Improving the Performance of Geothermal Heat Pumps through Borehole Grout Materials

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ABSTRACT

The performance of Geothermal Heat Pump (GHP) systems depends on the efficiency of the heat transfer process in the ground heat exchangers. Much of the interest by the geothermal industry has focused on how to reduce the cost and increase the efficiency of GHPs. A critical issue that needed to be addressed in response to such interest is the material used to fill the boreholes in vertical loop systems. The boreholes in GHP installations were traditionally filled with bentonite grout. Such grout is a relatively poor thermal conductor and also prone to severe cracking and shrinkage under drying conditions. Water table fluctuation has an adverse effect on the ability of the ground heat exchanger to perform its function in boreholes filled with such materials. Long-term effects with shrinking grouts can be assessed by considering that the heat exchanger loop within the borehole has a reduced contact with the surrounding formation. An improved cement-sand grout material (Mix 111) was developed in the laboratory to address shortcomings in conventional grouts and subsequently was subjected to field validation tests in different geologic environments. This paper describes the grout properties, field performance and commercial use.

Enhancing Material Behaviour

Much of the research performed concentrated on how to increase the thermal conductivity of the grouts used to backfill the heat exchanger loops in the boreholes. Thermal conductivities up to three times higher than bentonite and neat cement grouts were achieved through appropriate selection of grout ingredients and mix design. The developed grout consists of cement, water, silica sand and small amounts of superplasticiser and bentonite. The mix proportions are given in Table 1. Its behaviour was investigated by a series of rigorous laboratory tests including: thermal conductivity, permeability, shrinkage, coefficient of thermal expansion, bond strength, sulfate resistance, durability under wet-dry cycling, compressive strength, splitting tensile strength, flexural strength, elastic modulus and Poisson's ratio, thermal resistance, ultrasonic pulse velocity, freeze-thaw durability and infiltration rate. Graphical comparison of Mix 111 cement-sand grout thermal conductivity with other grouts of interest is presented in Figure 1. This shows the significant increase in thermal conductivity achieved when silica sand filler is incorporated in grout and the retention of conductivity under drying conditions. Table 2 presents a summary of properties for the developed grout. Further details of the grout development and properties are given in Allan (1997), Allan and Philippacopoulos (1998; 1999) and Allan (2000). The impact of grout thermal conductivity on required bore length is discussed in Allan and Kavanaugh (1999) and Kavanaugh and Allan (1999).

Material	Proportion
Cement (kg/m³)	587.7
Water (l/m³)	323.3
Sand (kg/m³)	1251.8
Bentonite (kg/m³)	6.5
Superplasticiser (l/m³)	8.8

Table 1. Mix Proportions of Superplasticised Cement-Sand Grout (Mix 111).

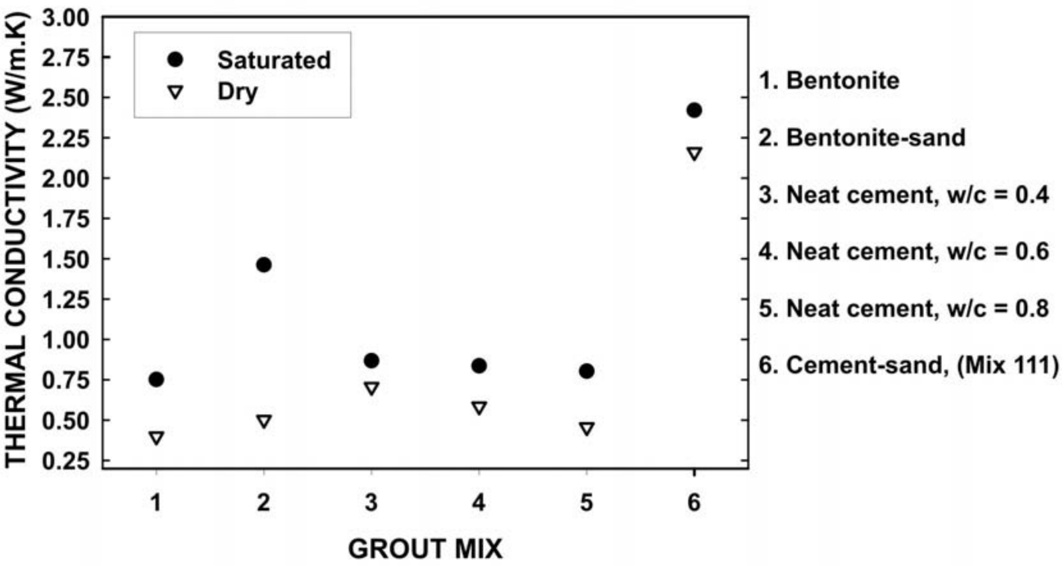

Figure 1. Thermal Conductivities of Superplasticised Cement-Sand Grouts (Mix 111), Neat Cement Grouts with Water/Cement Ratios (w/c) of 0.4-0.8 and Bentonite Grouts.

