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Experimental study into erosion damage mechanism of concrete materials in a wind-blown sand environment

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HIGHLIGHTS

- The concrete erosion rate increases with the impact velocity and the impact angle.
- The erosion rate is most obvious as the abrasive feed rate at a certain range.
- Erosion of concrete has no apparent incubation period but has a rising and stable period.
- It can predict the actual erosion time by similarity analysis.

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ABSTRACT

Based on the knowledge that concrete structures in the mid-west of Inner Mongolia are subject to erosion caused by the wind and sand environment over a long period of time, sediment-air injection method was used for an experimental study into erosion on concrete in the wind-blown sand environment, and then involving analysis of concrete erosion features and erosion behavior law. The results show that: The erosion rate increases with the increasing impact velocity, the two have an empirical power law relationship, and under same erosion condition, it is found that the velocity exponent (n) in the erosion rate equation ($E = kV^n$) increases with the increasing concrete strength; as the impact angle increases, the concrete erosion rate also increases; the erosion resistance of concrete is first decreasing then increasing with the erodent feed rate, the erosion rate is most obvious as the abrasive feed rate at a certain range (in this paper, the abrasive feed rate is around 90 g/min); under the same conditions, for concretes with different strengths, the erosion rate decreases with an increase in strength; erosion of concrete has no apparent incubation period but has a rising and stable period, and the accumulative mass loss due to erosion almost increases linearly. The surface micrograph of concrete specimen after erosion were observed by scanning electron microscope (SEM), then the concrete erosion damage mechanism was discussed and it was proposed that there were two mechanisms: surface scratch failure mechanism at low impact angles and impact indentation crushing mechanism at high impact angles during the concrete erosion, which can provide an explanation for failure of concrete materials. The relationship between the experimental results and the actual wind-blown sand erosion conditions was obtained by similarity analysis.

1. Introduction

Scholars both at home and abroad had made a great deal of researches about erosion wear; it was Finnie who first put forward the first erosion wear theory- erosion of micro-cutting theory [1,2]. In 1966, when Sheldon and Finnie were making erosion wear experimental study of hard brittle material, they found that erosion behavior of the hard brittle material is different from that of plastic material, the wearing capacity of brittle material escalated with the increase of impact angles, when the impact angle comes to 90°, the wearing capacity reached its maximum limit, and it can also be observed that defective parts of target will appear annular crack-Hertz crack, therefore the first model of erosion for hard brittle material was established [3,4]. In 1975,

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Lawn and Swain observed in experiment that radial crack that was perpendicular to target surface and transversal crack that was parallel to the target surface, they also pointed out that it was radial crack that caused the degeneration of the strength of the material, and that transversal crack was the fundamental reason for the loss of the material [5]. In recent years, many scholars had studied the erosion wear characteristics of different materials. Yungui Zhu and others studied the gas particle erosion wear characteristics of the epoxy adhesive composite coating by using high-pressure gas solid injector, finding that erosion rate occurs at 75° impact angle, the erosion rates increase with increase of injection density and jet velocity of the particular. When the attack angle was small, the abrasion was mainly appeared as delamination of slices on the order of organic matters in the coating; while the attack angle was large; the abrasion was mainly appeared as elastic debacle of slices on the order of organic matters in the coating and seriously crushed of packings [6]. Goretta and others made check experiments of Portland cement, cement concrete and atomic energy waste glass, the particle erosion adopt to SiO_2 and Al_2O_3, the research found out that glass showed the erosion behavior of regular hard brittle material, erosion destruction was the most severe when the angle was 90°; and the cement reached the highest level when the angle was 20°, but no specific reason was provided; research of concrete was only limited to discrete type, analyzing effect of fracture toughness property [7]. Scholars did some research on wind-resistant performance of concrete, they first studied the influence that impact parameter on erosion wear of concrete, and then putting different protective coverings on the concrete to study wind-resistant performance of different protective coverings through simulating Aeolian environment, result showed that surface of the concrete which was processed by epoxy resin plus polyurethane coating has the most excellent erosion-resistant performance, and the second was PPG paintings, water-borne silicone-acrylate emulsion was the worst [8,9]. These studies provide a variety of theoretical basis which, however they cannot be fully applied to all materials. This article will do some exploratory research about concrete in a wind-blown sand environment.

