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FUNDAMENTAL PROPERTIES AND DURABILITY OF SLOPE PROTECTION SPRAY MORTAR REINFORCED WITH BAMBOO FIBERS

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Abstract. In order to enhance resistance against cracking and durability, short fibers such as steel and organic fibers have been conventionally mixed into spray mortar used for slope protection. In this research, fundamental properties of bamboo-fiber-mixed spray mortar were examined by laboratory tests. The mechanical properties of spray mortar containing bamboo fibers were examined under cyclic wet and dry conditions along with its resistance against freezing and thawing by a spray test. It was confirmed that 0.75% mixture of bamboo fibers in spray mortar most successfully improved mechanical properties and durability. These include adhesion strength to the base surface following exposure to cyclic wet/dry conditions and overall resistance against freezing and thawing. In addition, higher compressive strength and adhesion strength to the base surface were achieved by further mixing in vinylon fibers or fly ash in combination with bamboo fibers.

Keywords: Adhesion strength, bamboo fiber, cyclic wet and dry condition, fly ash, resistance against freezing and thawing, spray mortar, vinylon fiber.

1. Introduction

The spray application method of mortar for slope protection has been widely used because it can help preserve bedrock conditions from weathering and erosion. However, it has been observed at many sites that sprayed mortar cracks, peels and flakes due to aging. Sprayed mortar is directly influenced by the external environment immediately after construction and initial cracking occurs in certain weather conditions. Therefore, in recent years, the use of spray mortar mixed with short fibers such as organic and inorganic fibers has been increasing for the purpose of reducing initial cracking and improving flexural toughness [1].

Bamboo forests are abundant in Japan and have been a familiar source of natural materials. However, proper forest management is somewhat being neglected due partly to the lack of successors who take care of the forests recently. When proper management is neglected, the bamboo forests may trigger landslides and other disasters caused by crowded bamboo growth density and shallow rooting system. As part of the efforts to widening the scope of bamboo material applications, experiments have taken place in the use of short bamboo fibers as a reinforcement medium in concrete and mortar. Past experiments [2] have found that bamboo fibers mixed in concrete improve flexural toughness and resistance to crack development.

Based on these findings, the fundamental properties of bamboo-fiber-mixed-mortar for slope protection were tested in laboratory. Then, the durability of bamboo fiber reinforced mortar was tested by spraying on formworks in the actual working spray facilities. The durability examination included two mechanical property tests (for compressive and adhesion strength) under Cyclic Wet/Dry Conditions (hereinafter referred to as "CWDC"), and a resistance test in freezing/thawing conditions.

2. Experimental program

2.1. Properties of fibers

The bamboo fibers used in this study were prepared using fibers collected from a bamboo tree with a unique rotating knife. Bamboo trees used were anywhere from three to five years old and the cultivar is called Moso bamboo grown in Awaji, Japan. Prepared bamboo fibers were then classified by fiber length to $L = 20 \pm 10$ mm using $1.2 - 5.0$ mm sieves. The classified bamboo fibers were air dried indoors for about three weeks prior to actual experiments. Additionally, commercially available vinylon fibers were mixed into spray mortar to facilitate comparison with spray mortar reinforced with bamboo fibers. The material properties of the bamboo and vinylon fibers are shown in table 1. The dry surface state was defined as a state where the fibers absorbed water for 24 hours and then dehydrated until the fiber surface was dry. To achieve this dry surface state, the fibers that absorbed water were dehydrated for three minutes using a centrifugal dehydrator.

	Bamboo	Vinylon
Density: Air-dry (g/cm^3)	0.77	1.09
Density: Dried surface (g/cm^3)	1.27	1.17
Water absorption rate (%)	87.2	12.1
Fiber length (mm)	19.8 (Av.)	18.0
Fiber diameter (mm)	0.59 (Av.)	0.2
Aspect ratio (–)	34	90
Tensile strength (MPa)	154	490

Table 1. Material properties of bamboo fiber and vinylon fiber.

