Research on failure of cementitious materials under rotary cavitation test

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Abstract. Utilizing the rotating cavitation erosion test device invented by Nanjing Hydraulic Research Institute (NHRI) to perform the persistent cavitation experiment on hardened cement paste and mortar, observing and analyzing the differences and similarities between cavitation and abrasion zone. Observing the cavitation erosion on the surface of cement-based materials and researching on the destruction of cement hydrations under cavitation process by adopting multiple modern material analysis apparatus, such as Scanning Electron Microscope (SEM), Energy dispersive X-Ray(EDX), X-Ray Diffraction(XRD) and thermal analysis(TG&DSC). Results implied that after continuous cavitation test for 2 hours, the microscopic structure of original defects becomes smooth, to be specific, the flake, rod shape-crystals are basically disappeared and the bottom of cavitation pits are shaped like some melted organizations. Hence the cavitation erosion on cement paste is not only a simple mechanical failure but also lead to the thermal decomposition on hydrations, which could cause the remarkable loss of hydration products on the surface of test blocks. The specific figures are as follows: the mass loss of cementitious substances is no less than 40% so as the loss of slaked lime is more than 25% during a 2 hours cavitation experiment. In that way, the considerable hydration mass loss is capable to cause a huge affection on deterioration of concrete structures.

1. Introduction

As we know, most of high concrete dams are impacted by high speed streams all the year round, it is easy to cause the cavitation damage in the negative pressure region of the flow. According to the recent stats, nearly 40% hydropower facilities of China are facing serious cavitation damage problems[1-2]. In an other word, cavitation is almost an unavoidable problem in the operation of super high dams. The surface of concrete constructions can be suffering from high impact pressure in cavity fracture zone, in that situation, which could lead to the shedding of concrete surface of the whole discharge surface. With the emergence of large and giant concrete dams of 200~300m, the flow velocity of the discharge structure reaches or even exceeds to 50m/s[3-6]. In spite of the use of high strength anti abrasion concrete, the problem of erosion and abrasion of hydraulic concrete materials is still remaining. Nowadays, researches on the mechanism of cavitation erosion for hydraulic concrete in China are still limited to mechanical failure mechanism. The current specifications explain the cavitation erosions as
follows: cavitation erosion is the instantaneous pressure on the surface of the solid boundary when the negative pressure bubble collapses. According to this mechanism, the design conception of anti-cavitation concrete is to use high strength concrete for hydraulic structures. Yet from the actual results, this method cannot fundamentally solve the problem, the correlation is relatively low between cavitation resistance and mechanical properties of materials. Recent research proves that even utilize the ultrahigh-strength-concrete(UHSC) with the strength of 200MPa, the performance of anti-cavitation erosion at high speed cannot satisfy the requirements of design[7-9]. In this paper, a serial of cavitation tests on cement-based materials was carried out to explore the failure process of cement-based materials under cavitation erosion, with the assistance of modern material analysis and testing methods.

2. Experiment

2.1. Testing material
The cavitation specimens used in the test are made of two different materials. One of them is hardened cement paste with a water binder ratio of 0.4, the other is hardened cement mortar and the ratio of cement/sand/water is 1/3/0.5. All the cement utilized in the test is provided by Anhui Conch Cement Co. The test block is made with a height of 150mm, a circular arc of an outer edge of 40°, and a curtained shape inside the inside edge. To be specific, the angle between two sides and interconnection of vertexes are 10° and 20° as in Fig.1(a). It demands 9 such test blocks for the test, among them, there are 9 blocks of hardened cement paste and mortar reserving in stand curing condition for different time of 3 or 28 days.

2.2. Devices and Methods
The cavitation equipment utilized in the research is the rotating scaling cavitation device invented by NHRI[10]. The framework schematic diagram are shown in Fig.1(b). The testing blocks are placed on the cavitation chamber, forming into the shape of a circle. The experiment goes as follows: Turning on the motor and water circling system to accelerate the water flow to a certain velocity, then let the high velocity flow sweep over the surface of blocks to created the damage of abrasion. When the water flow comes to the angle of block surface on the inside edge, the sudden change of the shape can lead to the cavitation effects. In that case, the cavitation area happens on the side of sharper angle on the block surface. For the detail, the flow rate is setting on 40m/s, the liquid filled in the equipment is pure water and the testing time lasts for 2 hours.

![Specimen and equipment for rotating cavitation test](image_url)

Fig.1 Specimen and equipment for rotating cavitation test
3. Results and discusses

3.1. Results of cavitation experiment

Features of surfaces of different testing blocks after 2 hours rotating cavitation are presented on Fig.2. The SEM diagram of hardened cement paste after cavitation test are shown on Fig.3, it can be clearly implied that cavitation pits and affected area around them. In addition, the curve of quantity of cavitation pits per square centimeter and the duration of cavitation test is fitted in Fig.4. Considering the diameter of the pit and the total area of the pit surface, we can draw from the picture that the test specimens for curing 28d are better than those of 3d of curing time in cavitation erosion resistance. Meanwhile, due to the uneven adhesion between various components and the interfacial zone of cement paste and aggregate, the number of surface pitting and pit area formed by mortar test in cavitation test is outnumbered than that of paste specimen under the condition of rotating cavitation test.

