

Performance Evaluation of Sprayed Ductile Fiber-Reinforced Mortar as a Repairing Material

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(Received June 18, 2007, Revised, October 25, 2007, Accepted February 28, 2008)

Abstract: Most of existing repair materials have some shortcomings such as brittle fracture, imperfect interface bonding and marked difference in modulus of elasticity compared with the structures. These problems make their repair inefficient. Some researches on using a fiber-reinforced mortar as an alternative to enhance the efficiency have been carried out recently. This paper presents the results of an experimental study on the performance of sprayed PVA fiber-reinforced mortar as a repair material. We evaluated its mechanical properties, durability and strengthening effect. This study shows that the sprayed PVA fiber-reinforced mortar is remarkably effective as a repair material.

Keywords: repair, fiber reinforced, mortar, PVA fiber, spray.

1. Introduction

Various fiber-reinforced mortars made of large quantities of PVA fiber or steel fiber have been developed recently, and studies to find their applications in diverse domains are being conducted actively.¹⁻⁴ With regard to its economical efficiency, the fiber-reinforced mortar of high toughness is more effective when it is applied as a repair material in small quantities rather than its casting of large volume as the main body of a structure in the field. The authors have developed a wet spraying technique using PVA fiber-reinforced ductile mortar and attempt to explore its use as a rehabilitation material.^{5,6} Spraying system is composed of mixer, mortar pump, air compressor, and spray gun as you can see in Fig 1. Owing to spray gun which has two steps to increase the air pressure, pumping efficiency can be improved. Consequently it can increase the bond strength and reduce the rebound of mortar. Unlike previous polymer-type or epoxy-type restorative materials, the coefficient of thermal expansion and the elastic modulus of the sprayed fiber-reinforced ductile mortar are similar to those of concrete, which allows it to behave similarly to the concrete members. In addition, the relatively small quantity of shrinkage of the material during and after hardening leads to remarkable dimen-

sional stability, making it possible to expect an increase in bond strength with the concrete structure. Moreover, the admixing of PVA fiber improves the flexural and tensile strength as well as the ductility and provides excellent resistance against impact loads, which is believed to enhance the load bearing capacity and the long-term durability. However, inadequate attention has been devoted by researchers to examine systematically the extent of the improvement brought by such fiber-reinforced ductile mortar comparing with existing restorative materials

and techniques. Accordingly, this study investigates the repair effects of the sprayed PVA fiber-reinforced mortar through estimation of its strength, shrinkage, change of mechanical properties before and after freezing and thawing cycles, as well as its durability and flexural performance in order to secure its stability for the use in the field.

2. Experimental materials and methods

2.1 Materials

Table 1 summarizes the features and types of the repair materials selected for the tests. A water to mortar ratio of 0.2 (W/M) has been set for all the repair materials. The sprayed PVA fiber-reinforced mortar is characterized by the admixing of 1.2% (by volume) of PVA fiber to the mortar composed of cement, fly-ash and CSA-type expansion agents. Table 2 shows the mix proportion of the sprayed PVA fiber-reinforced mortar and the characteristics of materials. The same tests have also been carried out on the existing product R using natural cellulose fiber in the mortar composed of polymer and the existing product C without the fiber in order to allow its comparison with the sprayed fiber-reinforced mortar.

2.2 Test methods

Compression, tension, bond and impact tests were conducted in order to examine the strength characteristics of the sprayed fiber-

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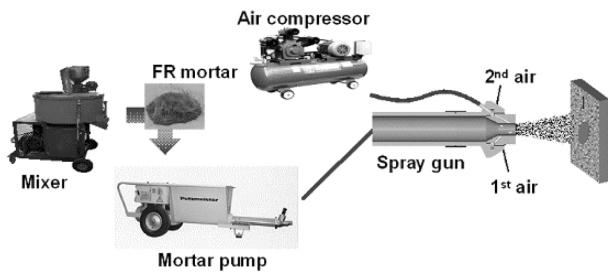


Fig. 1 Spraying system.

