**PRELIMINARY STUDY ON IMPROVEMENT OF CEMENTITIOUS GROUT THERMAL
CONDUCTIVITY FOR GEOTHERMAL HEAT PUMP APPLICATIONS**

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PRELIMINARY STUDY ON IMPROVEMENT OF CEMENTITIOUS GROUT THERMAL CONDUCTIVITY FOR GEOTHERMAL HEAT PUMP APPLICATIONS

ABSTRACT

Preliminary studies were performed to determine whether thermal conductivity of cementitious grouts used to backfill heat exchanger loops for geothermal heat pumps could be improved. Grouts containing selected additives were compared with conventional bentonite and cement grouts. Significant enhancement of grout thermal conductivity was readily achieved. Additives such as sand, alumina grit, steel fibres, and silicon carbide increased the thermal conductivity to values ranging from 1.7-3.3 W/m.K (0.98-1.9 Btu/hr.ft.°F). This compares with typical values of 0.70-0.80 W/m.K (0.40-0.46 Btu/hr.ft.°F) for unfilled, high solids bentonite grouts (Remund and Lund, 1993) and 0.65-0.80 W/m.K (0.32-0.46 Btu/hr.ft.°F) for conventional cement grouts. Furthermore, the developed grouts retained high thermal conductivity in the dry state, whereas conventional bentonite and cement grouts tend to act as insulators if moisture is lost. The cementitious grouts studied can be mixed and placed using conventional grouting equipment.

Other research conducted at Brookhaven National Laboratory on similar grouts indicates that the thermally conductive grouts will have low shrinkage, low permeability and superior durability to conventional grouts. At this stage of the study the grouts have not been optimized for thermal conductivity. Thus, scope for further improvement exists and this has the potential to reduce borehole length and enhance heat pump performance. Future work to optimize thermal conductivity and economics and characterize relevant properties is suggested.

INTRODUCTION

The efficiency of geothermal heat pumps is partially dependent on the thermal conductivity of backfill material placed between ground heat exchanger loops and native soil. Ground heat exchanger performance can be significantly enhanced as a result of improved heat transfer if backfill conductivity is increased. Bentonite grouts are typically used as backfill materials. However, Remund and Lund (1993) have shown that the thermal conductivity of unfilled bentonite grouts is relatively low and that filler materials need to be incorporated in the mix to enhance conductivity. Shadley and Den Braven (1995) have studied thermal

conductivity of different backfill materials including sandy soil and various additives to bind sands.

Bentonite grouts are subject to shrinkage and seepage and this can result in loss of bond to heat exchanger pipes. Bentonite grouts tend to form a bentonite rich filter cake on soil walls as the water component seeps into surrounding permeable soil. Similar shrinkage problems can occur when soil or sand-based backfill undergoes loss of moisture. Shrinkage results in formation of an air gap between piping and backfill with consequent reduced heat transfer and unsatisfactory performance.

It is evident that scope for improvement in the thermal and physical properties of backfill materials exists. Remund and Lund (1993) have demonstrated that the thermal conductivity of bentonite grouts can be increased by 100 to 200% through use of such additives as quartzite sand.

Properly designed and mixed cementitious grouts offer several potential advantages over bentonite grouts. These include low permeability, long term durability in subsurface environments, high strength, low shrinkage, and retention of thermal conductivity under drying conditions. Cementitious grouts are relatively inexpensive, easy to work with, and readily available. Any additional cost of cementitious grout compared with bentonite grout is likely to be compensated by the superior long term performance and potential savings induced by reducing the length of the ground heat exchanger.

A series of preliminary tests was performed to determine the magnitude of thermal conductivity of cementitious grouts and how this may be improved through the use of additives. Bentonite and cement-bentonite grouts were also studied for comparison.

EXPERIMENTAL PROCEDURE

Thermal conductivity was measured after 14 days of wet curing and after drying in an oven at 40°C to determine how conductivity changes with moisture content. The cementitious grouts were all designed to be mixable and pumpable with conventional grouting equipment. Previous research at Brookhaven National Laboratory has investigated the necessary grout properties and mix proportions for tremied grout. The major effort was directed at reducing the water content of the grout mix. By lowering the water/cement ratio, the porosity of the cured grout is decreased. This in turn results in higher thermal conductivity. Lowering the water/cement ratio also improves such properties as permeability, strength, and durability.

