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Effect of elevated curing temperature on ceramsite concrete performance

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HIGHLIGHTS

- The ceramsite concrete used as shotcrete lining in high geothermal environments was put forward.
- An optimum mix proportion for ceramsite concrete was determined through an orthogonal experiment.
- A function that correlates compressive strength with curing temperature was established and presented.
- The performance of ceramsite concrete at various curing temperatures was analyzed.
- This study provided an insight into the behavior of ceramsite concrete in geothermal environments.

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ABSTRACT

The good overall properties of ceramsite concrete give it more potential value in the application of shotcrete lining in high geothermal environments. In this study, an orthogonal experiment was employed firstly to determine an optimum mix proportion for ceramsite concrete at a curing temperature of 20 °C, 40 °C and 60 °C, and then an accelerating agent was added to the concrete mixture. As a result, compared with the 20 °C curing condition, the long-term compressive strength of ceramsite concrete cured at 60 °C decreased significantly and declined even more on account of the accelerating agent, nevertheless the long-term compressive strength cured at 40 °C decreased only when the accelerating agent was added. The ceramsite concrete exhibited good permeability resistance and thermal insulation. And as the curing temperature raised the permeability resistance decreased, whereas the thermal insulation increased. The variation of microstructure with curing temperature was analyzed by scanning electron microscope (SEM) and mercury intrusion porosimetry (MIP). The compressive strengths at certain curing temperatures were plotted against the curing age, and correlation functions were established.

1. Introduction

Lightweight aggregate concrete (LWAC) conforms to the trend of concrete development in the future due to its obvious advantages, such as reducing structural dead load, improving thermal insulations, seismic resistance and environmental friendliness, and has been widely applied in the construction of high-rise buildings, long span bridges and marine structures in harsh environments [1–3]. However, little literature information is available about the use of LWAC in shotcrete.

Currently, with the deepening development of mine shaft engineering and modern tunnel engineering, the more practical constructions are spreading in high geothermal areas [4–8]. The highest rock temperatures of 45 °C and 42 °C are found in Gotthard Base Tunnel and Lötschberg basis tunnel respectively in Switzerland [6], and the rock temperature in Lhasa-Xigaze Railway tunnel in China is as high as 60 °C [8]. Based on this fact, geothermal effect has increasingly become a prominent issue. The elevated temperature has a significant effect not only on the construction process [4–6], but also on the mechanical properties and durability of shotcrete lining used in high geothermal environments [9–12].

In high geothermal and low-humidity environment, the shrinkage of the concrete increased due to the water loss and the adhesion strength of the shotcrete-surrounded rock decreased accordingly [13], meanwhile the ability of carbonation resistance and chloride ions penetration resistance decreased [14]. A gradual decrease of the adhesion strength was also found when

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temperature increased from 50 °C to 90 °C in a simulated high geothermal tunnel, regardless of the relative humidity [15]. However, the adhesion strength could be improved as steel fibers [16] and fly ash added in shotcrete [9].

With the aim of reducing the adverse effect posed by the geothermal heat, in this paper the ceramsite concrete used for shotcrete lining is proposed as a viable material. Due to its attractive characteristics, especially good thermal insulation and low elastic modulus [17], the effect of elevated temperature on ceramsite concrete could be significantly less than on ordinary concrete. Moreover, the ceramsite with water absorption/release characteristic on account of porous structure, as internal curing element, could slow down moisture loss and in turn facilitate the hydration process under elevated temperature conditions [18], resulting in the densification of the microstructure. In particular, the densification occurred at the interfacial transition zone due to a greater degree of hydration [19], and the interlocking of the cement paste partially penetrating the lightweight aggregate [20]. This contributed to a more dense and more homogeneous microstructure that was equivalent to that of the bulk cement paste, compared with concrete with conventional aggregate [21,22]. Furthermore, it would lead to the mechanical properties of the interfacial transition zone in ceramsite concrete very similar to bulk cement paste [23].

The hydration process of cement at elevated temperature is significantly different from that at room temperature and brings about a notable effect on concrete performance. Previous studies had revealed that the curing process at elevated temperature could greatly improve the early strength of cement paste and concrete, but the long-term strength might be decreased as a higher porosity and less uniform microstructure formed [10,24–27]. An increased shrinkage had been found as the concrete cured at elevated temperature [11,24]. When curing temperature was 50 °C or above, a decrease of the amount of ettringite occured as calcium monosulphoaluminate as well as very short ettringite needles had formed at the expenses of ettringite, which led to the reduced strength [28]. In case the curing temperature dropped when cement paste had completely hardened, the delayed ettringite formation could bring about the decline of strength and the damage of concrete even [29,30]. As the curing temperature increased a denser calcium silicate hydrate (C-S-H) phase exhibiting a heterogeneous distribution was found [27,31], and the bound water content of C-S-H significantly decreased [25,32]. Moreover, the durability performance of the cement and concrete was also affected by elevated curing temperature. The curing process at such temperatures could cause the increasing of water absorption [33], and the decline of resistance to the penetration of chloride ions [10]. The rate of initial hydration reactions increased proportionally with the raise of curing temperature [34] and the linear relationship of compressive strength with curing temperature was established [35]. Besides, prior research had shown that the curing temperature up to 30 °C could provide favorable conditions for the development of long-term strength [11].

