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Quality Control and Troubleshooting for Grouts Used with Geothermal Heat Pumps

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ABSTRACT

Vertical boreholes for geothermal heat pumps (GHPs) are completed with grout materials to provide heat transfer and prevent groundwater contamination. Typically, grouts are either bentonite or cementitious. Modifications to these materials are usually made in order to improve thermal conductivity. The efficient performance of GHPs relies on the properties of the grout and the quality of the grout placement. Therefore, it is necessary to ensure that the grouting material conforms to specification requirements and that appropriate quality control testing is undertaken to verify mix proportions and pumpability. This paper considers field quality control and post-grouting tests applicable to bentonite and cementitious grouts and how these can best be implemented. In addition, problems that can arise during mixing and placement of grout are discussed and recommendations are made on how these pitfalls can be avoided.

1. INTRODUCTION

Pumpable grout materials are used to backfill vertical boreholes used as heat exchangers for geothermal heat pumps (GHPs). The grout serves two primary functions. The first is to enable heat transfer between the U-loop with circulating fluid and the surrounding formation. The second function is to seal hydraulically the borehole and therefore prevent groundwater contamination and cross-contamination of aquifers. Grout materials are therefore required to have the following properties:

- Suitable thermal conductivity under a range of moisture conditions, including in the vadose zone
- Flowability and pumpability
- Volume stability
- Low hydraulic conductivity (coefficient of permeability)
- Adequate sealing to both the U-loop and surrounding formation
- Durability
- Ability to withstand thermal and physical stresses in the borehole environment
- Easily mixed and pump with available equipment
- Comprised of readily available materials
- Cost effectiveness

Bentonite or cementitous grouts are commonly used to complete boreholes. Regardless of the materials selected, grouts and grouting techniques need to be effective in order for a GHP to operate efficiently over a prolonged period and for groundwater to be adequately protected. Quality control testing during and after grouting can detect non-conformances, enable rectification and give confidence that the GHP design and performance will be achieved. This paper reviews appropriate grout testing techniques, identification of problems and how issues that may compromise performance can be prevented.

2. GROUTING OF BOREHOLES

2.1 Grouting Requirements

Grouting of boreholes is usually covered under state environmental legislation. The grouting requirements and permissible materials are regulated by the relevant authority. In addition, guidelines are given in publications (e.g., IGSHPA, 2000; GSHP Association, 2011; NGWA, 2010).

2.2 Grout Materials

Bentonite-water grouts or neat cement-water grouts have poor thermal conductivity and are prone to shrinkage and cracking. Enhancement of thermal conductivity of both bentonite and cementitious grouts can be achieved with addition of filler materials and tailoring of mix proportions. Numerous thermally enhanced bentonite products have been developed for use with GHPs. A thermally enhanced cementitious grout was developed by the author and is used throughout the USA. The grout is known as Mix 111. In the development of this material, a variety of fillers were initially tested to improve thermal conductivity of cementitious grouts including silica sand, steel grit, steel fibres, silicon carbide, alumina and coke breeze (Allan and Kavanaugh, 1999). Of these, silica sand was found to provide the best balance of properties, retention of thermal conductivity under drying conditions, cost and availability. Subsequently, a superplaticized sand-modified cementitious grout was optimized for use (Allan, 1997; 2000; Allan and Philippacopoulos, 1998; 1999a).

A study of grouting materials for water wells and geothermal boreholes was conducted by Lackey et al (2009) in Nebraska to investigate cracking and sealing capability. It was found that a cement-sand grout performed best overall and was superior to bentonite and bentonite-sand grout formulations used in geothermal applications. The cement-sand grout evaluated had a water/cement ratio of 0.62 and sand/cement ratio of 0.63. Further improvements in performance of this material are predicted by

lowering the water/cement ratio, increasing the sand/cement ratio and incorporating a small proportion of superplasticizer to aid pumpability as was used for the Mix 111 grout developed GHP boreholes.