reinforced mortar. The strength test was performed after water curing and at a pre-determined age. Plastic shrinkage, autogenous shrinkage and drying shrinkage tests were also executed. Additionally, a confined drying shrinkage test was performed to evaluate the crack control performance. The change in mechanical properties has been examined by means of freezing-thawing cycle tests. The durability has been examined by means of carbonation, salt attack and freezing-thawing cycle tests. The carbonation depth was measured at pre-determined ages using a 1% phenolphthalein solution on $\phi 100 \times 100$ mm specimens exposed to 5% concentration of CO_2 , temperature of 30°C and humidity of 50% after 14 days of water curing. The resistance to salt attack was tested according to ASTM C 1202 on a $\phi 100 \times 50$ mm specimen with epoxy coating applied on the lateral faces after 14 days of water curing. The resistance to freezing and thawing cycles was examined according to ASTM C 666-B, and the corresponding relative

Table 2 Mix proportion of PVA fiber-reinforced mortar and the characteristics of materials.

Type	Properties	Mass Proportion	
Mortar	Cement	OPC Density: 3.15 g/cm^3	1.0
	Fly ash	Blaine: $3400 \text{ cm}^2/\text{g}$ Density: 3.15 g/cm^3	0.15
	Expansion agents	CSA type Density: 2.80 g/cm^3	0.5
	Sand	Size: 0.1~0.25 mm	1.1
	The others	Superplasticizer, shrinkage reducing agents, etc.	-
Water/Mortar		0.2	
PVA fiber	Diameter: $39 \mu\text{m}$ Length: 10 mm Tensile strength: 1,620 MPa	1.2 vol.%	

dynamic modulus of elasticity was evaluated. The flexural strength and bond strength were measured before and after the freezing and thawing test. The details of each method are summarized in Table 3.

Specimens with dimensions of $300 \times 300 \times 2,400$ mm were manufactured as shown in Fig. 2 in order to examine the flexural

Table 1 Features of the tested repair materials.

Type	Components of mortar	Fiber	Main Purpose
Sprayed PVA fiber-reinforced mortar	Inorganic materials	PVA fiber	Repair / reinforcement
Product R	3 component-type polymer resin	Natural cellulose fiber	Crack and spalling repair, filling
Product C	SBR-type polymer	No fiber	Rust proof /restoring

Table 3 Details of each test method.

Properties	Testing Method	Specimen	Condition
Compressive strength	KS L 5105	$50 \times 50 \times 50$ mm	Curing at $20 \pm 3^\circ\text{C}$ for 28days
Tensile strength	KS L 5104	Dog-bone shaped	
Bond strength	KS F 4042	-	
Impact strength	KS F 2221	-	
Plastic shrinkage	PVC-Ring Method	$500 \times 500 \times 500$ mm	Temperature: $30 \pm 3^\circ\text{C}$, Humidity: $40 \pm 3\%$ Wind : 4~4.5 m/sec, 24hours
Autogenous shrinkage	KS F 2586	$100 \times 100 \times 400$ mm	Temperature: $20 \pm 3^\circ\text{C}$, Humidity: $60 \pm 5\%$
Drying shrinkage	KS F 2424		
Crack resistance	KS F 2595		

