Advanced materials and improvements for borehole heat exchangers - Final results from project GEOCOND

Javier F. Urchueguía[1], Burkhard Sanner[2], Rosa Gonzalez[3], Giedrius Zirgulis[4], Ayten Çaputçu[5], Burçu Saner Okan[6], Antonio Bayonas[7], Flavia Bartoli[8], Michael Shuster[9], Borja Badenes[1], Miguel Á. Mateo[1], Hossein Javadi[1]

[1] Instituto de Aplicaciones de las Comunicaciones Avanzadas, ITACA, Universidad Politécnica de Valencia, Camino de Vera s/n; ES-46022 Valencia, Spain

[2] UBeG GbR, Reinbergstr. 2, D-35580 Wetzlar, Germany

[3] AIMPLAS- Plastics Technology Centre, Calle Gustave Eiffel, 4 Parque Tecnologico de Paterna, ES-46980 Paterna/Valencia, Spain

[4] RISE-CBI, Drottning Kristinas väg 26, SE-10044 Stockholm, Sweden

[5] ÇİMSA SA, Toroslar Mah. Tekke Cad., Yenitaşkent, TR-33013 Mersin, Turkey

[6] Sabançı University, Orhanli Tuzla, TR-34956 Istanbul, Turkey

[7] CAUDAL, Autovía del Mediterráneo KM 661, ES-30890 Puerto Lumbrera, Murcia, Spain

[8] Spin-PET srl, viale R. Piaggio 32, I-56025 Pontedera, Italy

[9] Carmel Olefins, Hahistadrut Avenue, P.O.Box 1468, IL- 31014 Haifa, Israel

Correspondence: jfurchueguia@fis.upv.es , b.sanner@ubeg.de

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ABSTRACT

Advanced materials for borehole heat exchangers (BHE) were developed in project GEOCOND. Material scientists, manufacturers, and geothermal experts cooperated in thinking of new approaches for pipes and grouts with improved properties, starting from research at a low Technology Readiness Level (TRL).

The pipe development resulted in a material based on polyethylene with substantially increased thermal conductivity and exhibiting longevity and similar ease of handling as the classic PE100. Development of grout for sealing the BHE annulus led to a further increase of thermal conductivity beyond the current state-of-the-art while maintaining handling and sealing properties and showing resilience to freezing-thawing cycles. Another development concerned the addition of phase-change material (PCM) into the grout to increase the short-term thermal storage capacity of a BHE.

The new material was first tested in the laboratories, including tests for BHE with PCM-grout in a "sandbox" at RISE Stockholm. Then sufficient material was produced to manufacture pipes and grout for shallow tests at a test field at UPV in Valencia (10-15 m deep BHE). Results from these tests allowed for the selection and improvements of the final materials, produced in a sufficient amount for real-size tests. Two BHE of 100 m depth with pipes and grout of high thermal conductivity were installed and tested in Germany, and one BHE of 50 m with PCM grout for storage temperatures at 50-60 °C was installed in Sweden. The results for high thermal conductivity confirmed a reduction of the borehole thermal resistance of >20 % compared to a BHE with state-of-the-art materials at the same site, while the PCM-test was less conclusive and needed further evaluation.

The development was accompanied by surveys of appropriate target values for thermal conductivity (incl. the use of Geographic Information Systems, GIS) and the work on a digital material selection support system. Life cycle analysis of energetic, economic, environmental, and social impacts have been performed and proved the viability of the developed materials and concepts, provided the expected cost reductions in mass production can be achieved. With GEOCOND materials, either improved efficiency due to better ground-side temperature developments could be achieved, or substantial reductions in required BHE length while maintaining the efficiency of a design with standard materials.

In the tests within the project, the materials fulfilled the different requirements set by standards and regulations. However, for grout and pipes to be brought to the

market, further work is required for testing and certification, for optimization of manufacturing, and most importantly for cost reduction.

This paper focusses mainly on the development and the testing of the full suite of new materials.