2. Experimental study

2.1. Sample preparation

The test piece is ordinary concrete. Fig. 1 shows the appearance after erosion. The strengths grade of concrete are C20, C30, and C40 from left to right. Taking into account the limitations of laboratory equipment in weighing the mass, the accuracy of determination of test piece mass loss during the experiment and the accuracy of erosion rate calculation, the size of concrete test piece is determined to be 80 mm × 40 mm × 20 mm. Raw materials of concrete test pieces: Tangshan Jidong Cement P.O 42.5; medium sand (river sand) with fineness modulus of 2.81; stones with particle size of 3–5 mm; ordinary tap water. The mix ration is decided according to specification for mix proportion design of ordinary concrete [10]. The 12 mm bamboo plywood is used as the template of the concrete material and the template is made according to code for design of timber structures [11].

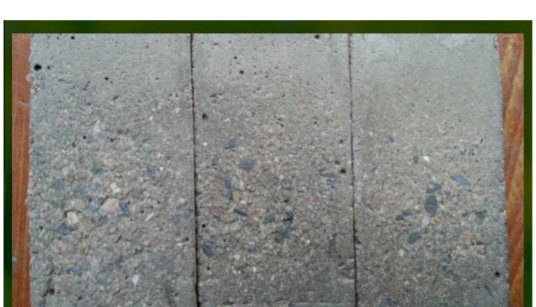

Fig. 1. Concrete specimens after erosion (from left to right C20, C30, C40).

2.2. Test method and equipment

Based on the characteristics of desert wind-sand flow environment, the erosive wear tests of concrete materials were carried out by sediment-air injection method, which is easy to operate and low-cost, and is an ideal simulation method. The schematic diagram of the erosion rig is displayed in Fig. 2. The experimental system consists of high pressure pneumatic system, sand source system that can control abrasive feed rate, erosion control system and test piece erosion chamber. Erosion control system can adjust the distance from nozzle to test piece. Test piece erosion chamber consists of fixture, erosion box and sand collection box, where the fixture is used to fix test piece and adjust impact angle (0–90°), and sand collection box is used to collect the sand after erosion. The abrasive feed rate range was from 0 to 500 g/min through the sand feeder control system. During the experiment, gas pressure was measured and impact velocity was determined as a function of pressure using double-disc method [12]. Table 1 shows the correlation between impact velocity and air jet pressure for gas blast erosion apparatus.

2.3. Selection of sand for experiment

The sand used in the experiment was from Hobq Desert located at the Ordos Plateau, Inner Mongolia. Hobq Desert is one of the main sand sources of sand and dust weather in the northern region, and the sand particles are appropriate for testing and providing engineering background. The abrasive particle size distribution is shown in Fig. 3(a). SEM micrograph shows irregular angular shaped sand particles as shown in Fig. 3(b).

2.4. Selection of experimental program

Erosion wear factors of concrete material in a wind-blown sand environment included: impact velocity, abrasive feed rate, impact angle and erosion time, etc. According to distribution regularity of gale weather in Inner Mongolia area [13], we have made a conclusion of the distribution regularity of the wind-force, and then the impact velocity was been selected accordingly. A classification of dust and sand storm based on sand-dust concentration was proposed through the statistic of concentration of particulate matter (PM) during sand-dust weather in China since recent years [14], then different abrasive feed rate of the sand has been set to simulate sand storm in central and western regions in Inner Mongolia area; The principle to choose impact angle in this test contained low angles and high angles; and the selection of erosion time depended on the requirements of the test. They are shown in Table 2.

2.5. Determination of concrete test piece weight loss and erosion rate

To measure the weight loss, the samples before and after the test are weighted using a microelectronic balance with an accuracy of 0.00001 g. The weight loss and erosion rate are then calculated accordingly. Erosion rate (mg/g) was used to characterize the erosion performance of the target materials. However, there are several ways to define erosion rate. Here, we follow the definition in [15], in which the erosion rate(mg/g) is defined as the ratio of the cumulative mass loss of the target material to the total sand particle weight, that is,

$$\text{erosion rate} = \frac{\text{cumulative mass loss of target materials}}{\text{impact particles weight}} \quad (1)$$

3. Results and discussion

3.1. Impact of sand flow impact velocity on concrete material erosion rate

Fig. 4 shows the curve of concrete erosion rate of test piece at different impact velocities with 45° impact angle, abrasive feed rate of 240 g/min and erosion time of 12 min. Fig. 4 shows that erosion rate of concrete increases with the of increasing impact velocity at same strength, As expected, higher particle velocity leads to higher material removal from the surface as observed in other erosion studies [16]. This is because of the fact that higher impact velocity results in more material removal due to higher kinetic energy. The effect of the concrete strength is more significant at higher velocities than at low velocity (Fig. 4). It is believed that when the impact velocity is low, hence, low kinetic energy, the majority of particles have lower energy which only results in low damage of the concrete [17]. With impact velocity increases, more particles attain the required critical energy to result in deformation and material removal. That is, at low impact velocity most of the