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Sulfate attack of Portland cement concrete under dynamic flexural loading: A coupling function

Demei Yu [a,b], Bowen Guan [c], Rui He [c], Rui Xiong [c], Zhuangzhuang Liu [a,c,*]

[a] School of Highway, Chang'an University, Xi'an 710064, China
[b] College of Technology, Purdue University, West Lafayette, IN 47907, USA
[c] School of Materials Science and Engineering, Chang'an University, Xi'an 710062, China

HIGHLIGHTS

- Coupling function of sulfate attack and dynamic flexural loading on cement concrete is studied.
- The sulfate attack stages under dynamic loading are summarized.
- The improvement on mechanical behavior will be offset by the dynamic flexural loading.

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ABSTRACT

In saline regions, infrastructures (e.g., structures under earthquake, pavement slabs, bridge decks, airfield runways, railway sleepers and railway bridges, even high-speed railways and concrete structures in ocean) are attacked by sulfate compounds (Na_2SO_4, $MgSO_4$, etc.), coupled with dynamic loading. This report studied the flexural strength, relative dynamic elastic modulus and sulfate content under sulfate attack incorporating with dynamic flexural loading (stress level = 20%, 40% and 60%), and also analyzed the microstructure and atom ratio of attached samples via SEM and EDS. The result shows that solution concentration and stress level are two primary and important factors in sulfate attack cases. Meanwhile, opposite with the static attack case, dynamic loading will also make the strength loss occur earlier, especially under high stress level of dynamic loading (60%). The reinforcement contributed by new phase forming on flexural strength is offset because of the additional dynamic loading. Additionally, the experimental result revealed that the relative dynamic elastic modulus can be used to semi-quantitatively evaluate the long-term sulfate attack samples, but is not suggested to be used on short-term sulfate attacked samples because the result does not match the flexural strength trend. Based on the updated data in this study, sulfate attack stages coupled with dynamic flexural loading are summarized.

1. Introduction

Environmental conditions affect the mechanical performance and durability of cement concrete and other construction and infrastructures. To date, sulfate attack is still a big problem in those regions where contain amounts of SO_4^{2-} in soil or solutions [1]. For example, in western China, there are lots of salt lakes [2] and regions covered by the soil with abundant of sulfate, e.g., Na_2SO_4 and $MgSO_4$. Lots of money and resource are costed on the structure rebuilding and repairing in there regions. Actually, it is believed that the present knowledge about the sulfate attack, through chemistry approach [3], material analysis method [4–6], mechanical research [7,8], and thermodynamic modeling [9,10], is sufficient to combat sulfate attacking [11]. However, the environmental effect on sulfate attack in field condition is much more complicated. These above studies were mainly focused on individual sulfate attack, ignoring the gaps between the theoretical mechanism and field working conditions [11].

Recently, the coupling function of sulfate attack with other environmental factors also attracts researchers' attention, such as the sulfate attack under drying–wetting cycles [12], freeze–thaw cycles [13], temperature evolution [14] and static flexural loading [14]. These studies revealed that environmental conditions can absolutely promote the sulfate attack and structure or materials failure. However, to some special structures, e.g., structures under earthquake, pavement slabs, bridge decks, airfield runways, railway sleepers and bridges, even high-speed railways and concrete structures in ocean, they have to bear dynamic loading

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* Corresponding author at: School of Highway, Chang'an University, Xi'an 710064, China.

E-mail address: liuzhuangzhuang1986@gmail.com (Z. Liu).

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[15]. These previous researches did not consider the coupling function of sulfate attack with the so-called dynamic loading, which was the main working condition in their service life. Even to date, there are still few reports relating to this issue.

In application approach, the sulfate attack is also a confused problem because current test methods are not indicative of the field situation [16] although the present understanding about the natures of Portland cement and sulfate attack are practicable. The present research attempts to provide improved knowledge about the cement-based material behavior under dynamic loading condition, as well as the sulfate attack. Thereby, it can prevent misdiagnosis and improper or unnecessary repair in practice. To simulate the dynamic loading on structures, such as pavement slabs, flexural loading were carried out on the concrete beams dynamically beyond expected time, while immersed in sulfate solution. The dynamical loading process also can be considered to be an accelerated test for other constructions which are also under dynamical loading condition, e.g., piers, concrete constructions of railway while the difference is that the dynamic loading is not that frequent. After the designed dynamic flexural loading and sulfate attack, flexural strength, RDEM, and sulfate concentration in layered sample were measured. As well, the microscopic image of attacked solid was analyzed.

This present research aims to enlarge the knowledge of the behavior of cement and concrete under sulfate attack coupling with dynamic loading factor. The published data will provide new approaches to deal with the sulfate attack in sulfate-sufficient regions, preventing the misdiagnosis and improper or unnecessary repair.

2. Materials and methods

2.1. Raw materials

The chemical composition of Portland cement (produced by Qinling Cement Company, Shaanxi China) is detailed in Table 1. It should be noted that the used ordinary Portland cement is also marked as P.O. 42.5 according to the national standard of China (BG 175-2007, Common Portland Cement, 2007).