1. INTRODUCTION

In the framework of the European GEOCOND project "Advanced materials and processes to improve the performance and cost-effectiveness of shallow geothermal systems and underground thermal storage", new advanced materials for borehole heat exchangers (BHEs) have been developed. The project, formed by a consortium of leading companies and research institutions in the field of Shallow Geothermal Energy Systems (SGES) and advanced material manufacturing, was focused on four key development areas in a synergistic and system-wide approach: new pipe materials, advanced additives and grouting concepts, advanced Phase Change Materials (PCMs) and system-wide simulation and optimisation.

2. PIPE DEVELOPMENT

Two compounds for pipes with enhanced thermal conductivity were used: Compound 1 (with expanded graphite, EG) and Compound 2 (with EG + nanographite, NG). Also, pipes with low thermal conductivity were manufactured, e.g. for the upper part of a BHE or as inner pipes for complex coaxial geometries.

The maximum thermal conductivity achieved in laboratory samples was almost 1.2 W/(m·K). For the full-size BHE, pipes with about 1.0 W/(m·K) of thermal conductivity were produced (Figure 1). The mechanical properties, longevity, handling and welding should be as similar to standard PE100 as possible.

Figure 1: Pellets of Compound from Extruder at SILMA facilities (upper left), foot of a complete BHE manufactured by CAUDAL (lower left) and part of the coiled BHEs after arrival in Germany (right).

3. GROUT DEVELOPMENT

The objectives of GEOCOND project were the development of new products that will increase the thermal efficiency or reduce the need for drilling in a shallow geothermal installation. Two types of application were targeted:

- BHE grout with high thermal conductivity (Table 1)
- BHE grout for thermal energy storage, providing enhanced latent heat with a given phase change temperature, achieved through the incorporation of PCM (Table 2 for the high temperature variant)

The proposed GEOCOND solutions matched the target grout properties and met the requirements that are specified in member countries of the EU.

Table 1: Evaluation of new grout with high thermal conductivity for borehole testing in Germany (lab test values).

	Target	Test	Status
Water to cement ratio	n/a	1.02	–
Marsh Cone time (sec)	50–100	102	Pass
Flow (cm)	26–30	31.1	Close
Bleeding of water (%)	<2	0.8	Pass
Density (g/cc)	>1.3	1.8	Pass
Segregation/Settlement	No	No	Pass
Compressive strength 7 days (MPa)	> 1.0	13.86	Pass
Thermal conductivity W/(m·K)	>2.0	2.174	Pass
Freezing-thawing resilience	VDI 4640-2, Annex E		Pass

Table 2: Evaluation of new grout with enhanced latent heat for borehole testing in Sweden (lab test values).

	Target	Test
Water percentage by weight of dry mix (%)	n/a	45
Marsh cone time (sec)	80–120	110
Flow (cm)	26–30	34.25
Density (g/cc)	>1.3	1.45
Bleeding of water (%)	<2	0.74
Compressive strength 7 days (MPa)	> 1	8.33
Latent Heat (J/g)	n/a	20
Thermal conductivity at 35 °C (W/(m·K))	> 1.0	1.192

The exact composition of the grout cannot be given due to IPR considerations; the main components are cement, sand, expanded graphite, and additives. The properties of a lab sample of grout with very high thermal conductivity, higher than that achieved in the production mixing for larger quantities for field testing (cf. Table 1) and showing the theoretical possibilities, are given in Table 3. The composition of grout with PCM is based on the same components as for high thermal conductivity, with different ratios, and the addition of the PCM (either shape-stable or micro-encapsulated). The exact type of PCM varies according to the intended target temperatures.

Table 3: Properties of high thermal conductivity grout produced in lab in small batches.

