Durability Evaluation of a Geothermal Grout

Pascal Monnot, Christophe Poinclou, Philippe Blanc, Amandine Rojo, Laurent Molez, Christophe Lanos

Durability Evaluation of a Geothermal Grout

Monnot Pascal [1], Poinclou Christophe[2], Blanc Philippe[1], Rojo Amandine[3], Molez Laurent[4], Lanos Christophe[3](*)

[1] BRGM, Direction des Geo-ressources, Orléans, France
[2] ANTEAGROUP, Olivet, France
[3] Univ Rennes, LGCGM EA 3913, Rennes, France,
[4] Univ Rennes, INSA, LGCGM EA 3913, Rennes, France,
(*) christophe.lanos@univ-rennes1.fr

Abstract. The durability of a geothermal grout used to seal vertical geothermal probe is evaluated. The study integrates an experimental approach and geochemical models simulations. The accelerated ageing of the geothermal grout is evaluated in laboratory subjecting the grout to realistic geochemical and thermal aggressions to which the grout can be subjected. The parameters related to the thermal conductivity and the permeability are particularly monitored. An experimental setting is developed to reproduce the operating conditions of a geothermic probe under realistic containment conditions. The experimental results are the input of the geochemical degradation models leading to the simulation of long time scale degradation around the probe. Conclusions relating to the service life rise from this study.

Keywords: geothermal grout, thermal conductivity, permeability, geochemical model, freeze thaw cycles.

1 Introduction

The durability of geothermal grouts is a major issue, because the construction of vertical geothermal probes (VGP) is confronted with the difficulty of "continuously and permanently" sealing the equipment (probe loops) in the boreholes drilled in the surrounding ground. In such a context, the main objectives of good cementation are to ensure the protection of the environment by avoiding surface infiltration or the connection of several aquifers, to ensure the balance of mechanical stresses in the well, but also to optimize the transfer of energy (hot and/or cold) between the subsoil and the heat exchanger. The particularity of the thermomechanical behavior of the grout in a geothermal probe is mainly related to the thermal stresses due to the operation of the heat pump (in hot or cold cycle), as well as to the peaks of operation at maximum power which can lead, in the case of an unsuitable design of the heat exchanger, to the freezing of the grout and the ground.

To guarantee, in the long term (at least for the operating time of the heat pump, if possible more), the proper sealing of the structure and the thermal performance of the geothermal installation, the grout must be able to preserve its heat transfer capacity

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

(thermal conductivity), as well as its initial mechanical properties and physico-chemical stability. The main objective of the work carried out within the framework of the DURACIM project is to characterize, at lab scale, the accelerated ageing of the geothermal grout, by reproducing the operating conditions of a geothermal probe and the geochemical stresses to which the grout can be subjected. The observed physical phenomena and the appearance of possible pathologies were coupled with a geochemical model to extrapolate, over the long term, the durability of the grout.

2 Experimental approach and model of degradation process

The methodology used to assess the durability of geothermal grouts is based on the development of two grout characterization devices: the interpretation of thermomechanical data in relation to accelerated aging of samples in the laboratory and the development of two geochemical models to extrapolate accelerated aging over a 25-year period. On the experimental level, the project is structured around two major axes:
- The development of a coupled device, allowing to reproduce, on a reduced scale, the operating context of an VGP under conditions close to those of a borehole at a depth of ~200 m. This device makes it possible to recreate the grout containment conditions in a steel oedometric cell, under thermal, hydraulic and constant mechanical stress (Figure 1).
- The evaluation of the degradation conditions of geothermal grout samples by dissociating the different alteration mechanisms (decoupled device). This device allows the grout samples to be immersed in a thermo-regulated bath, filled with more or less aggressive solutions, under atmospheric stress. 3 types of solutions are used: tape water, water saturated with gypsum, water with sulfuric acid to ensure a sulfur content close to the higher content quoted in French groundwater.

The study was carried out on a grout produced by an industrial partner (Heidelberg Cement). The commercial product chosen is Thermocem, which is representative of the products available on the market. Grout durability is assessed by analyzing the evolution of two performance indicators:

- Thermal conductivity (λ), a parameter that influences the ability to transfer energy (hot - cold) from the ground to the heat transfer fluid of the geothermal probe, and thus the performance of the geothermal installation;
- Water permeability (K), a parameter that influences the grout's ability to prevent possible contamination from the surface into groundwater, but also to avoid connecting possible aquifers, and thus protect the environment.

