-Technical Paper-

THE MECHANICAL PROPERTIES OF SPRAYED DUCTILE FIBER-REINFORCED MORTAR AS A REPAIRING MATERIAL

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ABSTRACT

Most of the existing repair materials have some weaknesses such as brittle fracture, quite difference in modulus of elasticity compared with the structures and cracking. This paper presents the results of experimental study on the performance of sprayed PVA fiber-reinforced mortar as a repair material. We evaluated the mechanical properties and the strengthening effect of the material. 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 including large quantities of PVA fiber or steel fiber have been developed recently and studies to find applications in diverse domains are currently conducted actively [1-4]. Regard to economical efficiency, high toughness fiber- reinforced mortar becomes competitive when applied as repair material with small quantities rather than the casting of large volume for the main body of structures in field. The authors have developed a wet spraying technique using PVA fiber-reinforced ductile mortar and attempt to exploit it for rehabilitation [5, 6]. Differently from 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 dimensional stability making it possible to expect increased 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, poor attention has been devoted by the Korean researchers to examine systematically the extent of the improvement brought by such fiber-reinforced ductile mortar compared to existing restorative materials and techniques. Accordingly, this study investigates the repair effects of the sprayed PVA fiber-reinforced mortar through estimating strength, shrinkage, change of mechanical properties before and after freezing and thawing cycles and flexural performance in order to secure its stability for use on field

2. TEST PROGRAMS

2.1 Materials

Table 1 resumes the features and types of the repair materials adopted for the tests. A value of 0.2 for the water to mortar ratio (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 by cement, fly-ash and CSA-type expansion agents. The same tests have also been performed on the existing product R using natural cellulose fiber in the mortar composed with polymer and the existing product C without fiber in order to allow comparison with the sprayed fiber-reinforced mortar.

2.2 Test Methods

Compression, tension, bond and impact tests

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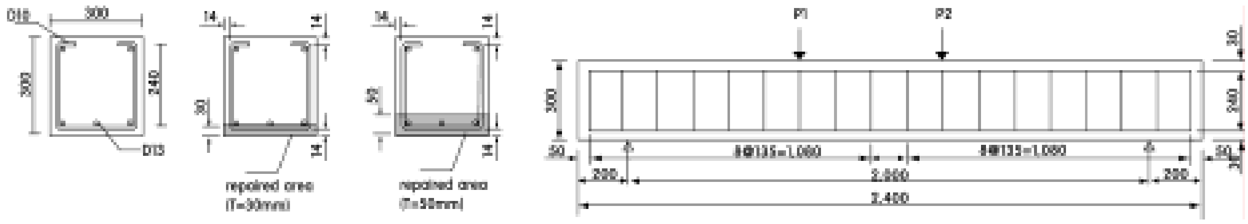


Fig.1 Specimens for flexural tests

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

have been conducted in order to examine the strength characteristics of the sprayed fiber-reinforced mortar. The strength test was performed after water curing and at definite age. Plastic shrinkage, autogenous shrinkage and drying shrinkage tests were executed. And also confined drying shrinkage test was performed to evaluate the crack control performance. The change of mechanical properties has been examined by means of freezing-thawing cycle tests. The resistance to freezing and thawing cycles was examined according to ASTM C 666-B and the corresponding relative 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 2.

Specimens with dimensions of 300×300×2,400mm were manufactured as shown in Figure 1 in order to examine the flexural load bearing capacity of the repaired structure with the sprayed fiber-reinforced mortar. Table 3 summarizes the details of the specimens and the applied techniques. Two non-reinforced specimens (Plain) were manufactured. Three specimens applying the sprayed fiber-reinforced mortar were fabricated to present a reinforcement thickness of 30mm and 50mm with proportions of PVA fiber set to 1.2% and 1.5%. Specimens applying used polymer-type repair mortar and one layer of carbon fiber sheet widely used for rehabilitation purpose were also manufactured for comparison with the sprayed fiber-reinforced mortar. The concrete used for the specimens makes use of coarse aggregates with maximum dimension of 25mm and exhibits design strength of 24MPa. 13mm diameter steel rebars with yield strength of 350MPa were used.

