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Technical Paper

Performance evaluation of basalt fiber reinforced mortar under freeze-thaw and chloride-rich environments

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Abstract: Mixing short fibers is one of the effective methods to improve tensile properties and even durability of mortar and concrete. Basalt fiber is a new material that is purely made from basalt rocks. Comparing with traditional steel and synthetic fibers, basalt fiber is environmental-friendly, strong, corrosion-free, high-temperature resistant, and less expensive. Though some research have been carried out on the properties of basalt fiber reinforced cement and concrete, their durability against freezing-and-thawing and chloride ion penetration still remains unclear. In addition, the optimized fiber content and performance evaluation of basalt fiber reinforced mortar and concrete are not well defined. This paper deals with the durability of basalt fiber reinforced mortar under combined freeze-thaw and chloride-rich environments, and proposes the optimized fiber content and the mechanism of basalt fiber for enhancing the durability of mortar. As the results, basalt fibers significantly improve the durability of mortar. Compressive strength of basalt fiber reinforced mortar slightly increases when the fiber content is less than 0.1 vol.%. Bending strength of mortar increases with increase in fiber content. It was also found that basalt fibers improve resistance against chloride ion penetration of mortar.

Keywords: basalt fiber, durability, chloride ion penetration, freeze-thaw cycle, water absorption.

1. Introduction

Many existing concrete structures deteriorate faster than expectation because of various deterioration factors, which causes huge economic losses every year. Durability is a very important performance requirement for a structure which should be fully considered during the design stage with reliable prediction of deterioration progress and application of avoidance-of-deterioration measures. As a fragile material, low tensile strength can easily cause cracking in mortar and concrete, which is one of the shortcomings for not only mechanical properties but also for durability.

In relation to these facts, adding short fibers has often been adopted as one of the effective methods for enhancing durability of mortar and concrete because it can control the crack propagation there. Steel short fibers have a long history for this purpose, and currently synthetic short fibers such as polypropylene (PP), polyethylene (PE), polyvinyl alcohol (PVA), nylon etc. become popular because of their lightness, soundness, corrosion-free, and costs [1]. Basalt fibers have also been widely used as well. Basalt fiber is produced by using basalt rocks. Basalt is a natural material that is found in volcanic rocks originated from frozen lava [2]. Table 1 lists the properties of basalt fiber compared to those of other kinds of fiber. As listed in Table 1, the general properties of basalt fiber are superior to those of the other fibers particularly in terms of tensile strength. Furthermore, basalt fiber is environment-friendly, good chemical resistance, corrosion-free and inexpensive [3]. While various aspect ratios of fibers can be found, the aspect ratio of basalt fiber used for the experiment is 1,125.

While some research have carried out on the properties of basalt fiber reinforced mortar and concrete, durability of basalt fiber reinforced mortar and concrete against frost damage and chloride-induced deterioration still remains unclear. Moreover, the optimized basalt fiber content and performance evaluation of basalt fiber reinforced mortar and concrete are not well defined [4]. To make those problems clear, this paper mainly discusses durability of basalt fiber reinforced mortar under coupled freeze-thaw and chloride-rich environments. The optimized basalt fiber content is proposed, and the mechanism of basalt fiber reinforced

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Table 1 – Properties of basalt fiber compared to those of other kinds of fiber

Materials	Density (g/cm^3)	Tensile strength (GPa)	Elastic modulus (GPa)	Softening point (°C)
Steel	7.85	0.5	210	500
Polypropylene	0.95	0.27-0.65	38	165
E-glass	2.60	3.45	76	850
Basalt	2.65	4.65-4.8	100-110	960

mortar to enhance its durability is discussed.