2.2. Laboratory test for fundamental properties

2.2.1. Mix proportions of mortar and specimen preparation

Table 2 shows the mix proportions of mortar for fundamental property tests in laboratory, normal mortar with C = 400 kg/m^3, W/C = 55% and S/C = 4.2 was named "N" as a standard composition of spray mortar. Based on N, compositions with bamboo fibers added with mixing ratios of 0.25%, 0.75% and 1.25% in volume were each named "B0.25," "B0.75" and "B1.25." In addition, 20% in fine aggregate of B0.75 was replaced with fly ash, which was named "B+FA." In B+FA, W/B was 32% when the binder included fly ash. Furthermore, a composition N with 0.75% vinylon fibers was named "V," and the N mortar with 0.375% each of bamboo fibers and vinylon fibers was named "B+V."

Readily available Portland cement (density: 3.16 g/cm^3) was used. Crushed sand manufactured in Naruto, Japan was used as fine aggregate (density: 2.57 g/cm^3, fineness modulus: 2.63). Moreover, type II fly ash (density: 2.33 g/cm^3, specific surface area: 3240 cm^2/g, ignition loss: 2.8%) specified under the Japanese Industrial Standard (JIS A 6201) was used.

The mortar was mixed in accordance with the cement physical test method (JIS R 5201), and the fibers were immersed in the mixing water. All compositions in this experiment were stiff consistency mortar with low fluidity close to zero slump. In mortar spraying operations on the field, mortar is sprayed on the bedrock by compressed air generated by a compressor. Thus, the sprayed mortar not only adheres to the bedrock but is also compacted. Since fundamental property tests are conducted indoors, the specimens were prepared by an elaborate compaction to obtain effects similar to spray compaction without spraying. Cylindrical specimens (⌀ 50 × 100 mm) for the compression test were compacted every three layers by tamping down with a thrust bar.

2.2.2. Curing and various tests

All specimens went through indoor air curing for 28 days (room temperature: 20 °C , 75% R.H.), being sealed except for the upper surfaces of the specimens to simulate site conditions.

Two cases of compression tests were conducted. In the first case, the compressive strength was measured after air curing for 28 days. In the second case, the specimens were subjected to CWDC for 12 days after air curing for 28 days. CWDC were based on the method for the accelerated rock slaking test (JGS 2125) to simulate the environment of natural weathering after spraying on slope surfaces. The specimens were dried at 40 °C for 48 hours, then immersed in water at 20 °C for 24 hours, and then dried at 110 °C for 24 hours. This cycle was repeated three times.

A porosity test was performed using cylindrical specimens (⌀ 5 × 10 cm) with a material age of 28 days. The mortar porosity was determined by equation 1, which was consisted of the mass of the specimen dehydrated in a drying furnace at 80 °C for 24 hours (Wd) and the mass of its surface-dried state immersed in water at 20 °C for 48 hours (Ws).

$$\varepsilon = \frac{Ws - Wd}{\rho \times V} \times 100 \ \ (\%) \tag{1}$$

where ε is porosity (%), ρ is density of water and V is volume of specimen.

2.3. Spray test using actual plant

2.3.1. Mix proportions of mortar and spray method

For the spray test, the amount of mixed fibers was determined to be 0.75% as found to perform the best by the laboratory test. Five kinds of mortar compositions, N, B, V, B+V and B+FA were selected. It is presumed that the viscosity gets too high due to the influence of the fly ash that replaced fine aggregate in B+FA, and there is a risk of clogging the material hose and nozzle. Consequently, the replacement rate of fly ash was adjusted to be 7%, and W/B was 45% when fly ash was used as the binder.

Mortar spraying was conducted in the facilities normally used for wet spraying. The fibers were mixed in in a small portion at a time to prevent unevenness, and the mixing duration was set to be two minutes per batch.