A recent development in GHP borehole completion has been the use of graphite in bentonite and cementitious grouts to increase thermal conductivity (Delaleux et al, 2012; Lee et al, 2010; 2012; Borinaga-Treviño et al, 2013a; b). These grouts exhibit relatively high thermal conductivity and are commercially available. However, Delaleux et al (2012) found that bentonite-graphite grouts undergo significant reduction of thermal conductivity if the grouts were subjected to drying conditions. Published studies on other important properties of graphite-enhanced grouts such as permeability, shrinkage, crack resistance, durability and in-situ performance are limited. Erol and François (2013) have tested thermal behavior, permeability and strength of grouts containing different types of graphite additives and it would be useful to see further laboratory and field test data to fully assess these materials.

2.2 Grout Mixers

Mixing of grouts for vertical closed loop installations is usually performed in a paddle type grout mixer. For cementitious grouts it is considered preferable to use a high shear colloidal type mixer. Colloidal mixers are more efficient, can enable reduction of water content and produce a more pumpable grout (Warner, 2004). However, the GHP industry usually employs paddle mixers and cementitious grouts have been tailored to suit such equipment. The type of mixer used needs to be compatible with the grout material and in accordance with the manufacturer's or developer's guidelines. Use of alternative mixers or non-standard equipment is problematic and unlikely to produce a uniform stable grout. For example, mixing of grout in a concrete transit truck is not an effective or acceptable means of mixing materials. Grout mixing equipment should include an agitator tank so that there is a constant supply of grout and that the grouting operation is continuous. Grouts need to be kept agitated prior to pumping so that they remain fluid and segregation of particles can be avoided. This is particularly important for thixotropic grouts and grouts containing fillers.

2.3 Grout Batching and Mixing

Proprietary prepackaged grouts only require addition of potable water for mixing. The quantity of water specified by the manufacturer needs to be strictly followed otherwise the grout properties will not be achieved. Grouts which are not prepackaged must be batched and mixed in accordance with the developer's specification. An example of this for thermally conductive cement-sand grout (Mix 111) is given by Allan (1999). It is important that the solid ingredients are correctly measured or supplied in pre-weighed bags and that liquid ingredients are measured by volume. Some grouting equipment allows metering of water so that the correct amount can be added.

Grouts should be mixed using the order of addition and mixing time recommended by the manufacturer or developer. Changing the order of addition may result in alteration of the rheological properties or mixing and uniformity problems. For a thermally conductive cement-sand grout the correct order of addition is water, superplasticizer, bentonite, cement, fly ash or slag (if used) and sand. If a colloidal mixer is not used for a cementitious grout then the bentonite needs to be well mixed and hydrated before addition of the cement and typically requires the use of a drill (Jiffy) mixer rather than a paddle mixer. The cementitious materials should be added slowly and the mixer speed increased to ensure thorough dispersion and avoiding formation of lumps.

Omission of ingredients is also likely to cause problems as these have been included by the manufacturer or developer for a specific reason. Likewise, substitution of ingredients will alter the grout properties and potentially compromise the design intent of the grout material. For example, increasing the water/cement ratio of a cementitious grout will cause the following changes:

- Decreased thermal conductivity
- Increased shrinkage and likelihood of cracking
- Increased permeability
- Increased bleed and segregation
- Decreased strength
- Reduced durability

Figure 1 shows the effect of water/cement ratio on thermal conductivity of neat cement (no filler) grouts. Of particular note is the reduction in thermal conductivity if the grouts are dried out. The data presented is from Allan (1997). Increasing the water content of bentonite grouts will have a similar negative impact on thermal conductivity, shrinkage and permeability. Hence, care in controlling water content of grouts is required.

The type, purity and particle size distribution of filler materials can also affect grout properties in both the unhardened and hardened states. Thus, substitution of one source and gradation of silica sand for another may not give the same pumpability or thermal performance. Figure 2 shows the effect of sand/cement ratio on thermal conductivity of cement-sand grouts with different types and proportions of sand. The data is for grouts with water/cement ratio ranging from 0.45 to 0.55 and further details are given by Allan (1997). The plot shows a near linear relationship between thermal conductivity and sand/cement ratio for a given sand type and better retention of thermal conductivity under dry conditions compared with neat cement grout in Figure 1. Sand 2 was less pure than the others and had lower thermal conductivity. Similarly, Delaleux et al (2012) found that the type, particle size and shape of graphite used in bentonite-graphite grouts influences thermal conductivity. It is, therefore, important that material substitutions are not made on the assumption that equivalent performance will be achieved.

