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Relationship between flexural strength and pore structure of pavement concrete under fatigue loads and Freeze-thaw interaction in seasonal frozen regions

Aiqin Shen, Senlin Lin *, Yinchuan Guo, Tianqin He, Zhenghua Lyu

Key Laboratory for Special Region Highway Engineering of Ministry of Education, Chang'an University, Xi'an 710064, Shaanxi, China

HIGHLIGHTS

- Interaction function of fatigue load and freeze–thaw on pore-structure is investigated.
- The properties of pore-structure and flexural strength are studied.
- Interaction effect accelerates the deterioration rate of the pore-structure.
- The relationship between flexural strength and pore structure is analyzed using gray relational analysis.

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ABSTRACT

To explore the correlation between the flexural strength decay and the pore structure evolution of pavement concrete in seasonal frozen regions, 4 stages of an interaction experimental scheme were designed. The characteristic parameters of pore structure under the interactions were quantitatively characterized, and the correlation between the flexural strength decay and the microstructure evolution was discussed. The results show that the flexural strength of concrete under this interaction presents a parabolic attenuation trend. The specific surface area, the most probable aperture and the less harmful pores were the most important microstructure parameters affecting the flexural strength of concrete; their gray correlations were 0.8 or greater. Further, the regression analysis shows that there is a good linear relationship between the flexural strength attenuation and the pore structure evolution; the regression coefficient reaches 0.845.

1. Introduction

Pavement concrete undergoes fatigue load and freeze–thaw interaction in seasonal frozen regions, accelerating the deterioration rate of the concrete structure [1,2]. The performance and durability of pavement concrete will deteriorate due to microstructural damage occurring in the early stage of life [3,4]. As a result, the development and application of concrete pavement were restricted in seasonal frozen regions [5]. Pavement concrete is a porous material, and the strength of the concrete was affected directly by the internal pore structure. The pore structure deterioration was the attenuation mechanism of flexural strength [6–8].

Omkar et al. compared the pore structure of concrete before and after fatigue load, and they concluded that an increase in pore volume fraction by approximately 10% resulted in a reduction in the compressive strength by approximately 50% [9]. Zhang et al. determined that the pore grading transferred from a smaller pore to a larger pore by studying the structure of concrete pores under the action of the freeze–thaw cycle [10]. Park et al. found that the long-term strength loss of concrete was caused by an increase in the total porosity and amounts of smaller pores in the material [11]. Some other literature showed that the loss of long-term strength is induced by an increase in porosity and an increased incidence of microcracking in cement paste [12,13]. On the other hand, some research has been conducted on the correlation between the macroscopic properties of concrete and its pore structure. Ozturk et al. established the relationship between concrete strength and porosity by regression analysis of a large number of experimental data [14]. Older et al. studied the strength and pore structure of concrete with different water-cement ratios and established a model of the relationship between strength and pore size

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* Corresponding author.
E-mail address: lsl421357732@163.com (S. Lin).

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distribution using a linear regression method [15]. Kumar et al. introduced the average pore size to establish the relationship between the concrete strength and pore structure based on the porosity [16]. Zhou et al. found that there was a good linear correlation between porosity parameters and strength [17]. Jin SS et al. established a multivariate model of the fractal dimension and strength of concrete through regression analysis [18].

Therefore, a considerable amount of research has been reported on concrete strength and pore structure. However, the current studies mainly focus on the compressive strength of the concrete and the effect of a single environmental factor on the concrete. The deterioration of the flexural strength of pavement concrete was more important than the compressive strength [19]. The pavement concrete in seasonal frozen regions is subject to load fatigue and freeze–thaw cycles, causing pore damage and attenuation of flexural strength [20]. Little studies involve the external environment that cannot reflect the true relationship between the pore structure and pavement concrete strength.

This paper aims to determine the relationship between the pore structure of pavement concrete and its flexural strength under the interaction of fatigue load and the freeze–thaw cycle. Furthermore, the gray relational method was used to analyze the pore structure and flexural strength under this interaction. Finally, the model between the deterioration of the flexural strength of pavement concrete and the evolution of microstructures was established.

2. Materials and methods

2.1. Materials

The cement selected in this study is P.O 42.5R Portland cement with a density of 3112 kg/m^3. Its chemical composition is listed in Table 1. Fly ash with a specific area of 270 m^2/kg produced by Datang Hangcheng Co. Ltd. and mineral powder with a specific area of 560 m^2/kg produced by Yaozhou Co. Ltd. were both added to improve the performance of the concrete pavement.