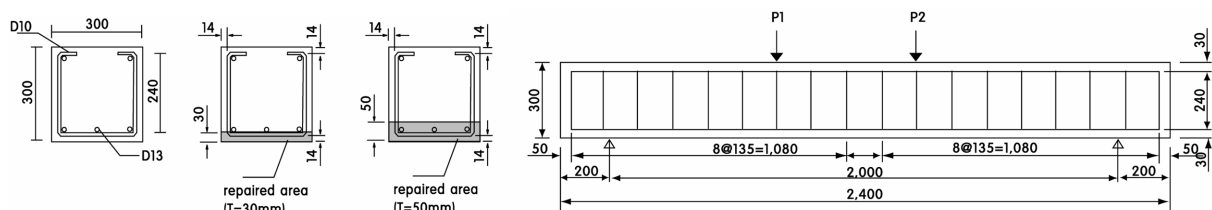


Fig. 2 Specimens for flexural tests

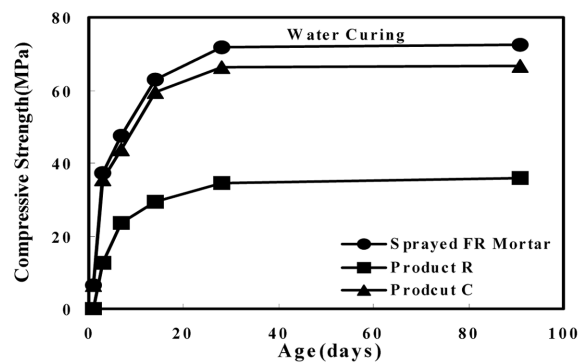
load bearing capacity of the repaired structure with the sprayed fiber-reinforced mortar. Repaired structures were made by applying the mortar after removing the area to be repaired. Table 4 summarizes the details of the specimens and the applied techniques. Two non-reinforced (plain) specimens were manufactured. Three specimens were fabricated with the sprayed fiber-reinforced mortar to possess a reinforcement thickness of 30 mm and 50 mm with proportions of PVA fiber set to 1.2% and 1.5%, respectively. Specimens with used polymer-type repair mortar and one layer of carbon fiber sheet, widely used for rehabilitation purpose, were also manufactured for the comparison with the specimen with sprayed fiber-reinforced mortar. Carbon fiber sheet has the depth of 0.11 mm, tensile strength of 3,550 MPa, and elastic modulus of 235 GPa. The concrete used for the specimens used coarse aggregates with the maximum dimension of 25 mm and exhibited design strength of 24 MPa. Steel rebars of 13 mm diameter with yield strength of 350 MPa were also used.

3. Experimental results

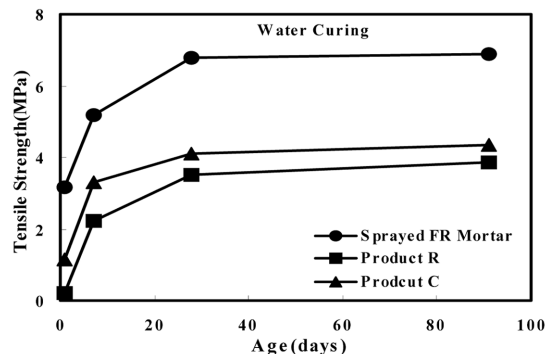
3.1 Strength properties

Fig. 3 plots the compressive strength according to the type of repair material. The sprayed fiber-reinforced mortar exhibits remarkably higher tensile strength than existing repair materials. This is due to the high strength of the repair mortar itself and to the use of PVA fiber, which increases the tensile strength significantly. Fig. 4 compares the elastic modulus of the sprayed fiber-reinforced mortar with those obtained by existing predictive formula. It can be seen that the elastic modulus of the material is underestimated compared to the values predicted by the formulae proposed by the Korean concrete structural design specifications and by the ACI Committee 363. However, this modulus is slightly larger than that obtained through the formula proposed in the design and construction guidelines for high-performance fiber reinforced cementitious composites (HPFRCC) of the Japanese Society of Civil Engineers under the condition of the same strength.¹ The elastic modulus of HPFRCC in these guidelines was 1/2 -2/3 of ordinary concrete. On the other hand, considering the fact that repair is unnecessary for high strength structures and assuming that structures requiring repair generally uses the concrete with strength below 30 MPa, it can be said that the elastic modulus of the sprayed fiber-reinforced mortar is similar to that of concrete structures requiring repair.

Fig. 5 presents the resistance to impact according to the type of repair material. All of the existing repair materials failed before 50th free dropping cycles, which reveals their brittle fracture mode. However, the first micro-crack appeared at the 97th free dropping



(a) Compressive strength



(b) Tensile strength

Fig. 3 Compressive and tensile strengths according to the type of repair material.

