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Geothermal Ground Heat Exchangers in Malta: Thermal Performance Assessment of Infill Grouts

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ABSTRACT: The aim of this paper was to assess the thermal conductivity of proprietary grout mixes versus local ones in Malta. Ground source heat pump (GSHP) systems consume 75% less electricity than conventional environmental control systems and have lower maintenance costs. On the other hand the installation costs of GSHPs are comparatively higher. Attention has therefore been focused to try to lower the costs of installing the borehole heat exchange system. The grout is one of the key factors that influence the efficiency of ground source heat pumps, being the principal conductive medium to the natural terrain. This paper explores the variations in the thermal conductivity of different sand-cement grouts. It compares and evaluates options for the suitability of these materials for backfilling vertical boreholes of ground heat exchangers. In this study sixteen different sand-cement grouts have been designed, evaluated and compared with materials, which have been conventionally used to fulfil this purpose. Imported silica sand and local sand mixes were formulated, tested and compared so that the potential use of local sands could be closely examined. Output results prove that local sand-cement grouts improve thermal conductivity values by 27% and are also 17% less expensive when compared to silica sand-cement and bentonite grouts. This win-win scenario points towards improvements in both in thermal conductivity and cost effectiveness when using local resources.
Keywords: Ground source heat pump (GSHP), ground heat exchanger, thermal conductivity, infill grout.

INTRODUCTION

Europe set its 20-20-20 targets to reduce greenhouse gas emissions by at least 20%, obtaining 20% of the energy consumption from renewable resources and a 20% reduction in primary energy use by increasing energy efficiency. The United Nations has designated 2012 as the *International Year of Sustainable Energy for All* [1], the United States President Obama challenged law makers in the United States to set a new goal; that by 2035, 80% of the nation's electricity will come from clean energy sources. In China, President Hu has included alternative energy as one of the country's new "seven strategic industries". These are all indications of the importance which sustainable energy is being given internationally.

To ensure a sustainable growth the world must use its energy more efficiently and concentrate on the development of all forms of renewable energy: hydro, wind, solar, biomass, geothermal, etc. [2]. A single renewable technology on its own will hardly ever be able to satisfy the demand of energy in a constant manner. Each technology has its advantages and disadvantages and might work better in certain places. If renewable technologies are used in conjunction, intelligently and are strategically located there might be a possibility for these technologies to be able to supply sufficient energy to meet the demand. By installing any one or a combination, renewable energy technologies will not only benefit from lower electricity charges, but will also be making a contribution to the quality of life.

BACKGROUND

Heat pump applications enable geothermal energy to be used in sub-tropical areas where the first few meters below the ground are known to have a stable temperature of 18°C. Equally in Malta, based on precedent studies at a depth of 20m ground temperatures are known to correspond to an annual mean of 20°C [3]. In fact geothermal water within temperatures of 20°C to 40°C is too low for direct application of geothermal energy in space heating but it is ideal for a heat pump system. These make it versatile for most countries to utilise the earth's temperature for heating/cooling.

Heat pumps essentially remove heat from the earth through a fluid, normally water. This energy uptake is then "upgraded" by the heat pump and transferred to the indoor air. One advantage that heat pumps have over other geothermal energy systems is that this process can be reversed seasonally.

A ground source heat pump (GSHP) is a low maintenance system. Moreover, it consumes 75% less electricity when compared to conventional ECS (environmental control systems). GSHP systems are also known to shed off a reduction in GHG emissions by over 66% [4]. Their only drawback however is that they typically cost more to install than conventional ECS since they require an underground borehole and pipe array setup. Perhaps that is why research has been focused internationally on the reduction of their installation costs.

In 2008, The European Geothermal Energy Council (EGEC) issued a list of priorities for research and development in the geothermal sector aimed at reducing the costs, and therefore attracting more financing for the said systems by 2020. The strategies proposed by the EGEC revolve around a main keynote which is the reduction of drilling costs. Owing to the fact that two thirds of the costs associated with geothermal systems are due to the drilling of the wells, a priority should be to reduce drilling costs by 2020 [5].

