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Cement Slurries with Modified Thermal Conductivity for Geothermal Applications

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ABSTRACT

Geothermal energy is becoming increasingly popular not only in the scientific community but also in the oil&gas industry. Companies are building strategies for acquiring energy from the Earth's heat, investing in R&D departments, and taking steps to reduce their carbon footprint. This proves the worldwide positive direction aimed at replacing some of the energy obtained so far from fossil fuels, with energy from renewable sources. In recent years, the use of deep geothermal energy has been investigated more frequently, especially regarding areas with less favourable geological conditions for the construction of shallow geothermal installations. Such a solution requires greater investment capital, but brings an individual set of benefits. Due to the high cost of drilling, and a large number of existing wells, a frequently debated topic is the possibility of adapting old wells for geothermal purposes. In this context, it is worth considering preparing a well for exploitation of both oil&gas, and later geothermal energy, already at the planning stage of a given well. It is known that heat losses negatively affect the efficiency of a geothermal installation. In the case of deep borehole heat exchangers, these losses occur due to the interaction of the heated working fluid with the colder fluid in the annular space. They also occur when the working fluid in the annular space has a higher temperature than the surrounding rocks. The second of the presented cases also takes place in geothermal wells, where hot water is transported to the surface, often from a depth of several kilometres. Reducing the heat loss will allow a higher water temperature at the outlet of the borehole. This may be assisted by the appropriate selection of the parameters of the cement slurry located between the casing and the rock mass, in particular the thermal conductivity coefficient. Adjusting it to suit the geological conditions of the future geothermal well will contribute to achieving optimal operating conditions. The work describes the methodology and laboratory tests results of cement slurry formulas with the end goal of reduced thermal conductivity. These tests were carried out in the laboratories of the Faculty of Drilling, Oil and Gas, AGH in Krakow. The influence of individual additives on the thermal conductivity coefficient, measured with a heat flow meter, are presented.

1. INTRODUCTION

An increasing interest in geothermal energy exploitation can be observed worldwide. The mandates for greenhouse gas emissions reduction introduced to companies are surely influencing the growing popularity of renewable energy. Amongst renewable energy sources, geothermal energy has the advantage of being independent of meteorological conditions, and therefore presents a versatile solution that can be used almost everywhere [Templeton et al., 2014]. This is especially true for borehole heat exchangers, as the lithology of a given location has a negligible impact on the effectiveness of their application.

Geothermal resources in Poland are mostly low-temperature. The heat flow values vary between 20 and 90 mW/m^2, and the geothermal gradient is between 1 and 4 degrees Celsius per 100m. There are however prospective regions for geothermal heat extraction, with high heat flux and appropriate hydrogeological parameters, with growing industries based on geothermal waters [Tomaszewska et al., 2018]. Even though such resources are generally used for heating and cooling of buildings, by leveraging new technology they can be converted into electricity with special system layouts [Nian and Cheng, 2018].

The common denominator of geothermal energy extraction methods is the presence of a borehole. The cost of drilling a new wellbore is approximated by various authors to be between 40 and 60% of the cost of the entire geothermal installation. Therefore, adapting an existing well to geothermal purposes could be a viable solution to reduce the initial costs. Another option would be to consider adjusting the design of a planned fossil fuel exploitation well to favourable parameters for prospective geothermal energy exploitation which could occur once the primary purpose of the well is completed. Well cementing, and more specifically the thermal conductivity coefficient of a hardened cement slurry, is an avenue that could be influenced to suit geothermal needs later on.

2. ADAPTATION OF EXISTING WELLS

It is commonly known that drilling is the most expensive part of every geothermal investment. This is especially true for areas with less favourable geological conditions, where geothermal waters are located deep underground. Therefore, the topic of adapting an existing well for geothermal purposes is being discussed more often in the literature. The profitability of such an investment depends on the geological conditions of a given location as well as the technical conditions of a given well. In some cases, converting the well to geothermal can be much cheaper than the cost of abandoning it [Gharibi et al., 2018].

Poland has a lot of potential for re-using existing wells due to the number of drilled boreholes which is shown in Figure 1. Many of those boreholes have been created for research and exploration purposes, and therefore are deeper, wider and more thoroughly sampled than the average exploitation well [Bujakowski, 2015].