2. Experimental procedure

2.1 Materials and specimens

High-early-strength Portland cement and chopped basalt fiber of 16 μm in diameter and 18 mm in length were used for making test specimens. The mix proportion of mortar is 1 (water): 2(cement): 6 (sand) in their mass. The river sand used for mortar has the surface-dry density of 2.71 g/cm^3 and the maximum particle size of 2.0 mm. Basalt fibers are mixed with 0.05%, 0.10%, 0.15% and 0.20% of the volume of mortar. Mortar prisms of 40 mm high, 40 mm wide and 160 mm long were used for the freeze-thaw and mechanical tests. Mortar cylinders of 50 mm in diameter and 100 mm high were used for chloride ion penetration and water absorption tests. Immediately after mixing mortar, flow diameter and density of fresh mortar were measured according to JIS R 5201 [5].

2.2 Freeze-thaw test

The specimens were divided into two groups; that is, Group A which was tested in tap water and Group B which was tested in 3.0% sodium chloride solution. The test parameters for the freeze-thaw test were designed according to ASTM C666, in which the test temperature was ranged from –20 to +10 °C, and a freeze-thaw cycle was 3.5 hours. To ensure the freeze-thaw cycles proceeded completely, 4 specimens were put into one sleeve, and the gaps between the test specimens were filled with some planks and foam boards as shown in Fig. 1.

Masses and relative dynamic moduli of elasticity of the tested specimens were regularly measured: every 5 days for Group A specimens and every 3 days for Group B specimens. Every time just before measuring, the specimens were washed by distilled water and then water on the surface of specimen was mopped up. The freeze-thaw cycle was terminated when mass loss or relative dynamic modulus of elasticity reached to 5% or 60% of their respective initial values.

Fig. 1 – Mortar specimens in the sleeve

2.3 Loading test

Two groups of specimens were prepared: one group represented the specimens without frost damage and the other group was the specimens of Group A after the freeze-thaw test. Three-point bending test and compressive strength test were conducted by reference to JIS R 5201 [5]. The compressive strength test was conducted by using the broken specimens after the bending test. During the tests, the load applied was continuously recorded and failure mode was observed.

2.4 Water absorption test

Water absorption rates of the specimens were calculated by weighing the specimens with Eq. (1).

$$Q = (m_w - m_d)/m_d \quad (1)$$

where Q is the water absorption rate; m_d is the mass of the specimen after drying under 80 °C for 24 hours; and m_w is the mass of the specimen after soaking in water for 48 hours.

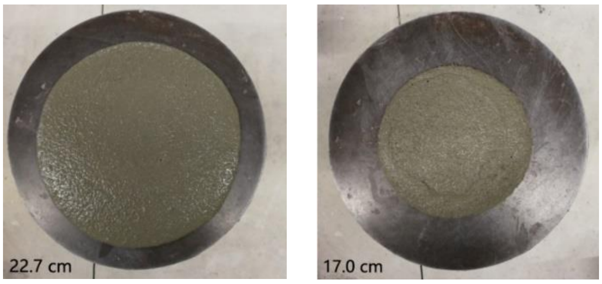
2.5 Chloride ion penetration test

Chloride ion penetration test was carried out by reference to JSCE-G 572 [6]. The top and bottom surfaces of the specimens were sealed with epoxy. Then the specimens were submerged in 3.5% sodium chloride solution at the same depth for 12 days. The specimen was cut into two pieces from the middle part and the cross sections were slightly grinded. 0.1 mol/L silver nitrate solution and 0.1 mol/L fluorescein were sprayed on the cross sections of specimen for measuring chloride ion penetration depth.

3. Results and discussions

3.1 Fluidity and density

Figure 2 shows the flow diameter of (a) plain mortar and (b) 0.2 vol.% basalt fiber reinforced mortar. It was observed that fluidity and bleeding of mortar decreased obviously with increase in basalt fiber content. It is considered that the randomly oriented short fibers hold sand and avoid water moving in mortar and some slurry adhered to the surface of basalt fibers simultaneously reduces the moving water [7]. The density of basalt fiber is higher than mortar as listed in Table 1, however, as indicated in Fig. 3, the average mass of mortar specimens decreased with increase in basalt fiber content. This can be explained that the supporting function formed by randomly oriented basalt fibers increased the porosity of mortar. Accordingly, the density of mortar decreased.