Boreholes used with closed loop vertical heat exchangers for geothermal heat pumps (GHP) are backfilled with grout to meet performance and environmental requirements: To meet performance requirements this grouting material should promote heat transfer between the heat exchanger and the surrounding formation and form a hydraulic seal to prevent ground-water contamination and prevent leakage of surface contaminants to aquifers or cross contamination between aquifers to meet its environmental requirements.

The argument set out by the EGEC is backed up by a number of studies which, by using different backfill compositions, attempt to increase the thermal performance of the heat exchanger so that, subsequently, drilling lengths, pipework, amount backfill material required and pump size can all be reduced. The idea brought forward by such studies is that the more efficient the heat transfer between the fluid in the U-loop and the ground formation, the shorter is the depth of excavation which is required to provide the desired heat transfer.

LITERATURE REVIEW

The backfilling material within a GSHP vertical borehole configuration does not only have the task to secure the heat exchanger into the ground, but it should also be capable of sealing the lengths of the bore and act as a thermal conductor so that the medium carried within the exchanger will be able to reach equilibrium with the ground temperature.

Previous studies have shown how the efficiency of ground source heat pump systems can be improved using backfilling materials with an enhanced thermal conductivity. This would theoretically require a shorter length of borehole to obtain the same amount of heat exchange, which would bring with it a reduction in the drilling costs [6].

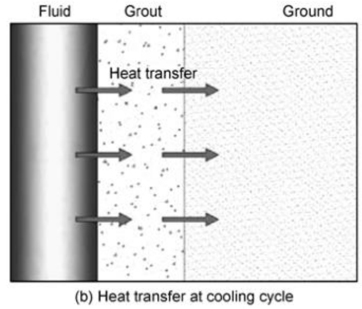

Figure 1 Heat Transfer From Fluid to Ground (7)

Such a reduction is significant since the drilling costs are the most substantial costs involved when installing a geothermal ground source heat pump system, therefore a reduction in the drilling costs could result in a substantial reduction in the installation costs of a GSHP system [7].

METHODOLOGY

This study is centred on the formulation of sand-cement mixes as well as the assessment of their properties to find out the adequacy of the said mixes for use within GSHP configurations: Sixteen different grout mix compositions involving different materials were produced, cured and tested for thermal conductivity. The thermal properties of grouts made with locally available materials were assessed and compared to grouts made using foreign materials which were suggested by previous studies [8].

The hypothesis behind this paper lies in the possibility that if the grouts made using local materials prove to be thermally adequate, these would not only imply a possible reduction in the drilling depth, and costs, but it would also cause a reduction in the cost of the materials used to backfill the boreholes.

The cement used in all the mixes was type II Ordinary Portland Cement. Two types of super-plasticizers were used separately in different mixes, Master Builders Rheobuild 1000 and Rheobuild TDS. The super plasticising admixture Rheobuild 1000 was used as a water reducer, dispersant and grout fluidity enhancer. Rheobuild TDS on the other hand is normally applied to obtain low concrete permeability and high resistance to the attack of sulphates, chlorides, carbon dioxide and alkalis which could be present within the soil/ground.

The mixes for this study were designed using three different types of sand, separately: Silica sand, local upper coralline limestone (UCL) sand and local lower coralline limestone (LCL) sand. Prior to mixing, these sands were tested for water absorption. All the sand was oven dried for 48 hours prior to use so as to remove all the moisture. This, together with the water absorption test, helped in identifying how much mixing water was being absorbed by the sand and therefore how much water needed to be added to the mix to obtain the desired water-cement ratio. The grouts were mixed using a drum mixer. The super-plasticizer was first added to the water (together with the bentonite, when used) which was in turn added slowly to the dry mix of cement and sand.

In one embodiment of the grout, Mix 17, Dramix steel fibres were added to the mix so that their effect on the thermal conductivity could be assessed. The steel fibres were used as sand replacement by weight and were added last to the particular mix. Each mix was cast into 150mm cube moulds according to BS EN 12350-1 and left to set for twenty-four hours, after which they were de-moulded and placed in water-filled curing tanks under controlled temperature conditions for 28 days. Where there was a doubt about the pump-ability of the mix, a slump test was carried out according to BS EN 12350-2.

