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GEOTHERMAL HEAT PUMP GROUTING MATERIALS

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ABSTRACT

The thermal conductivity of cementitious grouts has been investigated in order to determine suitability of these materials for grouting vertical boreholes used with geothermal heat pumps. The roles of mix variables such as water/cement ratio, sand/cement ratio and superplasticizer dosage were measured. The cement-sand grouts were also tested for rheological characteristics, bleeding, permeability, bond to HDPE pipe, shrinkage, coefficient of thermal expansion, exotherm, durability and environmental impact. This paper summarizes the thermal conductivity, permeability, bonding and exotherm data for selected cementitious grouts. The theoretical reduction in bore length that could be achieved with the BNL-developed cement-sand grouts is examined. Finally, the FY 98 research and field trials are discussed.

INTRODUCTION

Key to the successful widespread use of geothermal heat pumps is reduction of installation costs. One way of tackling this is decreasing drilling costs by reducing the required bore length. This, in turn, can be achieved by increasing the thermal conductivity of grout used to seal the annulus between the borehole and heat exchanger loop. The grout provides a heat transfer medium between the U-loop and surrounding formation, controls groundwater movement and prevents contamination of water supply.

Properly designed and mixed cementitious grouts have potential for use as GHP grouts and may prove superior in thermal properties, long term performance and overall economics than bentonite grouts in current use. Cementitious grouts are relatively inexpensive, safe and easy to work with, comprising readily available materials and have a long history of use in geotechnical and civil engineering applications.

This project involves characterization of cement-silica sand grouts for thermal conductivity and other properties pertinent to backfilling vertical boreholes for GHPs. Cost analysis and calculations of the reduction in heat exchanger length that can theoretically be achieved with such grouts are being performed by the University of Alabama. Experimental work focuses on optimization of grout formulations in order to improve thermal conductivity while meeting requirements for mixing and pumping with conventional equipment, permeability, shrinkage, bonding to U-loop, durability, ease of handling, durability and economics. This paper describes some of the major results to date. Further details of the research, including testing for other properties such as rheology, shrinkage, durability, environmental impact and coefficient of thermal expansion, can be found in the FY 97 Progress Report (Allan, 1997).

EXPERIMENTAL PROCEDURE

Materials

The grouts delineated as having potentially suitable characteristics for GHP applications consist of Type I cement (ASTM C 150), silica sand, water and superplasticizer. Work in FY 97 also examined sulphate resistant cements and the use of fly ash (FA) and ground granulated blast furnace slag (BFS) as partial replacement for Type I cement in some of the grout formulations. These supplementary cementing materials are recognized for their ability to enhance durability in adverse environments (e.g., aggressive groundwater), reduce heat of hydration and reduce cost. The fly ash conformed to ASTM C 618 Class F. This is a low calcium fly ash produced from combustion of bituminous coal. The blast furnace slag was ASTM C 989 Grade 100.

The superplasticizer (SP) used was a sulfonated naphthalene type with a solids content of 42% by mass and was supplied by Master Builders Technologies (Rheobuild 1000). This chemical admixture functions as a dispersant and increases grout fluidity. Thus, superplasticizer allowed the water content of the grout to be reduced while maintaining pumpability. The aim was to keep the water/cementitious material ratio (w/c) as low as possible in order to improve thermal properties, reduce permeability, and increase durability.

Silica sand was chosen as a particulate filler to increase thermal conductivity of the cementitious grouts. This decision was based on previous data that showed the efficacy of sand for improving thermal properties (Allan and Kavanaugh, 1998), ready availability, low cost, compatibility with grout mixing and placement equipment and ease of use. Different gradations of sand were evaluated in FY 97. Of these, sand conforming to the gradation suggested by ACI Committee 304 (Grading 1) gave the best combined performance. The ratio of sand to cementitious material (s/c) by mass for grouts discussed in this paper was varied from 2.0 to 2.5. Comparisons were made with neat cement grouts (i.e., no sand added).