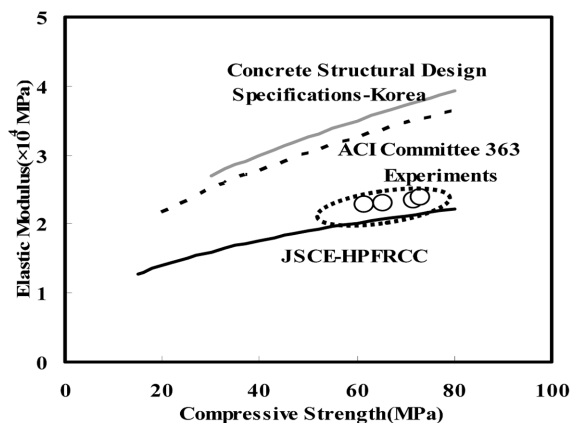


Fig. 4 Comparison of the elastic moduli of the sprayed fiber-reinforced mortar predicted by existing methods.

cycle for the sprayed fiber-reinforced mortar without the appearance of other cracks or failure up to the 500th cycle. Such remark-

Table 4 Features of the tested repaired materials.

Classification	Notation	Number of specimens	Dimensions	Volume fraction of fiber (V_f)	
Standard specimen	Plain	2	Standard specimen	–	
Repairing	Sprayed fiber-reinforced(FR) mortar	VF1.5-T30	1	T = 30 mm	1.5 %
		VF1.2-T50	1	T = 50 mm	1.2 %
		VF1.5-T50	1	T = 50 mm	1.5 %
	The existing	Product R	1	T = 50 mm	–
Reinforcement	The existing	Carbon fiber sheet	1	1 layer reinforced	–

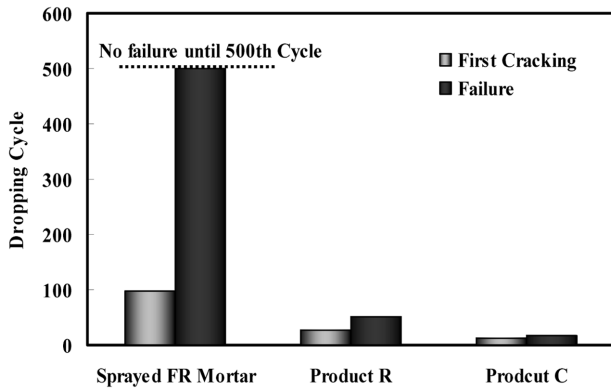


Fig. 5 Impact strength according to the type of repair material.

able resistance to impact of the sprayed fiber-reinforced mortar can be explained by the improvement of the shock absorption performance due to the mixing of PVA fiber into the test specimen.

3.2 Shrinkage properties

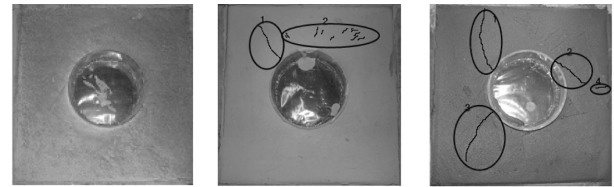
Table 5 summarizes the results of the plastic shrinkage test and Fig. 6 shows images of specimens after plastic shrinkage. The existing products R and C developed cracks of about 56 and 715 mm², respectively, under plastic shrinkage, while the sprayed fiber-reinforced mortar did not manifest any crack.

Fig. 7 summarizes the results of the autogenous and drying shrinkage test. The autogenous and drying shrinkage strains, developed by the sprayed fiber-reinforced mortar, appear to be smaller by about 30~40% and 20%, respectively, compared to those of existing repair materials. The small shrinkage developed in the sprayed fiber-reinforced mortar is due to the use of shrinkage reducing agents and CSA-type expansion agents as well as the admixing of PVA fiber.

Fig. 8 arranges the result of the crack control performance according to the type of repair material. The products C and R developed cracks after approximately 10 days, and cracks appeared after 13 days for the sprayed fiber-reinforced mortar. The product R and C experienced cracks at first to present brittle cracking mode while the sprayed fiber-reinforced mortar exhibited ductile cracking mode without the large development of cracks even after first cracking owing to the bridging action of the PVA fiber.

