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Study on the durability of engineered cementitious composites (ECCs) containing high-volume fly ash and bentonite against the combined attack of sulfate and freezing-thawing (F-T)

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HIGHLIGHTS

- The effects of FA and bentonite under freezing-thawing and sulfate are analyzed.
- Water, sodium sulfate, and magnesium sulfate under freezing-thawing are analyzed.
- SEM of ECC subjected to freezing-thawing in sulfate solutions is conducted.

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ABSTRACT

This study investigated the durability of engineered cementitious composites (ECCs) containing bentonite and high-volume fly ash under coupled action of sulfate attack and freeze-thaw cycles. The proportions of fly ash and cement (FA/C) in ECCs were 1.2:1, 1.8:1 and 2.4:1, at the same time, in each FA/C ratio bentonite with three replacement ratio of 0%, 3% and 6% by weight was adopted, then specimens were exposed to water, 10% sodium sulfate solution, and 10% magnesium sulfate solution under 150 freeze-thaw cycles. In the experiment, compressive strength, relative dynamic elastic modulus (RDEM) and microstructure were evaluated for the resistance of the cement-based composite material in different sulfate solution under freeze-thaw cycles. The experimental results show that with the increase of the content of fly ash and bentonite, there is a corresponding reduction in the residual compressive strength after 150 freeze-thaw cycles, what's more, the residual compressive strength of specimens in the 10% magnesium sulfate solution was the highest after 150 freeze-thaw cycles. Moreover, the resistance of ECCs to freeze-thaw cycles and sulfate damage increased continuously during the first 50 freeze-thaw cycles, and then continued to decrease at the next 100 freeze-thaw cycles in 10% magnesium sulfate solution, while the performance of ECCs in water and 10% sodium sulfate solution continued to decrease during all the 150 freeze-thaw cycles. In addition, specimens with FA/C ratio of 1.8:1 and 0–3% bentonite showed obvious resistance to coupled attack of sulfate and freeze-thaw cycles. The deterioration of the durability of ECCs is related to both the freezing and thawing cycles and the sulfate attack. Meanwhile, durability performance of cement-based composites after 150 freezing and thawing cycles in different solutions is: 10% magnesium sulfate solution >10% sodium sulfate solution > water.

1. Introduction

Concrete structures have been in existence for hundreds of years since their inception, and concrete is widely used in construction industry, underground engineering, bridge and transportation engineering, water conservancy and seaport engineering by virtue of its advantages, such as lower raw material prices, simple casting process, better physical and chemical stability. However, durability problems with the concrete structure cause a huge decrease in the structural performance and safety index, which could be harmful to human safety. It has been reported that sulfate-enriched soil areas, salt lakes and coastal areas are widely distributed throughout the world, such as Southern California in the USA, Japan, Alpine area, Arabian Gulf region, Australia, northwest and north China. In these areas, the service life of concrete

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structures is affected by both freeze-thaw cycles and sulfate attack. Therefore, studying concrete durability against combined freezing and thawing cycles and sulfate attack will be a great help to improve the service life of building structure in the affected area.

In order to improve the resistance of concrete to sulfate attack and freeze-thaw cycles, some studies have already proposed adding different types of supplementary cementitious materials (SCM) to ordinary concrete, such as fly ash [1–5], limestone powder [6], blast furnace slag [7], metakaolin [8], etc. Usually the addition of supplementary cementitious materials to conventional concrete can reduce its porosity and make the permeable voids existed in concrete relatively finer, which in turn increases the resistance to chemical reactions between hydration products and corrosive ions. This can reduce the ingress of sulfate ions to concrete and reduce the amount of ettringite and gypsum, which are the main cause of deterioration of concrete. Thus, SCM can improve the concrete durability against water-induced corrosion like frost damage and sulfate attack [9–11]. Supplementary cementitious materials can not only reduce the amount of cement in ordinary concrete, resulting in reducing carbon dioxide emissions and alleviating the greenhouse effect, but also could increase the service life of building structures in harsh environments [11–15].

There are several researches on the concrete resistance of freezing and thawing produced with supplementary cementitious materials. Yazıcı [16] studied the durability of concrete to freeze-thaw cycles when class C fly ash was used to replace 30–60% cement. The experimental results showed that even in the case of low cement content, concrete still had excellent resistance to freeze-thaw cycles. Fan [17] evaluated the effect of nano-kaolin against freeze-thaw cycles, in which the replacement rate of nano-kaolin to cement were 0%, 1%, 3% and 5%. The results suggested that the concrete added 5% nano-kaolin exhibited the highest compressive strength, relative dynamic modulus and chloride ion diffusion resistivity after 125 freeze-thaw cycles. Kim [18] investigated the effect of Waste glass sludge (WGS) on resistance of freeze-thaw cycles, and he found that the addition of WGS and fly ash at the same time greatly improved the compressive strength of specimens after freeze-thaw cycles.