Thermal Conductivity, Saturated (W/mK)	2.42
Thermal Conductivity, Dried (W/mK)	2.16
Coefficient of Permeability (cm/s)	1.6×10^{-10}
28 Day Compressive Strength (MPa)	36.7 ± 4.2
28 Day Splitting Tensile Strength (MPa)	6.01 ± 0.48
Static Elastic Modulus (GPa)	13.8 ± 0.9
Poisson's Ratio	0.21 ± 0.02
Bond Strength to HDPE (kPa)	150 ± 20.5
Specific Gravity	2.18

Table 2. Summary of Properties for Superplasticised Cement-Sand Grout (Mix 111).

Numerical Studies

Phenomenological analysis reveals that the stress regime in ground heat exchangers is complex. This was confirmed by numerical modeling which demonstrated the presence of tensile stresses in the grouted borehole. Grouts are required to withstand such stresses without cracking which reduces the heat transfer between the exchanger loops and surrounding media. The developed cement-sand grout has high stress capacities which were demonstrated in laboratory as well as in field tests. The heat transfer in vertical heat exchanger loops was evaluated using finite element analysis. The models incorporated sections of vertical ground closed loops of typical GHP configurations and material properties from laboratory tests.

The thermal conductivities of the pipes, grout and surrounding formation were: 0.40, 2.42 and 1.73 W/m.K, respectively. The entering (EWT) and leaving water temperatures (LWT) were: EWT=5 °C and LWT=2 °C for the heating mode. The corresponding values for the cooling mode were: EWT=30 °C and LWT=36 °C. These values were taken as worst case averages considering their variation with depth. Additional boundary conditions were imposed for the thermal stress analysis models so that they are adequately constrained. Thermoelastic properties considered for each of the materials were: a) HDPE pipe: E=1.4 GPa, ν=0.45, α=2.16x10^{-4} m/m°C; b) grout: E=13.8 GPa, ν=0.21, α=1.65x10^{-5} m/m°C; and c) formation: E=2.0 to 5.5 GPa, ν=0.33, α=1.65x10^{-5} m/m°C (E=elastic modulus, ν=Poisson's ratio and α=coefficient of thermal expansion). The results were obtained with the ANSYS code.

The steady state temperature distributions for heating and cooling modes are shown in Figure 2. Since the response inside the borehole is of primary interest, only results within the borehole are

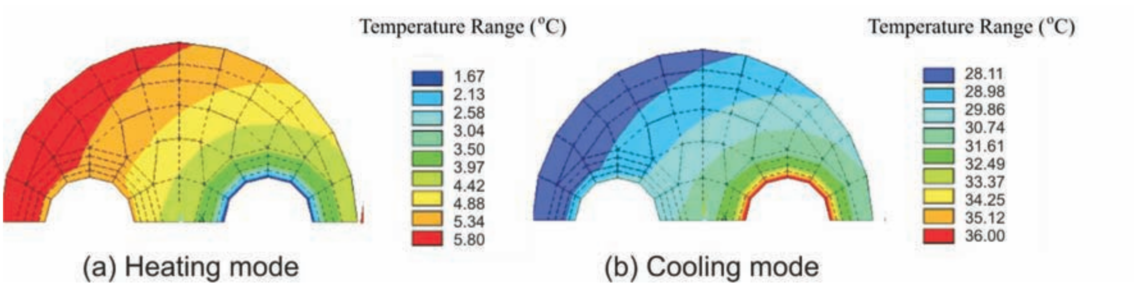

Figure 2. Temperature Distribution in Grouted Borehole.

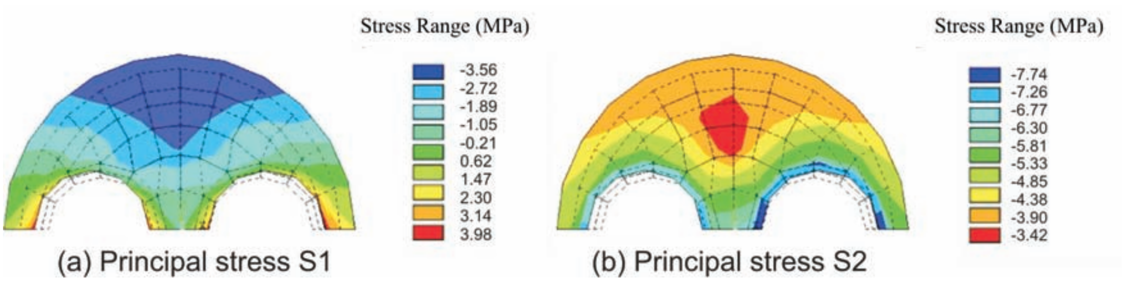

Figure 3. Thermal Stresses for Cooling Mode of Operation.