2.3.2. Specimen preparation and various tests

Figure 1 shows an outline of the formworks sprayed with mortar and the specimens cut out. Two types of wooden formworks in the figure were prepared for each mortar composition. Three cylindrical specimens (⌀ 50 × 100 mm) for compression test and four specimens for adhesion test were made in a formwork with dimensions of 850 × 300 × 150 mm. In the attempt to take actual spraying on bedrock or existing concrete surfaces into account, two kinds of specimens for the adhesion test were prepared by spraying on rock pieces (⌀ 75 × 25 mm, compressive strength: 207 N/mm^2) and on a flat concrete

	Fiber type [−]	Fiber addition rate [vol. %]	W/B [%]	Unit amount [kg/m³]				
				C	W	S	Fiber	PA
N	–	–	55	400	220	1679	0	0
B0.25	Bamboo	0.25	55	400	220	1676	1.93	0
B0.75	Bamboo	0.75	55	400	220	1670	5.78	0
B1.25	Bamboo	1.25	55	400	220	1663	9.63	0
V	Vinylon	0.75	55	400	220	1662	8.14	0
B+V	Bamboo, Vinylon	0.375, 0.375	55	400	220	1674	2.89, 4.07	0
B+FA	Bamboo	0.75	32	400	220	1356	5.78	280

TABLE 2. Mix proportions of mortar in laboratory test.

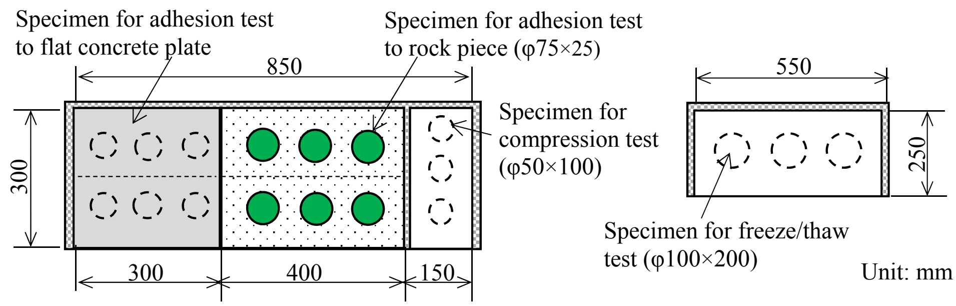

FIGURE 1. Top view of formworks for spraying and sampling of specimens.

plate (300 × 300 × 60 mm for interlocking block, flexural strength: 5.5 N/mm^2). Rock pieces were cut out from sandstone with a stone cutter. The cross section of the stones for bonding with mortar became smoother than the surface of flat concrete plate. Moreover, two cylindrical specimens for freeze/thaw test (⌀ 100 × 200 mm) were cut out of mortar sprayed on a wooden formwork with the size of 550 × 250 × 250 mm.

The sprayed formworks were cured outdoors exposed to natural weather for 28 days from 11/24 to 12/22. During this period, the average temperature was 8.3 °C, and it rained for seven days. Each specimen except for freeze/thaw test was cut out at a material age of 25 days. When the age reached 28 days, the compression strength test (JIS A 1108) and the first case of the adhesion strength test (JSCE-K 561-2013) were conducted. An adhesion strength testing device of Building Research Institute method was used for the adhesion test. After outdoor exposure for 28 days, two specimens for the adhesion strength test were exposed to CWDC for 12 days. Then the second case of the adhesion test was performed. Three cylindrical specimens (⌀ 50 × 100 mm) were cut out of mortar after the second adhesion test, and used for the second compression test.

56-day-old specimens were cut out and used for the freeze/thaw test. In this test, 300 cycles of freezing and thawing in water were conducted according to the freeze/thaw test method of concrete (JIS A 1148, procedure A), and the relative dynamic modulus of elasticity and the mass reduction rate were obtained. The relative dynamic modulus of elasticity was determined by the ultrasonic propagation velocity with reference to the previous study [3].

