



Freeze–thaw durability of cement-based geothermal grouting materials



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HIGHLIGHTS

- The aggregate type influence on the mortar properties is higher than the freeze thaw cycles applied.
- The use of aggregate on mortars prevented the damage caused by freeze–thaw cycles.
- Damage caused on the neat cement probes did not alter its thermal conductivity.
- Mortar water dosage and volumetric content indicated the probe core non-saturation.

ARTICLE INFO

Article history:

Received 22 September 2013

Received in revised form 12 January 2014

Accepted 13 January 2014

Available online 13 February 2014

Keywords:

Freeze
Thaw
Durability
Geothermal
Grout
Mortar
Borehole
Thermal
Conductivity

ABSTRACT

The required vertical closed loop geothermal heat exchanger size highly depends on the peak demand of the building when no complementary heat source is included. If grouting materials were able to resist freezing temperatures, a mean-demand designed geothermal heat exchanger would be sufficient to fulfill the energy requirements of the building, either preventing the oversizing of the geothermal heat exchanger or the necessity of an hybrid system and therefore saving their associated cost. This paper analyzes the freeze–thaw durability of five cement based geothermal grouting mortars. One was a neat cement (N) and the rest contained either limestone sand (L), silica sand (S), electric arc furnace slag (EAF) or Construction and demolition waste (CDW). Mortars were either exposed up to 25 freeze–thaw cycles or to continuous water curing to analyze the influence of both treatments on the volumetric water content, flexural, compressive and pipe to mortar adherence loads and on the thermal conductivity of the resulting mortars. Results show no significant damage due to the freeze–thaw cycles applied to all the mortars but the neat cement, probably due to the non-saturation of the core of the probes. Although neat cement presented no flexural resistance to freeze–thaw cycles and the probes were severely damaged, no influence was observed on the thermal conductivity of the core material, denoting that any loss of efficiency of a geothermal heat exchanger must be due to the increment of the contact thermal resistance between the pipe and grout or the creation of new contact resistances in the fractures of the grout itself.

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1. Introduction

Geothermal heat pump systems take advantage of the year-round constant ground temperature to obtain higher efficiencies than any other system, as stated by the Environmental Protection Agency [1]. Instead of using ambient air as a heat source or sink, closed geothermal heat pump systems (CGHP) use a heat carrying fluid which flows through a buried pipe circuit and exchanges heat indirectly with the ground. When vertical heat exchangers are used, the closed pipe circuit is introduced into a vertical borehole reaching depths of up to 200 m. To protect the heat exchanger pipes from the possible collapse of the borehole walls, borehole

is filled with a grouting material. This material must present good mechanical and thermal properties to transfer heat from the pipes to the ground or vice versa and to ensure the borehole wall stability.

Apart from the base demand, the design of a geothermal system is highly dependent on the peak demand of the installation, leading to highly over-dimensioned geothermal systems. Since the construction of a ground heat exchanger is much more expensive than any other conventional HVAC system, geothermal installations are normally designed for base demand, while peak demand is usually covered by more economic alternatives (solar thermal energy, boilers, cooling towers, etc.). It would be possible to cover short-term peak demands if the heat carrier fluid was allowed to reach temperatures below water freezing point (0 °C). However, freezing the grout might lead to a permanent reduction of the system

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Table 1

Previous studies of the damage caused by freeze–thaw cycles in concretes and mortars.

Material	Reference	Freezing cycle			Thawing cycle			#Cycles	Standard	Tested property	Conclusion
		T (°C)	t (h)	Ambience	T (°C)	t (h)	Ambience				
Concrete and (FRP)	Quiao and Xu [5]	−18	16	Air	22	8	Air	50/100	ND	Bond 3 point flexural strength	Significant damage
Concrete and CFRP	Colombi et al. [6]	−18	5	ND	4	5	ND	100/200	ASTM C666	Pull out debonding test	No significant damage
Concrete and CFRP	Green et al. [7]	−18	16	Air	15	8	Water	300	ASTM C310	Bond strength	No significant damage
Reinforced concrete	Hanjari et al. [8]	−20	12	Water at surface	20	12	Water at surface	^a	RILEM TC 176-IDC	Compressive, bond and splitting strengths, etc.	Significant reduction of all parameter.
EAF and limestone-based concretes	Manso et al. [9]	−17	18	Air	4	6	Water	25	ND	Weight and compressive strength	Durability of EAF concrete is similar to that of standard concrete
Masonry mortar and stone	Maurenbrecher et al. [10]	−12/−20	8/8	Air/Air	15	8	Water sprayed	24/60	ND	Bond strength	Bond failure is general after 60 cycles
Cement mortar	Cao et al. [11]	−20	0.66	Air	50	0.66	Air	ND	ND	Electric resistivity	Progressive damage during cool cycle due to the thermal contraction
Silica sand -based mortar	Allan et al. [3]	−18	5	Air	4	5	Air	300	ASTM C666	Ultrasonic pulse velocity and bond integrity	No significant damage
Cement-based geothermal grout	Park et al. [4]	−5	240	HCC	50	120	HCC	1	ND	Compressive strength, thermal conductivity, hydraulic conductivity	Reduction of compressive strength with the freeze–thaw cycle

