect the balance from overheating. Optionally, the measurement chamber can be mounted hermetically using a hydraulic sealing, see Figure 4.

Continuous gravimetric measurement is enabled with the experimental set-up. The accuracy of the balance, which works according to the principle of electromagnetic force-compensation, is given with 0.1 g at a maximum load of 16 kg. The balance has been modified by the manufacturer, allowing an accuracy of 0.01 g for a load range of 6 kg (within the 16 kg maximum load). The weight of the scale including insulation is in the range of 4 to 5 kg.

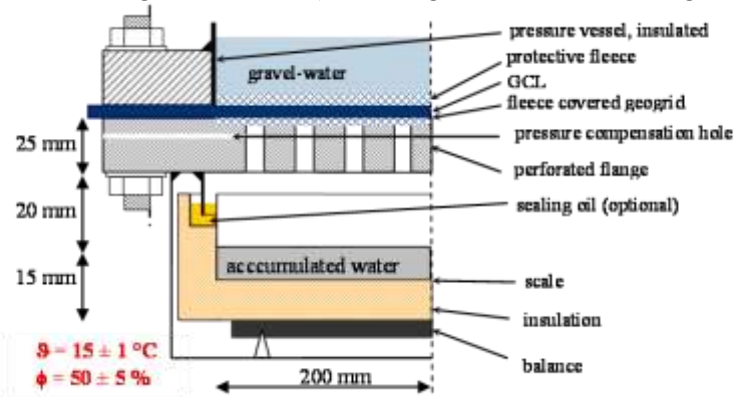

Figure 4: Schematic configuration of the measurement device (non-scale)

The measured mass increase, temperatures (water, perforated flange, balance, ambient), the relative humidity and pressures of the vessel and the pneumatic cylinder are continuously monitored and stored on a PC using Labview® software. The reading of the measured data starts when steady state is reached (up to 24 h, depending on the target temperature).

Specimens

For the measurements a needle-punched and themal bonded GCL (sodium bentonite) was chosen. Measurements were conducted with six specimens of the same product. Specimens with a diameter of 700 mm are required. The measurement area is 1392 cm² corresponding to a diameter of test area of approx. 400 mm. Due to the comparably large measurement area it is possible to yield high fluxes. Thus, the resolution of the measurement device is enhanced. Further advantages are that deviations of the thickness of the GCL are levelled out and that when preparing the specimens the risk of losses of bentonite in the measurement area is reduced.

Figure 5: GCL specimen after measurement

Measurement Results

Liquid water transport

Measurements were conducted in a temperature range from 10 to 93 °C for varying head differences and heights of the gravel cover. Detailed discussion of the results can be found in Brellochs (2004). In Figure 6 the measured Darcy velocity is plotted as a function of the hydraulic gradient with the height of the gravel-water column (GW) as parameter.

In contrast to the theory the best linear fit curves do not cross the origin. The measured permeation rates in absence of a hydraulic gradient can be explained by superimposed water vapour transmission due to diffusion as shown in Figure 6, right hand side. The driving force for the diffusion is a vapour pressure gradient as a result of a temperature gradient. As the water vapour transmission is only a function of temperature, the permeation rate due to diffusion can be determined graphically by extrapolating to the ordinate intercept.