(a) Plain mortar (b) Mortar with 0.2 vol.% basalt fibers

Fig. 2 – Flow diameters of fresh mortar

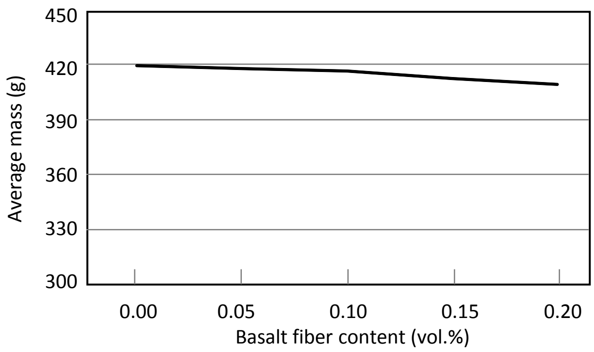


Fig. 3 – Change in mass with increase in basalt fiber volume content

3.2 Durability

Figures 4 and 5 show mass changes with freeze-thaw cycles of Groups A and B specimens, respectively. Figures 6 and 7 show changes in relative dynamic modulus of elasticity with freeze-thaw cycles in Groups A and B specimens, respectively.

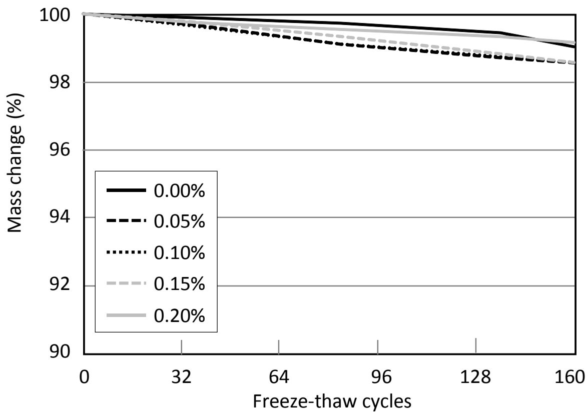


Fig. 4 – Changes in mass of Group A specimen

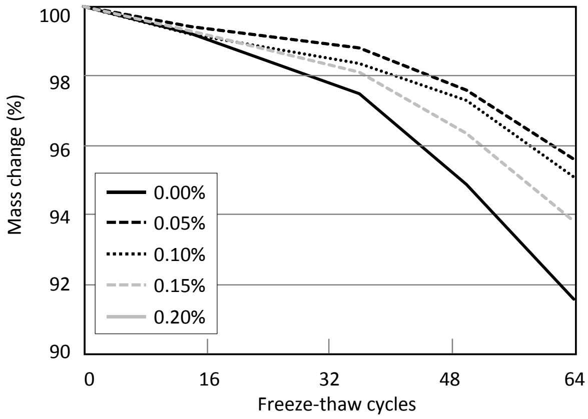


Fig. 5 – Changes in mass of Group B specimens

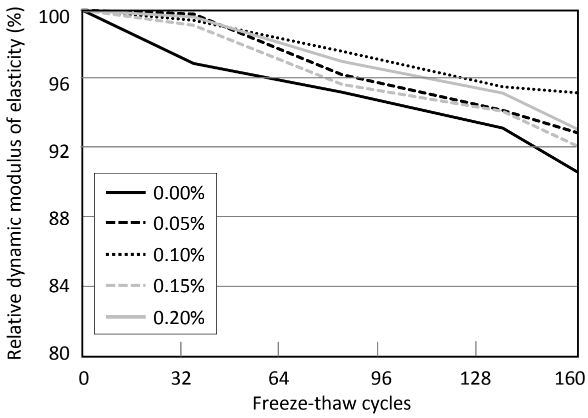


Fig. 6 – Changes in relative dynamic modulus of elasticity of Group A specimens

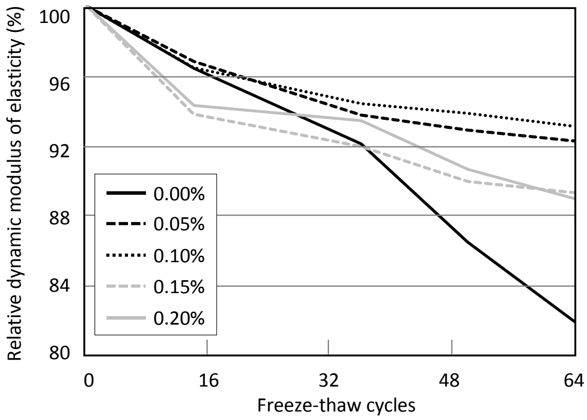
