Shotcrete

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With the swift global development of tunnels, mines, subways, water conservancy and hydropower projects, and so on, shotcrete, as an advanced support method, is widely applied to surrounding rock control and roadway closure. Shotcrete is a kind of concrete formed by mixing concrete materials, such as gel material, aggregate, and so on, into the ejection equipment, by means of compressed air or other power transmission, and sprayed onto the spray surface at high speed. Shotcrete technology was first used in mining and civil engineering by the United States in 1914. It has a history of more than 100 years.

Keywords: high temperature ; shotcrete ; mechanical properties ; microscopic properties

1. Introduction

Shotcrete is used in underground and tunnel support, infrastructure repair and rehabilitation, slope stabilization, and in areas difficult to reach with conventional concrete, such as bridge piers and beam soffits [1]. Shotcrete has the characteristics of high compressive strength, good durability, and wide range of strength grades [2][3][4]. As a supporting material of roadway, shotcrete can not only prevent the oxidation of surrounding rock, but also plays a supporting role for the roadway. With the development of deep mines and deep tunnels, shotcrete is facing great challenges. Especially deep underground, high temperature accelerates the deterioration of shotcrete [5][6][7][8]. According to relevant reports, the rock wall temperature of Sangzhuling Tunnel in the Yarlung Zangbo River Canyon in China reached 89 °C, and it was identified as a class I risk tunnel. The high temperature of 75 °C and the extreme temperature of 170 °C were encountered in the construction of Anfang tunnel and the third hydropower station of Heibu in Japan. The highest original rock temperature is 46.8 °C, at −980 m level in Sanhejian coal mine. The underground rock temperature of the Mbonig gold mine in South Africa reaches 65.6 °C.

Many scholars have shown that there is a certain relationship between temperature and depth, and the rock temperature gradient is about 3–4 °C/100 m [9][10][11]. However, in a deep environment, due to the different rock properties and the possible existence of large fault zones, the change of temperature with temperature gradient is not obvious. **Figure 1** shows the distribution of temperature with depth in deep tunnels and deep mines in some projects. From the figure, it could be concluded that the variation between temperature and depth in underground projects was a nonlinear relationship, that is, the ground temperature in deep environments shows an abnormal pattern [12][13].

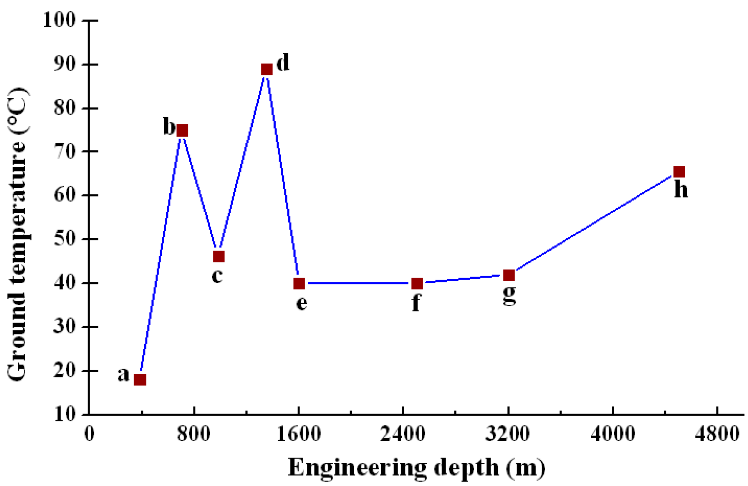

Figure 1. Temperature distribution of tunnels and mines with different depths.

In **Figure 1**: a—Albert tunnel in Austria; b—Anfang highway tunnel in Japan; c—Sanhejian coal mine in China; d—Sangzhuling tunnel in China; e—Qinling tunnel of Xikang railway in China; f—Franco-Yibulangfeng highway tunnel; g—

Kolar gold mine in India; h—Mponig gold mine in South Africa.

When shotcrete as support structure contacts with high-temperature rock wall, the performance of shotcrete may change. High temperature leads to the deterioration of shotcrete structure and the weakening of roadway stability. In recent years, many scholars have studied the mechanical properties and micro-morphology of shotcrete under high temperature. For example, Lee and Yang et al. [14][15] studied the variation of shear properties of shotcrete with granite cementation surface roughness and temperature. The results showed that there were critical values for the effects of granite cementation surface roughness and temperature on shear strength. Moreover, the temperature was the most important factor affecting the shear performance of shotcrete. Wang et al. [16][17] studied the impermeability of shotcrete under standard working conditions and variable temperature conditions. The results showed that the temperature destroys the dense structure inside the shotcrete, resulting in an increase in the impermeability of the shotcrete. Wang and Cui et al. [18] studied the effect of temperature on the bond strength between shotcrete and rock surface, and found that the bond strength first increased and then decreased with the increase of temperature. Dong et al. [19] studied the fracture process of the interface between shotcrete and rock, and found that under high temperature, the structure of shotcrete fracture surface was loose and powder particles increased. Yang et al. [20] studied the internal damage mechanism of shotcrete under high temperature based on CT technology and X-ray, and the results showed that the internal pores of shotcrete present the trend of small holes gradually developing into large pores with the increase of temperature. Lu et al. [21][22] studied the residual properties of shotcrete after high temperature, and found that the main factors affecting the residual strength were curing conditions and cooling methods. Kjellsen et al. [23] studied the consolidation process of concrete in a thermal environment, and found that the compaction degree of the concrete decreased, and internal cracks occurred during the solidification process. Then, the microstructure of concrete was scanned by scanning electron microscopy (SEM), and it was found that the cracks developed along the interior of the aggregate. Akca et al. [24] studied the structural performance of high-performance shotcrete under high temperature, and concluded that the overall strength of shotcrete showed an upward trend under high temperature.