THERMAL CONDUCTIVITY MEASUREMENTS

An apparatus was built for the measurement of thermal conductivity of the grout cube samples which measures the thermal conductivity of building materials using the transient hot wire method. The setup is based on a study published by Alessandro Franco [9] in which an apparatus for the routine measurements of building materials with thermal conductivities ranging between 0.2 and 4 W/mK is designed and described.

In order to place the reader in the right perspective it must be emphasized that so far no single method has been developed to find the thermal conductivities of all the shapes and sizes of different materials under different conditions [9]. Several methods have been employed in the past for finding thermal conductivity values, amongst which, is one of the most popular methods used so far; the transient hot wire method proposed by Carslaw and Jaeger .

TRANSIENT HOT WIRE METHOD

Transient methods measure readings as a signal is sent out to create heat in the sample. The method proposed by Franco [9] is a variation of the hot wire method proposed previously by Carslaw and Jaeger.
The ideal theoretical model by Carslaw and Jaeger, around which Franco [9] designed the equipment, assumes an infinitely thin and infinitely long line heat source. This continuous source is set up to produce a constant, continuous thermal pulse for a pre-defined time interval. Taking a one-dimensional radiant heat flow model, one could assume that a source placed at the centre of a specimen would produce cylindrical, coaxial isotherms in the infinitely sized specimen. This is portrayed in figure 2.

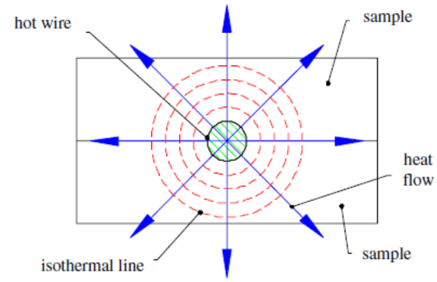

Figure 2: The principle of the hot wire radial flow model. [9]

Through a simple derivation the thermal conductivity of the material containing the hot wire could be found using the following expression:

$$\lambda = \frac{Q}{4\pi[T(t_2) - T(t_1)]} \ln\left(\frac{t_2}{t_1}\right)$$

Where λ is the thermal conductivity (W/mK), Q is the power supply per unit length of the heating source and T is the temperature measured by the thermocouple at the pre-defined time intervals t_1 and t_2. As can be seen in the standard technique explained above, the hot wire is embedded within the specimen. For clarity's sake one could imagine the hot wire between two halves of a cube sample. Franco [9] realized that this solution would not be practical to measure the thermal conductivities of various building materials and goes on to propose a solution in which the line source of heat lies between the surfaces of two different materials; the specimen surface and the surface of an insulating materials as shown in the figure 3 below.

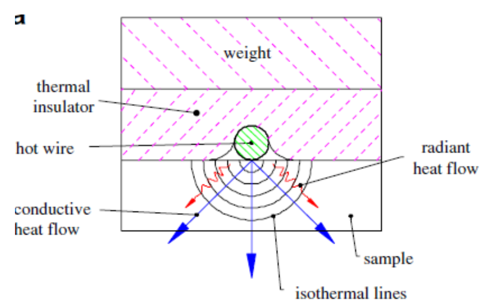

Figure 3: Sectional arrangement in Hot Wire Technique [9]

In this manner the thermal conductivity on the upper 'half' and lower 'half' are in parallel and the thermal conductivity of the insulating material is to be added to the thermal conductivity of the sample being tested. The thermal conductivity of the latter can then be found using:

$$\lambda = K\frac{P}{[T(t_2) - T(t_1)]} - H$$

Where t_1 and t_2 are the time intervals at which temperature readings are measured by a thermocouple, P is the electric power supplied to the wire. K and H are both characteristic values depending on the instrument and are found by calibration procedures [9].