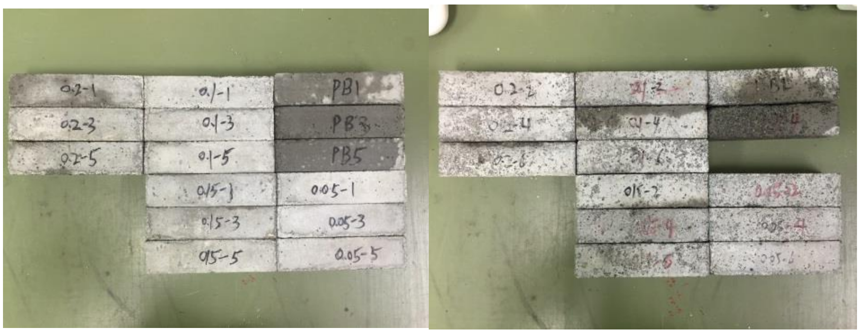


Fig. 7 – Changes in relative dynamic modulus of elasticity of Group B specimens

As these figures indicate, basalt fiber mortar showed better durability against freeze-thaw cycles than plain mortar both in Groups A and B. As Figs. 4 and 5 show, the mass losses of Group B specimens were more distinctive than those in Group A specimens with increase in freeze-thaw cycles. As Figs. 4 and 6 indicate, while the mass losses of Group A specimens were not severe, dynamic modulus of elasticity was obviously decreased with increase in freeze-thaw cycles. As shown in Fig. 8, Group B specimens showed severe scaling at the early stage of freeze-thaw cycles. However, the scaling of Group A specimens was not obvious even at the end of the freeze-thaw cycles.