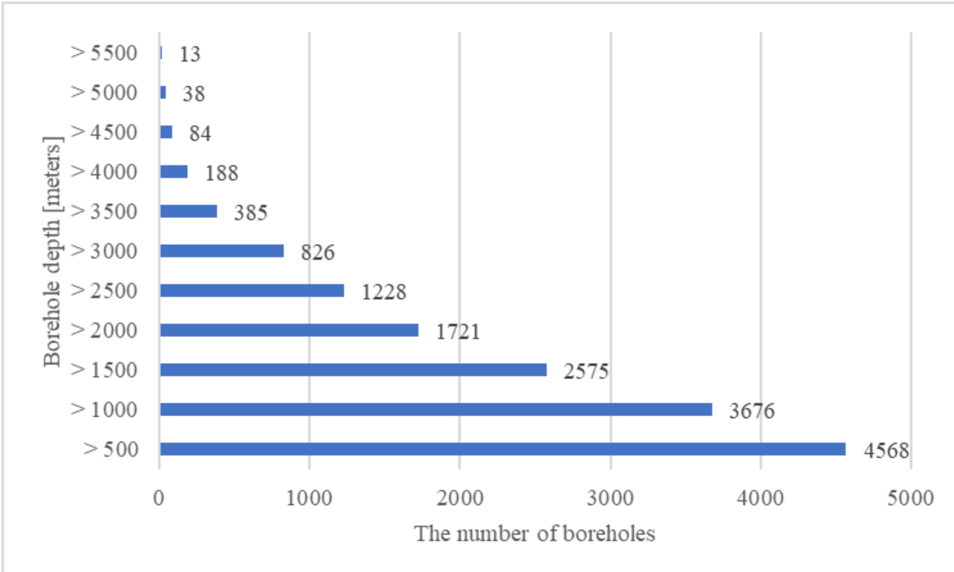

Figure 1: The number of boreholes drilled in Poland since 1980 according to the Polish Geological Institute [access 07.09.2021]

Reconstruction of an existing well carries a risk of an unprofitable investment. In case of poor technical conditions of the wellbore, the capital spent on initial work, such as permits or logging, will be lost. Despite the financial risk, multiple investments where an existing well was either fully or partially reconstructed have been successfully carried out in Poland [Bujakowski, 2015].

3. HEAT LOSS

The significance of the impact that heat loss has on the wellhead conditions during geothermal water exploitation has been discussed in the scientific literature for a long time. In the 90ties, Kanev et al. have conducted a numerical analysis of heat conduction from the borehole to the rock mass, and noted that the heat loss effect is major in low flow-rate wells, especially during the initial exploitation [Kanev et al., 1997]. Very similar observations were made in a much more recent work of Phuoc et al. They have determined that the conduction heat loss is the most dominant type of heat loss they investigated, and concluded that it can impact the efficiency of a low flow-rate well, even for the duration of the entire geothermal operation [Phuoc et al., 2019].

In borehole heat exchangers, especially those with depths greater than 300 metres, heat loss due to re-cooling of the working fluid is often described, due to the thermal interference between the cooled-down and the heated fluid, as well as due to the much lower temperature of the surrounding rock mass in the upper part of the well. The conduction heat loss can be limited by reducing the thermal conductivity of the materials used in the construction of the well, such as pipes and sealing slurry. A project using three cement slurry mixtures with different thermal properties (insulating in the upper part of the well, normal in the middle, and conducting in the bottom part) has been successfully implemented in a deep borehole heat exchanger in Aachen, Germany [Dijkshoorn et al., 2013].

[Wu et al., 2017] in their work regarding heat extraction and heat loss concluded that by preventing heat conduction along the well through a thermal insulation layer, the heat production can be enhanced. A cement sheath with reduced thermal conductivity placed in the upper part of the wellbore can play the role of such layer, influencing the effectiveness of a given geothermal well.

4. CEMENT SLURRY WITH REDUCED THERMAL CONDUCTIVITY

According to the literature, the optimal combination of thermal conductivity of pipes and cement slurry is not always the combination with the highest value of the lambda coefficient [Badenes et al., 2020]. The thermal properties of the cement slurry should be designed accordingly to the geological conditions of the installation site, because if the thermal conductivity of the slurry is much greater than that of its surroundings, the thermal resistance of the borehole starts to assume a constant value [Zhang et al., 2018].

Reducing the thermal conductivity in concrete has been widely studied for the needs of the construction industry. Thermal insulation plays an important role in the building's energy efficiency, reducing heating costs and its impact on the natural climate. Multiple works concluded that aerated concrete yields good results as an insulating material, since air is a very good insulator. However, the occurrence of pores and fissures in the hardened concrete decreases its mechanical strength [Remesar et al., 2017]. The construction industry's experience with cementitious materials can prove useful in researching cement slurries for wellbores. This work investigates the influence of two materials that have successfully been used as thermal insulators when added to construction concrete – rubber crumbs and glass microspheres.