Investigations on sulfate solutions resistance of concrete added with supplementary cementitious materials had also been conducted by prior researchers. Nie [19] considered the durability of mortar specimens added with fly ash and blast furnace slag under sulfate environment, meanwhile mortar specimens produced with anti-sulfate cement were also made for the control group, it was discovered that test pieces adding 25% fly ash or 30% slag had better anti-sulfate attack resistance than the specimens added sulfate-resistant cement. Ganjian [20] investigated concrete mixed with silica fume against sulfate corrosion under dry and wet circulation conditions in the ocean tidal zone, and it was observed that compressive strength decreased with the increase of the silica fume content. Liu [21] concluded that the engineering cement-based composites still had superior mechanical properties in the environment of sulfate, sulfate and chloride ions after 200 days. Yang [22] found that the concrete resistance to sulfate damage increased with the content of slag under dry and wet cycles environment, and mercury intrusion porosimetry (MIP) experiment revealed that the porosity inside concrete increased with number of dry and wet cycles. Chen [23] systematically studied the durability of concrete made with fly ash and slag under the condition of chloride ions and sulfate ions under dry-wet cycles through test methods such as mass changes, loss of relative dynamic elastic modulus, chloride ion penetration depth, MIP, XRD and TG/DSC. The results showed that after 300 days of dry and wet cycles, fly ash and blast furnace slag modified concrete had better durability than ordinary concrete.

The coupled attack of F-T and sulfate to the durability of concrete containing supplementary cementitious materials also can be discovered in literature. Jiang [24] studied concrete added 20% fly ash under freeze-thaw cycle in 5% sodium sulfate and 5% magnesium sulfate solution. Mass loss, relative dynamic modulus and compressive strength were used to characterize the freeze-thaw damage in different solutions. The results revealed that concrete damage in magnesium sulfate solution was the largest after freeze-thaw cycles. Li [25] found that adding a small amount of fly ash to recycled aggregate concrete helped to increase the resistance to the double damage of freeze-thaw and sulfate attack, on the contrary, the large amount fly ash could get the opposite effect. Wang [26] concluded that durability in freeze-thaw cycles and sulfate environments can be substantially improved in the case of 25% fly ash and 5–8% silica fume. Liu [27] studied concrete mixed with fly ash under freeze-thaw cycle in sulphate environment. The experimental results showed that after 450 freeze-thaw cycles, the compressive strength of the specimens in the sulfate and freeze-thaw environment decreased by 52%.

Engineering cementitious composites (ECC) is a kind of newly developed fiber reinforced concrete, due to the bridge effect of randomly distributed fiber in the matrix, ECC show properties of high toughness and multiple cracking. ECC has numerous applications like bridge decks, weight-bearing structures and airport runways, under harsh environment, cracks produced in ordinary concrete due to low tensile ability will give passages to corrosive substances, causing internal steel bars corrosion, resulting in structural performance deterioration, on the contrary, ECC has good ability of crack width control, thus it can effectively reduce the amount of corrosive substances into structure through concrete cracks, as a result, the durability of structure can be significantly improved [28], and durability of ECC under F-T and sulfate was investigated by former researchers. Nam [29] compared the influence of polyvinyl alcohol (PVA) fiber and polypropylene (PP) fiber on the concrete frost resistance during 300 freeze and thaw cycles and found that PVA specimens exhibited higher compressive strength than PP specimens. Şahmaran [30] also confirmed that the addition of PVA fiber to ECC can significantly enhanced the frost resistance. Liu [31] indicated that ECC containing 65% fly ash and 5% silica fume had good toughness after 200F-T cycles. Rong [32] found that the addition of 10% metakaolin can improve the flexural and compressive strength of ECC, moreover, X-ray CT results showed that metakaolin contributed to the uniform distribution of steel fibers in ECC.

Although there are many studies on the durability of concrete under the condition of sulfate attack and freeze-thaw cycles, the durability study of ECCs made with high-volume fly ash and bentonite under freeze-thaw cycles in different types of sulfate environment is very limited. Bentonite is a kind of material with natural pozzolanic property and it can be added as supplementary cementitious material to concrete to improve the mechanical properties through continuous pozzolanic effect. At the same time, fly ash is also known for its pozzolanic effect. In the authors' previous research [33], the flexural characteristic of ECC containing bentonite and fly ash was investigated, and the flexural performance of ECC was evaluated by the flexural strength and flexural deformation capacity during the four-point bending test. It was found that ECC containing bentonite and fly ash show multiple cracking behavior and high flexural deflection capacity. The main content of this study is to investigate the effect of fly ash to cement ratio (i.e. Of 1.2, 1.8 and 2.4) and bentonite (i.e. Of 0%, 3% and 6%) on the durability of engineering cement-based composites in different kinds of high-concentration sulfate solution (10% sodium sulfate solution, 10% magnesium sulfate solution) and water. The residual compressive strength, relative dynamic elastic modulus changes and scanning electron microscopy experiments were adopted to