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Experimental study on mechanical and microstructural properties of cement-based paste for shotcrete use in high-temperature geothermal environment

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HIGHLIGHTS

- A simulation method for an 85 °C high-temperature geothermal environment was designed.
- The hydration state was stimulated by the high-temperature geothermal environment.
- Co-doping of fly ash and silica fume is recommended in this environment.

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ABSTRACT

In order to study the mechanical and microstructural properties of cement-based paste for shotcrete use in a high-temperature geothermal environment, the distinct environment was simulated in a laboratory where mechanical testing, thermogravimetric and differential thermal analyses, and scanning electron microscopy were conducted. Compared to the curing environment at 20 °C, the hydration state of the cement-based paste for shotcrete use was transformed to a state similar to that of cement-based paste for ordinary concrete within a shorter time, owing to the stimulation of the high-temperature geothermal environment. The cement-fly ash composite paste for shotcrete use cured in the high-temperature environment still exhibited lower strength in the early ages, yet slightly higher strengths at a 28-day age than pure cement-based paste. Furthermore, the strengths corresponding to each age of the cement-based paste co-doped with silica fume and fly ash increased more rapidly than those of the pure cement-based paste, particularly during the early ages. Therefore, considering the priority of rapid hardening and early strength, it is recommended to co-dope fly ash and silica fume into the shotcrete mixture in this environment.

1. Introduction

It is an indispensable practice to construct deep, long, large tunnels to overcome landform obstacles of high mountains and canyons, as well as to shorten distances and improve land transportation quality. With the development of design theories and construction techniques, more tunnels with complicated structures will be constructed in the fields of railway, highway, and hydroelectric engineering, as well as inter-basin diversion projects. Meanwhile, problems caused by high-temperature geothermy have become increasingly prominent [1–6]. One form of the high-temperature geothermy is hot and humid environment, where fractures or rock fragmentation exist and underground hot water gathers easily, leading to the formation of hot springs. The physical and mechanical indexes of shotcrete under such environments differ from those under normal temperature conditions. Therefore, certain problems, such as an increase in the shotcrete rebound and decrease in later-period strength, may occur under high-temperature geothermal environments. Existing research has mainly focused on improving tunnel environments by means of external or temporary measures, such as ventilation or artificial refrigeration, and few studies have examined the mechanical properties and deterioration mechanisms of shotcrete in high-temperature geothermal environments. Previous literature [7–11] has demonstrated that the mechanical properties of shotcrete at a 28 d age decreased due to the negative effects of high-temperature early curing, compared to standard curing conditions (20 °C with a relative humidity of ≥95%). The literature [7], which takes a 70 °C high-temperature geothermal environment as the

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Nomenclature

Aft	ettringite	C-S-H	hydrated calcium silicate
CH	calcium hydroxide ($Ca(OH)_2$)	DTA	differential thermal analysis
C_2S	dicalcium silicate	SEM	scanning electron microscope
C_3S	tricalcium silicate	TG	thermogravimetric

background, explored the influence of fly ash and slag powder on shotcrete bonding performance at the age of 28 d, demonstrating that adding a mineral admixture into the shotcrete, particularly fly ash, can reduce the negative effects of high-temperature early curing and improve the shotcrete bonding strength. However, it is not sufficient to focus only on the improvement effects of shotcrete at a 28 d age; rapid hardening and early strength are often higher priorities in tunneling, as rock mass displacements may occur soon after the rock excavation. If the hydration is slow, the bonding performance will be poor, resulting in the amount of rebound being large, which may even cause shotcrete failure. Obviously, the shotcrete early bonding performance and rebound are closely related to the cement-based paste hydration process, or the cement-based paste strength growth rate is determined by its hydration. During early ages, the hydration rate is higher, the early strength development is faster, and the bonding performance is superior. Therefore, increased attention should be paid to time-varying characteristics with shotcrete age, including the mechanical properties, hydration degree, and microstructure, in order to explore means of improving the shotcrete performance in high-temperature geothermal environments.

