Engineering properties of steel-making slag based controlled low strength material (CLSM) for possible use of Ground-Source Heat Pump system

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ABSTRACT

The Ground-Source Heat Pump (GSHP) system is energy-efficient renewable energy system. However, this system has been forward-thinking in Korea due to several technical problems and high cost. One of the ways to increase energy efficiency is to develop a heat transfer medium that has a high thermal transfer capacity, i.e., thermal grout, between the heat exchanger and soil or rock surrounding in boreholes. This study aims to develop the CLSM that can role the heat transfer medium based on the by-products (e.g., steel-making slag and fly ash) and to evaluate the general property including thermal conductivity of CLSM. Various laboratory tests, such as flowability, bleeding and unconfined compression tests, and thermal conductivity tests were carried out for samples having the different conditions. The results of this study demonstrate that the CLSM based on the steel-making slag has a good performance for flowability, bleeding, and unconfined compressive strength, and especially significantly enhances thermal conductivity.

Keywords: GSHP, Thermal conductivity; steel-making slag; controlled low strength material;

1 INTRODUCTION

The controlled low strength material (CLSM) have been used as backfills, structural fills, pavement bases, and void filling. This CLSM required low unconfined compressive strength less than 8.3 MPa and high flowability more than 20 cm (ACI 229R, 1999). CLSM generally consist of Portland cement, fly ash, fine aggregate, and water. A large amount of industrial by-products (e.g., iron and steel slag, coal ash, gypsum etc.) have annually generated from thermal power plants, chemical industries, and steel mills. These by-products have been reused for cement and concrete industries and development of new binder. However, even though these by-products have been recycled for many fields, the researches on highly valuable recycling and solving environmental problem are still needed. Recently, many researchers have been performed for developing the CLSM using industrial by-products (Kim et al. 2016). Most studies partially or fully used the cement as the representative binders in the CLSM.

The Ground-Source Heat Pump (GSHP) systems is energy-efficient renewable energy system. GSHP system can transform the geothermal source into the heating and cooling systems. However, this system has been forward-thinking in Korea due to several technical and cost problems. In order to resolve these problems, one of the ways to increase energy efficiency and to reduce the cost is to develop a heat transfer medium that have a high thermal transfer capacity, i.e., thermal grout, between the heat exchanger and soil or rock surrounding in boreholes. In general, the bentonite-based grout was used for only the purpose of water barrier material in boreholes of geothermal systems. However, longer heat exchanger was needed to develop high energy efficiency because the thermal conductivity of bentonite grout was fairly low, smaller than 0.85W/m·K. Hence, many researches for thermal grout to increase the thermal conductivity have been studied using cement, silica sand, axilat, and graphite (Xu and Chung 2000). However previously proposed thermal grouts still subject to the shrinkage, cracking, and high cost problems.

This study aims to develop the CLSM that can role the thermal grout based on the industrial by-products and to evaluate the general properties of CLSM and thermal conductivity. Various laboratory tests, such as flowability, bleeding, unconfined compressive strength, and thermal conductivity test were carried out for samples having the different conditions.

2 EXPERIMENTAL PROGRAM

2.1 Material and sample preparation

The CLSMs mixtures used in this study are composed of water, cement, fly ash, natural sand and steel-making slag. Ordinary Portland cement, and class F fly ash from a thermal power plant in Jeolla Province were employed. The natural sand and steel slag were considered as a fine aggregate according to ACI229R-99 (the content of particle size range from 4.75mm to 0.075 is 80-85%). The steel-making slag was collected from steel plant of Hyundai Corporation. The ground steel-making slag was prepared by grinding the raw steel-making slag for 90 minutes using a ball mill machine. In this study, 40 balls with a diameter of 40 mm were used to grind 1 kg of steel-making slag. The speed of the roller was kept constant at 240 rounds per minute. The particle size distribution of materials used in this study was presented in Fig. 1.

The proportions of all mixtures tested in this study are presented in Table 1. The CLSMs mixtures were prepared with different sand and slag contents to consider the effect of sand and slag contents and classified into two types, raw and ground slags, to identify the effect of particle size of slag for the results.