The addition of superplasticizers to the grout mixes enabled reduction of water/cement ratio while retaining pumpability. Superplasticizers are commonly used in the concrete industry and have been demonstrated to enhance grout properties. The superplasticizer used was a sulphonated naphthalene type with a solids content of 42% by weight and specific gravity of 1.2. Type

I cement was used, although Type II or V would be recommended for high sulphate environments. Alternatively, fly ash or blast furnace slag could be used to enhance durability in adverse environments, as well as reduce grout cost.

The bentonite used was sodium montmorillonite from Wyoming. Different bentonites suitable for grouting vertical loops are discussed in "Grouting Procedures for Ground-Source Heat Pump Systems" (Eckhart, 1991). In particular, coarse grade bentonites are favoured so that a high solids (>20% bentonite) grout can be used. This is necessary to meet low permeability requirements. It was not possible to produce a pumpable grout with >20% solids with the type of bentonite used in this preliminary study. Therefore, a lower solids content (7%) was used.

The filler materials studied were silica sand, alumina grit, silicon carbide grit, calcined coke breeze, steel grit, and steel fibres. Two different grades of alumina and silicon carbide were used. Alumina and silicon carbide grits are common abrasive materials. Condensed silica fume was also studied since this additive reduces the porosity and permeability of concrete and grout. Silica fume was used as a partial cement replacement at a level of 5%. The steel fibres were 38 mm long with a crimped shape and were added at a volume fraction of 0.5%. A shorter fibre length may be advisable for backfill grouts, although variation of fibre length was beyond the scope of this preliminary study. A small proportion of bentonite was added to the cementitious grouts to reduce bleeding and improve filler carrying capacity (i.e. reduce settling). The water/cementitious material ratio of the filled grouts was kept constant at 0.45 (by weight) so that the effect of filler on conductivity could be determined. The mix proportions of the grouts by mass are presented in Table 1 and the volume fraction of filler data are presented in Table 2.

Due to the different particle shapes and sizes of the filler materials, the proportion of filler could not be kept constant while retaining the same flow properties. Thus, the conductivity results are not solely a reflection of the filler composition, but also of the amount of filler that could be added. The greatest proportion by weight of filler added was for steel grit due to the high density. This was followed in decreasing order by coarse alumina, coarse silicon carbide, fine alumina and coke breeze (equal), sand, fine silicon carbide and steel fibres. The order of volume fraction of filler was coke breeze > coarse silicon carbide = steel grit > coarse alumina = sand > fine alumina > fine silicon carbide > steel fibres.

The cementitious grouts were cast as blocks 75 mm x 125 mm x 25 mm, except for the fibre reinforced grout which had a thickness of 50 mm to avoid alignment of fibres. The blocks were demoulded after 24 hours and placed in a water bath to cure. Since the bentonite grout formed a gel, thermal conductivity was measured in

the as cast state. The cementitious 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 7 days and re-tested to determine the effect of loss of moisture. Selected grouts were re-saturated after drying and thermal conductivity was re-measured.

Table 1. Mix Proportions of Cementitious Grouts by Mass

Mix	Cement	Water	Bentonite	Filler	SP
w/c = 0.8	55.05%	44.05%	0.9%	--	-
w/c = 0.4	69.83%	27.93%	0.56%	--	1.68%
Silica Sand	37.08%	16.69%	0.83%	44.50%	0.90%
Coarse Al ₂ O ₃	29.66%	13.35%	0.67%	55.61%	0.71%
Coarse Al ₂ O ₃ , Silica Fume	28.25%	13.38%	0.42%	55.75% Al ₂ O ₃ , 1.49% silica fume	0.71%
Fine Al ₂ O ₃	35.51%	15.98%	0.32%	47.34%	0.85%
Coarse SiC	34.13%	15.36%	0.77%	48.92%	0.82%
Fine SiC	38.51%	17.33%	0.87%	42.36%	0.93%
Coke Breeze	35.34%	15.90%	0.79%	47.12%	0.85%
Steel Grit	18.73%	8.43%	0.59%	71.80%	0.45%
Steel Fibres and Sand	34.26%	15.42%	0.77%	41.11% sand, 7.62% fibres	0.82%

(SP = superplasticizer)

Thermal conductivity of the grouts was measured using a Shotherm QTM-D2 Thermal Conductivity Meter. This meter uses the hot wire method and Equation 1 describes the principle behind the method.