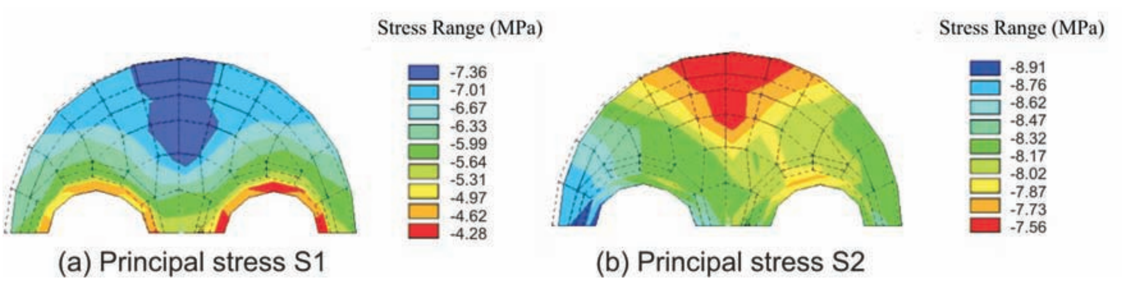

Figure 4. Thermal Stresses for Heating Mode of Operation.

displayed. Similarly, thermal stresses for the cooling and heating mode of operations are shown in Figures 3 and 4, respectively. Comparison of Figures 3 and 4 with Figure 2 leads to the conclusion that the stress fields are consistent with those of the temperature. Stresses are especially higher in the grout near the axis of symmetry in the exterior area. The modelling results show that the stresses are predominantly compressive for the conditions considered and that cracking of the grout due to thermal stresses is unlikely.

Field Verification Tests

The cement-sand grout was tested in the field and its performance was measured and compared to that of other grouts. Field tests were performed by Oklahoma State University and Sandia National Laboratories. The objective was to test the grout at different climates as well as geologic conditions. With completely instrumented boreholes, thermal resistance was recorded at different depths thus enabling monitoring of the heat transfer along the exchanger loop.

Tests were also performed at several boreholes filled with a variety of grouts including bentonite as well as thermally enhanced bentonites. Field data obtained from both tests clearly demonstrated that the developed grout had a decreased thermal resistance as compared to other grouts. Its resistance was 29 % and 35 % less compared with bentonite grouts for the two sites, respectively. Figures 5 and 6 depict the field test results. Further details are available in Allan and Philippacopoulos (1999).

Regulatory Approval and Field Use

The developed grout was successfully used to resolve environmental regulatory concerns in New Jersey. The New Jersey Department of Environmental Protection (NJDEP) had raised concerns