A small proportion of Wyoming bentonite (sodium montmorillonite) was added to some of the cementitious grouts to reduce bleeding, promote full-volume set, and improve sand carrying capacity (i.e., reduce settling). However, use of bentonite was later discontinued in order to simplify the grout mix.

The cementitious grouts were intended to be mixable and pumpable with conventional grouting equipment. The mix proportions of some of the neat cement (Mixes 1 to 3) and cement-sand grouts covered in this paper are given in Table 1. The terms w/c, s/c and SP/c refer to water/cementitious materials ratio by mass, sand/cementitious material ratio by mass and superplasticizer dosage in ml/kg cementitious material, respectively. Mix 5 has a s/c value corresponding to two 100 lb bags of sand added for one 94 lb bag of cement. This ratio was chosen for ease of field mixing. Mixes 7 and 8 contain blast furnace slag and fly ash at a cement replacement level of 40%, respectively.

Table 1. Mix Proportions of Selected Grouts

Mix No.	w/c	s/c	SP/c (ml/kg)
1	0.4	0	20
2	0.6	0	0
3	0.8	0	0
4	0.5	2	20
5	0.55	2.13	15
6	0.6	2.5	10
7 (40% BFS)	0.6	2.5	10
8 (40% FA)	0.6	2.5	10
9	0.75	2	0

Thermal Conductivity Measurements

The cementitious grouts were cast as blocks 75 mm x 125 mm x 25 mm. Three specimens per batch were cast. The blocks were sealed to prevent evaporation, demoulded after 24 hours and placed in a water bath to cure. The hardened grouts were tested for thermal conductivity at an age of 14 days. The grouts were then dried in an oven at 40°C over a period of seven days, allowed to cool, and re-tested to determine the effect of loss of moisture.

Thermal conductivity was measured using a Shotherm QTM-D2 Thermal Conductivity Meter. This meter uses the hot wire method to calculate the thermal conductivity, . The hot wire test is a transient method and therefore overcomes the problem of moisture migration and subsequent decrease in thermal conductivity that would occur with a steady state method. Further details of the test method are available in the FY 97 Progress Report (Allan, 1997). Three measurements per specimen were made.

Permeability

The water permeability (hydraulic conductivity) of the grouts under saturated conditions was measured in a flexible wall triaxial cell permeameter on cylindrical specimens. The experimental set up followed that given in ASTM D 5084-90. Two series of permeability tests have been performed to date. The first series was on bulk grouts. The second series was on an annulus of grout cast around an axial length of 1 in. ID (1.3 in. OD) HDPE Driscopipe7 5300 (Phillips 66). Since the permeameter was originally set up for 76 mm diameter cylinders, it was not possible to place two lengths of pipe in the specimens. All specimens were insulated for 24 hours after casting so that thermal effects similar to those which may occur in a borehole were simulated. Specimens were demoulded after 24 hours and cured for 28 days in a water bath. The ends of the pipe were plugged before conducting permeability tests so that water would flow either through the grout or between the grout-pipe interface. This indicated how permeability of the grout-pipe system may be influenced by grout shrinkage. Three specimens per batch were tested.

Bond Strength

The relative bond strength of selected grouts to HDPE was measured by push out tests. An annulus of grout was cast around an axial length of 1 in. ID (1.3 in. OD) HDPE Driscopipe7 5300 (Phillips 66). Mixes 1, 6, 7, and 8 were tested. The specimens were placed in a Geotest compression tester with modified platens so that the pipe could be pushed out. Movement of the pipe was monitored with a dial gauge and LVDT. The load required to push the pipe out 0.04 in. (1 mm) was recorded. Bond strength was calculated as the load divided by the surface area of the embedded pipe. Six specimens per grout batch were tested.