$$\lambda = \frac{q \ln(t_2/t_1)}{4\pi(T_2 - T_1)} \quad (1)$$

where λ = thermal conductivity (W/m.K)
 q = rate of heat flow per unit length (W/m)
 t_1 = time 1 (s)
 t_2 = time 2 (s)
 T_1 = temperature at t_1 (K)
 T_2 = temperature at t_2 (K)

Table 2. Volume Fraction of Filler in Cementitious Grouts

Mix	Volume Fraction Filler
Silica Sand	0.52
Coarse Al_2O_3	0.52
Coarse Al_2O_3 , Silica Fume	0.52
Fine Al_2O_3	0.48
Coarse SiC	0.54
Fine SiC	0.47
Coke Breeze	0.59
Steel Grit	0.54
Steel Fibres and Sand	0.05 fibres, 0.48 sand

THERMAL CONDUCTIVITY RESULTS

The results of the measurements are presented in Tables 3 and 4, along with description of the grout mix. An average of three different specimens is reported. Conventional bentonite, cement-bentonite and cement grouts without any superplasticizers or other additives are reported in Table 3. Results for superplasticized cementitious grouts with different additives are reported in Table 4. Note that 1 W/m.K is equivalent to 0.578 Btu/hr.ft.°F.

Table 3. Thermal Conductivity of Conventional Grouting Materials

Grout Description	Water/Cementitious Material	Thermal Conductivity (W/m.K)		
		14 Days	After Drying	% Change
7% bentonite, 93% water	-	0.559	- (cracked)	-
6% bentonite, 18% cement, 76% water	4.2	0.655	0.076 (cracked)	-88.4
Cement-water	0.80	0.803	0.456	-34.7

Table 4. Thermal Conductivity of Superplasticized Cementitious Grouts

Filler Material	Water/Cementitious Material	Thermal Conductivity (W/m.K)		
		14 Days	After Drying	% Change
None	0.40	0.868	0.706	-18.7
Silica Sand	0.45	1.731	1.605	-7.3
Coarse Al ₂ O ₃	0.45	2.318	2.128	-8.2
Coarse Al ₂ O ₃ , Silica Fume	0.45	3.259	2.986	-9.1
Fine Al ₂ O ₃	0.45	2.075	1.794	-13.5
Coarse SiC	0.45	3.302	2.493	-24.5
Fine SiC	0.45	2.725	2.147	-21.2
Coke Breeze	0.45	1.743	1.377	-21.0
Steel Grit	0.45	2.895	1.920	-33.7
Steel Fibres and Sand	0.45	2.639	2.397	-9.2

DISCUSSION

The thermal conductivity of the bentonite grout (7% bentonite, 93% water) was the lowest of all materials tested. This was partially due to the low solids content that was dictated by the rheology of the particular bentonite used, in addition to the

inherent low conductivity of bentonites. The effect of solids content on thermal conductivity of different unfilled bentonite grouts has been reported by Remund and Lund (1993). Thermal conductivity was found to increase slightly with increasing solids content. The values typically fell within the range of 0.65 to 0.90 W/m.K, depending on bentonite type. Thus, even with granular bentonites and higher solids grout, thermal conductivity remains relatively low.

The effect of water/cementitious material ratio (w/c) is demonstrated by comparing the results for mixes with ratios of 0.4, 0.8 and 4.2. Thermal conductivity increases with decreasing w/c. This is the result of reduced porosity of the final product.

Retention of thermally conductive properties despite loss of moisture is an important requirement since the backfill must maintain adequate performance if the grout dries due to a thermal gradient. The bentonite grout underwent desiccation, severe cracking, and loss of volume on drying. Thermal conductivity of the bentonite grout after drying could not be measured due to the deterioration of the material. Low thermal conductivity was also measured on the cement-bentonite grout. This grout underwent a mass loss 68% and exhibited cracking and friability. The thermal conductivity after drying was extremely low as a result of the formation of cracks and the loss of moisture. The cement-bentonite grout would act as an insulator if similar dehydration occurred during exposure.

Addition of filler materials to grouts can be used to improve thermal conductivity and reduce shrinkage and cracking. Maintenance of relatively high thermal conductivity under drying conditions is also enhanced through use of fillers. The mass change of the filled cementitious grouts on drying was typically 3 to 4%. The effect of the different filler materials is shown in Table 4. The highest thermal conductivities were achieved when silicon carbide or alumina plus silica fume were added. High values were also obtained for the grouts containing alumina grit, steel grit or steel fibres plus sand. Addition of steel fibres improved the conductivity of the sand filled grout by 52%.