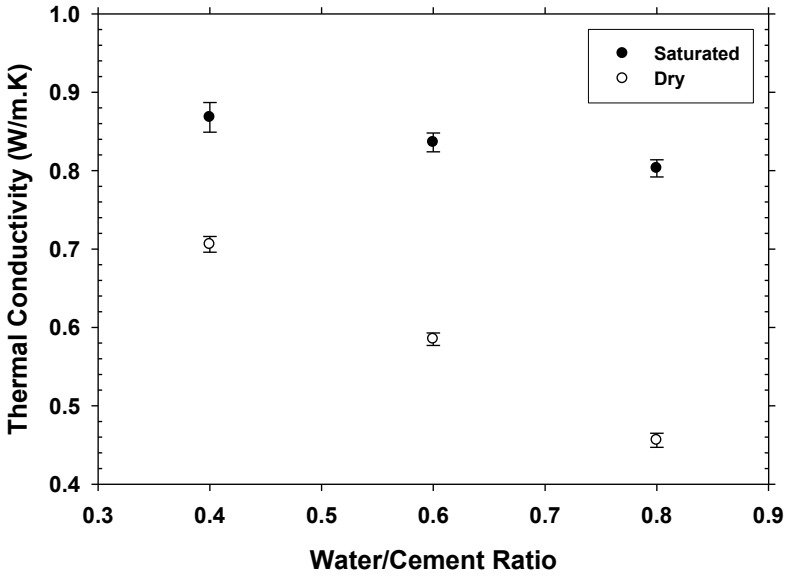

Figure 1. Effect of Water/Cement Ratio on Thermal Conductivity of Neat Cement Grouts. Moisture conditions indicated. Error bars represent one standard deviation.

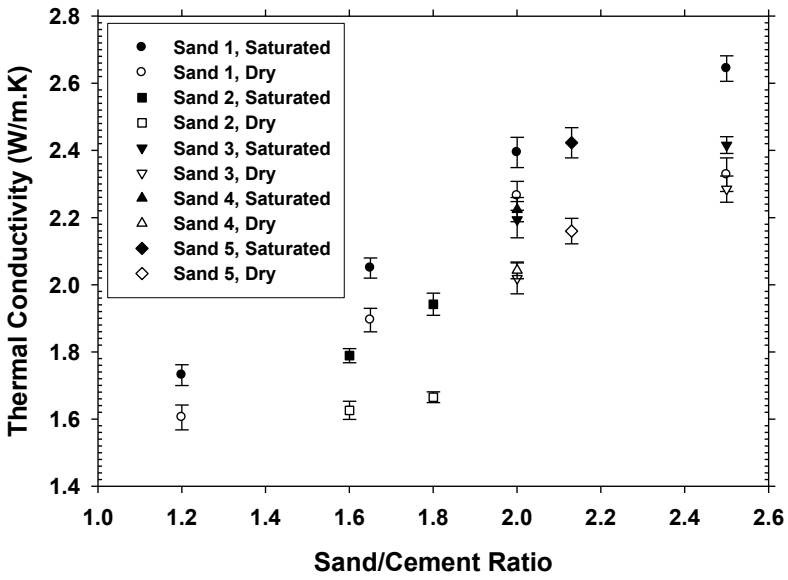

Figure 2. Effect of Sand/Cement Ratio on Thermal Conductivity of Cement-Sand Grouts. Moisture conditions indicated. Error bars represent one standard deviation.

2.4 Grout Pumps

Pumps for grouts are usually of the piston, ram, diaphragm or progressive cavity type. Grouts containing filler materials are best pumped with piston or ram type pumps to avoid wear on pump components. Further details of grout pumps are given by Warner (2004).