Temperature versus Time

Concerns have been expressed about the elevated temperatures generated during cement hydration and how this may effect bonding between the cementitious grout and U-loop. Thermal expansion and contraction of the U-loop would occur as the grout temperature increases and subsequently decreases. In order to investigate this issue, the temperature versus time was monitored for simulated boreholes. Tubes were grouted to determine temperature-time profiles and also check for grout pumpability and uniformity of grouting. The tests involved grouting 102 mm inner diameter 6 m long insulated Schedule 40 PVC tubes that contained an axial length of 25.4 mm (1 in) ID (33.0 mm/1.3 in. OD) HDPE Driscopipe7 5300. The insulation was 25 mm thick fibreglass. Thermocouples were embedded in the grout and temperature versus time was monitored with a data logger. One of the tubes was filled with Mix 6 and the other with Mix 7 (slag-modified). The grouts were mixed in a ChemGrout CG-550P paddle mixer and pumped with a piston pump. The temperatures at the grout set time and at the peak of the exotherm were measured. The grouted tubes were later sectioned to examine the microstructure of the grout/pipe interface and the uniformity of grouting throughout the length of the tube.

RESULTS AND DISCUSSION

Thermal Conductivity

The thermal conductivities in saturated and dry conditions of selected different neat cement and cement-sand grouts are compared in Figure 1. The mix numbers are those given in Table 1. The error bars indicate the standard deviation.

The figure shows that thermal conductivity of neat cement grouts increases with decreasing w/c. When the amount of water in the original mix exceeds that required for hydration of cement the excess can be evaporated, thus leaving pores in the hardened grout. High w/c grouts will have greater porosity and lower thermal conductivity than low w/c grouts. The neat cement grout with w/c = 0.8 (Mix 3) showed a significant decrease in mean thermal conductivity of 43.2% on oven drying. Comparison with the superplasticized grout with w/c = 0.4 (Mix 1) demonstrated that the percentage decrease in thermal conductivity on drying was reduced to 18.7% by lowering w/c.

Addition of sand increases the thermal conductivity substantially. The retention of conductivity under drying conditions is also improved and this is beneficial when heat is rejected into the borehole or in arid environments. Loss of conductivity for the cement-sand grouts with w/c = 0.5 to 0.6 and s/c = 2 to 2.5 ranged from 8.1 to 11.5%. Mix 9 (w/c = 0.75, s/c = 2) underwent a decrease in thermal conductivity of 31%. Therefore, this grout, while having a reasonable conductivity in the saturated state, would not perform well if moisture is lost. Selected grouts that had been oven dried were re-saturated and the thermal conductivity was re-measured. It was found that the thermal conductivity returned to its original value. Therefore, the decrease in conductivity is reversible.

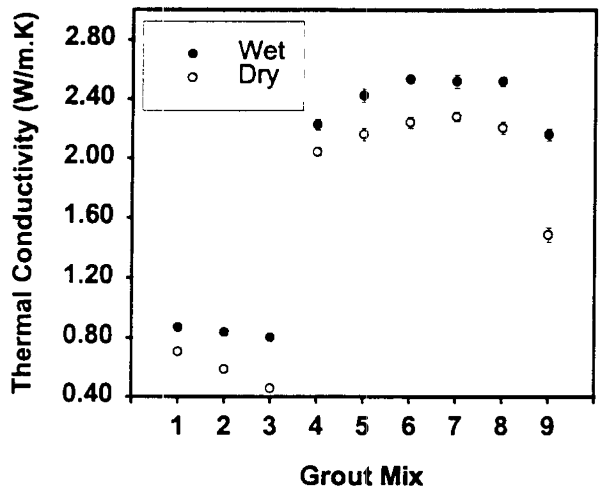

Figure 1. Thermal conductivity of different grouts.