Therefore, the temperature reading from the thermocouple depends on how able the material tested is to take up and dissipate heat. If the setup were to be placed on a material with very low thermal conductivity the temperature read by the thermocouples would be relatively higher, over the same period of time, than if a material with a higher thermal conductivity was used instead.

RESULTS

The following conclusions could be drawn from patterns which were observed in the thermal conductivity values obtained for the sixteen mixes.

Maximum thermal conductivity values

Experimental results demonstrated that the grout mixes with silica sand are the mixes which exhibit the highest thermal conductivity with values ranging from 1.95 – 2.36 W/mK. As suggested by Allan's work [6] this may be attributed to the high thermal conductivity of the silica sand particles which result in the cement-sand grout made with silica having higher thermal conductivity values.

However, grout mixes made with local sand exhibited good thermal conductivities which are still higher than the values for bentonite and some enhanced bentonite grouts stated by Allan [6]. Figure 4 shows a graphical representation of the maximum thermal conductivity values, which compares the materials studied in this dissertation to other conventional materials.

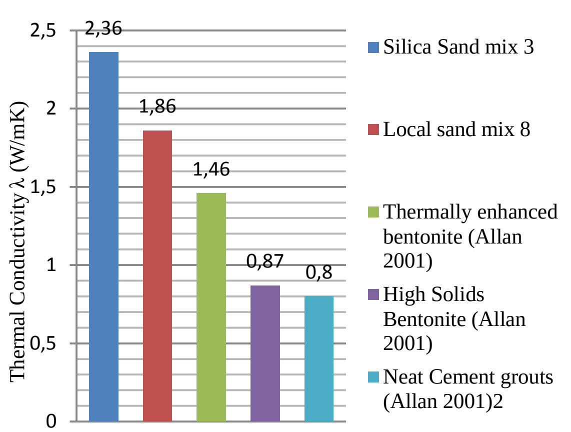

Figure 4 – Comparison of Thermal Conductivities of grout materials

Moreover, as shown in figure 5, all the silica sand-cement mixes and most of the mixes made with local sand have thermal conductivity values which are above the minimum value required by the engineers for the Valletta City Gate Parliament project Malta, which was 1.5W/mK [8].

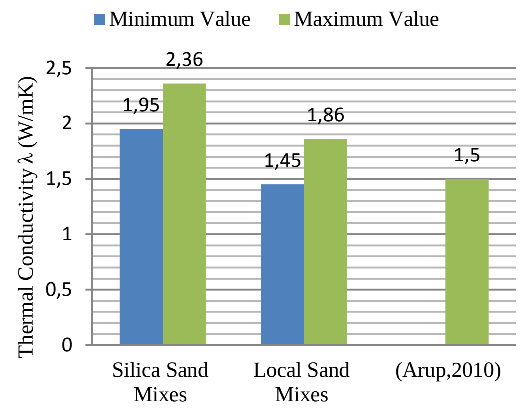

Figure 5 - Maximum & Minimum thermal conductivity values for different sand – cement mixes

Thermal conductivity values of mixes with different sands

As explained in the previous section, the mix samples which exhibited the highest thermal conductivity values are the ones made with silica sand; the mixes made with local sand exhibited a decrease in thermal conductivity of between 0.4W/mK and 0.5W/mK when compared to the former. Figure 5 shows the minimum and maximum values obtained with the different sands.

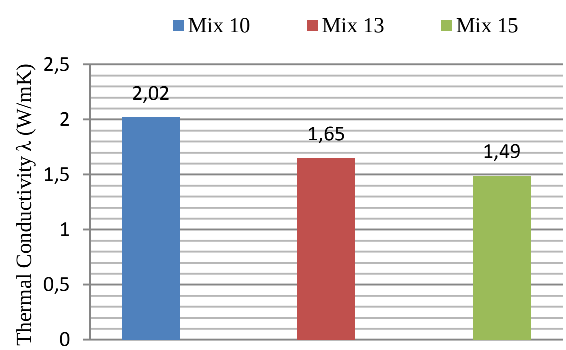

Figure 6 - Comparison of mixes with same proportions, varying only type of sand used

Mixes 10, 13 and 15 had corresponding proportions of water, cement and sand: Which means that they have the same water-cement and sand-cement ratios. The only difference in these 3 mixes is the type of sand used: Mix 10 was made with silica sand and mix 13 with Upper Coralline Limestone sand, while Lower Coralline Limestone sand was used for mix 15.