According to our knowledge, most present research has focused on the evaluation of temperature influence on ordinary concrete or cement paste, and rare research has systematically investigated the effect of elevated curing temperature on the hardening and physical performance of the LWAC. Based on the above analysis, the objective of this paper is to explore the effect of elevated curing temperature on ceramsite concrete performance and the influence mechanism to some extent. In order to take into consideration the high geothermal tunnel built up to now, the range of curing temperatures from 20 °C to 60 °C was chosen and studied, which could provide useful information for engineering construction.

2. Material and methods

2.1. Materials

Type I ordinary Portland cement (OPC) with a 28-day compressive strength of 42.5 MPa was used in this study, and its chemical composition and physical property are shown in Table 1. River sand with a fineness modulus of 2.6 was used as fine aggregate. In addition, the gravel-shale ceramsite with diameter ranging from about 5–15 mm, the bulk density of 710 kg/m^3, 1 h water absorption less than 11.5%, was used as coarse aggregate. A high-performance polycarboxylic superplasticizer (Henan Meiya Corp.) was used as water reducing agent and a non-alkali type accelerating agent (Jiangsu Sobute New Materials Co., Ltd.) was applied to speed up the concrete to harden, respectively.

2.2. Experimental

The ceramsite concrete was cured at the temperatures of 20 °C, 40 °C and 60 °C. The standard curing box was employed for curing at 20 °C, meanwhile the temperature adjustable curing boxes (with the relative humidity higher than 90%) were used to maintain the temperature of 40 °C and 60 °C for simulating high geothermal conditions.

Firstly, the orthogonal experiment was conducted to explore the influence of the four factors on cube compressive strength (f_{cu}) at different curing ages of ceramsite concrete. The four factors were curing temperature (A), water-cement ratio (B), cement content (C) and sand/aggregate ratio (D). And each factor was examined at three values, which were explored in the foregoing experiment in our laboratory. Besides, the water reducing agent at a rate of 0.9% of the cement weight was added in the orthogonal experiment. The orthogonal experiment levels for each factor are shown in Table 2.

The influence trend of curing temperature on ceramsite concrete strength was estimated, and the optimum mix proportion could be determined through orthogonal experiment. Then the accelerator was added to the ceramsite concrete mixture with optimum mix proportion, and the concrete was cured at the same three different temperatures.

Finally, the compressive strength at different curing ages was measured by YNS-300 universal testing machine (Changchun Mechanical Co., Ltd.). And the 28-day curing age concrete samples were adopted in other test items. The water permeability was measured by a HS-4S permeability instrument (Wuxi Jianyi Co., Ltd.). The chloride ion penetration resistance was detected by a NJ-DTL electric flux meter (Beijing Naijiuweiye Technology Co., Ltd.). The ceramsite concrete was cut into 200 × 200 × 10 mm specimens and pre-dried, and the thermal conductivity was tested by a DRL-III thermal conductivity tester. With the help of Autopore IV 9500 mercury intrusion porosimeter (MIP, Micromeritics Instr. Corp.) and Quanta FEG-250 scanning electron microscope (SEM, FEI Corp.), the porosity and microstructure of the bulk cement paste could be revealed.

Table 1
Chemical composition and physical property of cement.

Chemical composition (%)	OPC
Calcium oxide (CaO)	57.9
Silicon dioxide (SiO_2)	23.7
Aluminum oxide (Al_2O_3)	7.4
Ferric oxide (Fe_2O_3)	1.9
Sulfur trioxide (SO_3)	2.64
Magnesium oxide (MgO)	2.04
Potassium oxide (K_2O)	0.63
Sodium oxide (Na_2O)	0.31
Loss on ignition	3.36
Physical property	OPC
Fineness	358 m^2/kg
Initial setting time	175 min
Final setting time	220 min
3-day mortar compressive strength	28.8 MPa
3-day mortar rupture strength	5.7 MPa

Table 2
Form of values for each factor.

Level	A/°C	B	C/kg m^{-3}	D
1	20	0.36	450	0.46
2	40	0.38	460	0.49
3	60	0.40	470	0.52