ARTICLE IN PRESS

Construction and Building Materials xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

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

Damage process of concrete subjected to coupling fatigue load and freeze/thaw cycles

Yunfeng Qiao [a,b,*], Wei Sun [a], Jinyang Jiang [a]

[a] School of Material Science and Engineering, Southeast University, 211189 Nanjing, China
[b] School of Civil Engineering, Qingdao Agriculture University, 266109 Qingdao, China

HIGHLIGHTS

- Damage under simultaneous action was firstly studied by AE techniques and strains.
- The results of AE Hits/energy and strains reveal the periodical coupling damage evolution.
- The periodical damage evolution can be divided into acceleration stage and incubation stage.
- Damage accelerates in freezing phase and incubates in thawing phase.
- The quasi-Kaiser effect of AE was firstly found in the coupling damage evolution.

ARTICLE INFO

Article history:
Received 20 November 2013
Received in revised form 5 May 2015
Accepted 11 May 2015
Available online xxxx

Keywords:
Damage
Freeze/thaw
Fatigue
Coupling action
Acoustic emission
Strain analyzing

ABSTRACT

The coupling behaviors of concrete subject to simultaneous 4-point fatigue loading and freeze/thaw cycles were, for the first time, investigated by strain technique together with acoustic emission (AE) sensors. Damage evolution of samples is periodical under the simultaneous action, which can be divided into acceleration stage and incubation stage, respectively corresponding to freeze and thaw stage. The damage mainly takes place when temperature drops, and the rate of the temperature reduction has an evident influence on the damage evolution. The quasi-Kaiser effect was firstly found in the coupling damage evolution.

1. Introduction

The existing concrete structures undergo both mechanic loads and environment impacts simultaneously. For example, the bridges and highways in the cold regions are suffering from the coupling effects of fatigue loading and environmental factors such as freeze/thaw (F-T) cycles, and chloride ions, etc. The mechanical loads and environmental factors would influence each other, which accelerates the damage of concrete structures and shortens their service life. Therefore it is important to study behaviors of concrete under the simultaneous actions so as to estimate the service life of concrete structures accurately. There are lots of literatures on the damage of concrete under F-T cycles, fatigue load or the two alternative actions [1–6], but literatures on the simultaneous action studies are scarce [7,8].

The stresses in concrete under externally imposed loads and environmental effects cause the growth, propagation and joining of microcracks and lead to failure of concrete. The investigation on the growth of microcracks is important to study the damage evolution in concrete. Acoustic emission (AE) is one of the common techniques to monitor the microcrack growth. Lots of studies have been performed on the growth of microcrack inside the concrete by AE technique subjected to F-T cycles [9–15], as well as to fatigue loading [7,16–24], focusing on the real-time monitoring of microcracks or quantifying damage. Whereas AE research reports on damage evolution due to coupling actions of fatigue load and F-T cycles are rare.

By using axial servohydraulic dynamic system equipped with environment chamber, the damage evolution of concrete under simultaneous fatigue load and F-T cycles was studied by measuring strain and AE activity for the first time. The damage evolution of

* Corresponding author at: School of Material Science and Engineering, Southeast University, 211189 Nanjing, China.
E-mail address: yf.qiao@163.com (Y. Qiao).

http://dx.doi.org/10.1016/j.conbuildmat.2015.05.087
0950-0618/© 2015 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Qiao Y et al. Damage process of concrete subjected to coupling fatigue load and freeze/thaw cycles. Constr Build Mater (2015), http://dx.doi.org/10.1016/j.conbuildmat.2015.05.087

concrete subject to the simultaneous actions is found to be different from the one under individual fatigue load or F-T cycles. The results showed that the strains and AE Hits/energy changed periodically with the temperature cycles. Damage evolution in each F-T cycle can be divided into the acceleration stage and incubation stage, which correspond to the freezing stage and thawing stage, respectively. The quasi-Kaiser effect, which means that there is no obvious acoustic emission when the strain is less than the previous maximum strain, was firstly found in the coupling damage evolution.

2. Materials and methods

2.1. Specimens

2.1.1. Materials and mixture proportions

Type I Portland cement was used in this study. I Class F fly ash was used to replace 30% of cement by weight. Coarse limestone aggregate with maximum size of 15 mm and natural river sand with fineness modulus of 2.55 were used. The mix proportion for 1 m^3 volume is shown in Table 1.

2.1.2. Test specimen

The size of specimens was 70 mm × 70 mm × 280 mm and the ultimate load was 9.9 kN in the flexural strength test. The molds were removed 2 days after casting and the specimens were cured for 450 days with temperature of 20 ± 2 °C and relative humidity of 95%. The specimens were dried in the oven with temperature of 60 °C until constant weight, and then they were put in a dry box for 12 h. Strain gages were mounted on the surfaces of specimens. Before mounting the strain gages, surfaces of specimens were polished with #100 sand papers and then a layer of epoxy resin compound was spread on them at the location of strain gages to make the surfaces of concrete specimens smooth. After that specimens were dried for 24 h with temperature of 60 °C. The strain gages were stuck with the same epoxy resin under a pressure of about 40 kPa for 24 h with temperature of 60 °C. The specimens then were vacuum saturated. As shown in Fig. 1, the thermal couples were placed in the center of the specimens to measure the temperature. The specimens with thermal couples were put in water for 10 days and then connected to the wire. The strain gages, wires and surface of the specimens were covered by neutral Vaseline. AE sensors were fixed on the surfaces as shown in Fig. 1. Both strain gages and thermal couples were connected to data logger, TMR211 Multichannel Data Acquisition System, as shown in Fig. 2(b).