3. FUNDAMENTAL PROPERTY LABORATORY TEST RESULTS

3.1. POROSITY

Figure 2 shows the results of porosity test at a material age of 28 days. According to this figure, when the mixing amount of bamboo fibers increases from 0% (N) to 1.25% (B1.25), the porosity also increases. This increase is caused by fine bubbles introduced in the mortar with the fibers. The porosity of V mixed with vinylon fibers is the largest. One of the reasons is because the number of vinylon fibers per mortar volume is greater than the number of bamboo fibers. The diameter of vinylon fiber is about 1/3 that of bamboo fiber as shown in table 1. When the same volume of fibers (0.75%) is mixed, the number of vinylon fibers is about 10 times that of bamboo fibers. The porosity of B+V mixed with composite fibers (bamboo/vinylon), is almost the same as B0.75 mixture of bamboo fibers solely. Moreover, the porosity of B+FA with the combination of bamboo fibers and fly ash is the smallest because mortar voids are reduced by fly ash. Since fine aggregate was replaced with fly ash, voids were filled by the filler effect of fly ash with extra fine particles. In the long term, as the pozzolanic reaction of the fly ash proceeds, the porosity of B+FA will decrease further.

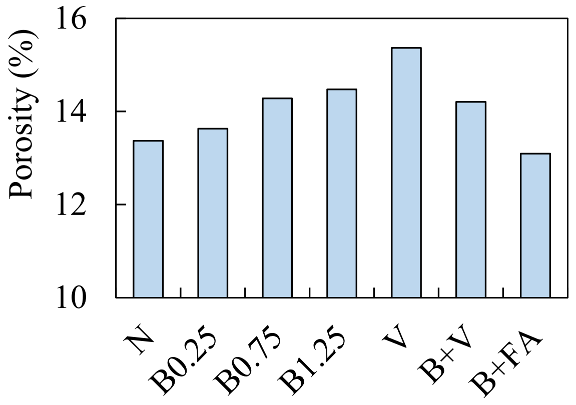

Figure 2. Porosity of mortar measured in laboratory test.

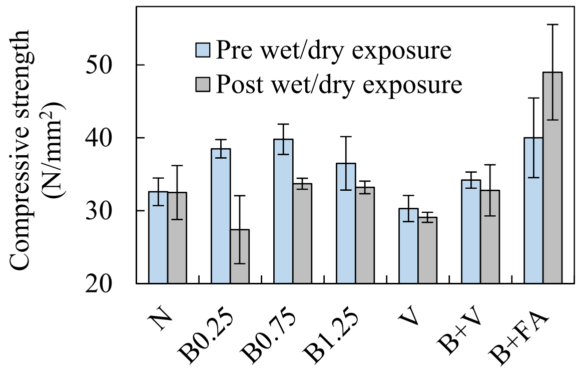

Figure 3. Compressive strength of mortar measured in laboratory test.

3.2. Compressive strength

The results of compressive strength test of 28-day-old specimens are shown in figure 3 "Pre wet/dry exposure." The compression strength increased when the addition rate of bamboo fibers increased from 0% (N) to 0.75% (B0.75), but it decreased when the rate further increased from 0.75% (B0.75) to 1.25% (B1.25). In general, the higher the porosity and organic content, the lower the compressive strength. However, when bamboo fiber content increased from 0% to 0.75%, not only the porosity, but also the compressive strength increased. The cause of the increase in compressive strength is inferred to be influenced by the internal curing of bamboo fibers. Since the specimens were cured in air, the moisture in the mortar (needed for the hydration reaction) tended to evaporate easily. Because moisture contained in bamboo fibers with high water absorption rate (as shown in table 1) is replenished inside the mortar as it dries, the strength of B0.25 and B0.75 is considered to increase from that of N. When bamboo fiber mixing ratio increases to 1.25%, the increased voids (as shown in figure 2) have a more negative effect on the mortar strength. It also becomes difficult to sufficiently disperse the fibers while mixing, so that the compressive strength of B1.25 seemingly decreased.

V in which vinylon fibers solely was mixed had a lower compressive strength than N due to its large porosity, and B+V in which bamboo and vinylon fibers were combined had comparable strength to N. B+FA in which bamboo fibers and fly ash were used in combination had the smallest porosity and the highest compressive strength. B0.75 also shows a similarly high-level of strength to B+FA. In terms of strength, approximately 0.75% of bamboo fiber mix ratio proved to be most desirable.