3. RESULTS

3.1 Strength Properties

Figure 2 plots the compressive strength according to the type of repair material. The sprayed fiber-reinforced mortar exhibits higher strength than existing repair materials with a remarkable tensile strength. This is due to the high strength of the repair mortar itself and to the use of PVA fiber, which increases significantly the tensile strength. Figure 3 compares the elastic modulus of the sprayed fiber-reinforced mortar with those obtained by former predictive formula. It can be seen that the elastic modulus of the material is underestimated compared to the values provided 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 of high-performance fiber reinforced cementitious composites (HPFRCC) of the Japanese Society of Civil Engineers under the same strength [1]. The elastic modulus of HPFRCC in these guidelines is

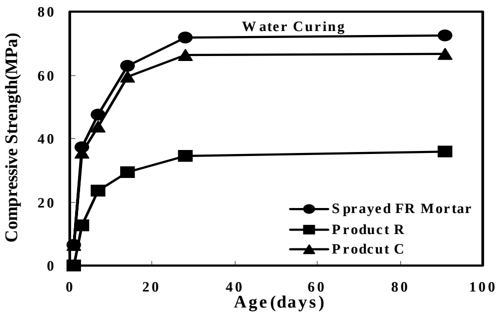
Table 2 The details of each test method

Properties	Testing Method	Specimen	Condition
Compressive strength	KS L 5105(JIS A 6203)	50×50×50mm	Curing at 20±3°C for 28days
Tensile strength	KS L 5104(ASTM C190)	Dog-bone shaped	
Bond strength	KS F 4042(JIS A 6203)	–	
Impact strength	KS F 2221(JIS A 1421)	–	
Plastic shrinkage	PVC-Ring Method	500×500×500mm	Temperature: 30±3°C, Humidity: 40±3% Wind : 4~4.5m/sec, 24hours
Autogenous shrinkage	KS F 2586(JCI 2002)	100×100×400mm	Temperature: 20±3°C, Humidity: 60±5%
Drying shrinkage	KS F 2424(JIS A 1129)		
Crack resistance	Ks F 2592(JIS A 1151)	–	

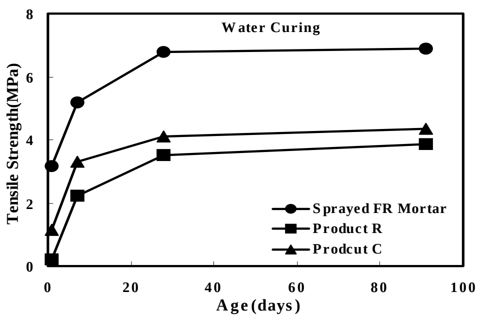
Table 3 Features of the tested repair materials

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 = 30mm	1.5 %
		VF1.2-T50	1	T = 50mm	1.2 %
		VF1.5-T50	1	T = 50mm	1.5 %
	The existing	Product R	1	T = 50mm	–
Reinforcement	The existing	Carbon fiber sheet	1	1 layer reinforced	–

corresponding to 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 are generally using concrete with strength below 30MPa, it can be said that the elastic modulus of the sprayed fiber-reinforced mortar is similar to that of concrete structures requiring repair.



(a) Compressive strength



(b) Tensile strength

Fig. 2 Compressive and tensile strengths according to the type of repair material

Figure 4 presents the resistance to impact according to the type of repair material. All of the existing repair materials are experiencing failure before 50 free dropping cycles, which reveals their brittle fracture mode. However, the first micro-crack appears at the 97th free dropping cycle for the sprayed fiber-reinforced mortar without appearance of other cracks or failure until the 500th cycle. Such remarkable resistance to impact of the sprayed fiber-reinforced mortar can be explained by the improvement of the shock absorption performance according to the introduction of PVA fiber.

3.2 Shrinkage Properties

Table 4 summarizes the results of the plastic shrinkage test. The existing products R and C developed respectively cracks of about 56 and 715mm^2 under plastic shrinkage, while the sprayed fiber-reinforced mortar did not experience any crack.