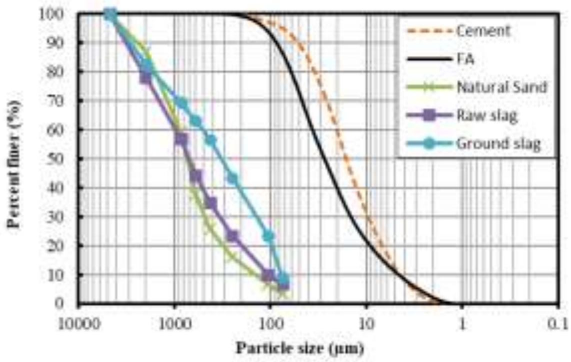

Fig. 1. Particle size distribution of materials used in this study

Table 1. The proportions of CLSMs mixture

Mix ID	Vol. proportion of sand and slag (%)		Unit weight (kg/m^3)				
			Binder		Sand	Slag	Water
	Sand	Slag	Cement	Fly ash			
Natural sand	100	0	113	320	1280	0	351
SS10	90	10	113	320	1152	147	351
SS20	80	20	113	320	1023	294	351
SS30	70	30	113	320	896	441	351
GSS10	90	10	113	320	1152	147	351
GSS20	80	20	113	320	1023	294	351
GSS30	70	30	113	320	896	441	351

2.2 Experimental methods

In order to evaluate the general properties of CLSM based on the by-products for the thermal grout use, the flowability, bleeding, and unconfined compression test were performed for various mixtures indicated in Table 1 in accordance with ASTM standards (2004): D 6103, C 940 and D 4832, respectively.

Thermal conductivity test was conducted for the samples at 28-day curing following to ASTM D 5334 to investigate the thermal transfer capacity of CLSM. In addition, the samples for test were prepared with saturation and dry conditions due to the fact that thermal grout can be differently located below or above groundwater table in the actual field. The temperature with a period of time was monitored using thermal needle probe applied by the current and voltage, and the relationship between the resistance and temperature was determined. The thermal conductivity K can be obtained from Eq. (1).

$$K = \frac{Q}{4\pi(T_1 - T_2)} \ln(\frac{t_2}{t_1}) \quad (1)$$

where K: thermal conductivity (W/m·K), Q: heat input (W/m), t_1 and t_2: time 1 (s) and time 2 (s), T_1 and T_2: temperatures at t_1 and t_2 (K).

3 RESULTS

3.1 General characteristics

Fig. 2 shows the properties of flowability and bleeding of CLSMs mixture with different content and different type of steel-making slag. The flowability is a very significant factor to consider the self-leveling ability and workability of CLSMs. The flowability ranged from 25 to 26 cm and it can be classified as high flowability (from 20 to 30 cm) mentioned in ACI. Proposed CLSM mixtures showed high flowability regardless of slag content and slag preparation type.