When the specimens were exposed to CWDC for 12 days after 28 days of outdoor air curing, the strength of the bamboo-fiber-mixed compositions except B+FA shows a relatively large decrease (see figure 3 "Post wet/dry exposure"). The decrease is assumed to be caused by the hollow cells of bamboo fibers [4]. It is presumed that shrinkage stress is generated in the mortar around the hollow cells while drying in wet/dry cycles, and defects have occurred inside the mortar. The strength of B+FA mixed with fly ash largely increases. Since fly ash used, overall amount of the binder increased. This resulted in increased amount of unreacted binder. It is possible that the hydration reaction of the unreacted binder progressed rapidly during water immersion in wet/dry cycles.

4. The results of spray test using actual plant

4.1. Porosity

Figure 4 shows the results of porosity test of 256-day-old specimens ($\varnothing\, 50 \times 100$) cut out in the spray test, together with the porosity of 28-day-old specimens in the laboratory test. According to figure 4, the values of B and V in the spray test are less than those in the laboratory test, and are similar to the value of N. The reason is because the spraying pressure purged the fine bubbles which were entrained while mixing in the fibers [5]. The value of B+FA in the spray test is drastically lower than that in the laboratory test. The decrease was caused by densification of mortar, in addition to bubbles vanished while spraying. Since the specimen material age reached as old as 256 days, the pozzolanic reaction of the fly ash progressed.

4.2. Compressive strength

Figure 5 shows the measurement results of compressive strength and density of cylindrical specimens ($\varnothing\, 50 \times 100$ mm) before and after Exposure to Cyclic Wet/Dry Conditions (hereinafter referred to as "ECWDC"). Before ECWDC, the compressive strength of B was similar to that of N and V, while the density of B mixed with bamboo fibers was the smallest. The moisture within the mortar easily evaporates during outdoor curing. In this situation, it is assumed that the bamboo fibers that have absorbed water gradually supplied moisture (the internal curing effect [6]) and the hydration reaction of B further

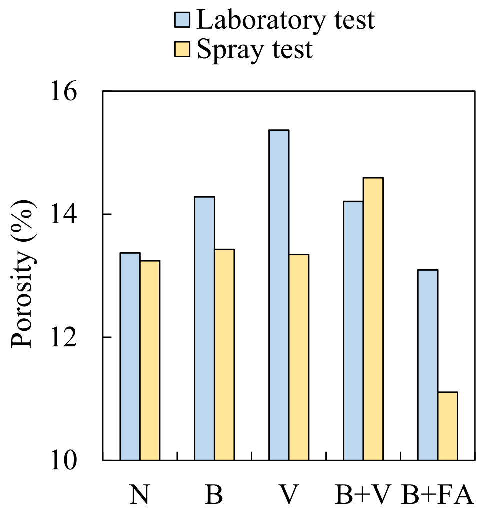

Figure 4. Porosity of mortar measured in spray test.

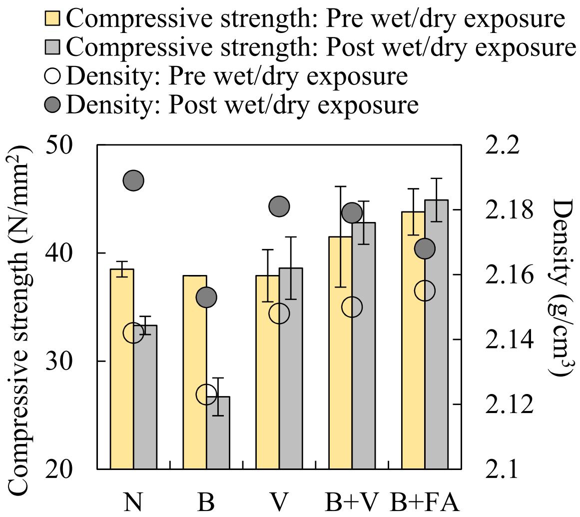

Figure 5. Compressive strength of mortar measured in spray test.

developed. That is why the compressive strength of B+V is greater than that of V. The reason why B+FA had the largest strength was that the dense mortar matrix was formed by the lower W/B, the filler effect of fly ash and the internal curing of the bamboo fibers.

