Construction and Building Materials 124 (2016) 1109–1119

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Review

Effect of temperature and humidity on the adhesion strength and damage mechanism of shotcrete-surrounded rock

Yang Tang[a], Guobin Xu[a,*], Jijian Lian[a], Hui Su[b], Chunlai Qu[b]

[a] State Key Laboratory of Hydraulic Engineering Simulation and Safety, Tianjin University, Tianjin 300072, China
[b] School of Hydroelectricity, Hebei University of Engineering, Handan 056038, China

HIGHLIGHTS

- Adhesion strength at the shotcrete–rock contact in a geothermal and humid environment was got.
- CT scanning technology was used to evaluate shotcrete-surrounded rock internal defects.
- The mechanism of adhesion strength under the effects of temperature, relative humidity and curing time was analysed.

ARTICLE INFO

Article history:
Received 13 November 2015
Received in revised form 18 August 2016
Accepted 28 August 2016
Available online 3 September 2016

Keywords:
Highly geothermal environment
Adhesion strength
Shrinkage
Shotcrete-surrounded rock
Damage mechanism

ABSTRACT

A novel test control system is used to assess the effects of temperature and humidity on the adhesion strength of shotcrete-surrounded rock. Analysis of the internal structure and defect volume reveals that the adhesion strength increases with relative humidity (RH), whereas higher temperatures and longer setting times increase the risk of shotcrete dehydration through an increase in porosity. The critical temperature at which adhesion strength is lost also increases with RH. This shows that temperature, RH and setting time all greatly influence the adhesion strength of shotcrete-surrounded rock, which is of relevance to diversion tunnel construction in highly geothermal environments.

Contents

---

* Corresponding author.
E-mail addresses: sunny_1677@163.com (Y. Tang), xuguobin0404@163.com (G. Xu), jjlian@tju.edu.cn (J. Lian), suh-26@163.com (H. Su), 413586554@qq.com (C. Qu).

http://dx.doi.org/10.1016/j.conbuildmat.2016.08.126
0950-0618/

1. Introduction

The development of tunnels in deep strata that has occurred in many countries has made the damage caused by highly geothermal environments an increasingly significant issue in underground engineering [1–4]. As this damage can seriously affect tunnel construction and operation, there have been a number of studies into the effects of high temperature on concrete performance. Chen [5] and Lee [6], for example, investigated the influence of a hot spring curing environment on the performance of concrete and shotcrete. It is known that a high-temperature environment results in bubbles being more easily produced in concrete, which causes moisture to evaporate more quickly and means that cement hydration readily loses heat [7]. This creates a series of problems during subsequent setting of the concrete such as a reduction in compactness and strength, and the generation of internal cracks [8,9]. Though all of these issues can have an impact on the structural stability of a diversion tunnel, no consensus has yet been reached on what mechanism has the most influence on concrete growth in high temperature environments.

The mechanical properties of concrete are largely determined by its microstructure [10], and it was through microstructural analysis that it was found that high temperatures produce a rapid rate of cement hydration [11]. This minimises the spread of hydration products and causes them to accumulate around cement particles, resulting in a loose structure and a reduction in concrete strength. Chen [12] have also used computed tomography to show the process by which shotcrete incurs microstructural damage in a freeze–thaw environment, whereas Wang [13] studied the hydration process and properties of shotcrete by using X-ray diffraction, thermal analysis, scanning electron microscopy, and mercury intrusion porosimetry.

When constructing a concrete support structure for a tunnel in a highly geothermal environment, shotcrete is directly bonded to the surrounding rock surface. Under these conditions, the temperature of the concrete and rock contact surface results in inadequate hydration of the cement and a poor distribution of hydration products owing to water loss. As this also increases the shrinkage of the concrete, the adhesion strength of the shotcrete-surrounded rock will decrease accordingly [14]. During the operational phase of a water diversion tunnel, the cold flow of water will cause a sudden drop in the temperature of the concrete, thereby creating a greater temperature gradient that generates tensile stress in the concrete [7]. This can ultimately generate and expand cracks in the surrounding rock support structure, as the difference in stiffness and thermal expansion between the concrete and surrounding rock makes it easy for the two to separate through tensile failure at their contact surface. The high ground stress and high water head in a deeply buried tunnel will exacerbate this trend, and can eventually lead to structural instability or damage. This makes it very important to understand the damage characteristics of the surrounding rock support structure in a highly geothermal environment. Currently,

Acoustic emission (AE) and computed tomography (CT) are currently the most widely used techniques for the non-destructive detection of microstructural damage in concrete materials. The high temperature effect test that is used for the development stage of a concrete structure utilises standard curing for pre-hardening, which is followed by high temperature curing for 16–24 h, and a final standard curing stage after the removal of shuttering [15]. However, as this curing environment differs widely from the actual conditions found a highly geothermal tunnel environment, it creates a big gap between the test results and the actual mechanical properties of a concrete support structure.

There are a number of methods for measuring the adhesion strength of concrete, making it important to select the most appropriate. Moorak [16], for example, found that the adhesion strength results from indirect tensile tests cannot be directly used to analyse the stability or safety of tunnel structures. It was therefore suggested that more direct test methods be used to measure the adhesion strength of shotcrete-surrounded rock, but this is something that has received very little research interest. This paper therefore looks at the influence of a high-temperature environment on the adhesion strength of C25 shotcrete, which is extensively used in underground engineering in China. This is combined with CT scanning techniques to identify any differences in the internal damage caused under several different test conditions that may reveal the nature of the damage mechanism. Technologies and methods for improving the bond strength of shotcrete-surrounded rock are also explored with the aim of providing a theoretical basis for ensuring the stability of the surrounding rock support structure for a diversion tunnel in a highly geothermal environment.

2. Experimental set-up, method and procedures

2.1. Background and highly geothermal environment design

Qirehataer Hydropower Station is located near the Tashikuergan River, and lies within the Tashikuergan Tajik Autonomous County of the Xinjiang Uygur Autonomous Region. Its diversion tunnel passes through a highly geothermal environment between Y7 + 010 and Y10 + 355, which has resulted in water vapour gushing into the entrance of the tunnel during construction owing to the high temperature in the main hole (Fig. 1). This geothermal zone has an overall length of 3345 m and consists of rock classified as gneissic granite. At present, the tunnel temperature and humidity tend to be stable, with the variation being either seasonal or the result of tunnel ventilation. Monitoring data for the surrounding rock indicates that the highest temperature in the tunnel was >60 °C, and that the lowest relative humidity (RH) was 25%. Based on this data, the working conditions selected for testing were a RH of 25 or 90%, and a temperature of 50, 60, 75, or 90 °C (Table 1).

For adhesion strength testing, a platform was needed for creating an indoor temperature and humidity test environment that

Fig. 1. Water vapour gushing into the entrance.