2. Challenges

At present, despite the plentiful results obtained in the field of high-temperature shotcrete research, most of the research is still in the field of tunnel engineering, and there are few studies in other underground engineering fields (such as mine engineering). Moreover, the environments of mine engineering and tunnel engineering are not the same. The mining depth of mine engineering is far greater than that of tunnel engineering. The mining environment is more severe, and the high-temperature environment is more complicated. Therefore, the research on sprayed concrete in the field of underground engineering still faces great challenges, as shown in **Table 1**.

Table 1. Challenges of shotcrete performance under high temperature.

Challenges	Current Technologies	Future Challenges
High temperature detection technology research	**Thermocouple temperature measurement, infrared temperature measurement, and other technologies. However, the temperature can change in the hot and humid environment of the roadway, and a complete test system has not been formed.**	**Develop a new temperature measurement method, establish a temperature measurement system, predict and forecast the high temperature area of the roadway, ensure that the construction environment is in a balanced state, and reinforce the area where the roadway sprayed concrete may be damaged in advance.**
Experimental device for performance of shotcrete	**Shotcrete is made by pouring or spraying. Then, constant temperature and a humidity curing box or high-temperature drying box are used to simulate high-temperature environment curing. There will be a gap in the simulation of the high-temperature environment, which will affect the experimental results.**	**Research and development of shotcreting equipment and performance testing system in high temperature. Accurately simulate high-temperature environment to improve the authenticity of research results. Provide reliable results for improving the development of infrastructure under high temperature.**
Shotcrete spray layer structure	**The existing research is based on the study of the adhesion of shotcrete under the action of temperature, but it has not involved research on the shotcrete spraying layer in the process of roadway reinforcement under high temperature.**	**Study the performance change trend of high-temperature roadway shotcrete with the thickness of shotcrete layer. Get the optimal spray layer thickness under high temperature. Study the adhesion between spray layers. Research and develop high-efficiency, environmentally friendly, and low-cost adhesives**
Performance of shotcrete in special environments	**Existing research is based on the permeability of shotcrete, and there is basically no relevant literature on the high-temperature conditions of the construction roadway in a high-water-spray environment.**	**Study the mechanical properties of shotcrete in high-temperature acid and alkaline environments. Investigate the non-linear relationship between the compatibility of the sprayed concrete and the cemented surface of the high-water-spray area and the interface's mechanical properties.**

Challenges	Current Technologies	Future Challenges
Microscopic properties of shotcrete	**The existing research has explained the deterioration performance of shotcrete at high temperature from the micro level, but it is still not perfect. There is no detailed study on the crack development process and deterioration mechanism of concrete in a high temperature environment.**	**Study the microscopic changes of shotcrete under high temperature. Establish a damage model of shotcrete under high temperature. Study the impact properties of shotcrete layers under high temperature. Establish a damage prediction model for shotcrete layer structure under high temperature, using acoustic emission technology to predict the development trend of shotcrete deterioration in advance.**
Optimization of shotcrete	**Existing research is mainly based on studies of thermal insulation sprayed concrete, which is mainly improved from the material ratio by adding inorganic materials. Although it has a certain thermal insulation effect, its thermal insulation performance is insignificant for the ultra-high temperature construction environment.**	**Study the modification of shotcrete. Choose low-quality, low-thermal-conductivity materials to reduce the potential energy of concrete. Preliminary research on the high temperature resistance between silica aerogel and shotcrete.**

3. Conclusions

(1) The leading role of rock thermal conductivity on temperature transmission was determined by introducing the multi-dimensional morphological formula in the process of heat conduction.

(2) Results concluded that the mechanical properties (including compressive strength, tensile strength, bond strength, shear strength) of shotcrete were affected by the critical temperature: before the critical temperature, the mechanical properties of shotcrete showed an increasing trend with the increase of temperature; after the critical temperature, the mechanical properties of shotcrete appeared to show the phenomenon of shrinkage. Through microscopic analysis, multiple studies have shown that when the temperature exceeds the critical temperature, the internal molecules of the shotcrete move violently and the molecules overlap in a disorderly way, the hydration reaction of shotcrete cement is terminated prematurely, and the brittle de-formation is enhanced, which leads to the weakening of shotcrete strength.

(3) It is concluded that taking cooling measures for a high-temperature construction environment will increase the recoverability of concrete after deterioration and reduce the deterioration degree of shotcrete. In terms of optimizing the performance of shotcrete, adding inorganic materials, such as vitrified microbeads, foam fibers, expanded perlite, and silica fume, will improve the heat insulation and heat resistance of shotcrete.

(4) It was found that the current temperature measurement system, high-temperature simulation equipment, and material ratio had limitations. At the same time, the challenges that high-temperature shotcrete faces in terms of the process structure, performance optimization, and its application in special engineering fields were summarized.

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