The results can be compared with those for bentonite-based grouts. High solids bentonite grouts that are in current use for backfilling boreholes have thermal conductivities ranging from 0.65 to 0.90 W/m.K (Remund and Lund, 1993). Thermally enhanced bentonite has an increased conductivity of 1.46 W/m.K due to addition of quartzite sand (Remund and Lund, 1993). These values refer to the moist state and significant decreases in conductivity for bentonite grouts occur on drying (Allan and Kavanaugh, 1998). Heat transfer studies by Braud (1991) and Braud and McNamara (1989) have shown that neat cement grout performs similarly to high solids bentonite grouts. This is in agreement with the relatively low thermal conductivity of the neat cement grouts tested in this work.

Permeability

The results of bulk versus bonded permeabilities are compared graphically in Figures 2 and 3. The permeability data in Figure 2 demonstrate that increasing w/c from 0.4 (Mix 1) to 0.8 (Mix 2) causes an order of magnitude increase in neat cement grout permeability. A dramatic increase in permeability for the grout-pipe specimens is observed for the high w/c of 0.8. This is attributed to a higher permeability pathway at the pipe interface which was confirmed by microstructure studies. For the cement-sand grouts in Figure 3, the value of w/c also controls permeability of the bulk grouts. Fly ash and blast furnace slag have slight effects on permeability. The results show that addition of sand to the grout decreases the permeability of the grout-pipe interface as compared to the neat cement grouts. The permeability of grout-pipe specimens for Mixes 5 and 9 have not been measured. Despite the increase in permeability associated with imperfect bonding, the values are below 10^{-7} cm/s, which is the recommended value for GHP grouts (Eckhart, 1991).

The permeameter is currently undergoing modification to accept 102 mm diameter specimens that will contain two lengths of HDPE pipe. This will give a better representation of the permeability of a grouted borehole. The effect of thermal cycling on the bond permeability will be investigated.

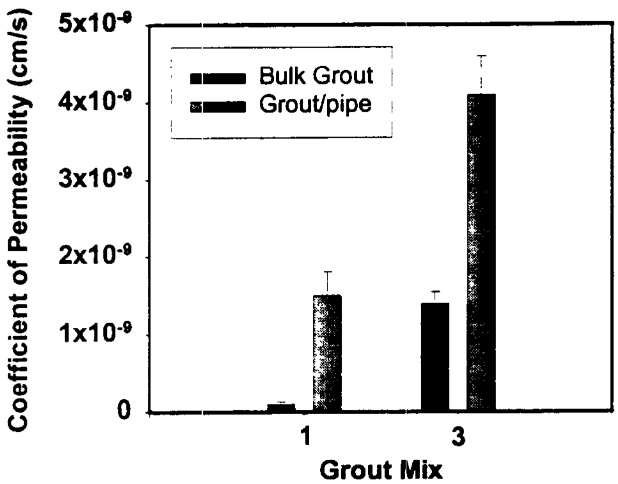

Figure 2. Permeability of neat cement grouts.

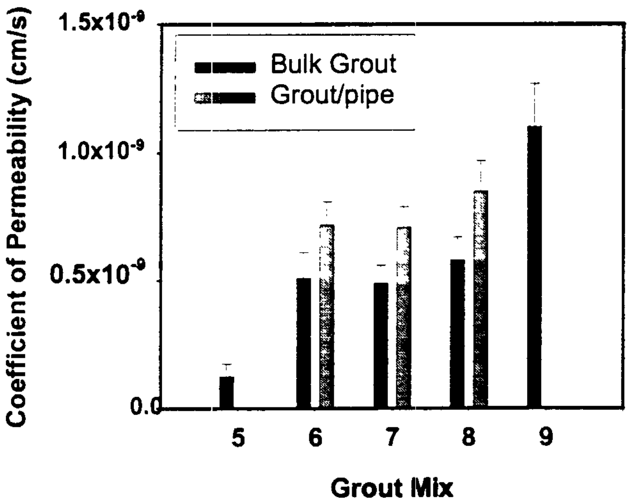

Figure 3. Permeability of cement-sand grouts.

