Construction and Building Materials 173 (2018) 381–393

Contents lists available at ScienceDirect

Construction and Building Materials

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

Evolution mechanism of microscopic pores in pavement concrete under multi-field coupling

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HIGHLIGHTS

- The evolution of micropore structure is investigated under multi-field coupling.
- The deterioration rules of micropore are discussed dynamically at the micro-scale.
- The quantitative analysis is realized by the optical method and fractal theory.
- The evolution mechanism of micropore in seasonally frozen regions is proposed.

ARTICLE INFO

Article history:
Received 13 December 2017
Received in revised form 2 April 2018
Accepted 3 April 2018
Available online 24 April 2018

Keywords:
Concrete pavement
Micropore
Deterioration mechanism
Coupling effect

ABSTRACT

To explore micropore deterioration and its mechanism in pavement concrete in seasonally frozen regions, multi-field fatigue tests were conducted. The mercury intrusion method, the optical method and scanning electron microscopy (SEM) were used to quantitatively characterize the pore structure of specimens in multi-field coupling conditions in terms of properties such as the porosity, mean pore size (MPS), pore size distribution (PSD), stomatal distance coefficient (SDC) and box fractal dimension (BFD). Next, the dynamic deterioration rules of micropores under different coupling levels were discussed at the micro-scale. The results show that the coupling effect significantly accelerates the deterioration of pavement concrete, while the stratified feature of micropores is weakened and the complexity of micropores is increased as more pores experience deformation, splitting and nucleation. Under the action of a single load, the porosity shows a 'initiating-closing-splitting' trend, while the MPS reveals a 'compressing-expanding' trend, and the BFD first increases and then decreases with the increase in loading cycles. The crystal expansion stress initiated by the fatigue load and freeze-thaw coupling effect weakens the ability to disperse internal stress, leading to the pore structure parameters showing a tendency of monotonous rapid deterioration after the turning point, and the concrete reveals fatigue failure with larger porosity and SDC compared to that of a single field. Under the triple-field coupling, a large shrinkage stress is generated rapidly; the system cannot be relieved through structural deformation in time, causing MPS to increase, the pore distribution complexity (BFD) to decrease, and more micropores to nucleate.

1. Introduction

In recent years, a considerable number of cement concrete pavements have been undergoing cracking, breaking, and plate outrunning in the course of 3 to 5 years of operation. This has caused not only a drastic decrease in durability but also a safety performance that is of concern. The reason for this issue is that the pavement concrete suffers from many nonlinear physical fields, such as bending load, temperature and humidity [1–3]. However, the coupling effect of multiple factors on pavement concrete has not been considered in the current design. In particular, in a seasonally frozen area, pavement concrete can easily increase the deterioration of internal structure under the continuous coupling cycles, eventually leading to fatigue failure, and previous studies indicate that the evolution of internal micropores and spatial distribution are the initial inducement of macroscopic instability.

Some scholars have investigated the concrete pore structure under certain experimental environments. Deo et al. [4] studied the pore structure under fatigue load and observed that the strength of concrete is affected by pore size and porosity, and the pore volume is increased by 10% with the strength reduced by 50%. By studying the pore structure of concrete under freeze-thaw cycling, Han et al. [5] found that the surface fractal

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https://doi.org/10.1016/j.conbuildmat.2018.04.022
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Table 1
Main physical indicators of the slag and fly ash.

Admixture	Grade	Active index/%	Density/(g·cm^{-3})	Specific surface area/(m^2·kg^{-1})	Flow ratio/%
Slag	S95	96	2.75	560	85
Fly ash	I	75	1.05	270	91

Table 2
Fundamental technical properties of the coarse aggregate.

Apparent density/(g·cm^{-3})	Crushing value/%	Needle plate content/%	Solidity quality loss/%	Sediment content/%	Organism content/%
2.80	7.0	4.5	4.2	0.4	0.4

Table 3
Composition of C40 pavement concrete.

