

GROUND WATER PROTECTION ISSUES WITH GEOTHERMAL HEAT PUMPS

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Keywords: Geothermal heat pumps, grouts, cement, permeability, infiltration, heat transfer, thermal conductivity, non-destructive testing

Abstract

Closed loop vertical boreholes used with geothermal heat pumps are grouted to facilitate heat transfer and prevent ground water contamination. The grout must exhibit suitable thermal conductivity as well as adequate hydraulic sealing characteristics. Permeability and infiltration tests were performed to assess the ability of cementitious grout to control vertical seepage in boreholes. It was determined that a superplasticized cement-sand grout is a more effective borehole sealant than neat cement over a range of likely operational temperatures. The feasibility of using non-destructive methods to verify bonding in heat exchangers is reviewed.

Introduction

Geothermal heat pumps (GHPs) are recognized as being beneficial to atmospheric quality in terms of decreased emissions of CO₂, NO_x and SO_x compared with other means of heating and cooling residential and commercial buildings. Together with relatively low operating costs, the positive environmental attributes have been used successfully to promote the use of GHPs throughout the US. Closed loop vertical boreholes containing the heat exchanger U-loop must be sealed with grout. One concern that has been raised is the potential for ground water contamination if sealing is inadequate.

Research at BNL has investigated means of improving grout thermal conductivity, durability and bond between grout and U-loop (Allan, 1997; Allan and Philippacopoulos, 1998; Allan and Kavanaugh, 1999). The objectives of this paper are to examine the function of grouts in terms of heat transfer and ground water protection, report on the hydraulic properties of cementitious grouts and discuss potential non-destructive tests (NDTs) for verifying bonding and grout quality within ground heat exchangers.

Grout Requirements

The function of the grout is to promote heat transfer between the heat exchanger and surrounding formation and to protect ground water. The first requirement is that the grout maintains suitable thermal conductivity during operation of the GHP. Sufficient heat transfer also demands sound thermal contact at all interfaces. Contact resistance between dissimilar materials needs to be minimized. The creation of gaps at the grout/U-loop and grout/formation interfaces due to either grout shrinkage, thermal contraction of high density polyethylene (HDPE) U-loop, or external conditions leads to an appreciable reduction of the overall conductivity of the system. Decrease in soil moisture content associated with heat rejection and subsequent shrinkage may result in loss of bonding to the grout and consequently reduce the effectiveness of the geothermal heat pump. Another undesirable scenario is inhomogeneity of the

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grout or incomplete borehole grouting that may arise due to problems with mixing or placement. Therefore, favorable heat transfer in the system requires that the issues of grout thermal conductivity, system component bonding and proper grouting techniques are addressed.

The possibility of interfacial gaps and the impact on GHP performance also need to be considered when modelling heat transfer and calculating required bore lengths. Most models of heat conduction in GHP heat exchangers assume perfect thermal contact between the components (e.g., Gu and O'Neal, 1998). Current work at BNL is examining the impact of contact resistance on heat transfer. Finite element models that can account for imperfect bonding by allowing the presence of gaps at pertinent interfaces are being used.

The specific environmental concerns with closed loop vertical boreholes are cross-contamination of different aquifers and transport of surface contaminants to aquifers. The risk of ground water contamination is primarily controlled by the integrity of the grout sealant. Potential pathways for inter-aquifer communication or contaminants are through the grout itself and at the grout/borehole wall and grout/U-loop interfaces. Thus, the grout should possess low permeability, resistance to shrinkage and cracking, and adequate coupling to the U-loop and surrounding formation under operating thermal loads.

It is clear that physical bonding between system components is important for both heat transfer and ground water protection. Mechanical bonding appears to be of less significance in GHP heat exchangers than physical bonding when considering potential contaminant transport. However, grouted boreholes in seismic zones may be at risk of compromised bond integrity that in turn could pose a threat to ground water quality.