Bond Strength

The results of the bond strength tests are presented in Figure 4. The average and standard deviation for six specimens are given. Relatively high shrinkage of superplasticized neat cement results in very low bond strength. Neat cement grout will also have a higher exotherm than a cement-sand grout and this will result in greater expansion of embedded HDPE pipe during curing. The bond strengths for Mixes 6 and 7 were virtually the same, despite the lower exotherm of the slag-modified grout. The fly ash-modified grout (Mix 8) had a significantly lower bond strength and this is attributed to higher shrinkage

Temperature versus Time

Temperature versus time data was obtained for the grout cast in the insulated 6 m x 102 mm PVC tubes. The peak temperature was 51.2°C for Mix 6 and this occurred at an elapsed time of 12 hours and 20 minutes. The set time of this grout was 8 hours and the corresponding temperature at this time was 32°C. For the slag-modified grout (Mix 7) the peak temperature was 36.7°C at 17 hours and 46 minutes after completion of grouting. The set time was 9 hours at which time the temperature was 25.3°C.

The circumferential coefficient of thermal expansion for the HDPE pipe used is 1.1×10^{-4}/°C. This can be used to calculate the expansion of the pipe at the set time of the grout. Subsequent cooling of the grout could possibly contribute to imperfect bonding at the grout/pipe interface. The change in circumference of the pipe at 32°C is 0.176 mm and the diameter change is 0.056 mm. For the slag-modified grout, the circumference and diameter changes at the set time are 0.095 and 0.03 mm, respectively. The assumption that the pipe and grout are at the same temperature is a simplification. Hence, the calculated expansions represent maximums for the studied system. Thermal expansion of the grout has been neglected in the calculations.

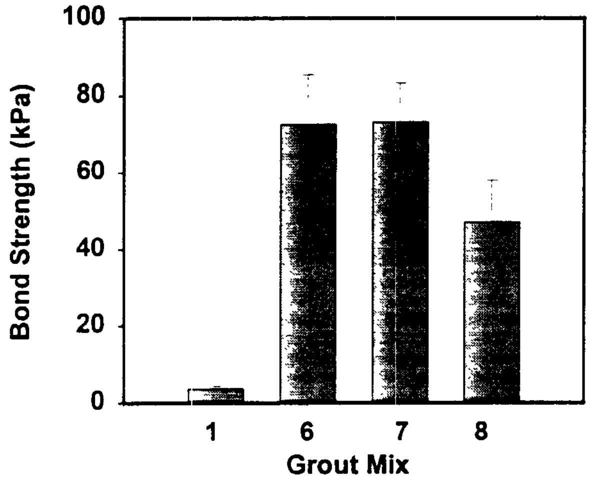

Figure 4. Bond strengths for neat cement and cement-sand grouts.

Microstructure of Grout/Pipe Interface

Specimens used in the permeability tests were sectioned and viewed under an optical microscope at 50 x magnification to examine the integrity of the grout bond to HDPE. In addition, the 6 m x 102 mm tubes were sectioned for analysis. For the 76 mm diameter permeability specimens it was found that those grouts without sand had the greatest gaps at the grout-pipe interface. Mix 1 had a gap of 0.02 to 0.4 mm. Such gaps would increase contact resistance and be detrimental to overall heat transfer. Addition of sand to the grouts was found to improve the bond integrity and this concurs with the permeability and bond strength results. Mix 6 exhibited regions where grout was intimately bonded to the pipe. Some discontinuous gaps 0.02 mm wide were observed. Similar observations were made for the sanded slag-modified grout (Mix 7). Hence, reduction of the exotherm by addition of slag to the mix did not improve bonding. This is attributed to the higher early shrinkage of the slag-modified grout (Allan, 1997) which counterbalances the benefit of decreasing temperature and subsequent expansion of embedded HDPE pipe. The sanded fly-ash modified grout (Mix 8) had a continuous gap at the interface around 0.02 - 0.2 mm wide, in addition to some voids.