After ECWD, the density of all compositions increased, but the compressive strength of N and B decreased. The decrease was especially drastic in B than in N. The air-dry density of the bamboo fibers is small as shown in Table **??**, and the inside of the bamboo fiber cells becomes hollow when drying [4]. Accordingly, it is considered that the internal defects of the mortar were caused by the stress of drying shrinkage. The compressive strength of V, B+V, and B+FA increased slightly. These increases are attributed to the hydration reaction of the unreacted binder that was promoted during the wet period of CWDC. V and B+V were also mixed with vinylon fibers which do not have a hollow structure like bamboo fibers. As for B+FA, the addition of fly ash resulted in increased amount of powder element that acted as a binding agent, which led to increased compressive strength. The increased compressive strength is assumed to be further improved by the pozzolanic reaction of fly ash over a long period.

4.3. Adhesion strength

Figure 6 shows the measurement results of adhesion strength between spray mortar and rock/concrete surfaces before and after ECWDC. Before ECWDC (material age of 28 days), since the rock surfaces cut with a rock cutter were smooth, the adhesion strength with the rock in all compositions was as small as approximately 1.0 N/mm^2. Peeling fracture also occurred at the adhered interfaces. As for concrete surfaces, the base concrete or spray mortar was destroyed, showing values exceeding 2.0 N/mm^2. These values can be regarded as close to the tensile strength of mortar and concrete. Regardless of the base type, the value of B+V using composite fibers was the largest.

Adhesion strength after ECWDC decreased on rock/concrete surfaces for all compositions. The decrease was caused by the changes in the mortar volume following ECWDC, increasing the shear strain on the adhered interfaces. For the rock surfaces, peeling fracture occurred at the interfaces. The values of B and B+V were about twice the value of N, and greater than V. For the concrete surfaces, the base concrete or spray mortar was destroyed. The values of B+V and B+FA were larger than other compositions. These results show that compositions with bamboo fibers mixed in have excellent adhesion strength. Bamboo fibers inside the mortar absorb water during the wet period of CWDC, and gradually supply moisture in the dry period. It means that drying shrinkage strain on the adhered interfaces are suppressed.

4.4. Resistance against freezing/thawing

Figure 7 shows the mass reduction rate and the relative dynamic modulus of elasticity in the freeze/thaw test results. With respect to the three compositions N, V and B+V, relative dynamic elastic modulus dropped sharply before reaching 200 cycles. These reductions were attributed to the peeling fracture of the mortar pieces at the corner portions of the cylindrical specimens. It is possible that the cracks progressed from the partial sand streaks generated during spraying and led to the peeling fracture. The sand streaks also existed on the specimens of B and B+FA mixed with bamboo fibers, but the relative dynamic elastic modulus showed a gentle decrease, with 89% and 57% at 300 cycles, respectively.

After the freeze/thaw test, deterioration due to scaling was observed on the specimen surfaces in all

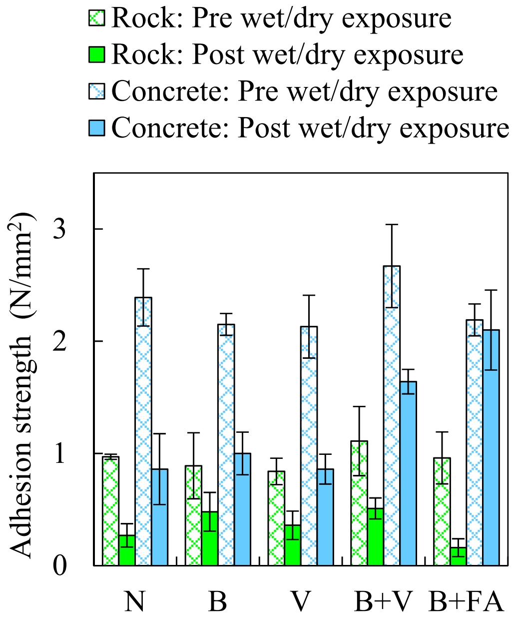

Figure 6. Adhesion strength between sprayed mortar and rock/concrete surfaces measured in spray test.