2.5 Grout Placement

Vertical boreholes are grouted using a tremie technique. After the heat exchanger loop has been placed in the borehole the grouting operation can proceed. A tremie pipe is placed to the bottom of the borehole and the grout is pumped through the tremie. As grouting continues the tremie pipe is slowly raised. However, it is important that the discharge end of the tremie remains submerged in the grout at all times during the placement operation and is not withdrawn above the grout level. Grout also needs to be placed in one continuous operation. Grouting should continue until the borehole is completely filled and the material exiting the borehole is free from excessive water or soil contamination. Placement of grout by pumping from the top down or free fall is not acceptable and will likely result in entrapment of air voids and water. Further details on grout placement are given by IGSPHA (2000) and NGWA (2010).

3. QUALITY CONTROL TESTING

Adequate quality control testing provides the designer, installer and end-user confidence that the grout has been proportioned and mixed as intended in a consistent manner. The testing requirements and frequency should be clearly stated in a specification and any reluctance on part of the installer to perform quality control testing viewed with concern. Independent witnessing of testing is also beneficial to confirm that the tests have been performed properly.

3.1 Grout Materials

All grout ingredients need to comply with certain standards to ensure that they comply with what is expected. Materials will usually be covered under ASTM or other national standards. Prepackaged materials need to conform with a quality assurance system so that a consistent product is supplied. All bagged products should have a traceable batch number and date of manufacture.

Whilst it is often assumed that prepackaged products are consistent and within specification, errors in the supply and use of these materials can still occur they are not foolproof. Problems with prepackaged materials used in the construction industry such as grout, mortar and concrete are discussed by Emmons et al (2014). Examples of issues resulting in substandard performance include contamination, batching errors for constituent materials, variation in bag weights, segregation, and exceedance of shelf life. Addition of a set quantity of water to an underweight bag of prepackaged material has the potential to lead to reduction in thermal conductivity. Similarly, incorrect proportions of filler materials or segregation of constituents could cause thermal conductivity to be low or inconsistent. Contaminated ingredients or material which has passed its use by date may not set properly or otherwise have deficient properties.

3.2 Storage and Handling

Grout ingredients of prepackaged products should be stored under dry conditions and on pallets. This includes sand or other filler materials and these should be bagged rather than sourced from loose, unprotected piles so that the moisture content does not vary.

3.3 Batch Records

Accuracy of batching grout ingredients is essential for achieving the design properties of the grout. Therefore, it is recommended that records of material quantities for each mixed batch be made. Of particular importance is the quantity of water used in mixing. The use of water meters improves the accuracy of added water content.

3.4 Specific Gravity

The primary field method to confirm the proper grout mix proportions is the measurement of specific gravity or density in the unhardened state. A mud balance is used for this purpose. The test is quick, inexpensive and readily detects aberrations in grout mix proportions. Most importantly, the test can be performed in advance of the grout being pumped and therefore can identify non-conforming grout before it is placed in the borehole.

The use of a mud balance to measure specific gravity or density is applicable to both bentonite and cementitious grouts and originated from testing of bentonite drilling muds. The test method is covered in API RP 13B-1 (2008) and API RP 10B-2 (2005). A pressurized mud balance is preferred as it removes entrained air. The mud balance has a resolution of 10 kg/m^3 (Domone and Jefferis, 1994).

The relationship between density and water/cement ratio for neat cement grouts is shown in Equation 1 (Domone and Jefferis, 1994). Similarly, Equation 2 shows the relationship for cement-sand grouts.

$$\rho_g = \frac{(1+\frac{w}{c})}{(\frac{w}{c.\rho_w}+\frac{1}{\rho_c})} \quad (1)$$

where ρ_g = density of grout, w/c = water/cement ratio, ρ_w = density of water and ρ_c = density of cement.

$$\rho_g = \frac{(1+\frac{w}{c}+\frac{s}{c})}{(\frac{w}{\rho_w}+\frac{1}{\rho_c}+\frac{s}{c.\rho_s})} \quad (2)$$

where s/c = sand/cement ratio and ρ_s = density of sand

Equations 1 and 2 can be modified to include additives and admixtures such as bentonite or superplasticiser or partial cement replacements such as fly ash or ground granulated blast furnace slag. The predicted effect of water/cement ratio on specific gravity of grouts is shown in Figure 3. The assumed densities used in the calculations are 1000 kg/m^3, 3150 kg/m^3 and 2650 kg/m^3 for water, cement and sand, respectively. The plot shows the sensitivity of specific gravity to water/cement and sand/cement ratios. Thus, the measurement of specific gravity can confirm whether mix proportions are correct. The actual density of sand will depend on the source and presence of any porosity and may vary between 2500 to 2800 kg/m^3. Entrained air in the grout will reduce specific gravity.