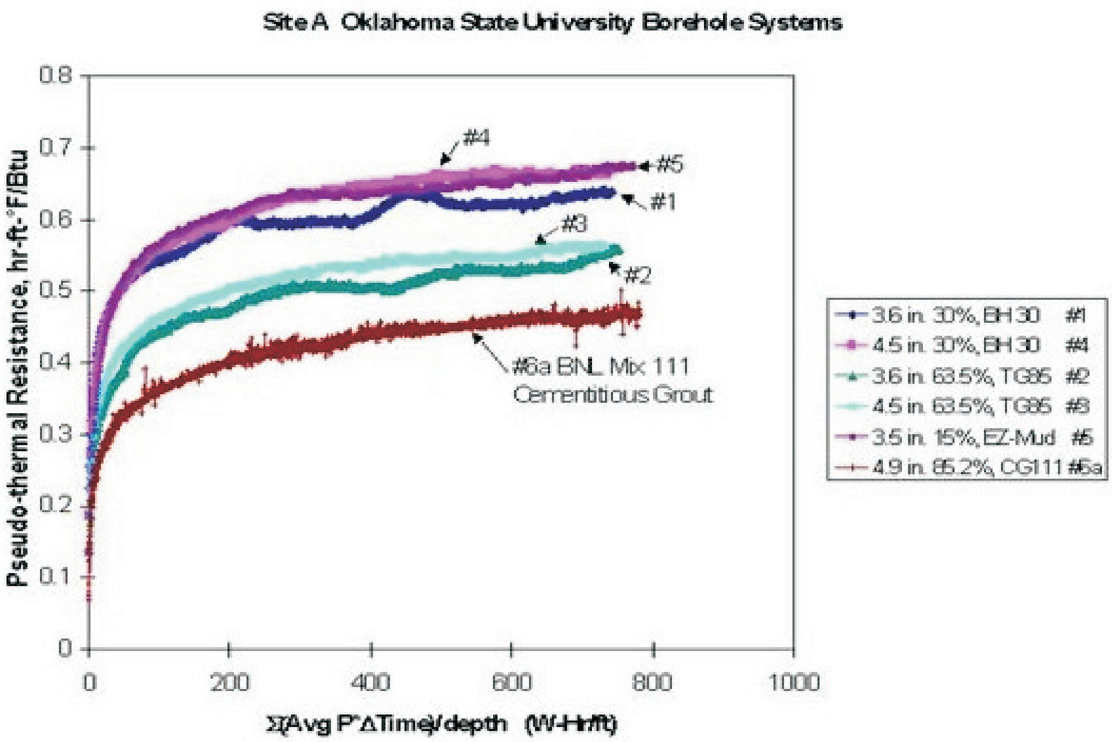

Figure 5. Results of Thermal Resistance Field Tests at Oklahoma State University.

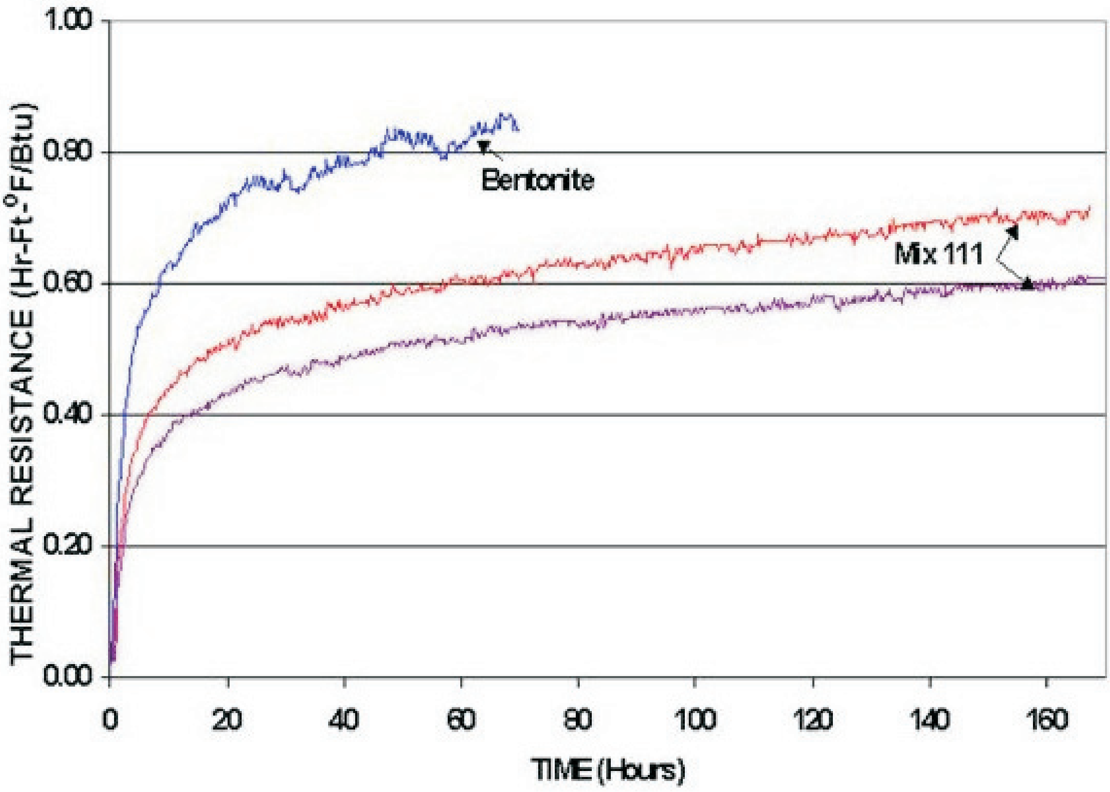

Figure 6. Thermal Resistance Field Test Results from Sandia National Laboratories.

regarding the questionable bond integrity between neat cement grout and U-loop and the possibility of aquifer contamination. The superior performance of the grout included characteristics such as: (a) reduced coefficient of permeability (b) lower infiltration rate (c) shrinkage resistance and (d) good bond strength to U-loop. Such characteristics convinced NJDEP that the environmental risk would be minimised by using Mix 111. Furthermore, numerical modelling by finite element analysis of the thermal stresses developed in the grouted borehole alleviated concerns of cracking induced by expansion of the U-loop. Based on such performance assessments, the grout was approved for use in both consolidated and unconsolidated formations. The State of New Jersey well permit conditions include specifications for mixing and pumping the grout and the grout is also approved by the Tennessee Department of Environment and Conservation for use with geothermal boreholes. The developed grout is currently used throughout the US and other countries. The properties of the grout make it suitable for use in Australian conditions. It has also been used successfully with Deep Well Direct Exchange (DWDX) systems that use copper rather than HDPE pipe by Earth to Air Systems LLC.

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