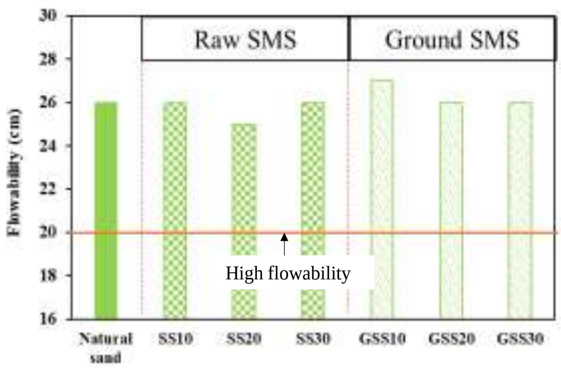

Fig. 2. Flowability of CLSMs mixtures

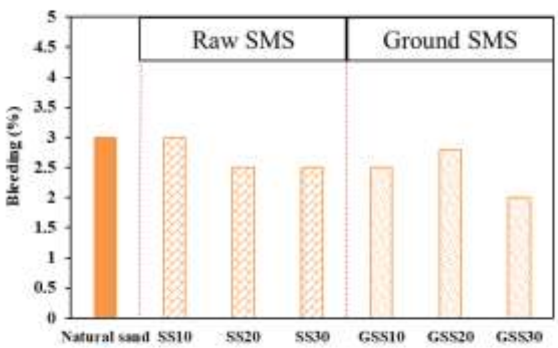

Fig. 3. Bleeding of CLSMs mixtures

The bleeding of CLSM is determined by the volume of water coming out over the initial volume of the sample. The bleeding value of all mixtures is lower than 3% satisfying the stable requirement for CLSMs material (ACI 229R-99) as shown Fig. 3. In addition, it is clear that the steel-making slag does not affect the fresh properties of CLSMs mixtures.

The steel-making slag consists of Dicalcium silicate (C_2S), Rhombohedral to Orthorhombic (R-O) phase (solid solution of CaO, FeO, MgO, and MnO), Tricalcium silicate (C_3S), Tetracalcium aluminoferrite (C_4AF), Dicalcium ferrite (C_2F), free-lime (f-CaO), Olivine, and Merwinite, and its chemical and mineralogy properties are similar to that of Portland cement (Qiang et al., 2016., Deng et al., 2017). It was called a weak Portland cement due to its low Tricalcium silicate content (C_3S) and Dicalcium silicate (C_2S) contents. Owing to mineral components of steel-making slag, the steel-making slag can be used as stabilizer with/without an activator to solidify soils instead of other binders, as well as aggregate in civil engineering works.

The unconfined compressive strength (UCS) of CLSMs mixtures with different content of raw steel-making slag and ground steel making slag is presented in Fig. 4. In general, the UCS increases with the increase in the curing time and all mixtures with steel-making slag have higher strength than the control mixture made with natural sand. Among the CLSM mixture with raw steel-making slag (SS10, SS20 and SS30), the mixture with the content of 10% raw steel-making slag has the highest UCS, which is 39.9% higher than that of the control mix (28 days UCS). The UCS of mixtures SS20 and SS30 slightly lower than that of mixture SS10. The possible reason for this reduction might be due to the inherent porosity of raw steel-making slag. Increasing raw steel-making slag content leads to an increase in the porosity of the mixture and result in the decreasing UCS.

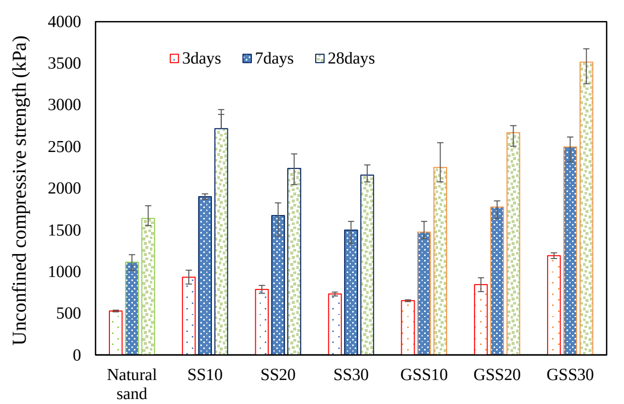

Fig. 3. The UCS of CLSMs mixtures with different content of steel-making slag

In contrast, the UCS of the CLSMs mixtures with ground steel-making slag increase with the increase in the ground steel-making slag content. Mixture GSS30 has highest UCS value (3.5 MPa) at 28 days, which is 118 % higher than that of control mixture (1.6 MPa). In the case of the ground steel-making, the main strength development mechanism might be chemical reaction, such as hydration and pozzolanic reactions, due to the increase of specific surface area by grinding the slag.