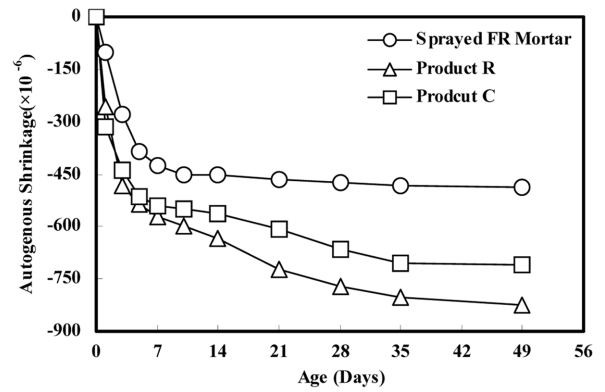
Table 5 Plastic shrinkage test results according to the type of repair material

type	Crack properties				
	No.	Length (mm)	Width (mm)	Area (mm ²)	Total area (mm ²)
Sprayed FR mortar	No crack				
Product R	1*	100	0.5	50	56
	2*	20~60	0.1	2~6	
Product C	1*	190	2	380	715
	2*	150	1	150	
	3*	160	1	160	
	4*	50	0.5	25	

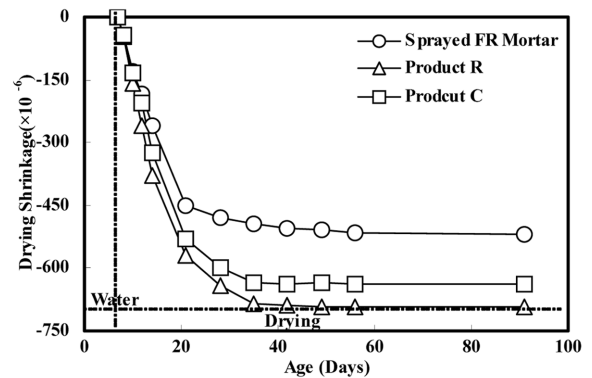


(a) Sprayed FR mortar (b) Existing product R (c) Existing product C

Fig. 6 Images of specimens after plastic shrinkage test.



(a) Autogenous shrinkage



(b) Drying shrinkage

Fig. 7 Shrinkage characteristics according to the type of repair material.

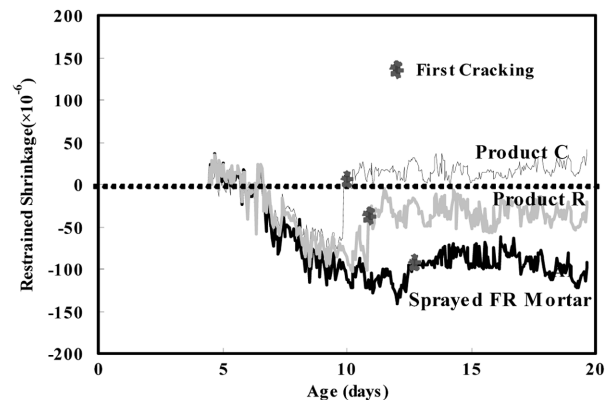


Fig. 8 Strains on the specimens due to confining shrinkages.

3.3 Durability

The resistance against carbonation was evaluated by the criteria set forth by KS F 4042. Fig. 9 shows the carbonation depth according to the type of repair material. The results show that the

sprayed fiber-reinforced mortar not only satisfy the criteria and but also is more resistant compared with product R and C.

Fig. 10 presents the analysis results with respect to the resistance to salt attack. Regardless of the repair technique, all the results were evaluated as “very low” according to the criteria proposed by KS F 2711. Even though all the experimental values satisfied the KS F 4042 to be below the electric charge of 1,000 Coulombs, the sprayed fiber-reinforced mortar appears to exhibit the most resistance to salt attack among all the considered repair methods.

The results for the relative dynamic modulus of elasticity are summarized in Fig. 11. The product R exhibited degraded resistance to freezing and thawing after the first cycle, with a 60% decrease in relative dynamic modulus of elasticity at the failure state after 120 freezing-thawing cycles. On the other hand, the sprayed fiber-reinforced mortar and the product C presented a remarkable relative dynamic modulus of elasticity, exceeding 80% even after 300 cycles at the completion of freezing-thawing. Especially, the sprayed fiber-reinforced mortar exhibited superior resistance to freezing-thawing with a relative dynamic modulus of elasticity of 98%.