The specific gravity (or density) of field mixed grout should be checked against the manufacturer's or developer's values to confirm that the batching is correct. Each batch of grout should be sampled and tested for specific gravity and the measured value recorded against a batch number. Non-conforming grout should be rejected as attempts to correct inaccurate mix proportions are unlikely to easily rectify batching problems.

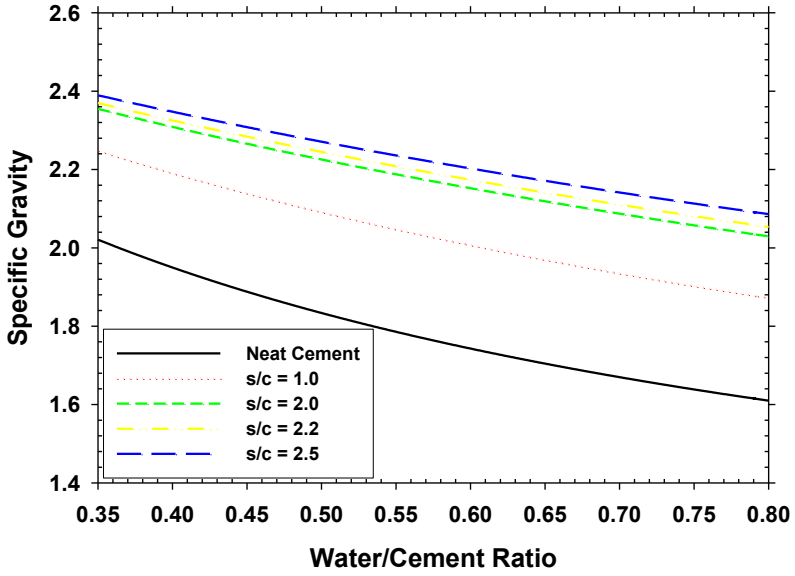

Figure 3. Predicted Specific Gravity of Cementitious Grout versus Water/Cement Ratio for Neat Cement and Cement-Sand Grouts with Different Sand/Cement (s/c) Ratios.

3.5 Flow Time

Measurement of flow, or efflux, time through a standard cone is an indirect indication of grout viscosity. Thus, the flow time can be used to check the fluidity and pumpability of the grout. Flow time is also strongly influenced by mix proportions, particularly water and admixture content, and the test can therefore detect incorrect mix proportions. Since grout rheology depends on the type of mixer used, the test is best used to verify uniformity of grout batches once the flow time is established for a given grout and mixer. Flow time tests are rapid and simple to perform in the field.

There are two types of flow cones. The first is a Marsh Funnel (or Cone) and is widely used to test drilling muds and neat cement or bentonite grouts. The time for a known quantity of grout to flow the funnel is measured. The test method is described in API RP 13B-2 (2005) and ASTM D 6910/D 6910M-09 (2009). For grouts containing fillers, the ASTM C 939-10 flow cone is better suited than the Marsh Funnel owing to the larger orifice. Like the Marsh Funnel, the ASTM C 939 flow cone measures the efflux time of a known volume of grout. Fluid grouts typically have flow times in the range of 10 to 35 seconds when measured by the ASTM C 939 method. Neat cement or bentonite grouts can also be tested by this method.

It is important that the correct procedure is used when measuring flow time and further details are given by Warner (2004). Furthermore, the material of construction for the flow cone can influence flow time owing to surface roughness and wettability. ASTM C 939 flow cones are typically constructed of aluminum. However, polyethylene flow cones are now available. Another recent variation is the orifice size. Previously, the flow cones had an orifice diameter of 0.5 inches, but 0.75 inch diameter orifices are obtainable. The type of flow cone, material of construction and orifice diameter should therefore be clearly specified for flow time tests.

Measurement of flow time for each batch of mixed grout is recommended as a quality control test. Flow cones should be thoroughly cleaned after use to ensure reproducible results.