The analysis and monitoring of the evolution of these two parameters is carried out on grout samples that have undergone thermal stress, freeze-thaw cycles and chemical aggression. As references, a number of studies have studied the influence of grout composition on its thermal conductivity: relative contents of pure cement, bentonite, water and quartz [1][2][3][4], even graphite [5][6]. These studies show that a grout mainly composed of sand, cement and water, with a very high sand/water mass ratio (between 2.0 and 2.4), has a thermal conductivity of about 2.3 $W.K^{-1}.m^{-1}$. The thermal conduc-

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

tivity of this material is not very sensitive to water content (desiccation), unlike bentonites or cements [7]. [3] Measured the hydraulic conductivity of a sample of this grout contained in a polyethylene (PE) tube and found it to be between 10^{-9} and 10^{-7} m.s^{-1}.

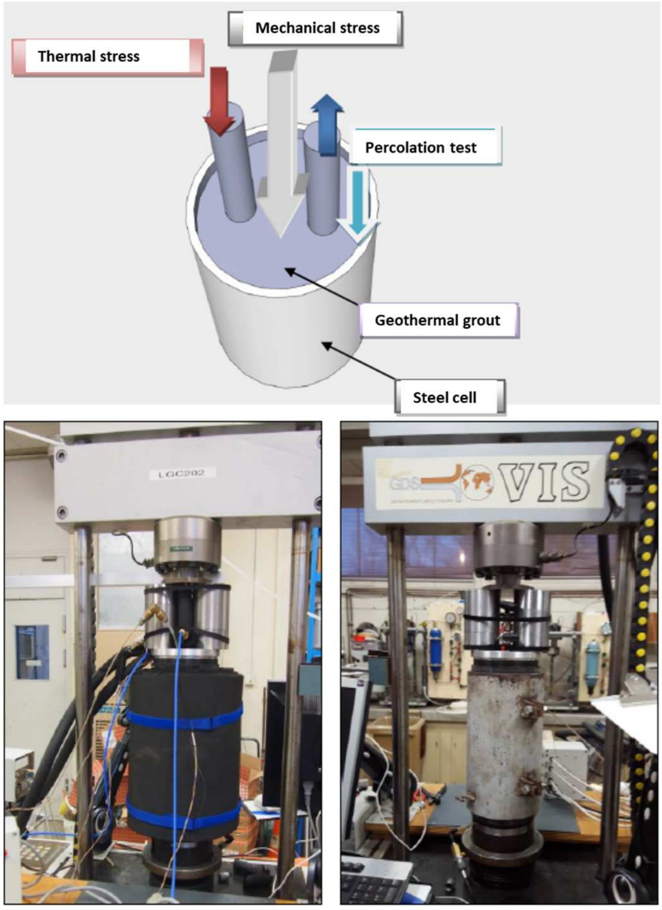

Fig. 1. Conceptual design and development of the oedometric cell.

In parallel with the development of the two experimental devices, two geochemical models are being developed [8]:

- The first, called the "grout model", is a geochemical model of grout alteration without chemical element transport. This model takes into account the influence of temperature as well as the different chemical solutions in contact with the grout. The model provides the mineralogical composition and the composition of the solution obtained after a theoretically infinite time. This model makes it possible to locate the changes in the parameters analysed as a function of time.

- The second geochemical model, called the "alteration model", allows the production of calculations with different hydrogeological context scenarios. Based on the results obtained on the test pilot (coupled device), the first geochemical model (grout

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

model) was completed by integrating a transport component, in order to simulate the percolation of the solution and the consequences on the chemical stability of the slurry. Taking into account the diffusion/advection of the percolation solution makes it possible to introduce a kinetic component into the simulation. The calculations carried out make it possible to evaluate the consistency between the physical parameters measured and the evolution of the chemical and mineralogical parameters.