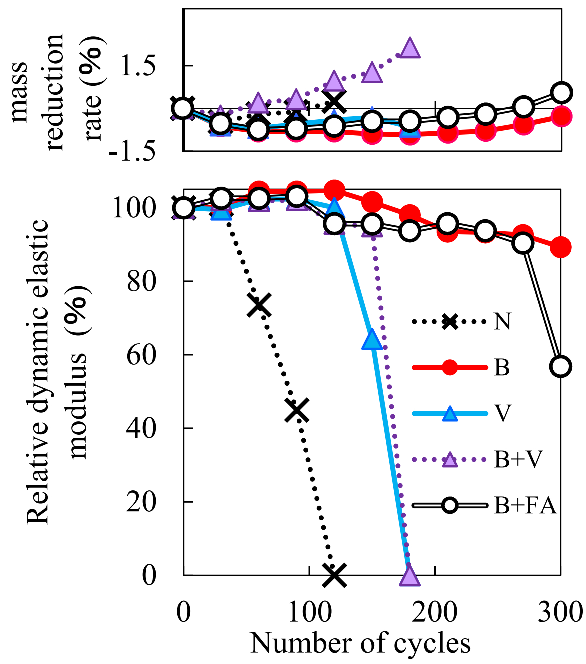

Figure 7. Variation curves of mass reduction rate and relative dynamic elastic modulus measured during freeze/thaw test in spray test.

compositions. As shown in figure 7, the mass reduction rate moved momentarily to the negative side in all compositions, but then shifted to the positive side. The cause of the negative shift was that fine cracks occurred at the early stage of the freeze/thaw action, then the mass increased due to the penetration of moisture into the cracks. As the number of cycles increased, scaling or peeling fracture occurred and finally the mass decreased.

In the previous study on sprayed concrete [5], it has been reported that helpful air bubbles for freeze/thaw resistance are lost by spraying pressure. When alternative measures were taken to obtain the benefits of bubbles (such as adding hollow microspheres to spray concrete mixed with vinylon fibers), fine cracks were suppressed and reduction in relative dynamic elastic modulus was hardly observed. In this freeze/thaw test, no special measures were taken to compensate for the bubbles lost by spraying pressure. Thus, V and B+V mixed with vinylon fibers are considered to have shown small resistance against freezing and thawing.

In contrast to N, V and B+V, the freeze/thaw resistance of B and B+FA mixed with bamboo fibers was greatly improved. It can be presumed that bubbles remaining in hollow parenchyma cells of bamboo fibers absorbed and relaxed the expansion pressure during freezing.

5. Conclusion

In this study, fundamental properties and durability of slope protection spray mortar reinforced with bamboo fibers were experimentally examined. The results and findings are summarized as follows.

1. As far as strength is concerned, 0.75% mixing ratio of bamboo fibers proved to perform the best. Compressive strength decreased following exposure to cyclic wet/dry conditions when only bamboo fivers were mixed. However, when bamboo fibers were mixed with vinylon fibers or fly ash, the decreased strength was improved.
2. Concerning spray mortar with 0.75% bamboo fibers mixed in, adhesion strength between the base rock/concrete and spray mortar after exposure to cyclic wet/dry conditions was increased by 180% for the base rock and by 120% for the base concrete, compared to mortar without fibers. The performance improvement was more remarkable when vinylon fibers or fly ash was mixed in in addition to bamboo fibers.
3. Spray mortar with 0.75% bamboo fibers had great resistance against deterioration caused by freezing and thawing, and relative dynamic elastic modulus remained at 89% after 300 cycles in the freeze/thaw test (mortar without fibers: 0% at 120 cycles). The mortar combining 0.75% bamboo fibers with fly ash remained at 59% at 300 cycles.

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