(a) Group A after 160 freeze-thaw cycles (b) Group B after 36 freeze-thaw cycles

Fig. 8 – Appearance of bottom surfaces of mortar specimens

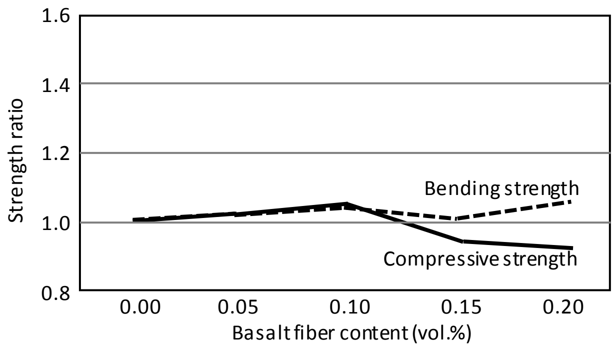


Fig. 9 – Strength ratios prior to freeze-thaw cycles

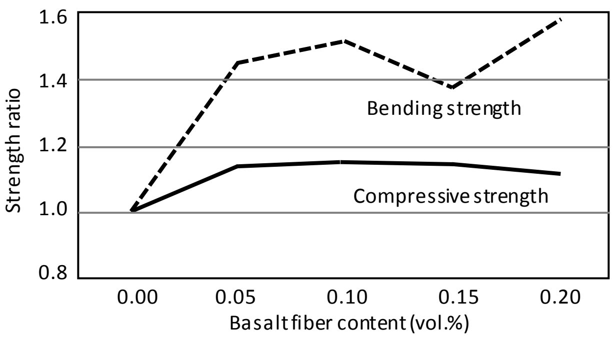


Fig. 10 – Strength ratios after 160 freeze-thaw cycles

It is considered that hygroscopicity is the main reason to accelerate the scaling speed of Group B specimens. When the pore water in the mortar surface starts to freeze, concentration of sodium chloride becomes higher, and therefore, more water will be absorbed in the capillary pores in the surface parts because of the differences in concentrations of chloride. High water saturation in capillary pores will cause high hydrostatic pressure during the freezing stage, which is considered to accelerate the scaling speed of mortar. Besides that, the specimens in sodium chloride solution suffered higher osmotic pressure during freeze-thaw cycles, which is considered as an important factor to accelerate the deterioration speed of mortar [8].

The mortar with 0.2 vol.% basalt fibers showed the minimum mass loss both in Groups A and B, while those with 0.1 vol.% basalt fibers showed the minimum reduction in relative dynamic modulus of elasticity both in Groups A and B. Plain mortar showed the maximum relative dynamic elastic modulus reduction both in Groups A and B. The plain mortar did not show the maximum mass loss in Group A, but showed the maximum mass loss in Group B. It is considered that for the plain mortar under water freeze-thaw environment, scaling is less progressive behind the inner frost damage. Therefore, it is speculated that more water penetrates into the plain mortar so that the mass loss of plain mortar was not the largest. As shown in Fig. 8, after taking out the specimens from the solutions for 30 minutes, the surfaces of plain mortar specimen were still wet comparing with those of the other specimens. It proved this assumption again; that is, inner damage in plain mortar was worse; and therefore, more water penetrates into the plain mortar. The bridging action of basalt fibers on crack openings is considered as one of the main reasons that improves the durability of mortar. Quantitative evaluation on the bridging action of basalt fibers on crack opening such as fracture energy and/or softening relation between cohesive stress and crack width will be investigated in the future.

Vibration during casting may cause bleeding and some water leak out from the bottom part of the mold. Therefore, the scaling degree at the casting surface of the specimens was considerably higher than that at the bottom surface. The water ratio is considered as an important factor that affects anti-freeze-thaw ability of mortar.

In this test, mortar with the four different amounts of fiber fraction did not provide obvious differences in mass loss and the reductions in relative dynamic modulus of elasticity. It is considered that because the mortar specimen is small in its size, the errors and uncertainties during casting and experiments are considered to more easily happen. Therefore, it was hard to reflect obvious performance differences with the change in fiber content.

3.3 Strength

Figures 9 and 10 show the ratios of mortar strengths over those of plain one (fiber content is 0) before and after the freeze-thaw cycles, respectively. Mixing less than 0.1 vol.% basalt fibers improved the compressive strength of mortar. However, the compressive strength decreased when the volume fraction was more than about 0.1 %. Bending strength of mortar increased with increase in basalt fiber content when the fiber volume content was not more than 0.2%. Mortar mixed with such the volume of basalt fibers can carry tensile stress through crack faces, which increases tensile stress carrying capacity of mortar regardless the mortar had been suffered from freeze-thaw damages.

Being compared to basalt fiber reinforced mortar, bending strength of plain mortar decreased more significantly subjected to freeze-thaw cycles. The variation in compressive strength of basalt fiber reinforced mortar became unobvious after freeze-thaw cycles. It is considered that within 0.2% fiber volume content, adding basalt fibers can decrease the strength deterioration speed of mortar under freeze-thaw environment.

3.4 Water absorption rate

Figure 11 shows water absorption ratios. The mortar with 0.05 vol.% basalt fibers showed the lowest water absorption. When the basalt fiber content is more than 0.05 vol.%, the water absorption tended to be high with increase in the basalt fiber content.

Porosity and cracks are considered to be an important factor that affects water absorption. Based on the research by Guo and Zhang [9], enclosed air will not affect water absorption so much, but capillary pores will do. Therefore, it is considered that the capillary pores formed between fibers and cement matrix enable more water to penetrate into the surface parts of mortar. However, the existence of basalt fibers can restrain initial micro crack propagation of mortar which can reduce water absorption of mortar. Therefore, that is why the water absorption rate decreased at first, and then subsequently increased.