3 Results

3.1 Grout properties

At fresh state, the density and the viscosity of the slurry are controlled. The fresh density is 1460 kg.m^{-3} and the Marsh flow time is 60 s. The water to binder ratio is 0.8. The slurry is casted to shape blocks 210 x 350 x 250 mm^3. The setting time is about 20 h. The blocks are sealed and placed in room at 100% relative humidity. Some measurements made on the reference hydrated product highlight the homogeneity of the samples core drilled in the top and bottom of cast blocks and the reproducibility of the measurements performed on 100 mm and 50 mm diameter samples. The hydrated product has a low density (in a saturated state): 1580 kg.m^{-3}. The propagation velocity of the compression and shear waves is 2340 m.s^{-1} and 1660 m.s^{-1} respectively. The Poisson coefficient thus obtained is 0.31°±°0.04. The elastic moduli then calculated are in the order of 5000 MPa. These results are in the same order than those obtained by acoustic resonance measurements. The thermal dilation coefficient is measured: 25.10^{-6} K^{-1}. This value appears high and remains eight time lower than the thermal dilation coefficient of HDPE used as pipe for the probe.

3.2 Coupled device

Several tests were performed in the coupled device. In order to reproduce the operating conditions of a VGP, during a test, different temperature cycles were performed, which could lead to freezing and thawing of the grout. During the test, a vertical load is applied to the grout and the upstream and downstream fluid pressures are controlled to generate a vertical gradient of fluid pressure. Temperatures are measured at different points in the grout section. The material studied is of very good quality and no alteration in its performance (from the perspective of a geothermal application) could be observed.

3.3 decoupled device

In the decoupled device, different degradation conditions are studied: in the first case, the grout samples are exposed to different aggressive solutions (water, gypsum water, acid water) under isothermal temperature conditions; in the second case, in addition to the aggressive solutions, the samples are exposed to freeze/thaw cycles (Figure 2). Sample density and acoustical velocity are not specifically changed during the freeze thaw cycles or during immersion in aggressive solutions.

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

Fig. 1. Left: Condition of specimens after each freeze-thaw exposure cycle (high: water, centre: gypsum water, down: acid water) - Right: Illustration of the conservation of the cores immersed in the trays placed in the thermo-regulated boxes during a test in isothermal condition (left: water, centre: gypsum water, right: acid water).

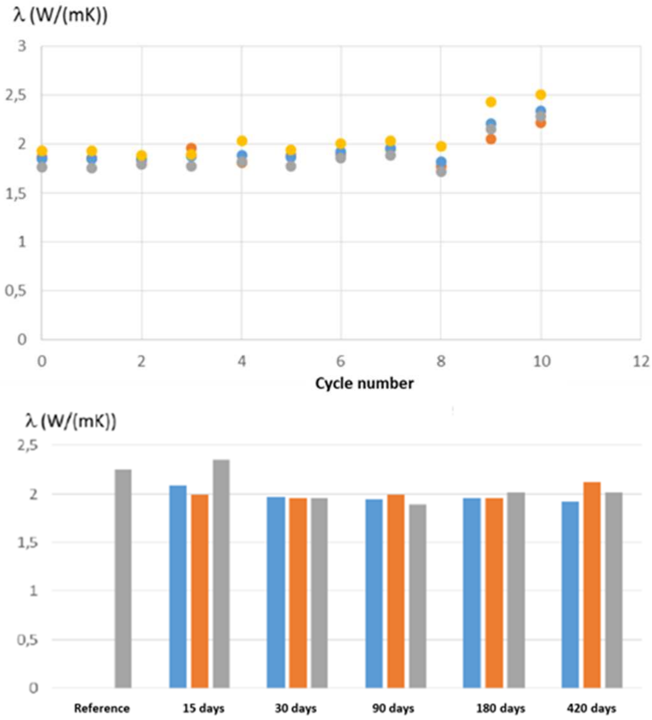

Fig. 2. Evolution of thermal conductivity - Top: after each freeze-thaw cycle for the three storage media - Down: at each maturity for the three storage media. Solution type: blue = water, orange = gypsum water, grey = acid water, yellow = x10 stronger acid water.

Thermal conductivity is measured after different exposure periods or freeze/thaw cycles. The thermal conductivity is measured under submerged conditions by the hot wire method in transient conditions. The standard deviation remains less than 10%. The results indicate that there is very little evolution, whether in the presence of freeze/thaw cycles or not (Figure 3). The thermal conductivity remains higher than 1.5 $W.m^{-1}.K^{-1}$ under freeze/thaw conditions, and around 2 $W.m^{-1}.K^{-1}$ under isothermal conditions

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

whatever the type of aggressive solution. This value is in the same order than the data in the literature and complies with the current standard [9].