The issues of grout bonding and sealing are not unique to GHPs. Other examples are structural, geotechnical and environmental applications such as grouted tendons and rock anchors, mini-piles for stabilizing soil, sealing of fissures in rock and sealing of nuclear waste repositories. Petroleum, geothermal, water, monitoring and other types of wells also require that the grout or slurry provide sound bonding to the casing and the surrounding formation. Relevant other publications on grout sealants include Lutenege and DeGroot (1994), Edil *et al.* (1992) Aller *et al.* (1989), and Kurt and Johnson (1982).

Grouting Regulations

Regulations governing grouting of vertical boreholes used with GHPs vary from state to state in the US. There are also variations within states. These regulations appear to be modified from existing requirements for water and monitoring wells. Regulatory agencies also specify the piping and any antifreeze used in the loop. The different regulations have been summarized by Den Braven (1998). The National Ground Water Association has prepared guidelines for construction of vertical boreholes (McCray, 1997).

Recently, the New Jersey Department of Environmental Protection approved a superplasticized cement-sand grout developed at BNL for use in consolidated and unconsolidated formations. Neat cement grouts had been permitted in that state in consolidated formations until concerns were raised regarding bonding of this type of grout to the U-loop. The

approved cement-sand grout has lower heat of hydration and lower shrinkage than neat cement grouts with similar water/cement ratios. Hence, better bonding and hydraulic sealing are achieved. The grout has higher thermal conductivity than conventional neat cement and bentonite grouts and thereby allows the required bore length to be reduced. This is also beneficial from a groundwater protection aspect. Further details on the grout properties are given in Allan and Philippacopoulos (1998).

Hydraulic Properties of Superplasticized Cement-Sand Grout

A range of different cementitious grout formulations has been tested for coefficient of permeability and bonding to U-loop in order to assess the ability of the grouts to function as an effective borehole sealant. The role of additives such as latex has also been studied. The grouts were tested for coefficient of permeability in the bulk state and when cast around two lengths of HDPE pipe to represent a U-loop. The experimental arrangement and procedure are described in Allan and Philippacopoulos (1998). Tests were performed in a flexible wall triaxial cell permeameter. All specimens were cured in water for 28 days and vacuum saturated prior to testing.

The specimens containing HDPE pipe were tested at different temperatures to elucidate the effect of thermal expansion and contraction on system permeability. Operation of a GHP in heating mode correlates with low fluid temperatures in the U-loop. Since the grout and HDPE have significantly different coefficients of thermal expansion, contraction of the loop could conceivably result in a high permeability pathway at the grout/U-loop interfaces and increase the risk of groundwater contamination. The pipes in the test specimens were sealed with wax so that flow was restricted to either the grout or the grout/pipe interfaces. Specimens were isothermally conditioned in a water bath to the temperature of interest. The permeameter tests did not replicate different temperatures in the legs of the loop associated with flowing heat exchanger fluid. However, ongoing infiltration tests discussed below will examine the effect of different fluid temperatures on hydraulic characteristics of grouted boreholes.

The results presented in this paper are for a superplasticized cement-sand grout that was selected as having the best overall performance in laboratory and field tests while retaining economic competitiveness and simplicity of mixing and handling. The grout was designed for compatibility with the type of paddle mixer commonly used in the GHP industry. The mix proportions are presented in Table 1 and the grout formulation is referred to as Mix 111. Neat cement grouts with different water/cement ratios were tested for comparison and the mix proportions are also given. Findings for other grouts are reported in Allan and Philippacopoulos (1998).