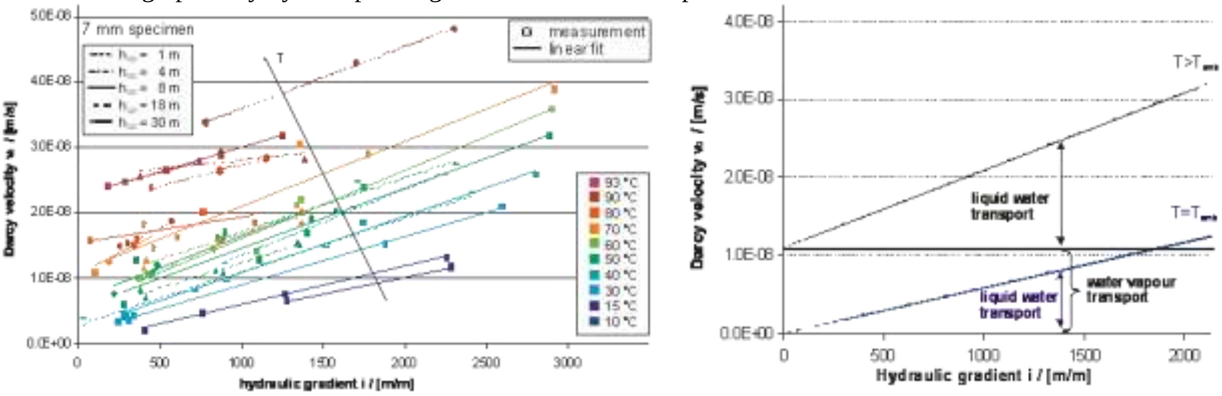

Figure 6. left: measured Darcy velocity as a function of the hydraulic gradient (i=ΔH/d) with the height of the gravel cover (h_{GW}) and the temperature (T) as parameter, right: schematic pure liquid water permeation rate as a function of hydraulic gradient and superimposed water vapour transport

By subtracting the share of the water vapour diffusion from the measured permeation rate (Darcy velocities from Figure 6) the remaining pure liquid water permeation rates (Darcy velocity) is yielded. The remaining pure Darcy velocity is shown in Figure 7.

For lower temperatures (<50 °C) the measured permittivity is in the range of 10^{-10} 1/s and agrees with the manufacturer information. However, according to theory, the Darcy velocity and consequently the hydraulic conductivity increase with increasing temperature. The slope should correspond to the increase of the reciprocal dynamic viscosity. In Figure 7 (right), the resulting hydraulic conductivity is plotted as a function of temperature. The comparison with the reciprocal dynamic viscosity shows that above temperatures of 60 °C, the behavior is different from theory. In spite of the theory, the measured hydraulic conductivity decreases with increasing temperature.

For both measurements, the fluctuation range increases with increasing temperature. An explanation could be measurement errors: diffusion from the accumulated water in the scale to the ambient could result in a measured mass increase that is too low. A further possible explanation could be that varying vapour content of the GCL may influence the hydraulic conductivity.

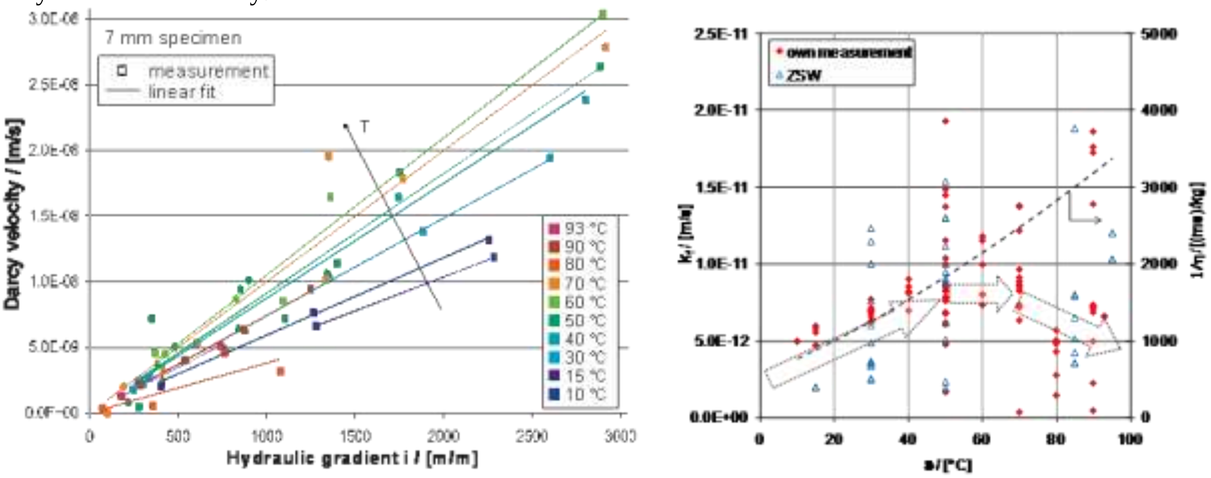

Figure 7. left: pure liquid water permeation rate in a temperature range from 10 °C to 93 °C as a function of the hydraulic gradient (i=ΔH/d) with the height of the gravel cover (h_{GW}) as parameter, right: reciprocal dynamic viscosity as well as measured hydraulic conductivity as a function of temperature, comparison of own measurements with measured data from ZSW.