![Fig.2 Partial surface of specimens after cavitation test for 2 hours](image1)

![Fig.3 SEM diagram of cavitation zone](image2)

![Fig.4 Statistical chart of corrosion pits after cavitation erosion](image3)

Fig.5(a)(b)(c)(d) indicate the original surface of cement paste under standard curing condition of 28 days, each represented the surface of abrasion zone and cavitation zone after 2 hours test. To be specific, Fig.5(a) shows original defects of cement paste on the surface. Fig.5(b) & (c) represents the overview and close-up detail of cavitation pits. Finally, Fig.5(d) shows the close-up detail of abrasion zone. Compare Fig.5(b) and (c), it can be clearly that there is a huge difference between the cavitation pits and the original surface defects of cement paste. According to the SEM diagram, it is obvious that cavitation erosion is affected on the surface of the specimen with the multiple pits. While in this kind of cavitation pits, the main hydration products of cement which shaped in rod or schistose structure, such as slaked lime crystals (hereinafter called CH) and ettringite, can no longer been observed. Instead, the bottom
surface of cavitation pits become smooth and round and the hydrations are forming into a gelatinous substance resembling a sponge or honeycomb. While from the surface morphology of the specimen in Fig.5(d), the surface of the abrasion zone is smoother under the continuous erosion of high-speed water flow yet the plate-like crystals of cement hydration products are relatively well preserved. From that point of view, it is safe to draw a conclusion that abrasion erosion is distinguished from the cavitation damage, because no significant change in the chemical composition of hydration products during the abrasion process.

Fig.5 Multiple damage forms on surface of cement paste after test

(a)Original defects of cement paste (Standard curing for 28days) (b) Cavitation zone (Standard curing for 28days)

(c) Bottom of cavitation pits (Standard curing for 28days) (d) Abrasion zone (Standard curing for 28days)

Fig.6(a)(b) indicate the result of energy spectrum analysis (EDX) of the surface material of specimens after different failure tests. According to Fig.6(a), the CH of hydration products in the pit has disappeared and a large amount of sponge like material is filled in the bottom, which is been proved as hydrated calcium silicate gel with the EDX diagram. Seen from that, we can conclude the influence of cavitation damage on concrete structure is not only reflected in mechanical shock but also results in the change of cement hydration products. Since the loss of CH, it plays an obvious role in the decrease of strength and alkalinity of concrete, the latter effect can lead to a decrease of concrete durability. Back to the abrasion zone, the results show that no significant chemical changes occurred except a mild surface carbonization, as in Fig.6(b).

In summary, using the rotating cavitation equipment for 2 hours test causes distinguished damage forms of abrasion and cavitation on 3 kinds of different cement-based specimens. During the test, the wear and tear of high-speed water flow presents the basic characteristics of physical damage, however,
cavitation erosion is not only characterized by mechanical failure but also can cause the chemical changes in chemical dehydration of cement hydration products.

![Cementitious substance in cavitation pit](image1)

![Laminated Substance on the surface of abrasion zone](image2)

**Fig.6** EDX of surface compositions of specimens under different failure forms

### 3.2. Analysis of hydration products on the surface of cavitation zone

The XRD patterns of Fig.7 respectively presented the three different kinds of sample. From the top to end it goes: Standard sample of hardened cement paste after 28d, cavitation sample of 2h rotating cavitation experiment. The diffraction pattern for the three samples has few common broad peaks represented as calcium hydroxide, calcium carbonate and dicalcium silicate. Especially, the peaks of calcium hydroxide are tended to decrease after the improvement of cavitation experiments. By quantitative calculation, it shows that after 2h ultrasonic cavitation, the character peak intensity of CH weighs only 46.4% as the one in standard sample. The XRD pattern reflects after different time of cavitation, the hydro-productions of cement went through the different levels of deterioration. To be specific, the content of CH in the cavitation sample had been greatly decreased to 25% for the detail value. In that case, the reduction of alkalinity of concrete would lead to a significant negative impact on the strength and durability of concrete.
The TG-DSC curves of Fig.8 respectively presented the standard and cavitation sample. Intuitively, there are three endothermic peaks emerged on the DSC curve near the temperature of 150°C, 450°C and 700°C. The endothermic peak around 150°C is mainly due to dehydration decomposition of C-S-H gel of hydro-production. The endothermic peak around 450°C indicates thermal decomposition of CH. At last, the endothermic peak around 700°C means the thermal decomposition of calcium carbonate. Compared to two TG curves between standard and cavitation sample, the crystal water of cavitation sample is decreased by 5%, as if the C-S-H gel in the hydration reaction is calculated by the ratio of calcium to silicon (Ca/Si) = water silicon ratio (H/Si) =1.5[11], the content of C-S-H gel in cavitation sample is 20% lower than standard sample. The reduction process of hydro-production is most likely due to thermal decomposition caused by cavitation.

4. Conclusion
To study the thermal effect of cavitation, several experiments have been conducted by equipping electric bubble germination device and utilising ultrasonic cavitation system. All the experiments and microscopic analysis mentioned above leading to few conclusions as follows:

(1) Under the condition of rotating cavitation test, three different test blocks suffered two kinds of failure forms, cavitation erosion and abrasion. It is worth noting that in the cavitation pits, rod and flaky crystals like CH has been greatly disappeared, the bottom of pits are filled with the amorphous cementitious substances. While in the abrasion zone, crystal structures have not been significantly changed, only the surface appeared a little altered because of carbonization process.

(2) It can be seen from the composition analysis of the hydration products on the surface of the cavitation pit, compared with the reference samples that have not been suffered cavitation erosion, the hydration products of the cavitation samples go through a significant damage. Especially for the dehydrations of C-S-H gel and thermal decomposition of CH crystals, both changes can lead to a huge loss of mechanical property and durability performance for concrete. According to that, the destruction of cement-based materials by cavitation erosion is not confined to mechanical failure, but a coupling destruction form of mechanical and thermal.

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