3.2 Thermal conductivity characteristics

The thermal conductivity of all CLSMs mixture with literature data is presented in Fig. 5. In the CLSMs mixtures based on the raw steel-making slag, the thermal conductivity decreases with the increase of slag content. While, in the case of the CLSMs mixtures based on the ground steel-making slag, the thermal conductivity increase with the increase of slag content. It was found that the changing trend of thermal conductivity is similar to that of UCS. In addition, the thermal conductivity value of dry condition ranged from 1.01 to 1.21 W/m·K and the thermal conductivity value of saturation condition varied from 2.09 to 2.35 W/m·K. Hence, it was observed that the thermal conductivity value under saturation condition of CLSMs mixtures is about 2 times higher than those of dry condition with the fact that the pores of mixture fully filled with water. Comparing the thermal conductivity with conventional grout materials, such as cement grout, high solids bentonite, and thermally enhanced bentonite, it is clear that the thermal transfer performance of the CLSM proposed in this study is much better than that of the conventional grout materials. Moreover, thermal conductivity of steel-making slag based CLSM is higher than pond ash based CLSM, which was recently suggested by Do et al. (2018). Maximum thermal conductivity value of pond ash based CLSM was 1.6 W/m·K. Natural sand based CLSM shows the high thermal conductivity (dry condition: 1.08 W/m·K and saturation condition: 2.33 W/m·K) with

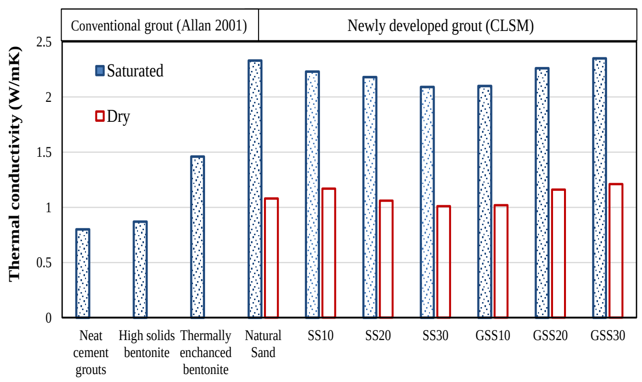

Fig. 2. Thermal conductivity of CLSMs mixtures with previous literature

relatively low UCS unlike the trend of CLSM mixture.

Even though the thermal conductivity value is high, the natural sand based CLSM might not be effective as much as proposed steel-making slag due to low economic benefit. Finally, the ground steel-making slag not only increases the UCS of CLSM, but also enhances the thermal conductivity of CLSM mixture (2.35 W/mK). Therefore, it can be concluded that ground steel-making slag can be used up to 30% to make CLSM as the thermal transfer material for GSHPs.

4 CONCLUSION

In this study, the general properties of steel-making slag based CLSM was evaluated by measuring flowability, bleeding, and unconfined compression strength, and thermal conductivity for the possible use of CLSM as a thermal transfer material. Based on the results of this investigation, the following conclusions can be drawn:

1. The flowability ranged from 25 to 26 cm and it can be classified as high flowable material according to ACI (from 20 to 30 cm). Proposed steel-making slag based CLSMs mixtures indicate very good flowability and workability regardless of slag content and slag preparation type.
2. The bleeding value of all mixtures is lower than 3% satisfying the stable requirement for CLSMs material.
3. Among the CLSM mixture with raw steel-making slag (SS10, SS20 and SS30), the mixture with the content of 10% raw steel-making slag has the highest UCS, which is 39.9% higher than that of the control mix (28 days UCS). Increasing the raw steel-making slag resulted in decreasing the UCS due to its inherent porosity inside of the steel-making slag.
4. The UCS of the CLSMs mixtures with ground steel-making slag increase with the increase in the ground steel-making slag content. Mixture GSS30 has highest UCS value (3.5 MPa) at 28 days curing, which is 118 % higher than that of control mix (1.6 MPa). In the case of the ground steel-making, the main strength development mechanism might be an enhanced chemical reaction such as hydration and pozzolanic reactions due to the increased specific surface area of slag by grinding.
5. The ground steel-making slag not only increases the UCS, but also enhances the thermal conductivity of CLSM mixture up to maximum 2.35 W/mK. Therefore, it can be concluded that ground steel-making slag can be used up to 30% to make CLSM as the thermal transfer material for GSHP.
6. It is clear that the steel-making slag does not affect the fresh properties of CLSMs mixtures. And thermal transfer performance of the CLSM proposed in this study is much better than not only those of the conventional materials such as cement grout, high solids bentonite, and thermally enhanced bentonite but also recently developed pond ash based CLSM.

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