Property	Result
Marsh Cone time (sec)	93
Flow (cm)	33.2
Bleeding of water (%)	0
Density (kg/m^3)	1960
Segregation/settlement	no
Compressive strength 7 days (MPa)	13.89
Thermal conductivity W/(m·K)	2.67

For the field tests, several tons of dry grout mix had to be prepared. As can be seen in Figure 2, badges of about 1 ton can be mixed in the facility used, situated in Germany. Sand was taken directly from the silo by screw conveyor, cement from big bags as delivered from Turkey was loaded through a dedicated hopper, and the other ingredients were weighed and added by hand. Mixing started with the grout of high thermal conductivity for use in Germany (without PCM) and finished with the mixing of dry grout for use in Borås, Sweden (with PCM).

Figure 2: Mixing facility in Treis, Germany.

Along with the preparation of grout, freezing-thawing tests were done with two variants of the improved material. Resilience to freezing-thawing cycles is crucial to use the GEOCOND grout in Central European GSHP systems with fluid temperatures that often fall below 0°C. UBeG had developed, with KED, Hamburg, a procedure and apparatus for this test that became the basis for stipulations in VDI 4640-2, Annex E. Three samples per variant were prepared in moulds, each with a piece of standard PE100 pipe in the centre (Figure 3, bottom), and set aside for curing. The test apparatus consists of 3 tri-axial cells for 3 parallel tests (Figure 3, top).

A total of 9 freezing-thawing cycles were performed. VDI 4640–2 states a maximum increase in permeability of one order of magnitude for the whole system (cell walls, grout and pipe) before freezing, starting from a permeability of 1×10^{-9} m/s for the grout alone. All samples met that criterion, with samples 2 and 3 even showing a reduction in permeability over the full cycles. The deviation among the last two consecutive values was much lower than 15% as allowed according to the guideline (Table 4). Hence, it can be stated that the mix of the GEOCOND grout is resilient against freezing-thawing cycles in the sense of guideline VDI 4640–2.

Figure 3: Tri-axial cells with samples of grout mix, seen at the end of a freezing phase (top) and samples of grout mix with central PE pipe, removed from the tri-axial cells after the end of the test cycles (bottom).

Table 4: Freezing-thawing resilience of high thermal conductivity grout mix.

Grout mix, sample	Start value (m/s)	End Value (m/s)	Total increase (m/s)	Deviat. last 2 cycles
1	6.54×10^{-9}	8.90×10^{-9}	2.36×10^{-9}	-0.34%
2	4.21×10^{-9}	8.98×10^{-10}	-3.31×10^{-9}	0.89%
3	4.47×10^{-9}	2.98×10^{-9}	-1.49×10^{-9}	7.38%
Average	5.07×10^{-9}	4.23×10^{-9}	-8.14×10^{-10}	2.65%

4. THERMAL TESTS

4.1 Sandbox in Sweden

As in interim stage between the lab tests and field tests, and continuing during the field tests for investigations into details, a large-scale lab test in a sandbox of 1 m^3

was set up at the RISE facilities in Stockholm. Figure 4 shows the principle; in a first step, tests with 1 grout and pipe combination were done, and later on, the setup was changed to 4 parallel grout/pipe installations in order to allow more different materials to be tested (Figure 5).

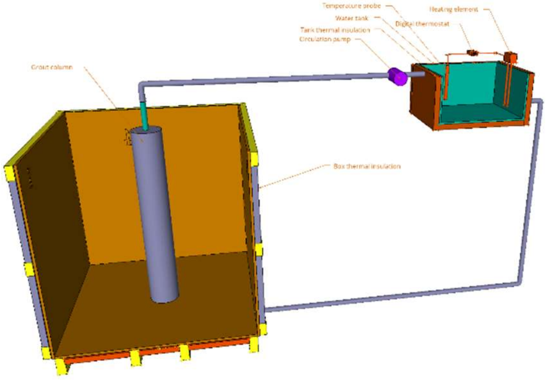

Figure 4: Schematic depiction of the "sandbox" test rig.

Figure 5: The four-columns "sandbox" test set up; filling with sand and saturating with water (upper photo) and test connected and closed, with thermal insulation of pipes and hoses (lower photo).