The addition of rubber crumbs in concrete was described by i.a. [Longvinenko, 2018] and [Zaleska et al., 2019]. In both cases, the rubber aggregate has been acquired from waste tyres, providing an economic and environmentally friendly avenue for recycling them. Both works report that the addition of rubber reduces the thermal conductivity of the sample, accompanied by a decline in mechanical parameters of the hardened concrete.

Glass microspheres are a common additive to cement in case of circulation loss in oil and gas drilling. Their effect on the slurry density was widely studied. The majority of works also indicate their thermal insulating properties, however the research is mostly done on dry samples. It is known that water saturation increases the thermal conductivity of cement, and this work presents results from samples submerged in water for 28 days.

5. LABORATORY EXPERIMENTS

It is commonly known that the composition of cement slurry is heavily dependent on the characteristics of the cemented borehole and that the technological properties of the slurry must meet multiple requirements [Kut, 2018]. Therefore, a prospective slurry design should be tested in a laboratory environment to find the balance between the rheological, mechanical and thermal parameters. Errors in the design of the slurry cause deterioration of rheological and mechanical parameters of the cement sheath [Stryczek et al., 2009].

The laboratory tests aimed to determine the influence of the rubber powder and glass microspheres addition on the properties of fresh and hardened cement slurry. The tests were conducted in the facilities of the Faculty of Drilling, Oil and Gas, AGH UST in Krakow.

Figure 2: Fine rubber powder used as an additive

The rubber powder used in the presented research was a commercially available fine powdered rubber (0-0,4mm) produced from recycled truck tires. The decision to use powdered rubber instead of bigger rubber crumbs was made based on a conjecture that the smaller particle size will reduce the negative effect of incompatibility between cement and rubber, which was described by Longvinenko [Longvinenko, 2018].

The microspheres used in the research were made from soda lime borosilicate glass (0-100µm). Glass microspheres are commonly used as an additive in case of lost circulation.

Slurry mixtures were based on commonly used in Polish drilling industry Portland cement CEM I 42,5R and room-temperature tap water, with the addition of either rubber powder or glass microspheres. One mixture was made with water and cement only. The exact designs of tested slurries are presented in Table 1.

Table 1: Cement slurry mixture designs (by weight of cement).

Mix name	Cement	Water	Rubber powder	Glass microspheres
Rec0	1	0.60	0.00	0.00
Rec1	1	0.67	0.11	0.00
Rec2	1	0.75	0.38	0.00
Rec3	1	1.50	1.50	0.00
Rec4	1	0.67	0.00	0.11
Rec5	1	0.63	0.00	0.05

Firstly, the properties of fresh cement slurries have been tested. The measurements were conducted in ambient temperature and pressure. The results are presented in Table 2.

Table 2: The parameters of fresh slurry mixtures

Mix name	Density [g/cm^3]	Apparent viscosity [Pa·s]	Plastic viscosity [Pa·s]	Yield point [Pa]
Rec0	1.825	69.00	55.00	39.74
Rec1	1.785	51.25	50.50	24.90
Rec2	1.770	54.00	44.50	30.40
Rec3	1.625	31.00	23.00	18.67
Rec4	1.625	41.00	33.00	23.46
Rec5	1.720	52.88	45.25	28.97

The slurry density was measured using a Baroid mud balance. It decreases together with the addition of either rubber powder or glass microspheres. The rheological properties were measured using Chan 35 viscosimeter. The results for all mixtures were input into the Rheosolution 3.02 software, and the Herschel-Bulkley model was estimated as the best description of rheology in all six cases.

After testing fresh slurry parameters, cement was poured into moulds in order to create samples for testing the properties of the hardened slurry. From each mix, 3 cylindrical samples (diameter approx. 55mm, thickness approx. 15mm), and 2 cuboid samples (40mm x 40mm x 160mm) were created. After thickening, they have been stored submerged in water for 28 days to simulate the curing conditions in a well.

The cylindrical samples were used to test the thermal conductivity of the hardened slurry. The conductivity was tested using LaserComp's FOX50 heat flow meter. The results presented in Table 3 are a calculated average from the measurement of all three samples.

The cuboid samples were used to test the mechanical parameters of the hardened slurry using Matest E183N hydraulic press.