The measured coefficient of permeability for bulk Mix 111 after 28 days of wet curing was $1.58 \times 10^{-10} \pm 5.2 \times 10^{-11}$ cm/s. This is relatively low and meets the required specification of less than 10^{-7} cm/s (Eckhart, 1991). The coefficients of permeability for the grout/pipe specimens at different temperatures are presented graphically in Figure 1. Mix 111 has a consistently lower permeability coefficient than neat cement grouts at all temperatures. The results clearly show that thermal contraction increases system permeability. The test arrangement permitted comparison of different materials under a given set of isothermal conditions. The variation of permeability coefficient with temperature under realistic operational

conditions will depend on the thermal distribution throughout the pipe and grout and the resultant thermally induced material deformations. Current finite element analysis at BNL is examining the thermal stresses and deformations in the GHP heat exchanger system and initial results indicate that the gaps caused by contraction will be non-uniform. The gaps will also vary with changes in loop temperature along the length of the heat exchanger. Confining pressure is also expected to influence the system coefficient of permeability.

Table 1. Mix Proportions for Tested Grouts

	Mix 111	Neat Cement (w/c = 0.4)	Neat Cement (w/c = 0.6)	Neat Cement (w/c = 0.8)
Cement (kg/m ³)	590	1369	1087	894
Water (l/m ³)	324.5	547.6	652.2	715.2
Sand (kg/m ³)	1257	0	0	0
Bentonite (kg/m ³)	6.5	0	0	0
Superplasticizer (l/m ³)	8.8	27.4	0	0
Specific Gravity	2.18	1.95	1.74	1.61

Insert Figure 1.

The grout/pipe specimens were subject to wet/dry and thermal cycles. The experimental details are given in Allan and Philippacopoulos (1998). The neat cement grouts underwent cracking and coefficient of permeability could not be measured. In contrast, Mix 111 grout did not fail. The coefficients of permeability for Mix 111 were slightly higher after the cyclic exposure. However, the values remained of the order of 10^{-7} cm/s at 21°C.

Infiltration tests are currently in progress to measure penetration of a head of water above a grouted borehole. The test configuration is similar to that used by Edil *et al.* (1992) to study the sealing characteristics of different grouts for water wells. The first set of experiments was performed on PVC pipes that contained a single U-loop and were sealed with either neat cement or Mix 111 grout. The tubes were 5.1 m long and 102 mm internal diameter. Each of the tubes contained a 25.4 mm ID U-loop so that interfacial conditions between grout and loop were taken into consideration. Grout was tremied from the bottom up into the tubes using a 25.4 mm diameter tremie tube. A 60 cm long, 102 mm internal diameter PVC tube was glued to the top of the grouted tube. A transparent sight tube was attached to the top tube for viewing water elevation. The top tube was filled with water to give an initial head of 58 cm. The infiltration rate was calculated as the change in elevation with time.

Mix 111 had a consistently lower infiltration rate than neat cement grout. The values after 133 days were 2.9×10^{-7} cm/s and 6.7×10^{-7} cm/s for Mix 111 and neat cement with w/c = 0.6, respectively. No outflow through the total length of the grouted tube was recorded. Infiltration decreased with time due to ongoing cement hydration and associated changes in pore structure. Also, since the grouts were not saturated at the commencement of the tests there may have been

some water absorption in the initial stages that contributes to the infiltration rate. Falling head permeability could not be calculated because the length over which flow occurred was unknown.

An arrangement has been constructed to enable infiltration rate to be measured as different temperature fluids circulate in the loop. The specimens are shorter than those used in the above tests in an attempt to reduce the time for outflow to occur and to possibly allow calculation of falling head permeability. The configuration is the same as that in the initial tests except that the grouted length is 80 cm and the initial head of water is 29 cm. The first set of experiments involves testing grouted PVC tubes. The tubes were grouted with either Mix 111 or high solids bentonite grout. The tests are currently being conducted at room temperature until equilibrium is established. The bentonite grouted tubes underwent rapid infiltration of the entire head of water within the first 15 hours. The bentonite itself oozed out of the tube outlet during this period. Therefore, the infiltration tests on bentonite were discontinued. The effect of circulating fluid temperature will be investigated once a steady infiltration rate is achieved in the tubes grouted with Mix 111. It is also planned to thermal cycle the grouted tubes and determine the impact on infiltration rate. The next set of tests will measure the infiltration rates in simulated boreholes in which the grout will be surrounded by soil.