Water permeability is measured initially and then after different time periods. The measurement is carried out in a triaxial cell under a pressure gradient in steady state (800 kPa confinement and 10 m hydraulic gradient). The results indicate in all cases that the permeability remains below 10^{-9} m.s^{-1}. Same types of results are obtained after freeze/thaw cycles. There is no clear evolution with time or with type of immersion, as clogging and unclogging phenomena certainly occur due to the precipitation and dissolution of chemical species in the porosity during the phases of curing/alteration.

Mechanical tests are carried out at constant displacement speed (2.5°mm.min^{-1}) on samples after immersion in aggressive solutions. Reference compressive strength at 28 days is 6 MPa but the mean value obtained during this study is 4 MPa. The performances appears quite not influenced by the type of solution used for immersion. The most interesting behavior quoted during the test is presented on figure 4 in the case of a cyclic compression test. The calculated stiffness is different between the beginning of the test and before the mechanical cycles performed. We observe an evolution of stiffness from one series of cycles to another (increase). However, the calculated stiffness is identical for a given series. This phenomenon is not observable for the third cycle presented because the material is already severely damaged. A phenomenon of material compaction is then observed. To complete the study, a creep test is performed at a stress of 2.5°MPa (50 % of compressive strength) on a specimen with a slenderness of 3 over a period of 100 minutes. The creep deformation reaches 600°µm.m^{-1}, which corresponds to a specific creep of 240°µm.m^{-1}.MPa^{-1}. This is certainly due to the migration of water into the material and compaction of the material: horizontal compaction bands are observed at the end of the test. The ductility of the grout favors the sealing of potential cracks.

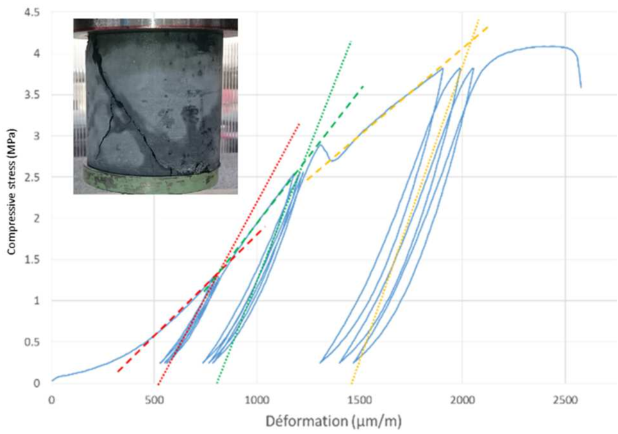

Fig. 4. Cyclic compression test on 28 days old specimen with a slenderness of 1.

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

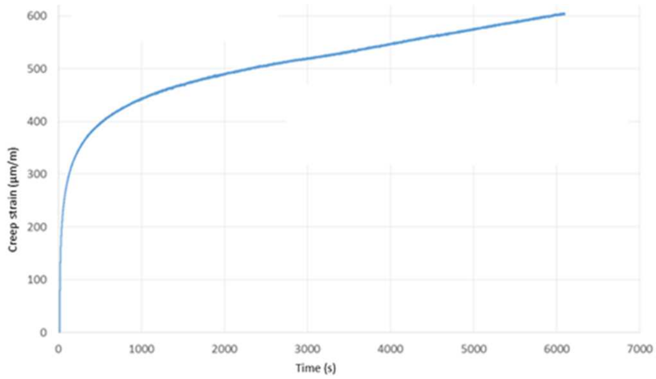

Fig. 5. Creep test on 28 days old specimen with a slenderness of 3.

3.4 Geochemical models

Geochemical models work with data evaluated from experimental developments (mineralogy, porosity, diffusion, diffusion coefficient, etc.). The models are in agreement with the small changes observed experimentally. SEM additional profiles performed on hydrated samples for 1 year seem to be in overall agreement with the model predictions. In addition, the model shows an agreement between the compositions of the solutions of the conservation baths acquired after one month and after one year of hydration, which supports the approach. From the point of view of the results of geochemical models, we can see that the only geochemical modeling applied to the evolution of thermal conductivity (λ) predicts an increase at the interface with the solution. But it also predicts, after 30 years (figure 6), a total disappearance of the hydraulic binder, in an area whose extension depends on the envisaged scenario (1 cm to 4 cm).