The results showed much higher efficiency of the grout developed with high thermal conductivity compared to the commercial reference grout in terms of heat transfer in both the grout column and the surrounding sand. Furthermore, the results showed noticeable influence of the PCM used in the respective grout formulations in terms of heat absorption/storage during the phase transition (from solid to liquid).

In addition, the results revealed the significant influences of the grout-pipe and the grout-formation interfaces on the heat transfer and the overall performance of the system.

4.2 Test field in Spain

The implementation of enhanced materials for pipes, grout, and new geometric distribution was done at the UPV test site in Valencia, Spain. Seven borehole heat exchangers (Table 5), with developed materials and new geometries, were applied to the testing laboratory at UPV. A new geometrical configuration is also implemented which is a hybrid between U-tube and the radially symmetric coaxial design. Figure 6 shows the situation after installing BHEs and restoring the surface.

Table 5: BHE properties in the UPV test field.

No.	BHE type	Pipe	Grout	Bore-hole Ø (mm)	Eff. depth (m)
2	Single U	EG	F1a	140	13.5
3	Single U	EG + NG	F1a	140	12.0
4a	New config	EG	F1a (BB)	220	10.5
4b	New config.	EG + NG	F1a	220	11.5
5	Single U	PE100	F1a	140	11.4
6	Single U	PE100	Cro PCM	140	11.8
7	Single U	PE100	Car PCM	140	13.0

Figure 6: Finished BHE field with restored surface and location of BHEs indicated at UPV test site.

The 7 GEOCOND BHEs located at Valencia can be divided into 5 single-U BHEs and 2 BHEs with new geometrical configuration. The cross-section of a single-U-BHE is illustrated in Figure 7. All BHEs are connected to a thermal test rig in the field laboratory building (Figure 8). In addition to the hydraulic connection, the sensors and electronic instruments were connected between the new boreholes and the test laboratory. To aid the design of the control system, the test site operation was simulated using TRNSYS 16.1 software, which is capable of designing and studying the thermodynamic performances of any hydraulics system. The basic constituents of the simulated plant are an air-water heat pump; a storage tank; and the BHE(s), reflecting the real installation. It was important to implement a model that effectively simulates the future operational conditions "on field" thus to determine the optimal configurations of the system.

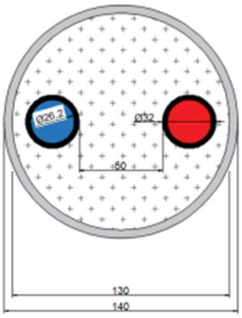

Figure 7: Cross-section of single U boreholes.

Figure 8: Connection of pipes from new BHEs to the control unit inside the UPV laboratory.

The main goal of the thermal tests is to determine the thermal conductivity of the ground and the thermal resistance of the BHE. The thermal conductivity results were compared with other previous thermal experiments, and the thermal resistance of the BHE allows for identifying improvement due to the new geometric distribution pipe, new materials implemented in pipes, and new grout mixtures. The TRTs delivered a temperature curve over time for each BHE. As the specific heat injection was set to the same value of 80 W/m for all BHE, the improvement in the heat exchange efficiency can be easily observed qualitatively when comparing the temperature curves (Figure 9). The higher the temperature increases, the lower the heat dissipation from the fluid in the pipes into the ground. As expected, the highest temperatures are found with the standard reference BHE, much lower ones with BHE 3 (both new pipes and grout), and the lowest with BHEs 4a and 4b, with the new geometrical configuration. Of course, the ones with PCM (BHE 6 and 7) cannot be compared to the rest. Repeated TRTs confirm the quality of the measurements and the test principle; the best example is BHE 3, where temperature curves for both cases fall onto each other.