Fig. 12 plots the variation of the flexural strength before and after the freezing-thawing test. Even if the existing products without the fiber reinforcement satisfied the criteria of KS F 4042 before the test, their flexural strength dropped below 6 MPa after the completion of the test. However, the sprayed fiber-reinforced

mortar showed an insignificant variation of the flexural strength before and after the freezing-thawing test, thus satisfying the KS standards. Consequently, the existing products exhibit degradation due to the action of freezing-thawing leading to the drop of the flexural strength below the KS criteria, which is likely to initiate cracking in the repair layer, while the sprayed fiber-reinforced mortar appears to be immune to the action of freezing and thawing.

Fig. 13 depicts the experimental results for the bond strength before and after freezing-thawing cycles. The test was repeated for 300 cycles. Before the start of freezing and thawing cycles, all the

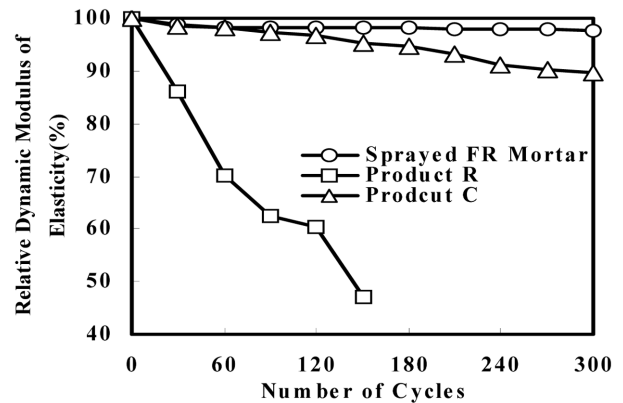


Fig. 11 Results of relative dynamic modulus of elasticity.

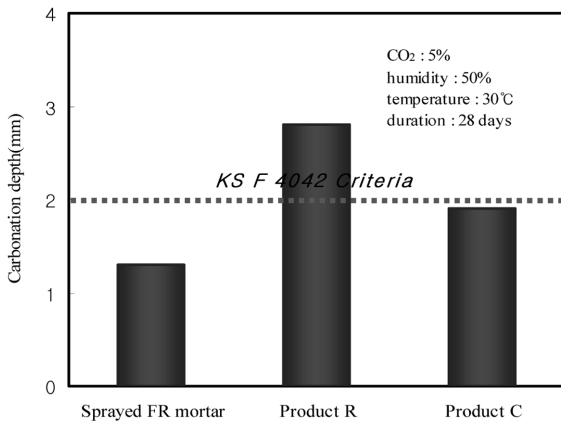


Fig. 9 Evaluation of the resistance to carbonation according to the type of repair material.

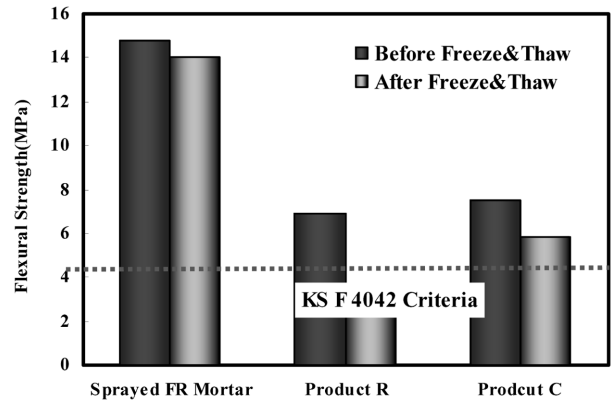


Fig. 12 Change in the flexural strength before and after freezing-thawing test.

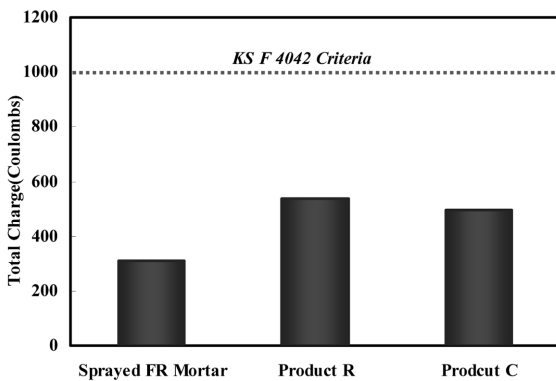


Fig. 10 Evaluation of the resistance to salt attack according to the type of repair material.