Grade	W/C	Dosage of concrete per cubic meter/kg						
		Cement	Slag	Fly ash	Water	Coarse	Sand	Superplasticizer
C40	0.34	315	63	42	143	1114	734	2.52

dimension decreases gradually with an increase in the number of freeze-thaw cycles. Qu et al. [6] studied the change trend of MPS and the porosity of concrete under the action of freeze-thaw cycling, and T.C. Powers [7] proposed that the pore stomatal distance coefficient can be used as a parameter to evaluate the frost resistance of concrete. Kuosa et al. [8] and Ferreira et al. [9] promoted the new tools for evaluating the synergetic effect of coupled deterioration based on 15 years of field tests. Pigeon and Malhotra [10] and Gao et al. [11] conducted freeze-thaw tests and porosity tests on roller-compacted concrete. The results indicated that the SDC of 0.25 mm is not necessary for obtaining the adequate freeze-thaw resistance. This conclusion was also validated by Zhang [12] through experiments. Jin et al. [13] revealed that PSD exhibited more significant influence on the freeze-thaw resistance of concrete than the pore spacing, and he also established a regression equation between BFD and the durability factors for prediction. Furthermore, fractal theory has been used by an increasing number of scholars to predict or characterize the effect of pore structure changes on the macroscopic properties of concrete [14–16] to perform a quantitative analysis of the pore structure.

In summary, there are significant studies on the micropore structure under a single field condition. However, the environment condition considered in these studies is not in good agreement with the actual working environment of pavement concrete in a seasonally frozen area, and most of them are concentrated on the static analysis of the structural characteristics of concrete micropores at a time point under a stationary force. Therefore, the dynamic evolution rule and mechanism of micropores under the seasonally frozen area requires comprehensive investigation to elucidate how the pore structure changes lead to deterioration of the pavement concrete.

The main objective of this paper is to explain the change process of the micropores and reveal the deterioration mechanism of pavement concrete in the practical working environment. The micropore structure was observed systematically through a multi-field coupling method including single, double and triple field. A mercury intrusion method and an optical method were used to evaluate the pore structure. Furthermore, the dynamic evolution mechanisms of micropores were studied using SEM imaging.

2. Materials and experimental methods

2.1. Materials

The cement used in this study is P.O 42.5R Portland cement with an apparent density of 3.112 g/cm^3 and a surface area of 365 m^2/kg. The slag is S95 grade, and the fly ash is I grade; their physical indicators are listed in Table 1. The coarse aggregate (limestone) is divided into 4.75–9.5 mm and 9.5–19.00 mm and the mixing ratio is 1:4; its technical properties are described in Table 2 [17]. The fine aggregate is river sand with a fineness modulus of 2.6 and an apparent density of 2.65 g/cm^3. The superplasticizer (KDSP-1) was used as an additive for all samples. The rate of water reduction can be 26%, and the gas content is approximately 3%–6% [18]. The water used is municipal water.

2.2. Mixture and sample preparation

Considering the heavy load condition, the 28 d flexural tensile strength of pavement concrete is no less than 4.5 MPa. Therefore, the C40 was chosen as the object of study. The curing period is set to 90 d so that the strength of concrete mixed with slag and fly ash can completely formed. According to ASTM C 684–1999 [19], all the molded prismatic specimens had dimensions of 100 mm × 100 mm × 400 mm; the concrete composition after durability optimum design is listed in Table 3 [20].

2.3. Test methods

The contact state between the vehicle load and the pavement changes dynamically [21,22]. Therefore, the fatigue load test adopted sine wave three-point loading using the MTS-810 apparatus. The loading level rate was 10 Hz, and the high-low stress ratio was 0.1. To simulate the coupling environment, the MTS-810 fatigue test machine and BE-T-H150H8 type programmable constant temperature and humidity box were assembled reasonably to provide a closed test environment for the concrete specimens, as shown in Fig. 1. The experiments were carried out

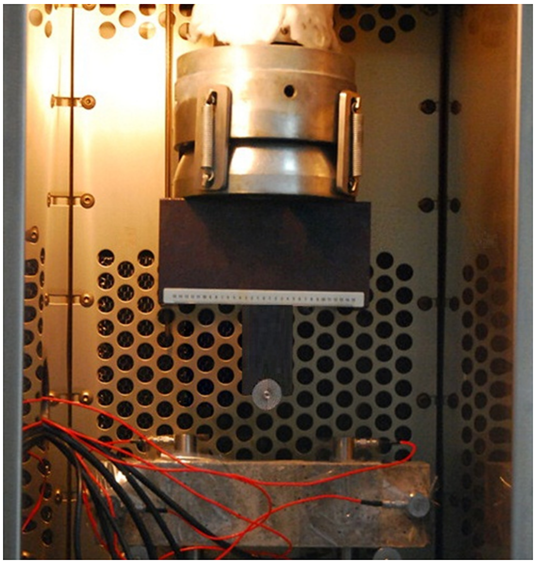

Fig. 1. Fatigue tester with coupling functionality.