Table 2 presents the concrete proportion, workability and flexural strength beyond 28 days of the control sample. In the following experiment, the flexural strength (28 d) was set as the initial stress with which the dynamic loading value can be calculated via stress level (minimum = 10%, maximum = 20%, 40% and 60%). The fine aggregate was river sand (fineness modulus = 2.82). The coarse aggregate was crushed limestone with maximum size of 20 mm, in which the mass proportion of 5–10 mm to 10–20 mm grains was 1.0. The tap water was adopted as mixing water. A commercial water reducer (HBY) was used to reduce the water–cement ratio. Here, the sulfate ion in HBY water reducer was less than 0.01% by mass thus the sulfate brought from admixtures can be ignored.

2.2. Test method

1. Dynamic flexural loading conditioner

As stated in Section 1, there no existed instrument to simulate the dynamic loading situation. A new experimental system was developed in this study, as shown in Fig. 1. A group of specimens (300 × 100 × 100 mm) were immersed in a stainless steel container filled with Na_2SO_4 solution. The loading program detailed below was controlled by a central system (controller). During the stress loading procedure, the loading and de-loading remained 2 min each, that was 4 min per cycling and 360 cycles per day. One cycling started from the maximum load (S_{max}) to the minimum load (S_{min}). In the system, the loading and de-loading period, loading ranges (S_{max} and S_{min}), solution concentration and sulfate type could be set according to the actual situation. In order to avoid the temperature effects, the room-temperature (20 ± 3 °C) was controlled by air-conditioner.

2. Flexural strength

After the sulfate attack and dynamic loading, flexural strength was measured via four-point bending (Fig. 1(b)) test and calculated via equation (1), as following:

$$f_{cf} = \frac{FL}{bh^2} \tag{1}$$

where F: damage loading, N; L: bearing space, mm; B: specimens width, mm; h: specimens heights, mm.

3. Relative dynamic elastic modulus (RDEM)

The RDEM was tested after 50 °C for 24 h, and calculated via equation (2).

$$E_{rd} = \frac{V_t^2}{V_0^2} = \left(\frac{T_0}{T_1}\right)^2 \tag{2}$$

where E_{rd}: the relative dynamic elastic modulus; T_0: ultrasonic spread time of concrete in curing room for the ultrasonic spread time of concrete under solution corrosion or corrosion fatigue for every 15 d until the end 180 d, s; T_t: ultrasonic spread time of concrete under solution corrosion or corrosion fatigue for every 15 d until the end 180 d, s.

4. SO_4^{2-} concentration in attacked layers

The specimens were cured for 28 days in a standard curing room (20 ± 2 °C and RH = 95%) after demolding. Specimens with five sealed sides with paraffin and one unsealed to bear up-loading as well as sulfate diffusion were immersed in a designed solution (5% or 10% sodium sulfate) and loaded with the dynamic flexural stress. Beyond expected sulfate attacking period, the powders were prepared per 5 mm layer from the surface of immersed sample. It should be noted that about 2.5 mm layer of the attacked surface was cut off to avoid the absorption effects from the solution. Whereafter, the sulfate content in the layers were measured via "Chemical Titrating Method" according to National standard of China (GB/T50476-2008), herein the initial sulfate-ion content of surface is 0.68%. That is, the final value obtained from chemical titrating method should be subtracted with 0.68%. The SO_4^{2-} content is expressed in percentage by total solid mass.

2.3. Experimental program

Table 3 details the experimental program of sulfate attack under dynamic loading condition. The water to cement ratio was 0.38 contributed by the water reducer (HBY). The sulfate concentrations in solution were 5% and 10% by water mass. As reported by Kumar Mehta [11] that the pH and concentration of solution were not stable during the laboratory simulation, the attacking solution used in this study was changed per month.

Dynamic loading (as shown in Fig. 2) started from stress level = 10% to stress level = 20%, 40% and 60%. The cycle continued during the whole sulfate attacking period. In this study, the load and de-load cycles were set as 64,800 (180 days needed), which reflected the field fatigues of pavement slabs, bridge decks, airfield runways, railway sleepers and bridges whose service life fatigue cycle number was believed between 10^3 and 10^6 [17,18]. Actually, the performance of cement concrete was observed during the whole immersing period from 30 to 180 days. For short, each group of samples were marked with simplified name which could be used in discussion section. It is noted that two groups of sample were immersed in solution without dynamic loading as a comparison, marked as ANN1 and ANN2. In order to reduce the uncertainty of the experiments, three specimens were produced for the mechanical test (e.g., compressive strength and flexural strength), as can be seen in Fig. 1b. The sulfate contents were calculated based on six samples selected from these three specimens. The data were analyzed based on "mean–variance model" in mathematical statistics.

3. Experimental results and discussion

3.1. Flexural strength

Fig. 2 gives out the flexural strength evolution of Portland cement concrete after sulfate attack coupled with dynamic flexural loading. As can be seen, the blue (ANN1) and red (ANN2) plots in Fig. 2(a) and the blue plots (ANN2) in Fig. 2(b), the flexural strength

Table 1
Chemical composition of ordinary Portland cement used in this study.

Chemical composition	CaO	Al_2O_3	SiO_2	Fe_2O_3	MgO	f-CaO	Alkali	Insoluble	Loss on ignition
Weight percent/%	59.98	5.24	26.63	3.47	1.27	0.68	1.04	0.07	2.58