3.6 Bleed

Grouts may be subject to settlement when undisturbed and this results in formation of a layer of water at the top of the grout column. This process is referred to as bleed. Excessive bleed can be avoided in cementitious grouts by limiting the amount of water, using a superplasticiser and a small quantity of bentonite and by mixing in a high shear mixer.

Bleed tests are often used for cementitious grouts, particularly where bleed can impact structural performance or durability, such as grouting of post-tensioning ducts in bridge construction or other applications involving filling of voids. The test method is given in ASTM C 940-10a. The test involves filling a measuring cylinder with a known volume of grout and then observing the volume of bleed water that forms. Since the test requires the grout to remain undisturbed for up to three hours, it is not of great value for field testing of GHP grouts. It is, however, useful in laboratory evaluation of grout formulations since excessive bleed is undesirable.

3.7 Thermal Conductivity

Sampling of grout for thermal conductivity testing is a valuable means of verifying compliance. Thermal conductivity of cementitious grouts can be measured using the hot wire method (ASTM C 1113/C 1113M-09) or guarded hot plate method (ASTM C 177-13). Bentonite grouts are often tested using the thermal needle probe method described in ASTM D 5334-08. Thermal conductivity testing is not suited to field use and should be performed by an independent laboratory. Testing offered by the grout supplier or manufacturer is not regarded as independent.

Samples of the grout should be poured into a suitable leakproof container, the dimensions of which depend on the equipment that will be used to measure thermal conductivity. The grout samples should be sealed or covered with plastic for 24 hours and maintained at temperature as close as possible to 20-25°C. In the case of cementitious grouts, after 24 hours the samples should be demoulded and immersed in a water bath at 20-25°C to cure for at least 7 days prior to testing. The sample preparation and test method used for verifying grout thermal conductivity need to be consistent with that used by the manufacturer or developer if direct comparison is to be made.

4. TROUBLESHOOTING GROUTING PROBLEMS

Problems may arise during mixing and pumping of grouts for GHP boreholes. Table 1 summarises common problems, possible causes and how such issues may be prevented. Consideration is given to the role of quality control testing in avoiding use of grout which is non-conforming.

Table 1. Grout Mixing and Pumping Problems

Problem	Possible Causes	Prevention
Grout too fluid	• Incorrect mix proportions • Excessive water • Excessive superplasticizer (for cementitious grout) • Insufficient bentonite (for cementitious grout) • Insufficient filler • Excessive moisture in filler materials • Inefficient mixer • Incorrect order of addition	• Accurate batching of materials • Correct order of addition for type of grout • Use of suitable grout mixer • Store all materials under cover and only use dry fillers • Test for grout specific gravity and flow time
Grout too viscous	• Insufficient water • Insufficient superplasticizer (for cementitious grout) • Excessive bentonite (for cementitious grout) • Excessive filler • Inefficient mixer • Incorrect order of addition	• Accurate batching of materials • Correct order of addition for type of grout • Use of suitable grout mixer • Test for grout specific gravity and flow time
Settlement of solids in grout	• Excessive water • Insufficient bentonite (for cementitious grout) • Excessive filler • Inefficient mixer • Insufficient agitation of grout before pumping	• Accurate batching of materials • Correct order of addition for type of grout • Use of suitable grout mixer • Test for grout specific gravity and flow time • Use agitator tank to keep grout mobile before pumping
Lumps in grout	• Solid materials added too quickly to liquids • Inefficient mixer • Insufficient mixing time • Mixing speed too low • Cement is old or water damaged • Hardened materials left in grout mixer	• Correct materials addition and mixing techniques • Test for grout specific gravity and flow time • Check manufacture date and condition of all materials • Cleaning and maintenance of grout mixer
Non-uniform grout	• Inefficient mixer • Insufficient mixing time • Mixing speed too low	• Use of suitable grout mixer • Correct mixing techniques • Test for grout specific gravity and flow time
Difficulty pumping grout	• Pump is unsuitable for type of grout • Pumping distance too long • Mechanical issues • Clogged hoses or tremie • Grout mix proportions incorrect • Filler material is too angular or of incorrect gradation • Lumps in grout • Settlement of grout solids • Solid materials reacting with residual water in grout hose	• Use of suitable grout pump • Cleaning and maintenance of pump • Minimisation of pumping distance • Test for grout specific gravity and flow time • Provide backup hoses and tremie • Use of suitable fillers • Accurate batching of materials • Preventive measures for lumps in grout and settlement of solids as above • Lubricate pump and hoses with neat cement slurry before full scale production
Poor borehole performance	• Inadequate grouting • Voids in grout • Incorrect grout mix proportions	• Accurate batching of materials • Correct mixing and placement techniques • Test for grout specific gravity and flow time • Test for thermal conductivity of grout samples