Higher thermal conductivities for the grouts filled with steel fibres or grit could have been expected due to the higher conductivity of steel compared with the other fillers. However, since the tested materials are composites, the lower thermal conductivity of the steel-filled grouts can be explained in terms of particle packing.

The differences in thermal conductivities obtained with different filler particle size demonstrate the need to have a high volume fraction in addition to high conductivity of the filler itself. The fine silicon carbide and fine alumina fillers gave lower conductivities due to the lower volume fraction that could be

added while maintaining flow behaviour. At this stage, the grout mix proportions and filler particle size distribution have not been optimized. Therefore, further improvement in thermal conductivity may be possible, particularly through manipulation to improve packing, volume fraction and contact between particles. For example, grouts with higher proportions of sand than those studied to date are used in tremie applications and increased sand content should enhance thermal conductivity further.

The effect of moisture content of the hardened cement-bentonite and cement-based grouts on thermal conductivity is indicated in Tables 3 and 4. The decrease in thermal conductivity on drying was dependent on w/c and this can be attributed to the pore structure of the grout. If 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. Increased porosity results in lower thermal conductivity since air has a lower conductivity than water. High w/c grouts will have greater porosity and, thus, lower conductivity than low w/c grouts. Grouts with lower w/c are also stronger, more durable and less permeable.

Tables 3 and 4 also show the percentage change in thermal conductivity on drying. The grouts containing silica sand, coarse alumina grit or sand plus steel fibres showed the lowest percentage decrease in conductivity associated with loss of moisture. Since the filled grouts all had the same w/c, the behaviour can be attributed to the filler material. It is possible that the bonding of the cement paste to coarse alumina and to silica sand is superior to that of the other filler materials, thereby improving conductivity between paste and particles. The improved retention of thermal conductivity for the coarse alumina as opposed to the finer material of the same composition may be due to improved resistance to microcracking. The filled grouts showed superior thermal performance after drying compared with the cement-bentonite and w/c = 0.8 cement grout which lost 88 and 43% conductivity, respectively.

The increase in thermal conductivity when filler materials were incorporated in the cementitious grout ranged from 99 to 280% as compared with the unfilled grout with w/c = 0.4. For cementitious grouts measured after one week of drying at 40°C, the increase in conductivity due to filler materials ranged from 127 to 323%. Comparison between filled grouts and conventional unfilled bentonite, cement-bentonite, and high w/c cement grouts shows that thermal conductivity can be increased by 115 to 490% when wet cured for 14 days and by 252 to 3830% when materials are dry. Re-testing after re-saturation showed that high thermal conductivity of the filled grouts was restored when the moisture level increased.

The values of thermal conductivity after 14 days wet curing for the filled cementitious grouts are similar to those measured by

Remund and Lund (1993) on 4 hour old, high solids bentonite grouts filled with 60-70% quartzite. The grout containing silica fume and coarse alumina had a higher conductivity than the filled bentonite grouts. Thermal conductivity of filled bentonite grouts can also be expected to decrease with loss of moisture.

The thermal conductivities of the filled cementitious grouts were compared with values for different types of soils with different moisture contents that were reported by Remund (1994). The better grouts (containing coarse alumina, silicon carbide or steel fibres and sand) had higher conductivities than saturated soils. Decrease in thermal conductivity of different soils from field capacity to wilting point ranged from 7.8 to 73.2%, depending on density and soil type (Remund, 1994). Therefore, the decrease in thermal conductivity of the coarse alumina and sand filled grouts is comparable to the lowest decrease that was measured on a high clay content soil.

The order of cost per unit weight of filler materials is silicon carbide>steel fibres>alumina>coke breeze>steel grit>sand. Based on the results obtained in this preliminary study, alumina and steel fibres plus sand appear to be the best of the filler materials tested. A sanded grout would be the most economic and further improvement in thermal conductivity should be possible by increasing the proportion of sand. However, the thermal conductivity may not be as high as that for a grout containing steel fibres.

Silicon carbide is prohibitively expensive and does not perform as well under drying conditions. The mass fraction of the particulate fillers ranged from 0.42 to 0.56 and the volume fraction ranged from 0.47 to 0.59. The grout containing coke breeze had a moderate thermal conductivity despite the high volume fraction added.