Certain studies have been conducted on cement-based paste properties in high-temperature environments. However, these studies have mainly focused on two types of cases. The first deals with the cement-based paste performance under steam curing conditions [12–21]. This type of curing process usually includes four stages (see Fig. 1): delay period (remain at room temperature), controlled heating period (increase to the maximum curing temperature at a constant speed), treatment period (remain at the maximum curing temperature), and controlled cooling period (reduce to room temperature at a constant rate). The second case involves the cement-based paste performance under high temperatures caused by fire, which affects the cement-based paste properties at a certain age following hardening, rather than during the hydration or early strength development process [22–27]. Obviously, compared to the high-temperature geothermal environment discussed in this paper, essential differences exist between these types of studies, as reflected in the curing conditions and systems. Furthermore, the focus and temperature ranges differ.

In a project that is under construction in China, temperature has been measured at 3 m from the advanced exploration hole, which is at the 1# adit of the Sangzhu Ling tunnel of the Lasa-Linzhi Railway, reaching 83.2 °C (Fig. 2). The cement-based paste properties in high-temperature geothermal environments remain to be studied and improved further. Moreover, as mentioned previously, the early mechanical properties and rebounding amounts of shotcrete are mainly reflected by the time-varying hydration properties of cement-based paste. Therefore, in this study, based on the above project, 85 °C was adopted as the high-temperature geothermal curing temperature. The water-cement ratio and setting accelerator dosage used in practice engineering were taken into consideration during the mix proportion design of the cement-based paste. Furthermore, the time-varying characteristics of cement-based paste under high-temperature geothermal environments were studied by means of mechanical property tests, thermogravimetric (TG) and differential thermal analyses (DTA), and scanning electron microscope (SEM) technology.

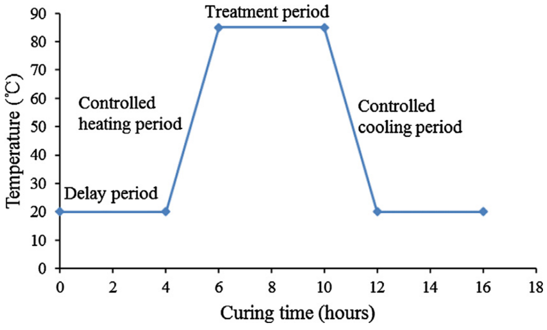

Fig. 1. Steam curing cycle.

2. Experimental design

2.1. Conditions and mix proportion design

Considering the requirements of rapid hardening, early strength and long-term performance of shotcrete support structure, three types of cement-based paste conditions and five curing ages, namely 2 h, 1 d, 3 d, 7 d, and 28 d, were designed. The condition symbols and their descriptions are displayed in Table 1.

The raw materials for the experiment were as follows: cement (P.O42.5 [28], density 3.15 g/cm^3, chemical compositions shown in Table 2); fly ash (grade I [29], 7.1% fineness, density 2.10 g/cm^3, chemical compositions shown in Table 3); silica fume (specific surface area 20 m^2/g, particle size distribution mostly 0.001 μm–1 μm, average particle size 0.12 μm, 3.72% loss on ignition, chemical compositions shown in Table 4); setting accelerator (JX-E3 type, non-alkali liquid, additive amount 4%, initial setting time 4 min 24 s, final setting time 10 min 23 s [30]). The water-cement ratio was 0.4 [31], and the mix proportions for each condition are displayed in Table 5.

2.2. Experimental method

After being stirred evenly, the cement-based paste should be cast rapidly into molds with sizes of 40 mm × 40 mm × 160 mm. Three specimens were formed for each condition. In this case, the casted specimens were manufactured by means of vibration technology with a vibrating table. Following final setting, all specimens

Fig. 2. Measured temperature.