Construction and Building Materials 152 (2017) 847–855

Contents lists available at ScienceDirect

Construction and Building Materials

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

Dynamic compressive strength of concrete damaged by fatigue loading and freeze-thaw cycling

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HIGHLIGHTS

- The effect of damage history on the dynamic compressive strength was investigated.
- The combination of applied fatigue load and freeze-thaw cycles was considered.
- Emphasis was placed on the influence of different action sequence.
- A variable was used to study the combined effect of load and environment effects.
- SEM was used to explain the damage mechanism from the micro perspective.

ARTICLE INFO

Article history:
Received 13 April 2017
Received in revised form 15 June 2017
Accepted 4 July 2017

Keywords:
Plain concrete
Fatigue load
Freeze-thaw cycles
Dynamic compressive strength
Strain rate
Action sequence

ABSTRACT

Uniaxial dynamic compression tests were carried out on 180 concrete prism specimens exposed to freeze-thaw cycles combined with fatigue compression loading. The effects of four categories of damage modes, such as fatigue compression loading (Mode F), freeze-thaw cycling (Mode FT), fatigue compression loading followed by freeze-thaw cycling (Mode F-FT), and freeze-thaw cycling followed by fatigue compression loading (Mode FT-F), on the dynamic compressive strength of concrete were investigated systematically. The variable K_c was introduced to characterize the combined effect of fatigue loads and freeze-thaw damage, and the influence of single factor of fatigue load or freeze-thaw cycles as well as the double factors with different sequence on the dynamic damage characteristics of concrete were discussed. The results showed that, when the number of fatigue cycles and the number of freeze-thaw cycles remained constant, just with different sequence, the values of K_c under damage Mode F-FT were obviously higher than that under damage Mode FT-F at the same strain rate. The trends in damaging effects on compressive strength of concrete were justified based on microscopic observation of the trends in micro crack growth under such damaging effects. In addition, concrete has apparent strain rate effect after exposed to freeze-thaw cycles combined with fatigue compression loading. The dynamic compressive strength of damaged concrete increases as the strain rate is increased.

1. Introduction

Any kind of concrete materials and structures are subjected to external loads while experiencing environmental effects [1]. The hydraulic concrete structures in the severe cold regions are often subjected to the combined action of fatigue loading and freezing-thawing cycles. Freeze-thaw cycles and fatigue loading cycles are both repetitive action and the joint action which may aggravate the damage of concrete and lead to severe deterioration of the long-term mechanical properties of concrete. This deterioration can be broadly divided into the two types of failure: drastic deterioration of the durability of concrete (i.e. permeability) and unstable propagation of the major fatigue cracks [2]. The damage behaviors of concrete under the single effect of fatigue load or freeze-thaw cycle have been studied by many researchers. Research of Soroushian et al. has indicated that the fatigue load increases the number of micro cracks, and the freeze-thaw cycle increases the width of micro cracks [3]. Changes in concrete properties and microstructure associated with different damaging effects were investigated. Most of the existing researches have studied the static damage performance of concrete under the coupling of fatigue load and freeze-thaw cycles [4,5]. Some studies were directed to the influence of load history on frost resistance of concrete [6,8] and freeze-thaw damage on the fatigue

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http://dx.doi.org/10.1016/j.conbuildmat.2017.07.046
0950-0618/

performance of concrete [9,10]. However there are few reports on the influence of different sequence of fatigue load and freeze-thaw cycles on the mechanical properties of concrete, especially on dynamic properties of concrete.

In the course of using, hydraulic structures are inevitably subjected to dynamic loads, such as waves, explosions and earthquakes. Researchers have carried out a lot of useful exploration on the dynamic characteristics of concrete after single load history or freeze-thaw cycles. With regard to the influence of loading history, the research shows that the load history has significant effects on the dynamic characteristics of concrete [11–14]. Wang et al. [15] studied the impacts of freeze-thaw and strain rate on the properties of fully-graded concrete under uniaxial compressive stress state, and established the unified failure criterion of fully-graded concrete considering the strain rate and freeze-thaw cycles. Yi et al. [16] established the viscoelastic-plastic damage model of porous asphalt mixtures and analyzed the mechanical behavior of porous asphalt mixture after freeze-thaw, and carried out uniaxial compression tests at different temperatures and loading rates to verify the correctness of the model. Chen et al. [17] studied the effect of freeze-thaw cycle on mechanical behaviors of ceramsite concrete through split Hopkinson pressure bar (SHPB) impact test. At present, there are few researches on the dynamic characteristics of concrete under different action sequence of fatigue load and freeze-thaw cycles. Due to the fact that the combined effect of load and freeze-thaw cycles will bring great uncertainty and risks to the future safety of concrete structure, relevant research is urgently needed.

In this paper, an experiment was conducted to see the effects of fatigue load and freeze-thaw cycles on uniaxial dynamic characteristic of concrete. Firstly, 180 concrete prism specimens were subjected to four kinds of damage modes, namely, the fatigue loading alone, the freeze-thaw cycle alone, the fatigue loading followed by freeze-thaw cycle, and the freeze-thaw cycle followed by fatigue loading. Subsequently uniaxial dynamic compression test of the damaged specimens was conducted. The effects of the single factor of fatigue load or freeze-thaw cycles, as well as the double factors with different sequence, on the dynamic compressive strength of concrete were investigated. The reasons for the deterioration of the macro mechanical properties of concrete due to different damage effects were investigated from the micro perspective. The research results of this paper can provide experimental data and mechanical properties for the design of hydraulic concrete structures in cold regions.

