Deterioration mechanism of interface transition zone of concrete pavement under fatigue load and freeze-thaw coupling in cold climatic areas

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HIGHLIGHTS

• Coupling function of fatigue load and freeze-thaw on ITZ of concrete is studied.
• The micro-structure properties of an ITZ are investigated.
• Impact of coupling effect on ITZ is determined using a chloride penetration test.
• Coupling effect accelerates the deterioration rate of the micro-structure of ITZ.

ARTICLE INFO

Article history:
Received 1 June 2017
Received in revised form 2 November 2017
Accepted 10 November 2017

Keywords:
Concrete pavement
ITZ
Deterioration
Fatigue load
Freeze-thaw
Coupling effect

ABSTRACT

In addition to stresses from dynamic loading, concrete pavements in cold climatic areas are often attacked by freeze-thaw cycling. The interface transition zone (ITZ) is the first section to deteriorate. To study the micro-structure changes of ITZ under the coupling function of fatigue load and freeze-thaw cycling, an indoor-accelerated coupling test was designed. The results show that the coupling effect accelerates the deterioration rate and increases the complexity of micro-crack structures with more pores including crack nucleation. Moreover, the coupling effect significantly reduces impermeability. DOD is the main factor that accelerates the speed of permeability attenuation of concrete.

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1. Introduction

The change of micro-structure in concrete has a major impact on concrete pavement performance. Because of the boundaries and bleeding effects, an interface transition zone (ITZ) can be formed between cement mortar and aggregates during the process of paving. Previous studies indicate that the typical width of ITZ is 20–60 μm [1,2], and there are many primary fractures and pores in the ITZ. Cracks in concrete often begin and extend along the ITZ, reducing the mechanical properties of concrete [3,4].

Rangaraju et al. [5] and Ouyang et al. [6] observed that the width of ITZ has a significant influence on compressive strength, dynamic modulus, and chloride permeability of concrete. Gu et al. [7] found that the bond strength of ITZ was about half of the matrix strength. Cwirzen et al. [8] and Juan et al. [9] found that the ITZ provides a channel for the movement of the pore solution, which triggers and accelerates the freeze-thaw damage of the concrete. In other words, concrete with a narrow width of ITZ has better frost resistance. Other studies show that the degree of deformation of the ITZ is higher than that of the aggregate and matrix owing to its porosity and low strength of ITZ. It was observed that, in general, there is a good correlation between the degree of deformation and the cracks in the ITZ [8,10,11]. Breton et al. [12] observed that permeability coefficient of chloride in the ITZ is 6–12 times larger than that of mortar matrix. Leemann et al. [13] also reported that there is a good correlation between the ITZ density and chloride permeability of concrete, indicating that high ITZ density can increase chloride ion permeability. However, Some other studies suggest that ITZ do not affect significantly the properties of concrete. Zheng et al. [14] proposed a numerical method to estimate the chloride diffusivity of mortars and concretes. They found that the diffusivity of concrete is governed by the volume of entire pore structure within the cement paste rather
than the ITZ, although its porosity and local diffusivity are higher than those of the bulk paste. Abyaneh et al. [15] observed that the ITZ width and aggregate size have less influence on diffusivity of concrete, while the aggregate shape and orientation are the dominant factors affecting diffusivity. Compared with the ITZ, the effects of aggregates are in predominance for the overall permeability of concrete [16]. Wu et al. [17] also found that the ITZ has an insignificant influence on the bulk transport properties of concrete.

Therefore, ITZ may be considered as a weak section in the concrete structures, especially for concrete pavements in cold climatic areas, where the ITZ structure deteriorates rapidly owing to the long-term vehicle load and freeze-thaw cycle coupling. There are significant studies on the performance of ITZ under a single environmental factor. However, there is lack of comprehensive research on the ITZ under the coupling of fatigue load and freeze-thaw, specifically for the quantitative characterization of the ITZ micro-structure. Therefore, in this study, the ITZ structure features were observed systematically through an indoor accelerated method, which was used to simulate the coupled effect of fatigue load and freeze-thaw.

The present research is aimed at proposing a quantitative analysis method and exploring the dynamic evolution process of the ITZ structure in concrete. Furthermore, chloride penetration in concrete under different coupling conditions were tested. Finally, the correlation between the micro-structure of the ITZ and macroscopic properties of concrete is discussed.

2. Materials and methods

2.1. Materials

2.1.1. Cement and cementitious materials

The cement used in this investigation is P.O 42.5R Portland cement, obtained from Shaanxi Qinling Mountains in northwest-China. Its physical properties are listed in Table 1. Slag with a density of 2.75 g/cm$^3$ and fly ash with a density of 2.05 g/cm$^3$, produced by Xi’an Datang Hancheng Co., Ltd, were added to improve the performance of the concrete pavement. The chemical composition of slag and fly ash are listed in Table 2.

2.1.2. Aggregates and water reducer

The appropriate aggregates (limestone) were obtained from Weinan in northwest-China. Sieve analyses of coarse aggregates were conducted and gradation curve was determined as can be seen in Fig. 1. The gradation limits of the aggregates used in this study is determined based on the JTG/T F30-2015 standard [18] for concrete mixtures. The selected gradation lay in the middle of the limits. The apparent densities of coarse and fine aggregates are 2.8 g/cm$^3$ and 2.65 g/cm$^3$, respectively.

A type of superplasticizer (KDSP-1), produced by Shanxi Kaidi Building Materials Co., Ltd, was used as an additive for all samples. The rate of water reduction can be as high as 26%, and the recommended dosage is about 0.8–1.2%.

2.2. Mixture and sample preparation

The concrete pavement—C40, which is widely used in China—was designed according to the standard [18] as listed in Table 3.

All test specimens were 100 x 100 x 400 mm in dimensions, and cured for 90 days under moist conditions at 20 °C and 90% relative humidity. After curing, fatigue load and freeze-thaw tests were carried out.

2.3. Test methods

2.3.1. Fatigue load test

The stress level of dynamic loading was 50% of the ultimate load of concrete, which reflected the field fatigue of pavement slabs [19,20]. The MTS-810 fatigue test equipment of Xi’an Jiaotong University was used for the test. Concrete specimens tested under a three-point sine wave function with a loading frequency of 10 Hz and a 0.1 ratio between low stress and high stress.

<table>
<thead>
<tr>
<th>Types</th>
<th>Water to binder ratios (%)</th>
<th>Mixture design (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cement</td>
<td>Slag</td>
</tr>
<tr>
<td>C40</td>
<td>0.34</td>
<td>315</td>
</tr>
</tbody>
</table>
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