The sections cut from the 102 mm diameter insulated tubes grouted with Mixes 6 and 7 showed gaps 0.06 - 0.075 mm wide at the interface, which is greater than that observed on the smaller permeability test specimens. The increased gap width is probably due the higher exotherm experienced in the tubes than in the 76 mm diameter cylinders.

Bore Length Design and Grout Costs

The required bore length depends in part on the thermal conductivity of the backfill grout. A team of Mechanical Engineering students (Daniel Suggs, Shane Peek and Jeff Rimel) at the University of Alabama conducted bore length calculations for different grout thermal conductivities, formation geologies and building load. Bore length design software developed by Prof. S. Kavanaugh (University of Alabama) was used. Calculations were based on a 4 in. diameter bore with a single U-tube. The analysis assumed that the buildings were located in Tuscaloosa, AL and the heating and cooling loads were as follows:

Residential heating and cooling load:	3 tons
Commercial heating and cooling load:	10.5 tons
School heating and cooling load:	75 tons

The results of the required bore length calculations for grouts with thermal conductivities of 1.46 (thermally enhanced bentonite) and 2.42 W/m.K (Mix 5) are presented in Table 2. The material costs for grouting the borehole are included and assume 55 gallons of grout per 100 lineal feet and no loss to the formation. The estimated cost of Mix 5 is \$0.626/gallon based on prices of \$5.15/94 lb bag of cement, \$3.00/100 lb bag of sand and \$5.25/gallon of superplasticizer. The cost may vary with freight charges. A price of \$0.80/gallon has been assumed for thermally enhanced bentonite. The specific gravities of the thermally enhanced bentonite and Mix 5 are 1.64 and 2.18, respectively. The drilling costs for the different lengths of boreholes can also be included in the cost calculations and will vary with geology and size of the job. A conservative estimate would be \$3/ft. Other studies of bore length design are reported in Allan and Kavanaugh (1998).

Table 2. Bore length and cost calculations for different grout thermal conductivities

Type	Grout $\lambda = 1.46$ W/m.K		Grout $\lambda = 2.42$ W/m.K	
	Bore Length (ft)	Grout Cost (\$)	Bore Length (ft)	Grout Cost (\$)
Residential				
Igneous	700	308	600	207
Metamorphic	720	317	620	214
Sedimentary	720	317	630	217
Commercial				
Igneous	2470	1087	2270	781
Metamorphic	2540	1118	2330	802
Sedimentary	2550	1122	2340	805
School				
Igneous	17910	7880	15480	5330
Metamorphic	18370	8083	15940	5489
Sedimentary	18430	8109	16000	5508

FY 98 ACTIVITIES

In FY 98 it is planned to conduct two field demonstrations in collaboration with Oklahoma State University and Sandia National Laboratories. In-situ thermal conductivity measurements will be performed and compared with laboratory data. Heat pump performance will be monitored over heating and cooling seasons. The field demonstration will enable quantitative comparison of the selected cement-sand grout with conventional grouts under actual working conditions. Specifications for mixing the grout will be developed. Further studies of bonding of cementitious grouts to U-tube will be conducted, including analysis of the effect thermal cycling. Freeze-thaw durability tests will be completed. Collaboration with the University of Alabama to measure thermal resistance per unit length for different grouts is ongoing.

CONCLUSIONS

Superplasticized cement-silica sand grouts have thermal conductivities in the range of 2.161 to 2.531 W/m.K for sand/cement ratios by mass of 2 to 2.5. Cement-sand grouts have significantly higher thermal conductivity than neat cement or bentonite grouts and retain conductive properties under drying conditions. The grouts have permeabilities of the order of 10^{-10} cm/s and improved bonding characteristics to HDPE U-loop over neat cements. The improvements in thermal conductivity are predicted to decrease required bore length, and therefore reduce drilling and materials costs associated with installation of vertically oriented heat exchangers for geothermal heat pumps. The forthcoming field trials will provide information on the in-situ performance of the cement-sand grouts.

ACKNOWLEDGMENT

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