FRP: Fiber reinforced polymer; CFRP: Carbon fiber reinforced polymer; ND: Not defined by the author; HCC: humidity controlled chamber; unsaturated conditions.

^a Process was finished when compressive strength was reduced in 25% and 50%, respectively.**Table 2**

Aggregate properties [12].

	L	S	EAF ^a		CDW ^b	
			EAF	F	CDW	F
Specific gravity	2.71	2.65	3.82	2.753	2.57	2.753
Water absorption (%)	0.52	0.16	1.83	N/A	5.07	N/A
Sieve (mm)	Passing percentage by volume					
4	100.0	100.0		100.0		100.0
2	99.3	100.0		99.9		100.0
1	61.3	78.6		57.4		75.7
0.5	40.1	65.6		37.6		52.1
0.25	27.7	46.9		32.5		35.1
0.125	20.5	27.2		28.5		24.7
0.063	15.7	17.5		23.5		17.6

^a EAF 75% and limestone filler (F) 25% by weight.^b CDW 90% and F 10% by weight.

efficiency. If grout is designed to resist such freeze–thaw cycles, there would be some benefits that could be exploited. The water high latent heat of fusion and the higher thermal conductivity of the ice over the water, 2.22 W/(m K) over 0.566 W/(m K) at 0 °C [2] should enhance grout thermal conductivity, reducing the bore-hole thermal resistance and hence improving the system's overall efficiency. This efficiency improvement could permit to satisfy peak demand of the system with a mean demand designed geothermal system, reducing its overall construction cost.

Influence of the freeze–thaw cycles in cement-based materials such as concrete or mortar has been studied by many authors, as it is summarized in Table 1. The type and number of freeze–thaw cycles as well as the tested properties depend on the type of exposure of the material. However, there is little bibliography on the effect of freeze–thaw cycles on the geothermal grouting materials. Allan et al. [3] evaluated the freeze–thaw durability of silica sand-based geothermal mortars by using the ultrasonic velocity test and also checking the pipe to mortar bond integrity, concluding that no significant damage was observed after 300 cycles. Recently, Park

Table 3

Mix proportions of the cement based grouting materials used.

	Grouting material				
	N	L	S	EAF	CDW
Cement (c)	CEM II/B(V) 32.5R				
Aggregate 1 (A1)	–	L	S	EAF	CDW
A1/c	–	2	2	1.5	1.80
Aggregate 2 (A2)	–	–	–	F	F
A2/c	–	0	0	0.5	0.20
Superplasticizer (SP)	Melment F10 [®]				
SP/c	0.02	0.02	0.02	0.02	0.02
Water to cement ratio (w/c)	0.3	0.39	0.43	0.42	0.66

et al. [4] analyzed the effect of the freeze–thaw cycles on the compressive strength of a cement-based geothermal mortar concluding that its value is reduced as the number of cycles increased. The main goal of this paper is to analyze the damage caused by the freeze–thaw cycles in the physical, mechanical and thermal properties of geothermal cement-based grouting materials. As each mortar used in the analysis contained a different aggregate type, its influence on the freeze–thaw durability is also determined.

2. Methodology

2.1. Materials and mix proportions

Aggregate properties, mix proportion design and initial characterization of the five different mix proportions used in this paper have been performed in a previous release [12]. Each mortar is made of cement (c), water (w), superplasticizer (sp) and a different aggregate type as basic constituent. Neat cement grout (N) has been used as reference material to represent the aggregate absence.

Most of the grouts used at present are thermally improved by the addition of quartz or siliceous aggregates, but any other alternative aggregate has been studied up to date. The use of alternative local aggregates would reduce grout shipping cost, and consequently its final cost. Furthermore, the utilization of recycled aggregates would permit the reuse of waste materials that nowadays are carried to landfill, reducing its final environmental impact. In this paper silica sand (S) is used as reference aggregate since it is the one most used nowadays. Limestone sand (L) is studied as an alternative natural aggregate, widely used in Spain for making structural concrete. Electric arc furnace slag (EAF) represents the recycled aggregates

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