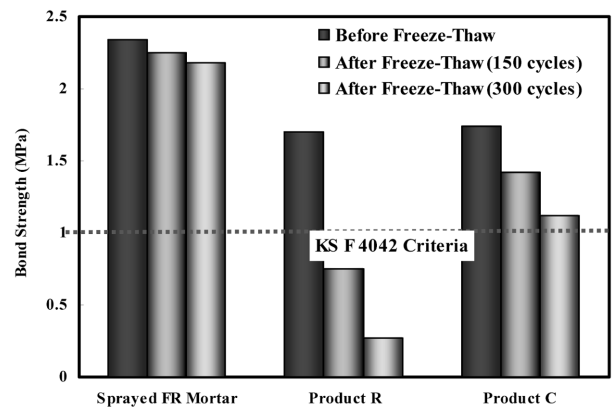


Fig. 13 Comparison of Bond Strength before and after freezing-thawing cycles.

materials satisfied the criteria of KS F 4042, which specifies that the repair material should be over than 1 MPa in bond strength. Especially, the sprayed fiber-reinforced mortar exhibited 1.35 times higher bond strength than that of compared materials. But after the freezing and thawing cycles, product R showed decreased bond strength to be below the criteria at 150 cycles and resulted in nearly zero bond strength at 300 cycles. Moreover, Product C showed a barely noticeable decrease in bond strength while satisfying the criteria both at 150 and 300 cycles. On the other hand, the sprayed fiber-reinforced mortar hardly showed a difference in the bond strength before and after the freezing-thawing cycles.

3.4 Flexural performance

The compressive strength of normal concrete was 26.4 MPa. The sprayed fiber-reinforced mortar, product R and product C had compressive strength of 68.6 MPa, 31.2 MPa and 64.3 MPa, respectively. Table 6 summarizes the results of the load-displacement relationship of the beam specimen and the strain of the tension rebar. Figure 14 and Figure 15 plot the corresponding curves. Assuming the yield strength of $f_y = 350$ MPa for the main rebar of 13mm diameter, the yield load of the main rebar is defined as the load P_y for which the yield strain μ_e is equal to 1,750. In addition, the yield load of the reinforced specimen is expressed in terms of the ratio of the yield loads of the carbon reinforced specimen (P_y) to those of the specimen without the reinforcement.

Since both the strength and the stiffness of the specimens using existing repair materials are not exhibiting any increase compared to the reference non-reinforced specimen, it is likely that no reinforcement effect should be expected for the specimens using existing repair materials. The specimen bonded with one layer of carbon fiber sheet, which corresponds to the reinforcement methods widely selected recently, is showing a reinforcement effect with an increase of 50.7% in the maximum strength compared to the reference specimen. However, debonding of the sheet occurs suddenly at a displacement of 15.6 mm, which reveals a significant reduction in the ductility. Accordingly, even if the carbon fiber sheet reinforcement technique results in a reinforcement effect with respect to the load bearing capacity at early construction, a careful attention should be paid to the sudden failure at the interface between the sheet and concrete that eventually leads to a brittle fracture at failure.

The increase in the maximum strength and stiffness was verified for all of the 3 specimens using the sprayed fiber-reinforced

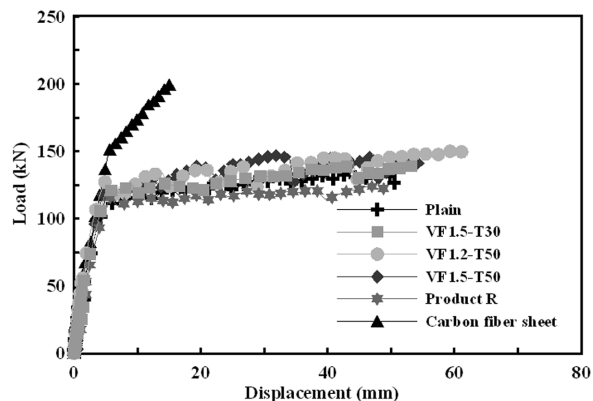


Fig. 14 Load-displacement relationships.