High water absorption is a negative factor that deteriorates freeze-thaw resistance of mortar. However, it is considered that randomly oriented basalt fibers in mortar formed more air pores and connected capillary pores that can help releasing hydrostatic pressure during freeze-thaw cycles [8]. More research about microstructure of basalt fiber mortar should be necessary in the future.

3.5 Chloride ion penetration

Figure 12 shows that anti-chloride ion penetration is improved with increase in basalt fiber content though pore might be increased by mixing basalt fibers. However, the improving effect is not so significant. This result implicates that modification of mortar microstructure by basalt fibers could provide a better blocking effect on chloride ion penetration because it can inhibit widening of micro cracks induced in mortar.

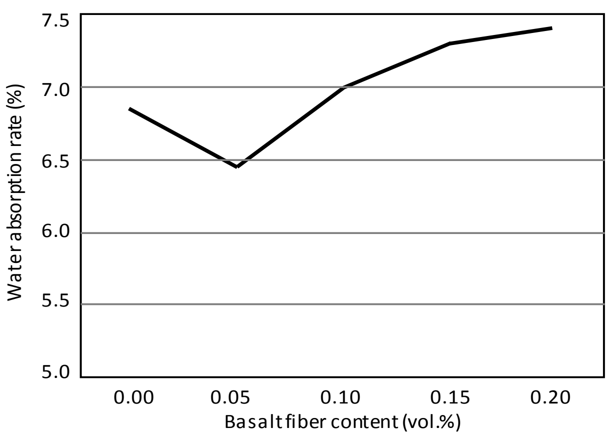


Fig. 11 – Water absorption rate

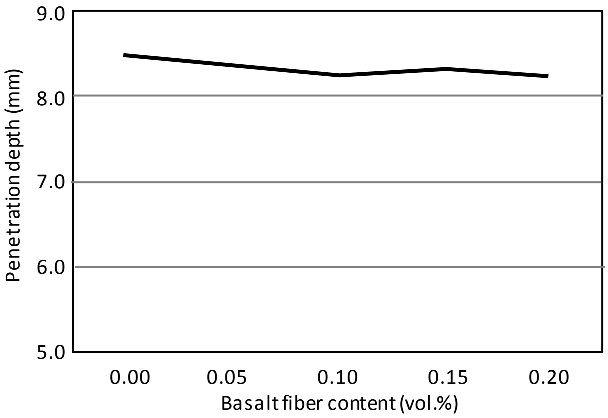


Fig. 12 – Chloride ion penetration depth

4. Conclusions

This paper experimentally discusses durability of basalt fiber reinforced mortar with various volume fraction of the fibers under coupled freeze-thaw and chloride-rich environments. The following conclusions can be drawn in this paper:

(1) Basalt fiber reinforced mortar shows better freeze-thaw resistance under both water and chloride-rich environments than plain mortar does. Volume fraction of 0.1% is considered as a relatively optimized mixing content for basalt fibers in cement-based material. The bridging action of basalt fibers on crack openings is considered as one of the main reasons that improves the durability of mortar. Quantitative evaluation on the bridging action of basalt fibers on crack opening such as fracture energy and/or softening relation between cohesive stress and crack width will be investigated in the future.

(2) A mixing content of less than 0.1 vol.% of basalt fibers can improve the compressive strength of mortar. With less than 0.2 vol.% fiber content, basalt fibers can improve the bending strength of mortar.

(3) Mixing basalt fibers increases the water absorption and porosity of mortar but improves anti-chloride penetration probably because of the blocking effect on chloride transportation.

Further studies will be necessary with focusing on microstructure of basalt fiber reinforced mortar. It will be interesting to investigate the effect of mixing moderate amount of fly ash into basalt fiber mortar from the porosity reduction point of view.

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