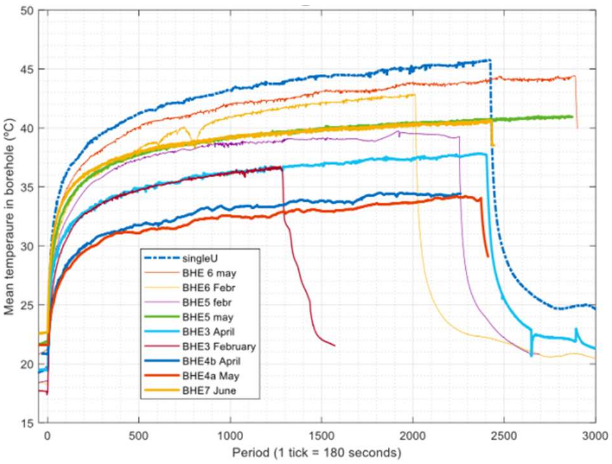

Figure 9: Summary of all TRTs performed at UPV laboratory.

4.3 Germany

The objectives of thermal tests conducted in Germany firstly were to prove that the materials can be produced, handled, and installed for real-life dimensions and environments and that the improvements shown in lab measurement and small-scale tests can also be identified in the full-size, real-life situations. Two sites were selected for drilling and installation: a location in Eastern Germany (A), where drilling and installation for one double-U BHE with GEOCOND materials and one reference BHE with standard materials were conducted, and a location in North-Western Germany (B), where drilling and installation for one single-U BHE with GEOCOND materials could done and existing BHE with standard materials could be used as reference. The two sites are located within different geological settings. One exhibits unconsolidated sediments of low thermal conductivity (A), the other consolidated Mesozoic sediments of average properties (B). Table 6 shows the key parameters of the reference BHE and the GEOCOND BHE in site A, and Figure 10 depicts the BHE installation and geological situation.

Table 6: Key parameters of the two BHEs in site A.

	Reference BHE	GEOCOND BHE
Depth	99.5 m	100 m
Drilling diameter	152 mm	152 mm
BHE type	Double-U	Double-U
Pipe material	PE 100, 32×3 mm	Compound 1, 32×3.6 mm
Expected pipe TC	0.42 W/(m·K)	1 W/(m·K)
Grouting material	Stüwa Therm© 2000 Z	GEOCOND high-TC grout
Expected grout TC	2.0 W/(m·K)	2.7 W/(m·K)

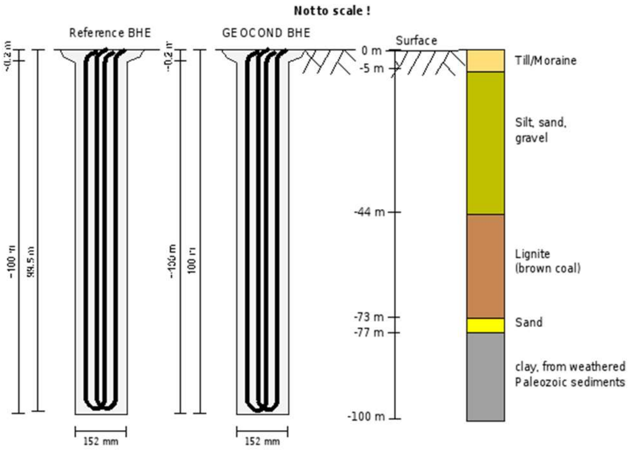

Figure 10: Final BHE installation in site A and geological column as found during drilling.

A weight was attached to the bottom end of the BHE pipes, and the insertion of the BHE pipes was done from a reel lifted above the borehole, as stipulated in VDI 4640–2 (2019) (Figure 11). The GEOCOND double-U-BHE could be installed to a depth of 100 m as planned. There were no noticeable differences in the handling of the GEOCOND BHE compared to standard PE100 pipes. Grouting was started immediately after the insertion of the BHE pipes was completed.

Figure 11: Insertion of GEOCOND double-U pipe from reel lifted above borehole.

Mixing of the GEOCOND grout with the colloidal mixer was effective and close to mixing in the laboratory (Figure 12). The average density of 1625 kg/m^3 and Marsh-funnel time of 53 seconds are lower than the laboratory values (which had used less water), but still in the range applicable for grouting in Germany as given in VDI 4640–2 (2019).