Figure 2: A cylindrical sample of a hardened cement slurry with a rubber powder additive.

Table 3: The parameters of hardened slurry mixtures.

Mix name	Flexural strength [MPa]	Compressive strength [MPa]	Thermal conductivity [W/m·K]
Rec0	5.329	29.060	0.817
Rec1	4.304	28.376	0.754
Rec2	5.237	26.415	0.722
Rec3	2.805	8.841	0.566
Rec4	4.523	21.747	0.641
Rec5	4.600	27.215	0.773

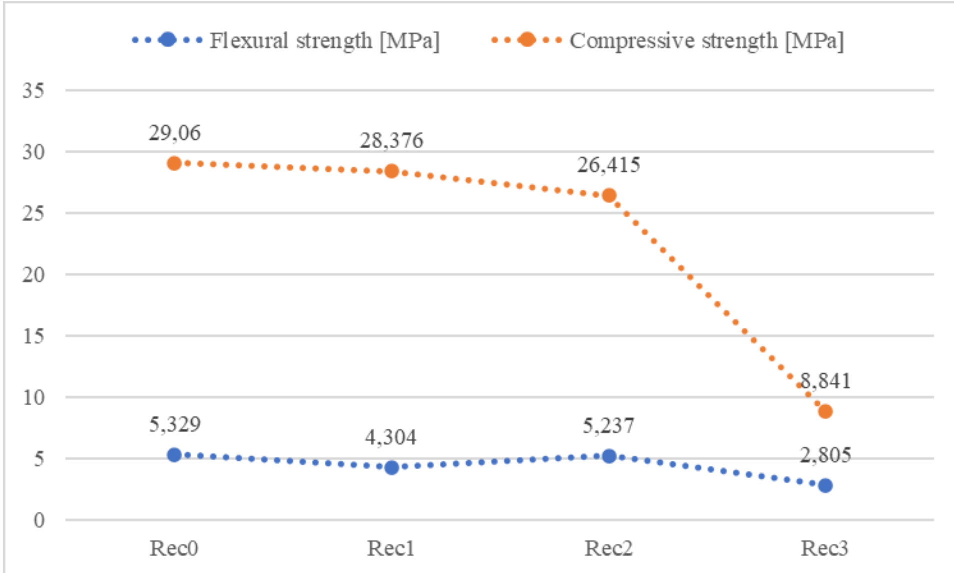

Figure 3: Strength measurements for samples with rubber powder addition, in order of increasing rubber content (Rec0 with no rubber content for comparison).

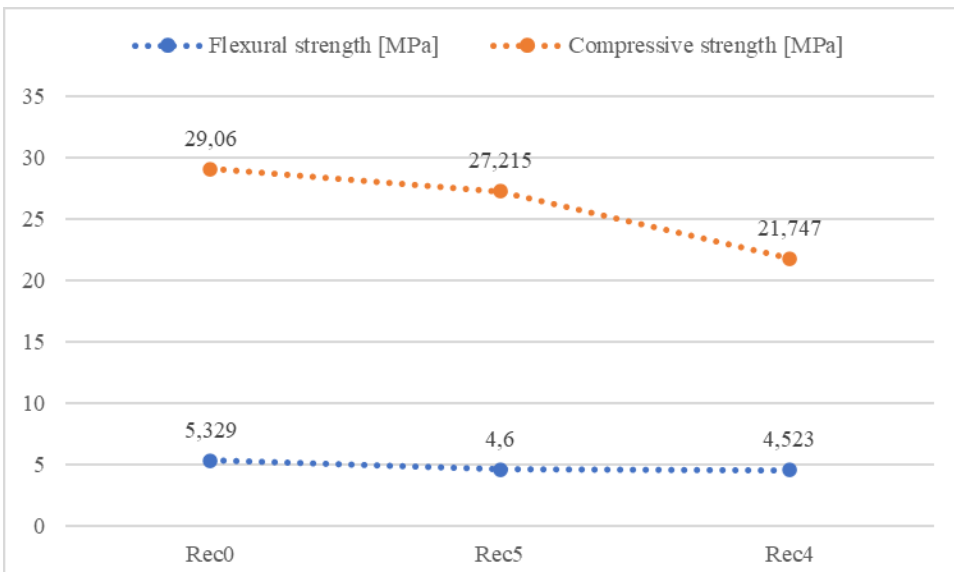

Figure 4: Strength measurements for samples with glass microspheres addition, in order of increasing microsphere content (Rec0 with no microsphere content for comparison).

