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Experimental study on mechanical property and pore structure of concrete for shotcrete use in a hot-dry environment of high geothermal tunnels

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HIGHLIGHTS

- The hot-dry environment was simulated in a laboratory.
- The effects of adding fiber materials on mechanical property and pore structure were investigated.
- The mathematical model of strength and pore structure was established.

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ABSTRACT

In order to examine the deterioration mechanism and improvement measures in 100 °C hot-dry environments of high geothermal tunnels, the mechanical experiments and pore structure determinations were performed to study the macroscopic mechanical properties and pore structure characteristics of concrete for shotcrete use. The results show that: (1) in the hot-dry environments, the compressive strength and splitting tensile strength of *basic mix proportion condition* (BP) both decrease sharply after 7 days. By adding steel fibers or basalt fibers into concrete mix, the two kinds of strength of concrete are obviously improved, and the effect of steel fiber is significantly better than that of basalt fiber. Moreover, the improving effect of waved steel fiber among three kinds of fibers on compressive strength is the best. Compared with that of BP, the compressive strength of *waved steel fiber condition* (SF-W) increases by 17.2%, 37.5%, and 119.4% at 1-day, 7-day, and 28-day age respectively. The improving effect of hooked end steel fiber among three kinds of fibers on splitting tensile strength is the best. Compared with that of BP, the splitting tensile strength of *hooked end steel fiber condition* (SF-HE) increases by 88.5%, 72.6%, and 110.6% at 1-day, 7-day, and 28-day age respectively. (2) The median pore diameter and average pore diameter of BP at each age are higher than those of mixed fiber conditions at corresponding age. With the increase of age, the total porosity and the porosity of harmful pore (pore diameter >100 nm) of BP condition in the hot-dry environments increase rapidly. The addition of fiber materials effectively reduces the total porosity and the porosity of harmful pore, and the optimization effect of steel fiber on pore structure is better than that of basalt fiber. Compared with BP, the total porosities of SF-HE and SF-W decrease by 54.6% and 60.1%, and the porosities of harmful pore of SF-HE and SF-W decrease by 73.7% and 77.5% respectively. (3) The compressive strength and splitting tensile strength of *double mix of steel fibers and silica fume condition* (SF-HE + Si) are obviously lower than those of SF-HE, and the total porosity and the porosity of harmful pore are obviously higher than that of SF-HE in the hot-dry environments. (4) Compared with Menger sponge model, the fractal dimension based on thermodynamic method can describe the pore size distribution in the whole test range more comprehensively, and it is more suitable for solving the fractal dimension of concrete in this kind of environments. (5) The multi-factor strength mathematical model considering the influence of fractal dimension and composite porosity is in good agreement with the experimental results, thus, it can accurately be used to describe the quantitative relationship between strength and pore structure parameters.

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Nomenclature

A_c	the load-carrying area of specimens (mm^2)
A_{st}	the splitting-surface area of specimens (mm^2)
C	Coefficient, a constant
D_m	the fractal dimension of Menger sponge model
D_t	the fractal dimension based on thermodynamic method
f	the strength of concrete
f_c	the compressive strength of concrete (MPa)
f_{st}	the splitting tensile strength of concrete (MPa)
F_c	the compressive failure load of specimens (N)
F_{st}	the splitting tensile failure load of specimens (N)
k	times of iterations
k_i	the regression coefficient
m	the number of parts of the side length
n	the times of intrusion of mercury
N_k	the number of the remaining cubes
p	the pressure applied to mercury (Pa)
$\bar{p}_i$	the average pressure at the ith intrusion of mercury (Pa)
P_c	the composite porosity (%)
P_1	the porosity of Macro pores (%)
P_2	the porosity of capillary pores (%)
P_3	the porosity of transitional pores (%)
P_4	the porosity of gel pores (%)
q	the number of selected small cubes
Q_n	$Q_n = V_n^{1/3}/r_n$
r_k	the side length of the remaining cube (m)
r_n	the pore diameter corresponding to the nth intrusion of mercury (m)
R	the side length of the initial cube (m)
S	the pore surface area of the tested material (m^2)
V	mercury intrusion volume (m^3)
V_k	the remaining cube volume (m^3)
V_n	the cumulative mercury intrusion volume (m^3)
V_p	the pore volume of the remaining cube (m^3)
ΔV_i	the mercury intrusion volume at the ith intrusion of mercury (m^3)
W_n	$W_n = \sum_{i=1}^{n} \bar{p}_i \Delta V_i$
α_i	the strength influence coefficient of porosity at each level
β_c	the compression strength reduction factor
β_{st}	the splitting tensile strength reduction factor
σ	the surface tension of mercury (N/m)
θ	the contact angle between mercury and the tested material