The mass fraction of steel fibres used in the sanded grout was 0.08 and the volume fraction was 0.005. Since only a small volume fraction of steel fibres is necessary to improve the conductivity of sanded grout, this combination appears economically favourable. Steel fibre reinforced grouts are compatible with conventional mixing and pumping equipment. An example of the use of tremied steel fibre reinforced grout is given by Bayasi and Downey (1995) and Bruce (1995). Steel fibres are readily available and used in the concrete industry. Smaller fibre lengths are available and a length of 19 mm may be more suited to backfill grouts to prevent voids in narrow spaces. Fibre-reinforced grout is also useful in unconsolidated formations to prevent excessive loss.

Cost of the grout could be further reduced by partial replacement of cement with fly ash or blast furnace slag. This would also be beneficial in high sulphate soils since fly ash and slag improve sulphate resistance (Allan and Kukacka, in press, a).

The permeability of the grout with sand was measured previously in another program and was found to be 3.2×10^{-10} cm/s after 28 days of wet curing (Allan and Kukacka, 1994; in press, b). Although permeability testing of the other thermally conductive grouts was beyond the scope of this preliminary project, the same order of magnitude low permeability can be expected. A similar sanded, superplasticized grout with w/c = 0.5 was evaluated tremied into the ground and cored after four months (Allan and Kukacka, 1993; 1994a). This grout was easily pumped and the tested thermally conductive grouts were designed to meet the same pumpability requirements. In-situ curing conditions also gave a permeability of the order of 10^{-10} cm/s. These low permeability values are important for meeting environmental regulations and preventing contamination of aquifers or other wells. Permeability less than 10^{-7} cm/s is desired for backfill grouts (Eckhart, 1991).

Sanded, superplasticized grouts have been found to exhibit low shrinkage on curing (Allan and Kukacka, 1993) and this is an important consideration when grouting heat exchangers. The developed thermally conductive grouts are also predicted to have high strength and durability. Use of these types of grouts in high sulphate environments would require either substitution with Type V (sulphate resistant) cement or addition of ground granulated blast furnace slag or fly ash. This is not expected to change the thermal conductivities significantly. The permeability and durability of sulphate resistant grouts has been studied at Brookhaven (Allan and Kukacka, in press a; b).

SUGGESTIONS FOR FUTURE RESEARCH

The positive results obtained for filled cementitious grouts have demonstrated that thermal conductivity can be readily improved, particularly under drying conditions. Further studies using the most suitable filler materials identified in this preliminary work are necessary to optimize the mix proportions and economics. For example, it should be possible to increase the sand content of grout while retaining pumpability. Other fillers of interest are copper fibres and copper particles due to the high thermal conductivity of copper. Copper fibres have been shown to increase thermal conductivity of concrete significantly (Cook and Uher, 1974). By increasing the volume fraction of filler and the inter-particle contact, the thermal conductivity could be improved. Response surface methodology would be used to determine optimum filler type and proportion in an efficient manner.

Changes in mix proportions would require monitoring of rheological properties to ensure that the grouts remain pumpable. It may be possible to reduce the cost of the grouts by partial replacement of cement with ground granulated blast furnace slag or fly ash. These materials have the added benefit of improving durability of cementitious grouts and reducing heat of hydration during curing. Further evaluation of the effect of service

exposure conditions on the long term performance of filled cementitious backfill grouts is also necessary. Quantitative comparison of heat exchanger efficiency for filled cementitious and bentonite backfill grouts would rationalize materials selection for future installations of geothermal heat pumps.

Other important properties of the thermal conductive grouts that require characterization are long-term durability, permeability, shrinkage, and adhesion to heat exchanger loop.

CONCLUSIONS

Cementitious grouts offer several benefits over bentonite grouts for use as thermally conductive backfill around ground heat exchanger loops. Preliminary research has shown that lowering the water/cement ratio of the grouts and addition of conductive fillers can increase thermal conductivity to 1.7-3.3 W/m.K (0.98-1.9 Btu/hr.ft.°F). Further improvement in grout thermal conductivity should be possible through mix optimization. The grouts can maintain relatively high thermal conductivity under drying conditions. In contrast, unfilled bentonite grouts undergo severe loss of moisture and cracking with resultant significant decrease in conductivity. Cementitious grouts also have lower permeability, lower shrinkage, and greater strength than bentonite grouts. The results of this preliminary work indicate that improved efficiency of geothermal heat pumps and reduction of heat exchanger length may be possible if filled cementitious grouts are used for backfilling vertical heat exchangers. Suitable filler materials include sand, alumina grit, and sand plus steel fibres. Further research is necessary to capitalize on the usefulness of thermally conductive grouts for improving ground heat exchanger efficiency and reducing borehole length.

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