2.2. Test setup and methods

2.2.1. Setup of loading system

The test system consisted of INSTRON 8802 Axial Servohydraulic Dynamic System and an environment chamber as shown in Fig. 2(a). The 4-point flexural fatigue loading, sinusoidal wave with stress level 0.65, stress ratio of 0.1 and a frequency of 10 Hz, were controlled by INSTRON 8802.

F-T cycles were controlled by environment chamber using air as cryogen. Temperature in the chamber varied from −25 °C to 20 °C, as shown in Fig. 3(a). Each cycle took 12 h:5 h at −25 °C and 5 h at 20 °C, connected by 1-h temperature drop and 1-h rise. The center and surface temperature of the sample monitored by thermal couples, which can be used to measure the thermal gradient, is shown in Fig. 3(b).

2.2.2. Acoustic emission

PCI-2 AE system was used to monitor the damage evolution by 4 AE sensors adhered on the surfaces of the specimens. As shown in Figs. 1 and 4 AE sensors were fixed on both sides of pure flexural section, where the damage mainly took place in the 4-point flexural fatigue loading test. An R15 sensor with a resonance frequency of 150 kHz was chosen, and the trigger threshold was set at 40 dB to reduce the noise from the surrounding environment. The preamplifier gain was set at 40 dB. In order to obtain accurate waveforms to process AE data, the PDT (peak definition time), HDT (hit definition time), HLT (hit lockout time) were set to be 50 μs, 200 μs and 300 μs, respectively. Vacuum grease was used as coupling agent. The trial tests showed that the setup enabled the AE system to receive signals only from the damaged zone instead of the noises from the surroundings.

Table 1
Mix proportion of concrete specimens.

Cement (kg)	Fly ash (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	Water (kg)
257.2741	110.2603	735.0689	1102.603	194.7933

2.2.3. Strain

The strains of the specimens subject to simultaneous fatigue loading and F-T cycles were measured by using the 50 mm-length strain gages which were stuck on surface of the specimens in the pure flexural section. The linear expansion coefficient of strain gages was the same as the concrete specimens, so that the thermal output of the strain gages could be eliminated. The strain gage was connected to wires in 1/4-bridge mode. The data were collected by TMR 211 as shown in Fig. 2(b). The sampling frequency was 250 Hz and the maximum and minimum strains in 1 min of every 11 min were plotted.

3. Results and discussion

Nine specimens were tested in the experiment. The fatigue life of the specimens were 434,329 times, 438,900 times 439,058 times, 465,824 times, 536,603 times, 449,480 times, 1,288,291 times, 1,391,883 times, 1,435,815 times, respectively. The specimen with fatigue life of 1,391,883 times was used as representative one, because the specimens with fatigue life of about 450,000 times (about 12.5 h) lasted only about one F-T cycle. However, it needs to be pointed that the damage characteristics of the specimens that underwent only one F-T cycle were identical to that of the representative specimen.

3.1. AE

Fig. 4 shows AE parameters changing with time, which illustrates that the sample experiences periodic change with the cyclic temperature.

Fig. 4(a) shows that plenty of Hits took place at the beginning of the first 20 °C thermostatic stage but the amplitude and the energy of AE, shown in Fig. 4(b) and (c), were much smaller than that occurred later on. It might be related to the generation of new microcracks or propagation of existing cracks formed during molding and curing under fatigue load in the matrix. Therefore the first 20 °C thermostatic stage can be seen as microcracks nucleation stage. The AE parameters whether the Hits number, the amplitudes or the energy increased substantially when the temperature changed from 20 °C to −25 °C. Microcracks grew rapidly for different mechanisms at the beginning of the temperature drop and the time when temperature was below 0 °C. The growth of microcracks at the beginning of the temperature drop mainly can be attributed to the thermal difference between the interior and exterior of the sample when the temperature dropped drastically, while the growth of microcracks when temperature was below 0 °C was mainly because of the phase transition of water. When the temperature increased from −25°C to 20 °C, except the last temperature rise, the AE parameters (number of Hits, amplitudes and energy) changed very little, which meant there was little growth of microcracks. Similar AE results were obtained in next cycle. The above observations indicated that microcracks mostly initiated and propagated during temperature reduction process.

Accumulated hits versus temperature is shown in Fig. 5. The curve is in stair-step shape, ascent part of which is the time when temperature dropped from 20 °C to −25 °C and maintained at −25 °C and horizontal part of which is when temperature arose from −25 °C to 20 °C and maintained at 20 °C.

The ascent part of the accumulated hits curve, approximately increasing linearly, represents the activity of the crack and the accelerated evolution, which can be called damage acceleration stage. According to the slope of the accumulated curve, the accelerated evolution can be divided into two stages. The first stage is when the temperature changes from 20 °C to −22 °C, and the second stage is when the temperature changes from −22 °C to −25 °C. The slope of the first stage is steeper than that of the second stage, which means the development of the cracks is quicker in the first stage than that in the second stage. The quicker evolutions in the first stage may be caused by the faster cooling speed and the

Please cite this article in press as: Qiao Y et al. Damage process of concrete subjected to coupling fatigue load and freeze/thaw cycles. Constr Build Mater (2015), http://dx.doi.org/10.1016/j.conbuildmat.2015.05.087