Figure 13 depicts the BHE installation in site B and the geological situation. Grouting was started immediately after the insertion of the BHE pipes was completed. The same colloidal mixer with an injection pump as in site A was used, while a different approach was tested for the water content (Table 7).

Figure 12: GEOCOND grout in the colloidal mixer (left) and exiting the borehole top (right).

Table 7: Amount of water for 100 kg dry mix for grouting the GEOCOND BHE in site B.

Batch #	Water	Dry mix
1 and 2	36.4 l	100 kg
3 – 5	40.0 l	100 kg
6 – 11	42.0 l	100 kg

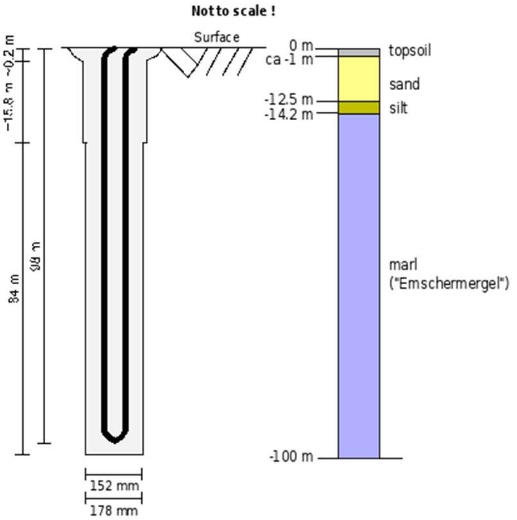

Figure 13: Final BHE installation in site B and geological column as found during drilling.

For the tests in site A, a mobile TRT rig from UBeG was brought to the site (Figure 14, left). An additional logging unit for readings directly at the BHE head in a higher time resolution was used here and in site B. A different mobile TRT rig from UBeG was brought to site B (Figure 14, right).

Figure 15 shows a comparison of the development of mean temperature between the inlet and outlet during both TRTs at site A. As could be expected, the temperature increase in the GEOCOND BHE is much less than in the reference BHE.

Figure 14: UBeG mobile TRT rig at the reference BHE in site A (left) and a smaller rig at the GEOCOND BHE in site B (right.

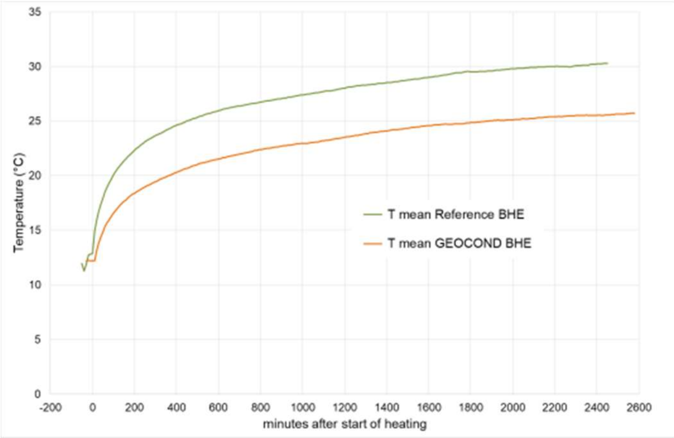

Figure 15: Comparison of mean temperature development during TRTs at site A.

4.4 Sweden

The benefits of including PCMs in grouts for underground storage (UTES) at elevated temperature for district heating systems were evaluated in a suitable BHE site. Sufficient heat supply was identified at a RISE facility in Borås (Sweden). While in a real-life installation for underground thermal energy storage (UTES) at temperature levels for district heating (DH), in the order of more than 70 °C, plastic materials with high temperature resistance would be required (e.g. PEX or Polybutene), PE100 pipes were chosen here due to cost reasons. The expected lifetime of these pipes when subjected to temperatures around 70 °C is about one year, which is well exceeding the period required for the different tests. CAUDAL provided a factory-welded single U-tube BHE with pipes of 40 mm outer diameter and 3.7 mm wall thickness (PE100 DN40).