Feasibility of Non-Destructive Testing

Non-destructive tests offer the potential to verify bonding integrity and quality of grouting in-situ. If an appropriate test could be developed to monitor changes in dimensions and bond integrity this would enable better comparison of in-situ performance of different grouting materials. Furthermore, in-situ tests to assure that the borehole is completely grouted would be very valuable both from heat transfer and environmental standpoints. Different non-destructive techniques used in the petroleum industry to verify bonding between well casing, cement and formation have been reviewed for applicability to ground heat exchangers (Allan and Philippacopoulos, 1998). A widely used approach to obtain material information in different wells is through acoustic or sonic logs (Goodwin and Carpenter, 1991). Pulsed Neutron Logging (PNL) has also been used for channel detection (e.g., Sommer *et al.*, 1993). Experience from field measurements has led to the conclusion that there are several advantages and disadvantages associated with both sonic and ultrasonic methods. The omnidirectional character of the transmitter and receiver in sonic measurements is a key disadvantage. First, it requires good tool centralization in order to obtain simultaneous arrivals from all directions. Second, the method is characterized by lack of azimuthal resolution. Therefore, it neglects material and bonding distributions around the pipe. Azimuthal averages usually provide misleading results. By contrast, the major advantage of the ultrasonic technique is that it provides such spatial resolution.

Shear coupling is important for the sonic technique. Lack of shear coupling is caused by the presence of microannuli. Therefore, a second major disadvantage of the sonic techniques is their sensitivity to microannulus effects (Jutten *et al.*, 1993). On the other hand, ultrasonic techniques are not sensitive to shear coupling. They operate by pulses generated to strike the wall surface at normal incidence. When sensitivity to shear coupling, however, is important, then sonic techniques are more efficient than ultrasonic ones. Experimental results from comparisons between the two techniques in a full-scale simulator have lead to the conclusion that

combinations of sonic/ultrasonic measurements should be used in field verification programs (Hayman *et al.*, 1995). Additional evidence for using a dual approach (i.e., sonic/ultrasonic) was obtained in an investigation conducted by the EPA (Albert *et al.*, 1988). While several successful measurements were made, the conclusion was that none of the tools used in the study was able to detect channeling in the cement smaller than 30 degrees. Cement channeling of the latter size is considered environmentally unacceptable.

One of the anticipated difficulties for using sonic or ultrasonic methods to evaluate bond integrity in GHP heat exchangers is the size of the tools because the diameter of the HDPE pipe is much smaller than that of injection or production wells and currently available tools will not fit in the typically used pipe. An additional complicating factor arises from the nonsymmetrical configuration of the GHP heat exchangers created by the presence of two pipes. This causes an unequal azimuthal distribution of the grout around each of the pipes. Any arrival times from waves reflected at the grout/formation interface are inherently unequal. In addition, pipe-to-pipe effects may be of importance when resonance is caused in one pipe. Sonic and ultrasonic measurements must be calibrated to take into account the polyethylene pipe vibrations which differ from those of steel pipe as well as the grout dynamic material properties. Engineering calculations, on the basis of the acoustic impedances of representative grouts, must be made to further evaluate the applicability of acoustic methods in determining the in-situ integrity of ground heat exchangers of GHP systems.

Low vibration methods such as those used in non-destructive testing of piles are another possibility. The proposed test procedure is as follows: A vibration transducer is placed at the top of the ground heat exchanger and causes it to vibrate in a specific mode, e.g., vertical motion. The vibration of the ground heat exchanger produces a set of waves that radiate away from it into the surrounding formation. These waves consist primarily of body waves; surface waves as well as interface waves depending on the stratigraphy of the formation. The motion is recorded at the top of the ground heat exchanger. Other locations may also be selected to provide additional response data. The force-displacement relationship for the particular mode of vibration excited during the test is recorded. The latter is conventionally presented in terms of impedance or compliance functions over a dimensionless frequency range which usually represent ratios of wavelengths to some dimension of interest, i.e., radius or height.