2. Experimental details

2.1. Materials and mix proportions

Chinese standard 42.5R ordinary Portland cement supplied by Jidong Cement Corporation in China was used. Tap water, river sand with fineness modulus of 2.8 and coarse aggregate of crushed limestone with a maximum size of 20 mm were used. Naphthalene series super-plasticizer with a water-reducing rate of 25% by weight and air-entraining agent were used. The concrete mix proportion was shown in Table 1.

Concrete prism specimens were cast in plastic molds of 100 × 100 × 300 mm, removed from the molds 24 h after casting, and cured in the condition of 20 ± 3 °C and 95% of relative humidity for 28 d. The experiment was carried out after storage for 3 months at room temperature (20 ± 5 °C) in accordance with the Chinese standard GB/T50082-2009 [18].

2.2. Test procedure

2.2.1. Preset damage history

According to the needs of practical engineering, the effects of the fatigue load, the freeze-thaw cycle and the combined action with different sequence, on the dynamic compression behaviors of concrete were studied, and the following four categories of damage modes are considered.

(1) Mode F: Fatigue compression loading. The fatigue compression load was applied by SDS500 electro-hydraulic servo static and dynamic universal testing machine. In order to accurately determine the fatigue stress level, a certain number of specimens were taken to determine the axial compressive strength, with a loading speed of 0.5 MPa per second in accordance with the Chinese standard GB/T50081-2002 [19], and the average static compressive strength f_c is equal to 51.1 MPa. A constant-amplitude sinusoidal waveform loading at a frequency of 5 Hz was applied on the concrete prism specimens in the fatigue test. The ratio of loading amplitude to static capacity ranged from 0.1 to 0.5. The number of fatigue loading cycles, n, were 5000, 10000, 20000, and 40000, separately.

(2) Mode FT: Freeze-thaw cycling. The freeze-thaw test was completed on the NELD-BFC concrete rapid freezing and thawing test machine in accordance with the Chinese standard GB/T50082-2009 [18]. All the specimens were immersed in water for 4 days at a temperature of 15–20 °C before freeze-thaw test. Each freeze-thaw cycle was completed within 2–4 h, and the time used for melting was not less than 1/4 of the whole freeze-thaw time. In each freeze-thaw cycle, the center temperature of the specimen was kept at −17 ± 2 °C and 8 ± 2 °C separately. The specimens were exposed separately to 0, 25, 50, 75 freeze-thaw cycles.

(3) Mode F-FT: Fatigue compression loading followed by freeze-thaw cycling. Firstly, the fatigue load was applied to specimens for 5000 or 10,000 times, and then the specimens were exposed separately to 25, 50, 75 freeze-thaw cycles. The procedure of fatigue test or freeze-thaw test is the same as the one mentioned above.

(4) Mode FT-F: Freeze-thaw cycling followed by fatigue compression loading. Firstly, specimens were exposed separately to 25, 50, 75 freeze-thaw cycles, and then the fatigue load was applied separately to the specimens for 5000 or 10,000 times. The procedure of fatigue test or freeze-thaw test is the same as the one mentioned above.

2.2.2. Uniaxial dynamic compressive test

Subsequently, a total of 180 concrete prism specimens that have been exposed to four categories of damage modes were tested under quasi-static and dynamic loading by using a 200 T electro-hydraulic servo universal testing machine. Quasi-static test consisted of testing three specimens of each of the four groups at strain rate of $10^{-5}s^{-1}$. The static tests provide the reference basis for the dynamic values. Dynamic tests were carried out at different strain rates of $10^{-4}s^{-1}$, $10^{-3}s^{-1}$ within the capability of the test device and specimen combination. All tests were conducted with controlling displacement increment method. The micromorphology of the specimens is observed by using the JSM-7610F ultra-high resolution thermal field emission scanning electron microscope. Non-contact displacement/strain video measuring instrument was used to real-time monitor the displacements of the specimens.

3. Results and discussion

3.1. Dynamic compressive strength

3.1.1. Damage Mode F

The dynamic compressive strength of concrete experienced to damage Mode F, namely under the single effect of fatigue load, is shown in Table 2. The values in the table are the average values of 3 concrete prism specimens. F1, F2, F3 and F4, in the specimen ID, stand for the fatigue cycle number (n) of 5000, 10,000, 20,000, and 40,000 respectively. D1, D2, and D3, in the specimen ID, stand for the strain rates of $10^{-5}\,s^{-1}$, $10^{-4}\,s^{-1}$, and $10^{-3}\,s^{-1}$ respectively. For example, the specimen ID of F1D1 denotes that the specimen had been applied 5000 cycles of fatigue load and the succedent uniaxial dynamic compression test was conducted at the strain rate of $10^{-5}\,s^{-1}$. The specimen ID of D3 denotes that the specimen was not subjected to fatigue loading history and the succedent uniaxial dynamic compression test was conducted at the strain rate of $10^{-3}\,s^{-1}$.

Table 1
Mixture composition (kg/m^3).

Cement	Sand	Coarse aggregate	Water	Super-plasticizer	Air-entraining agent
420	633	1175	172	2.94	0.084