A comparison of thermal conductivity values of these three mixes is shown in figure 6. The mix which exhibited the highest thermal conductivity was still the silica sand mix, followed by the mix with upper coralline limestone sand. There is only a marginal difference of 0.16 W/mK between the thermal conductivity obtained by mix 13 and that obtained for mix 15 which might be attributed to the only two differences between these mixes, that is, the type of sand and particle size distribution of the sand used.

Thermal conductivity and superplasticizer

Two different admixtures were used in this study: Master Builder's Rheobuild 1000 and Rheobuild TDS. Comparing mix 3 to mix 5, it could be deduced that when the amount of superplasticizer used in the mix was reduced the thermal conductivity of the hardened mix decreases. This deduction can be made since the only the only difference between mix 3 and mix 5 is the amount of superplasticizer used: mix 3 was made with 8.8 litres of Rheobuild 1000 per cubic metre of mix while 6.7 litres of Rheobuild 1000 per cubic metre of mix were used in mix 5. The thermal conductivities of these mixes was found to be 2.36 and 2.02 W/mK respectively as shown in Figure 7.

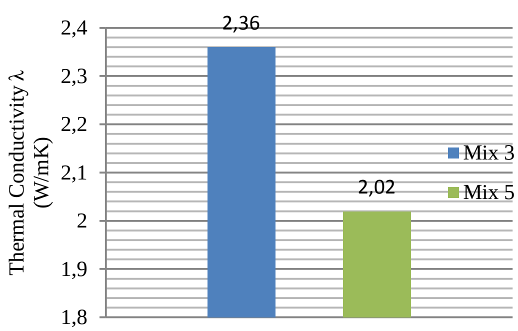

Figure 7 - Thermal conductivity of same mix with varied superplasticizer dosage

Thermal conductivity and steel fibres

In a study by Berndt and Philippacopoulos [10] the thermal conductivity of the baseline mix proposed was increased by the addition of steel fibres. In one of the mix embodiments, mix 17, 2% of the weight of sand was replaced by Dramix steel fibres. This mix has the same mix proportions as mix 15 but with 2% of the sand replaced by steel fibres. The results obtained confirm Berndt and Philippacopoulos's findings since the thermal conductivity of mix 17 is slightly higher than that of mix 15, which could indicate that a higher percentage replacement of steel fibres could give significantly higher thermal conductivity values.

Thermal conductivity of oven dried samples

For a ground source heat pump system to retain its efficiency it is important for the grout used within borehole configurations to retain its thermal conductivity properties in wet and dry conditions since as the amount of water in the ground surrounding the borehole changes, the moisture content of the grout will also change [6].

As the moisture content of the grout changes the pores, which in a saturated grout would have been filled with water, dry up and that water is replaced by air. Since the thermal conductivity of water is greater than that of air a decrease in the total thermal conductivity of the grout is expected.

The results of the oven dried samples confirm this theory: The thermal conductivity of all of the mixes decreased. Comparing results for the mixes with same proportions but different sand type 10, 13 and 15 the figure 8 below was obtained.

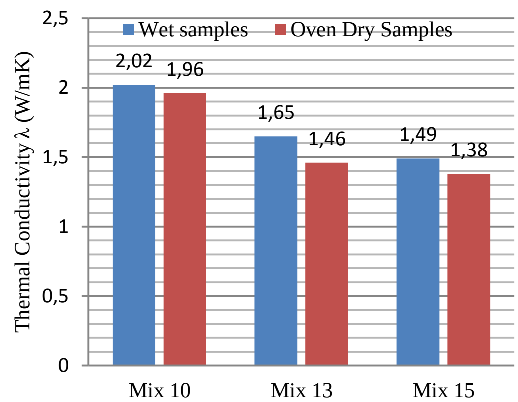

Figure 8 – Thermal Conductivities of Wet versus Dry Samples of the same mix

The thermal conductivity of the embodiment with silica sand, mix 10, decreased by 0.06W/mK which confirms Allan's assertion that the silica sand cement grouts are capable of retaining their thermal conductivity properties under dry conditions [6]. The thermal conductivity of mix 13, which was made using upper coralline limestone sand, decreased marginally by 0.19 W/mK while that of mix 15, done using lower coralline limestone sand decreased by 0.11 W/mk.