1. Introduction

With the development of tunnel construction toward longer, larger and deeper tunnels, thermal damage caused by high geotherm has become increasingly prominent [1–7]. There are mainly two forms for high geotherms in tunnel construction. One is hot and dry environments, where there are better geological formations and the internal heat of geological layer spreads to the tunnel surface through the rocks. The other is hot and humid environments, where there exist fractures, or rock crashes that underground hot water gathers easily, and then hot springs are formed. Among them, hot and dry environments are mainly due to volcanic radiation geotherm (radiant heat of geothermal water through the rock), radiant heat from radioactive elements fission, and the earth's mantle convective heat. However, it is the first two factors that result in damage to the tunnel engineering.

The survey on practical engineering shows there are hot and dry areas widely spreading in high geothermal environments. For example, the three branch tunnels of 2#, 3# and 4# of Bulunkou-Gongur hydropower diversion tunnel in Xinjiang Province are all dry, and the temperature of rock wall at the downstream excavation face of the 3# branch tunnel is up to 105 °C. The gas ejected from the diversion tunnel of Qirehataer hydropower station during the excavation reached a temperature of 174 °C, and the temperature of rock wall reaches 100 °C. Besides, the serious hot-dry rock surface problems have also been encountered during the construction process of Sangzhuling tunnel (under construction) on Lasa-Linzhi railway. At the same time, the on-site construction monitoring and relevant research [8–13] have shown that the high earth temperature brings difficulties to construction, and affects the quality and durability of the project. Especially in hot-dry environments, the rebound of shotcrete increases significantly, the strength of shotcrete decreases sharply, and even the shotcrete debonds with the rock interface, which leads to a failure of sprayed concrete. Due to the micro-structure and meso-structure degradation of cement-based material caused by too fast temperature rising and water loss, physical and chemical shrinkage of concrete, and non-uniform temperature effects of interface, the damage mechanisms of shotcrete performance are very complex. At present, the research on the damage mechanism of shotcrete in hot-dry environments is still lacking.

The microstructure of the material determines the macroscopic properties. The concrete materials are heterogeneous, multiphase (gas, liquid, solid) and multi-level (micro, meso, macro) composites with complex structure. The characteristics of macroscopic physics behavior such as irregularity, uncertainty, ambiguity, and nonlinearity are closely related to the complexity of their microstructure. The pore structure is one of the important contents of the concrete microstructure, which has a close relationship with mechanical properties and durability of concrete. Therefore, it is of great significance to study the pore structure of shotcrete in hot-dry environments to explore its deterioration mechanism and improvement measures.

At present, some research works on the pore structure of concrete have been performed [14–29], including the influence of water-cement ratio, curing conditions and curing age, fire-induced high temperature, and mineral admixtures (fly ash, metakaolin, silica fume, etc.) on the pore structure of concrete, and the relationship between pore structure and macroscopic properties of concrete. For this relationship between them, at first, some researchers considered that the macroscopic properties of concrete are directly related to porosity of concrete. However, with the further study, it was found that the macroscopic properties of concrete may be different when the total porosity of concrete is the same, and the macroscopic properties of concrete are also related to the pore morphology, pore size, and pore size distribution. In 1980, Wittmann [30] proposed the concept of "poreology", which extended the research scope of pore structure to pore size distribution and pore morphology. Then, scholars started to study the influence of pore structure parameters such as pore size distribution and pore morphology on the macroscopic properties of concrete, and those results shown that the model of relationship between macroscopic and microscopic characteristics considering the pore size distribution and pore morphology is more reasonable and effective than the model only considering the porosity. In spite of the above studies, so far, there is no literature on the pore structure of shotcrete (or concrete) in geothermal hot-dry environments, neither the characteristics of pore structure with time, the