Our own measured data have been compared with earlier measurements reported by ZSW (West, 2000). The results are similar, however fluctuations are even higher.

In the framework of this investigation three of six samples lost the sealing effect completely, however the failure occurred for high head differences but low load of the gravel cover ($h_w/h_{kw} > 2$). Application of GCL under those conditions is not recommended. A certain load is required to ensure the sealing effect of GCL. Hence, only a gravel-water or a soil/sand-water TES may be sealed using GCL.

Water vapour transport

The water vapour transmission determined by the ordinate intercept (Figure 6) is shown in Figure 8 (left diagram). An exponential increase with temperature can be seen. Using the water vapour transmission WVT the water vapour diffusion resistance factor μ can be calculated. Stefan diffusion applies due to the high vapour pressure. Water vapour resistance factors in the range of 5 to 20 are yielded, see Figure 8, right hand side.

According to theory the water vapour resistance factor of porous media is not a function of temperature. The fluctuations could be explained with measurement errors and the assumption of a constant thickness of the specimen. However, due to swelling or compaction the thickness of the specimens may be subject to change during the measurements.

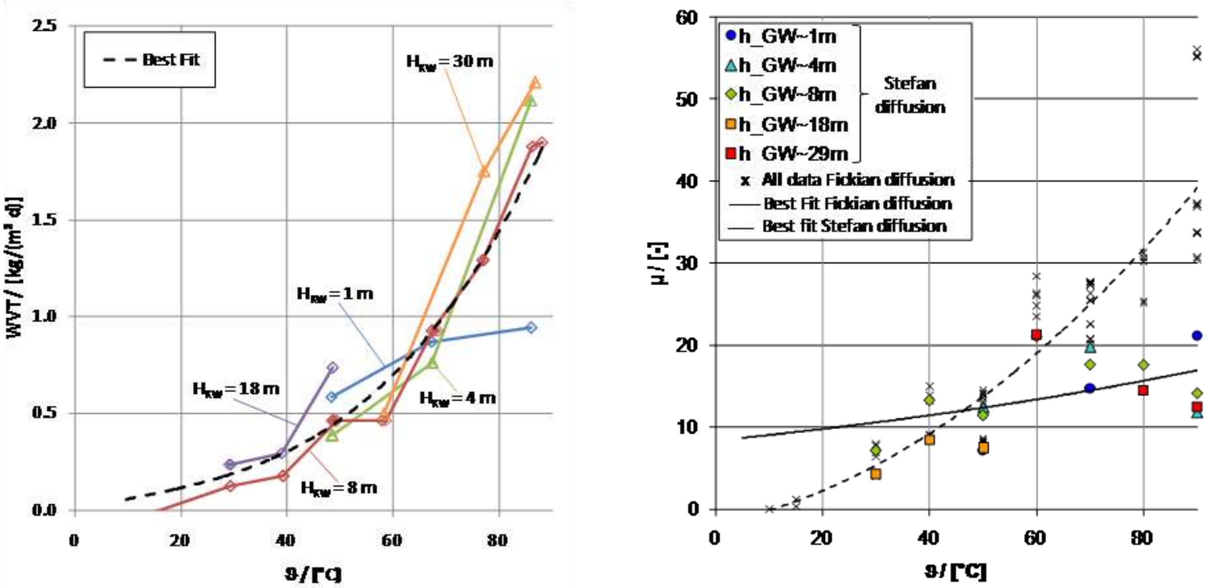

Figure 8. Water vapour transmission WVT as a function of temperature ϑ; Water vapour diffusion resistance factor μ determined according to the Fickian Law (x) and according to Stefan diffusion (filled marker)

In the case of the suggested concept, two layer of GCL, the water vapour diffusion would even be higher due to the higher pressure gradients in the case of diffusion from hot water to dry insulation.