Fresh properties and workmanship

It is important that the grout to be used for such purposes enables pumping with conventional equipment. All the mixes produced in this study had pourable consistency with a slump value greater than 75mm which is the value recommended by Neville [11] for pump-able mixes. However this test does not measure viscosity and consistency and therefore it does not classify the mix as ideal to be used with a pump. The consistency of the mix is a major issue when dealing with backfilling ground source heat pump boreholes. The mix needs to have a good enough consistency for it to be pumped from the bottom of the borehole however ‘run off’ of this grout into fissures in the rock substratum is not desired since this would result in excessive use of material which would not have been planned. On the other hand the advantages of filling these existing fissures with grout to improve thermal conductivity within the rock substratum are debatable.

Workmanship is another key issue that affects the efficiency of such systems. Measures must be taken to attain the best possible contact between the geothermal loop and the ground to ensure that heat is dissipated from and to the borehole into and out of the surrounding ground. This means that using the correct method for grouting the borehole is essential regardless of the thermal conductivity of the grout used.

Cost Analysis

Considering a system of 28 boreholes, each 140m deep with a150mm diameter throughout, and assuming that the U-tube will have an outer diameter of 40mm installed at 139m below the ground: The amount of grout required per borehole is estimated to be 2.12 cubic metres. The bentonite-grout formulation used for the City Gate Valletta project has a thermal conductivity of 1.78 W/mK and cost € 17152.25 in total.

From the cost breakdowns carried out using current market prices in Malta for costing the materials, it can be seen that the local sand mix which exhibited the highest thermal conductivity (Mix 8) not only has a thermal conductivity which is greater than the conductivity of the first grout but it is also more cost-effective since this mix is 17% less expensive than a bentonite based mix. The silica sand mix 10 proved to be more expensive, but since this mix is more thermally conductive than both mixes, it might need lesser borehole depth to achieve the same required heat transferred therefore the slight increase in price might not be significant.

OVERALL CONCLUSIONS

The thermal conductivity, method of placing and workmanship of the grouting process in vertical ground source heat pump configurations are all issues which affect the efficiency of the system and therefore its feasibility. Silica sand-cement mixes exhibit the highest thermal conductivity values which reach a maximum of 2.36 W/mk. The thermal conductivity of local-sand cement grout decreases by about 0.5 W/mK to 1.86 W/mk which is still a satisfying value when compared to the thermal conductivity values of materials which have conventionally been used to fulfil such purposes which ranges from 1.46 to 0.8 W/mk. Thermal conductivity tests on local sand-cement grout mixes show that there is a potential for these mixes to be used within ground source heat pump configurations. Although silica sand-cement grouts are more conductive than local sand-cement grouts, the latter exhibited thermal conductivity values which exceeded those of conventionally-used bentonite based grouts. Moreover local-sand cement grouts are 17% more cost effective than bentonite grouts and 27% more cost effective than silica sand-cement grouts and exhibit the potential of improvement both in cost effectiveness and thermal conductivity. The cement-sand mixes proposed in this study show a good retention of thermal properties even after they have been oven dried with values decreasing by marginal values of 0.06, 0.19 and 0.11 W/mK for silica sand, upper coralline sand and lower coralline sand mixes respectively.

Since grout mixes with local sands are more cost-effective than bentonite mixes and silica-sand-cement mixes, this study shows that favourable thermal conductivity values can be obtained at a lesser cost by using locally available materials. This study shows that favourable thermal conductivity values can be obtained at a lesser cost by using locally available materials.

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