According to the standard [21], the coarse aggregates were obtained from Fuping in northwest China. Crushed limestone with grain sizes ranging from 4.75 mm to 19 mm was used as coarse aggregates. Main properties of the coarse aggregates are listed in Table 2. Fine aggregates with a density of 2650 kg/m^3 were obtained from Ba Bridge, Shaanxi.

A high-performance superplasticizer (KDSP-1) produced by Shanxi Kaidi Building Materials Co. Ltd. was used as water reducing agent. The rate of water reduction can be as high as 26%, the gas content can reach 5%, and the recommended dosage is approximately 0.8–1.2%.

2.2. Mix proportion design

The mix designation of concrete (C40) can be carried out in accordance with the standard [22]. In order for the road concrete to have excellent mechanical properties and durability, the mixture must be optimized. An orthogonal $L_9(3^4)$ test was adopted here to optimize pavement concrete. The adopted slump, flexural strength (f_f), compressive strength (f_c), and the relative dynamic elastic modulus after 200 freeze–thaw cycles (D200) were as optimization indicators. The experimental plans and results are shown in Table 3.

The results of the orthogonal pavement concrete test were analyzed using the range analysis method, and the influence of the water to binder ratios, water reducing to binder ratios, admixture content and unit cement dosage on the workability, as well as the mechanical properties and durability of the pavement concrete, were determined. The optimization results are shown in Table 4.

All mixtures were cast in a mold with dimensions of 100 mm × 100 mm × 400 mm consolidated by a vibrating table and trowel finished. All samples were demolded after 24 h and cured for 90 days under a temperature of 20 ± 2 °C and relative humidity of approximately 95%. After curing, interaction tests were carried out.

2.3. Test methods

2.3.1. Interaction test

The freeze–thaw cycle in seasonal frozen regions usually takes a longer period, and the effect on the cement pavement is time-dependent. Both the role of traffic load on the pavement and effect on the cement pavement are instantaneous [23]. That means the relationship between freeze–thaw and fatigue load is not a complete coupling relationship but an interaction. Thus, the interaction of traffic load and the freeze–thaw cycles was simulated in this investigation.

Fatigue loading was completed by MTS-810, and the effects of ordinary traffic and heavy traffic on cement pavements were simulated by 0.5 and 0.8 of the ultimate load of concrete, respectively [24]. A three-point sine wave function with a loading frequency of 10 Hz and a 0.1 ratio between the low stress and high stress was adopted to simulate vehicle driving on the road [25]. The freeze–thaw test was carried out in accordance with the Chinese Standard GB/T 50082-2009 [26]. A fast freeze–thaw test device (KDR-III) was used to complete the freeze–thaw cycle. The freezing temperature of concrete ranged from -18 °C to 5 °C. The time for each freeze–thaw cycle was 4 h, which included 2 h for freezing and 2 h for thawing.

According to recommendations in the literature, a four-stage interaction of the fatigue load and freeze–thaw cycle was designed [27]. The interaction test is comprised of 7.2 million fatigue loads and 75 freeze–thaw cycles. Through the preliminary interaction test, it was found that the pavement concrete was destroyed prematurely under the interaction of high stress levels and the freeze–thaw cycle. Therefore, reducing the number of freeze–thaw cycles to 50 in each interaction test avoided excessive destruction of the specimen. At the same time, due to the slow pavement concrete damage in the early stage, the microstructure and strength of the specimens after the first interaction test were not tested. In all, the controlled concrete was defined as stage I, and the specimens after two interaction tests were defined as stage II. Then, the specimens subjected to every interaction test were defined as either stage III and stage IV. The detailed program of the interaction test is shown in Fig. 1 and Table 5.

2.3.2. Flexural strength test

The flexural strength test of pavement concrete was carried out by using a YES-300B tester. According to the standard [28], the loading rate ranged from 0.05 MPa/s to 0.08 MPa/s.

Every group with 3 specimens was tested with fatigue load and freeze–thaw cycle interaction under stress levels of 0.5 (0.5S and

Table 1
Chemical composition of P.O 42.5R.

Composition	C_3S	C_2S	C_3A	C_4AF	f-CaO
W (%)	57.46	21.88	7.03	13.14	0.59