After drilling to 50 m depth, the BHE pipe was inserted into the borehole with a single PE pipe for injecting the grout (“tremie pipe”). The grouting was done by mixing the dry grout from sacks with water in a mixing and pumping rig (Figure 16) and pumping the grout slurry down the tremie pipe to the bottom of the borehole. As grouting is not mandatory in Sweden and thus only rarely done, no colloidal mixer was available for the Borås installation. This means that the rheological properties of the wet grout might fall short of the desired laboratory values; luckily, the properties of PCM are not affected by that.

Figure 16: Grout mixing and injection at RISE Borås.

Figure 17 shows a schematic of the final BHE and related geology. PE pipes were connected to the fittings and laid in a trench to the building wall. The connection pipes are insulated with a styrofoam jacket, and additional insulation material was used to protect the pipes until the backfilling of the trench later on. Temperature sensors exist both at the DH heat exchanger and the top of the BHE, with flow volume measured at the DH heat exchanger. Also, the control of flow and temperature difference is done at the heat exchanger.

Before starting the tests to investigate the functioning of the PCM within the grout, the thermal conductivity of the ground surrounding the BHE had to be determined by TRT. For the case in Borås, it was decided not to bring a mobile TRT rig to the site but to use instead the heat source and sensors required for the subsequent PCM test.

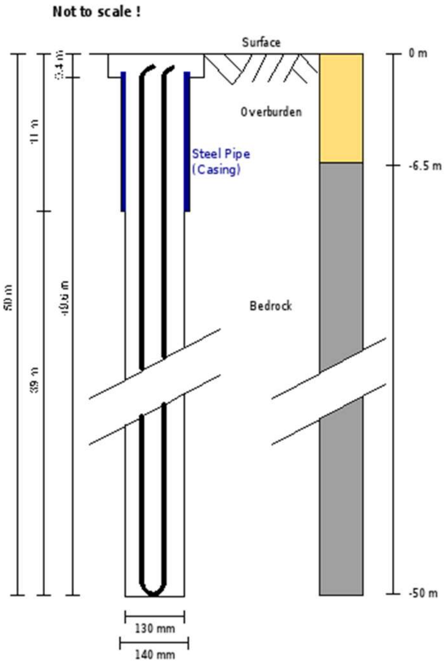

Figure 17: Final BHE installation in Borås and geological column as found during drilling.

The first test cycle for temperatures traversing the PCM activity range was started with heat injection supplied by the heat exchanger in the building and a target heat injection rate at the head of the BHE of 12 kW. Table 8 summarises the primary operational data from the four PCM test cycles. Controlling the heat injection rate was tricky and required manual intervention. The fluctuations were more substantial with a higher heat injection of 12 kW than with 6 kW and 5 kW, respectively, as with the TRT.

Table 8: Overview of the 4 PCM test cycles done in Borås.

Number of test cycles	Duration of heating	Injection rate			Temperature	
		Target	maximum	average	target	maximum
1	18.7 h	12 kW	16.8 kw	10.9 kW	70 °C	71.48 °C
2	48.3 h	12 kW	11.3 kW	10.8 kW	70 °C	70.96 °C
3	59.3 h	12 kW	14.4 kW	10.6 kW	70 °C	70.18 °C
4	27.9 h	6 kW	7.2 kW	6.5 kW	45 °C	48.11 °C

After PCM test cycle 1, which due to the strong fluctuations in the heat injection rate, could not be evaluated meaningfully, the heat supply system was changed to electric resistance heating. This was possible due to the shorter depth of the BHE installed (50 m) than initially planned (100 m), resulting in lower heat demand to reach the target temperature. The electric heater allowed much more suitable control, and fluctuations were substantially reduced. Two PCM test cycles (2 and 3) were performed using identical target values, 12 kW heat injection, and about 70 °C inlet temperature to the BHE. Temperature development is close in both cycles (Figure 18).