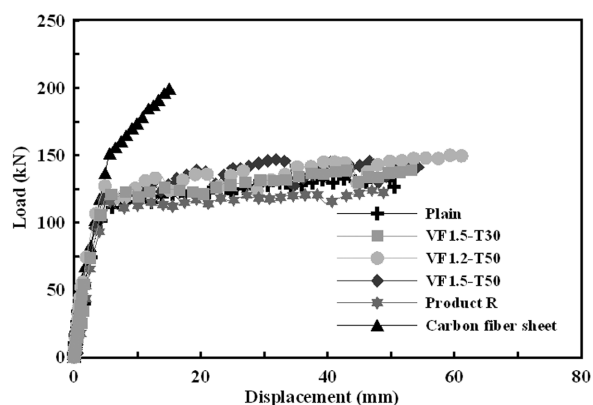


Fig. 15 Relationships of load versus strain of the rebar.

mortar. Among these specimens, the one with admixing of 1.5% fiber in the 50mm-thickness reinforcement manifested the largest increase in the maximum strength, corresponding to an augmentation of about 15% compared to the reference specimen as well as an approximately 17% increase in the yield strength. In addition, the yield strain increased by 1.2 times compared to the reference specimen regardless of the type of the specimens and the proportion of fiber and reinforcement thickness. Consequently, regarding the fact that the sprayed fiber-reinforced mortar also exhibits reinforcement effect and considering the durability and load bearing capacity globally, the sprayed fiber-reinforce mortar is evaluated to be sufficiently effective as a material combining both rehabilitation and reinforcement effects.

Table 6 Structural test results.

Specimen	Load-displacement results			At yielding of tension rebar		
	Max. load (kN)	Yield load (kN)	Yield displ. (mm)	P_y (kN, mean)	Reinforced/ Non-reinforced	Reinforced/ Carbon fiber sheet
plain 1	133.58	98.6	3.99	98.2	1.00	0.77
plain 2	129.89	97.9	4.19			
VF1.5-T30	140.89	121.7	5.04	121.7	1.24	0.95
VF1.2-T50	148.95	117.9	4.57	117.9	1.20	0.92
VF1.5-T50	151.87	121.0	4.27	121.0	1.23	0.95
Product R	125.09	99.3	4.57	99.3	1.01	0.78
Carbon fiber sheet	201.35	127.6	4.52	127.6	1.30	1.00

4. Conclusions

In order to explore the use of high-toughness fiber-reinforced mortar mixed with PVA fiber as a repair material, its strength, shrinkage characteristics and the change in mechanical properties before and after freezing-thawing cycles as well as the flexural performance of beam specimens were compared with those of existing repair materials, and the results are summarized in the following.

1) The sprayed fiber-reinforced mortar exhibited the strength, elastic modulus, bond and impact load significantly superior to existing repair materials.

2) The sprayed fiber-reinforced mortar did not initiate cracking under plastic shrinkage but manifested an approximately 30% reduction in the autogenous and drying shrinkages compared to existing repair materials. It also exhibited such a remarkable dimensional stability as its exceptional crack control performance.

3) The sprayed fiber-reinforced mortar presented no definite difference in the flexural and bond strength before and after freezing-thawing cycles, while the existing repair materials exhibited a considerable reduction in their bond and flexural strength.

4) The sprayed fiber-reinforced mortar showed not only a significant improvement in the load bearing capacity compared to existing restorative materials but also enhanced the ductility without the occurrence of interfacial failure or brittle fracture. The sprayed fiber-reinforced mortar also exhibited a reinforcement effect similar to an existing reinforcement method (95% of the reinforcement effect of one layer carbon fiber sheet).

Acknowledgements

This research was supported by a grant (05CCTRD09 - High Performance Construction Material Research Center) from Construction Core Technology Program funded by Ministry of Construction & Transportation of Korean government and WONHA Engineering & Construction Co., Ltd.

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