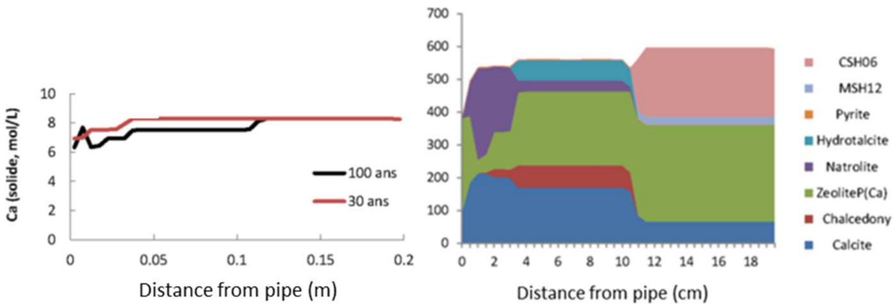

Fig. 6. Results obtained with the "alteration model". Left: Solid calcium concentration in grout versus probe pipe – Right: distribution of mineral composition (in $cm^3.L^{-1}$) after 100 years.

4 Conclusions and perspectives

The study showed that the experimental devices were suitable for studying the durability of vertical geothermal probes. The coupled and decoupled devices allow to study

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126

the phenomena of alteration of geothermal grouts with a good reproducibility of measurements. The material studied was of very good quality and no deterioration in its performance (from the point of view of geothermal application) could be observed. An intrinsic variability in the material may have masked the changes in the studied properties. However, geochemical models indicate possible alteration of the hydraulic binder in 30 years close to the probe pipe.

In terms of prospects, the following work is planned:

- Continue experiments on Thermocem grout over longer periods and/or a greater number of freeze-thaw cycles to identify the durability limits of this material;
- Apply the protocols established during this research project to different types of grout (geothermal or not), compositions and sources;
- Evolve protocols for standardization: identify the main parameters that influence the durability of a grout, possibly reduce protocols accordingly and propose a standard operating procedure routinely usable.

Acknowlegments

Duracim project was funded in the frame of the ADEME-BRGM-Université Rennes 1 agreement n°1405C0037.

References

1. Tang, A-M., Cui, Y-J. et Le, T-T.: A study on the thermal conductivity of compacted bentonites. Applied Clay Science, Vol. 41, pp. 181-189 (2007).
2. Park, M., et al. : Applicability of cement-based grout for ground heat exchanger considering heating-cooling cycles. SCIENCE CHINA - Technological Sciences, Vol. 54, 7, pp. 1661–1667 (2011).
3. Allan, M. L.: Materials characterization of superplasticized cement±sand grout. Cement and Concrete Research. Vol. 30, pp. 937-942 (2000).
4. Lee, C., et al. : Characteristics of thermally enhanced bentonite grouts for geothermal heat exchanger in South Korea. SCIENCE CHINA Technological Sciences, Vol. 53, 1, pp. 123-128 (2010).
5. Jobmann, M. et Buntebarth, G.: Influence of graphite and quartz addition on the thermo–physical properties of bentonite for sealing heat-generating radioactive waste. Applied Clay Science, Vol. 44, pp. 206-210 (2009).
6. Delaleux, F., et al. Enhancement of geothermal borehole heat exchangers performances by improvement of bentonite grouts conductivity. Applied Thermal Engineering. , Vol. 33-34, pp. 92-99 (2012).
7. Perry, R.L.et Smith, M.D.: Borehole grouting: field studies and thermal performance testing. ASHRAE Transactions, Vol. 105 (2009).
8. Blanc, P., Bourbon, X., Lassin, A., Gaucher, E.C.: Chemical model for cement-based materials: Thermodynamic data assessment for phases other than C–S–H. Cement and Concrete Research 40:1360–1374 (2010).
9. Standard NF X 10-970 « Forage d'eau et de géothermie – Sonde géothermique verticale (échangeur vertical en U avec liquide caloporteur en circuit fermé) » (2011).

Monot et al., 2019, Durability Evaluation of Geothermal Grout,
C. Ha-Minh et al. (eds.), CIGOS 2019, Innovation for Sustainable Infrastructure, Lecture Notes in Civil Engineering 54,
https://doi.org/10.1007/978-981-15-0802-8_126