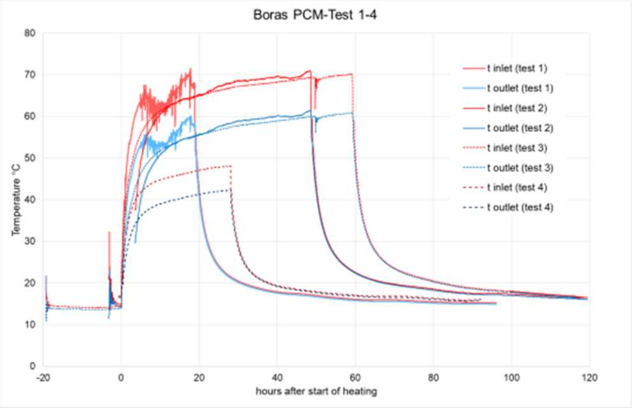

Figure 18: Temperature development over each of the four thermal tests in Borås.

In both cycles, however, no definite proof of PCM activity was achieved at first sight. Possible temperature plateaus are visible in PCM test cycle 2 when inlet temperature exceeds 65 °C and, to a lesser extent, in PCM test cycle 3 at more than 68 °C. In the first case, there is also a simultaneous drop in the output of the electric heater, probably due to a voltage drop during the beginning of work in the morning, offering an alternative explanation for the clear plateau. Another instance of PCM activity could probably be seen after heating in PCM test cycles 2 and 3; but might be masked by residual heat within the pipe network. In consequence, while signs for PCM activity exist in the temperature curves, they cannot be attributed unequivocally to latent heat storage in PCM. To investigate the temperature development without PCM influence for comparison, the 4th test cycle was limited to inlet temperatures around 45 °C, well below the PCM melting temperature. This PCM test cycle 4 was started with a target heat injection rate of 6 kW, and heating lasted slightly more than one day. Meanwhile, the control of heat injection was refined, and both heat injection and temperature curves were relatively smooth (Figure 18). Contrary to the PCM test cycles with temperatures exceeding the melting range of PCM correctly, no signs of a temperature plateau can be seen.

5. CONCLUSIONS

In the case of the UPV (Spain) analysis, the following results can be summarised:

- BHE 3, with the same geometry as the Reference BHE, reduces its borehole resistance substantially due to the combination of the new pipe with enhanced conductivity and the improved grouting.
- BHE 5, with the same geometry as BHE 3, also shows a significant reduction of the borehole resistance compared to the reference, only because of the improved grout.
- BHE 4a and BHE 4b represent the best boreholes in terms of borehole resistance due to the combination of grouting technology, advanced pipe materials, and optimized geometry.
- In BHE 6, from TRT's perspective, the borehole's behaviour is quite like a normal borehole with a passive grout. Extended testing procedures are needed to extract more helpful information about the capacity of the PCM – grout mixture to act as a heat store.
- Due to the difficulties in handling the PCM developed in BHE 7, it does not offer conclusive results about the functioning of the borehole since the injected mixture is heterogeneous and poorly distributed.

In the investigations carried out in Germany, the reduction of borehole thermal resistance R_b in the GEOCOND BHE in site A, compared to the reference BHE, is about 0.02 K/(W·m), or 21.4%. This finding demonstrates a substantial improvement in the efficiency of the BHE. However, the borehole thermal resistance translates not directly into the system efficiency, as other factors need to be included.

In the Borås (Sweden) test site, it was concluded that some qualitative indications of PCM activity were seen in temperature development and the effective heat injection rate. However, the signal is low and does not yet allow for an unequivocal verification of PCM reaction. To provide such proof and potentially determine some quantitative values, further work is done with a simulation of the thermal behaviour of the BHE, including the influence of phase change.

Other aspects like LCA, exergy analysis, and the mapping exercise are not covered here. Specific publications have been prepared to publish the related work, with some already published (see References).

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