OUTDOOR LABORATORY EXPERIMENTS

In spite of the above mentioned limits with regard to water vapour permeation, GCL offer a cost-effective alternative for the lining of a gravel-water TES. Outdoor experiments were conducted to proof the technical feasibility of the concept.

Experimental Setup

In the framework of the research project “Further Development of Pit Heat Storage Technology” several concepts and construction methods for seasonal TES have been investigated. For this purpose two research TES with roughly 150 m³ each have been built at ITW. With an extensive monitoring system a continuous measurement of storage and ground temperatures as well as the thermal losses (heat flux) through the composite wall of the research TES was conducted.

The experiment ‘controlled leakage’ with GCL was built in one of the two research pits similar to the concept shown in Figure 1. The pit, an inverted pyramid trunk with two 60° and two 80° slopes, was already entirely sealed with an EPDM liner and leakage proofed. The EPDM liner served as outer liner.

Figure 9. Installation of the GCL in outdoor laboratory

The drainage layer was built using a fleece covered geogrid embedded in a gravel drainage bed. For the pump a drainage well was placed in one corner of the pit.

The GCL was installed by overlapping the GCL in the edges of the pit as, see Figure 9. To protect the GCL from sharp edges and to distribute the load of the gravel, a 1200 g protective fleece was mounted on top of the GCL. Finally, the pit was filled with washed gravel (16/32 mm) and covered with a geomembrane and with thermal insulation. The level in the gravel-water research store was monitored continuously. The level in the drainage well was metered manually.

A simple charging and discharging system was realized by perforated PP tubes, one 50 cm above bottom and one 50 cm below top surface. The charging tubes were connected to the heating central by district heating pipes. Heating and cooling was realized by district heating and cooling. To enable heating to temperatures of up to 95 °C additionally a 170 kW gas boiler was provided.

Experimental Results

The GCL liner leaked. The level in the drainage well was equal to the level of the store. Several pumping attempts remained without success.

Deconstruction of the research store

As temperature measurements gave no indication on the location of the leakage, it was decided to deconstruct the research store. The deconstruction showed that the membranes were in good order. However several defects at the overlapping areas could be detected, see Figure 10.

Figure 10. Installation errors: left: folding at the edge of the pit; centre: fabric on fabric; right, formation of a folding due to slip of the GCL

Unfortunately, although improper installation caused the failure, the outdoor laboratory experiment could not be repeated due to shortage of budget and time.

CONCLUSIONS

The measured hydraulic conductivity is in the order of magnitude of the manufacturer information. The dependence of the height of the water column on the Darcy velocity according to theory (Darcy's Law) was confirmed by the measurements with sufficient accuracy for temperatures below 50 to 60 °C. The influence of temperature is considered by a temperature dependent dynamic viscosity.

A superposition of liquid water and vapour transport was discovered. In presence of a temperature gradient a non-negligible water vapour transport was measured. At temperatures above 50 to 60 °C the water vapour transport is even dominating. Consequently, at higher temperatures GCL are not feasible as single liner.

GCL do not offer 100% water proof sealing. For the application in seasonal TES, where the thermal insulation has to be protected from getting wet a single GCL is not a suitable solution. However, a concept with a controlled leakage would be possible using GCL in combination with a vapour barrier. Nevertheless, feasibility has to be demonstrated yet.

In addition to the proposed application as inner liner, GCL may be applied as outer liner to protect against ground water. On the outside with respect to the insulation, no significant temperature gradients occur. Hence, water vapour diffusion would not be a problem.

Acknowledgements: This project was supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit), FKZ 0329607E. The authors gratefully acknowledge this support and carry the full responsibility for the content of this paper.

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