5. GROUTED BOREHOLE TESTING

Once a GHP borehole is grouted tests can be performed to evaluate and confirm thermal behavior. Testing to detect defects in grout is currently not well developed. Nevertheless, methods used for testing wells and piles may hold potential for application to grouted boreholes.

5.1 Thermal Response Testing

In-situ thermal response tests are widely used to determine ground thermal properties for GHP design purposes and the thermal conductivity of grouted boreholes. Thermal response testing can also be used to evaluate different ground heat exchanger configurations. The test principle and applications are discussed by various authors including Beier and Ewbank (2012), Hemmingway and Long (2012), Mattsson et al (2007) and Sanner et al (2005). There is potential for applying the test to verifying the quality of grouting. Hemmingway and Long (2012) noted that lower than expected thermal conductivity determined by thermal response testing of a borehole may have been due to partial grouting, amongst other reasons. In a study of thermal response testing Banks et al (2009) found higher thermal resistance in a partially grouted borehole. The use of thermal response testing to identify poor quality grouting would require further research to correlate size and type of defects with borehole thermal behaviour.

5.2 Non-Destructive Testing

The feasibility of applying non-destructive test methods used in the petroleum and geotechnical industries to ground heat exchangers has been investigated (Allan and Philippacopoulos, 1998; 1999b). It may be possible to use certain techniques to assess the integrity of bonding between the grout and U-loop and also detect voids within grout. For example, pile integrity testing for involving tapping of cast in-situ concrete piles with a hammer to induce a compression wave and measuring the response. Voids in concrete are detectable by this technique (Lilley, 2000). Hence, it may be possible to apply a similar or modified principle test to grouted boreholes. The pile integrity test method is covered in ASTM D 5882-07.

A development in testing of concrete drilled shafts and augered cast in place piles involving measuring of internal temperature may also hold promise for non-destructive testing of GHP boreholes. This test is known as Thermal Integrity Profiling and is described by Mullins et al (2007). Embedded thermocouples located at different depths of the pile measure temperature increases generated during hydration of cement. Voids in the concrete are detected by anomalies in the thermal profile. This method may be applicable to boreholes completed with cementitious grout. Further study involving experimental and field testing would be necessary to evaluate the viability of this technique for non-destructive testing of grouted vertical boreholes.

6. CONCLUSIONS

Proper grouting of boreholes for GHPs is critical to ensure satisfactory thermal performance and hydraulic sealing. Grouting materials in common use are based on either bentonite or cement. Improvement in thermal conductivity is achieved by inclusion of filler materials. Other properties of importance such as hydraulic conductivity, shrinkage and durability can be optimized through selection and mix design of grouts. Irrespective of the type of grout used, successful completion of boreholes requires that grout is correctly proportioned, mixed and placed. Erroneous batching of ingredients, substitution of materials, inefficient mixers or inappropriate mixing techniques can result in problems pumping grout and ultimately compromise the thermal performance of the borehole heat exchanger. Quality control testing after mixing grout can be used to identify problems stemming from incorrect mix proportions, materials or mixing technique. Field and laboratory quality control test methods have been reviewed and recommendations made. In particular, measurement of specific gravity and flow time are quick, simple methods for detecting issues that may affect pumpability, thermal conductivity and other properties. Typical grout mixing and pumping problems are considered and potential causes and means of prevention presented. Post-grouting testing has also been reviewed. Thermal response testing and non-destructive methods used for verifying integrity of piles in geotechnical engineering may be relevant; however research would be required to correlate grouting defects with measured responses.

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