Theoretically, the ability of the ground heat exchanger to radiate energy away into the formation depends, among other factors, on the interface conditions between the grout and the formation. The better the bonding the more the radiated energy. This principle can be translated in terms of impedances. Specifically, loss of bonding due to the presence of channeling in the grout would influence the appearance of these curves in specific frequency windows. Therefore, by comparing to a full-bonding curve conclusions can be drawn with respect to the grout/formation interface. Specific ranges can be developed from laboratory testing where specimens can be subjected to vibratory motion. By recording their dynamic response, field specifications can be developed. Furthermore, dynamic analysis of the overall system should be performed using finite element techniques to calibrate these tests. This analysis is part of BNL's current research program.

Conclusions

The presence of gaps at grout/U-loop and grout/formation interfaces in closed loop vertical boreholes is detrimental to both heat transfer and ground water protection. Coefficient of permeability and infiltration tests have shown that the hydraulic sealing characteristics of cementitious grouts can be improved through appropriate mix design. Superplasticized cement-sand grout has significantly better bonding and sealing properties than neat cement grouts due to reduced shrinkage and heat of hydration. Furthermore, neat cement grouts were prone to cracking on wet/dry or thermal cycling which also makes them unsuitable for sealing boreholes. Thermal mismatch between high density polyethylene U-loop and grout causes the permeability coefficient to vary with temperature. Field verification is desirable to ensure that sufficient bonding exists in the grouted borehole. This could be achieved through in-situ permeability and in-situ non-destructive tests. Dynamic analysis of grouted boreholes is currently being undertaken to further explore non-destructive verification of bond and grout integrity.

Acknowledgement

This work was supported by the U.S. Department of Energy Office of Geothermal Technologies and performed under contract number DE-AC02-98CH10886.

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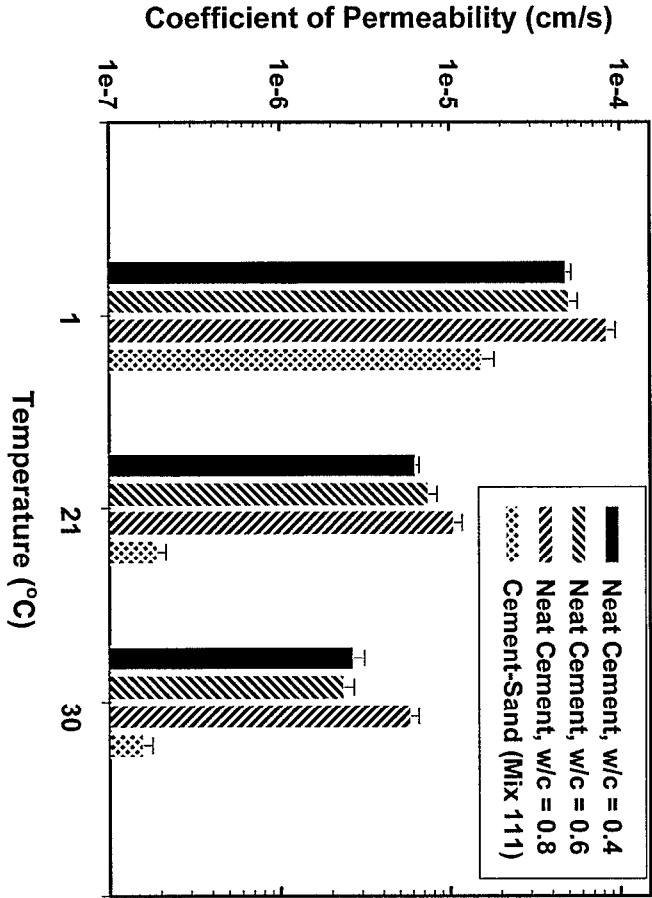


Figure 1. Coefficient of Permeability for Grout/Pipe Specimens at Different Temperatures.