As expected, the mechanical parameters of the hardened cement slurry did worsen with the addition of either rubber powder or glass microspheres. The lowest strength (both flexural and compressive) was measured for Rec3, which contained 150% rubber powder BWOC (BWOC – by weight of cement). It can be concluded that the design where the amount of rubber additive exceeds the amount of cement would not be viable for use due to low mechanical parameters – by factoring the future strength retrogression, the compressive strength will be too low to use in geothermal wells. The other two samples with the addition of rubber powder (Rec1 and Rec2) have shown a much slighter decrease in mechanical parameters, and could be further considered as viable options. The value of flexural strength of Rec2 is very close to the value of the default Rec0. The flexural strength for designs with glass microspheres (Rec4 and Rec5) is very similar in value, while the compressive strength decreases together with the increase of the glass microspheres content. The decrease in the compressive strength value is steeper for the glass microspheres addition in comparison to the rubber powder addition, most probably because the microspheres are, as their name suggests, empty inside. Therefore they are crushed when compressed with sufficient force.

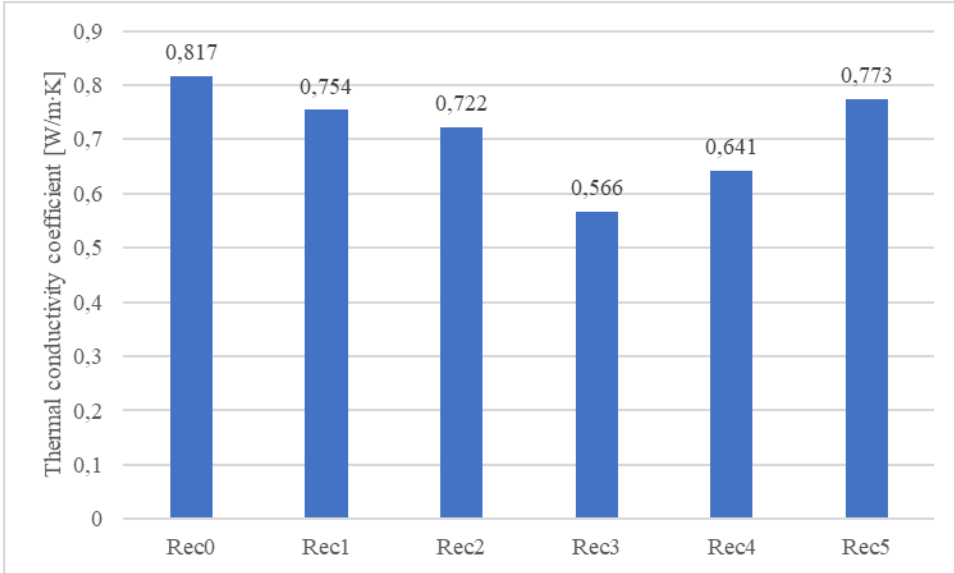

Figure 5: Thermal conductivity coefficient measurement results for all mixtures.

Thermal conductivity was reduced by 8% for Rec1, 12% for Rec2, 31% for Rec3, 22% for Rec4 and 5% for Rec5. Based on the results, it can be concluded that the glass microspheres have better insulating properties than the rubber powder. However, the economical factor of both additives should also be taken into consideration, as the glass microspheres are much more expensive than the rubber powder from waste tyres.

6. CONCLUSIONS

Based on the available literature and conducted laboratory research, the following conclusions can be drawn:

1. Modifying the thermal conductivity of cement slurry to suit the conditions of a given well has a positive influence on the operation of the geothermal installation.

2. The addition of either glass microspheres or rubber powder reduces the density of cement slurry. Glass microspheres have a stronger influence on the density than rubber powder due to their hollow inside.

3. For the mixtures with the same amount of additive (Rec1 with rubber powder and Rec 4 with glass microspheres), the flexural strength is very similar. The compressive strength however is 7MPa lower in the case of glass microspheres addition.

4. Considering the strength retrogression due to higher temperatures present in geothermal wells (the products of cement hydration at higher temperatures differ from those formed at room temperature), it is important to counteract the negative influence with other cement additives. A popular solution is the addition of silica flour or silica fume.

5. Glass microspheres show better thermal insulation properties than rubber powder. Rubber powder however is less expensive in comparison to the glass microspheres.

6. Further research will be conducted by authors to further investigate cement slurries with decreased thermal conductivity coefficient.

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