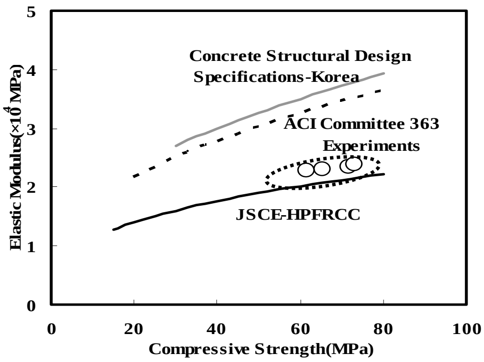


Fig. 3 Comparison of the elastic modulus of the sprayed fiber-reinforced mortar

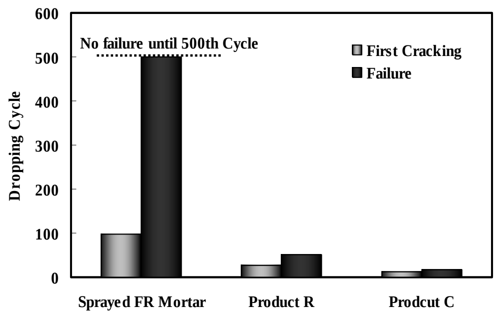
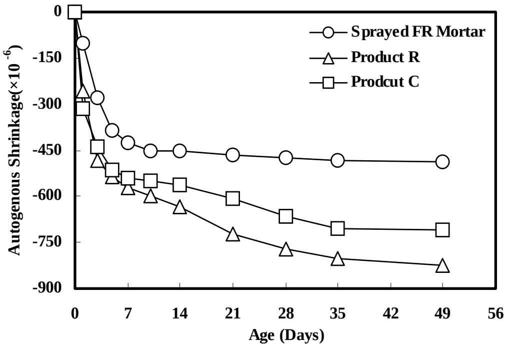


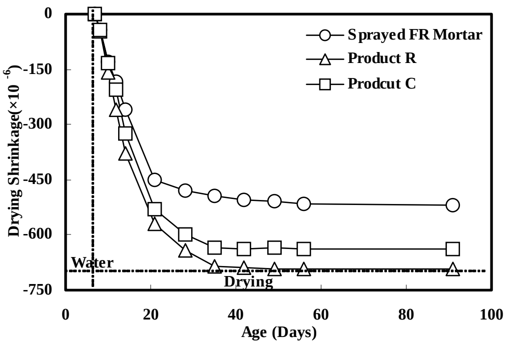
Fig. 4 Impact strength according to the type of repair material

Table 4 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) Autogenous shrinkage



(b) Drying shrinkage

Fig. 5 Shrinkage characteristics according to the type of repair material

Figure 5 summarizes the results of the drying shrinkage test. The autogenous and drying shrinkage strains developed by the sprayed fiber-reinforced mortar appear to be smaller respectively by about 30~40% and 20% 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.

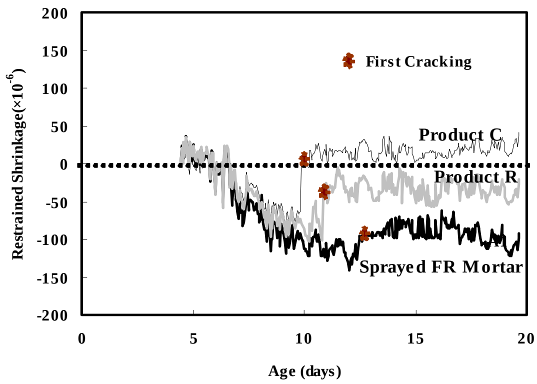


Fig. 6 Strain due to confining shrinkage

Figure 6 arranges the resulting 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 large development of cracks even after cracking owing to the bridging action performed by the PVA fiber.

3.3 Change in Mechanical Properties before and after Freezing and Thawing Cycles

The results for the relative dynamic modulus of elasticity are summarized in Figure 7. The product R exhibited degraded resistance to freezing and thawing since the first cycles with a decrease of 60% for the relative dynamic modulus of elasticity at failure after 120 freezing-thawing cycles. On the other hand, the sprayed fiber-reinforced mortar and the product C presented remarkable relative dynamic modulus of elasticity exceeding 80% even after 300 cycles corresponding to 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%.

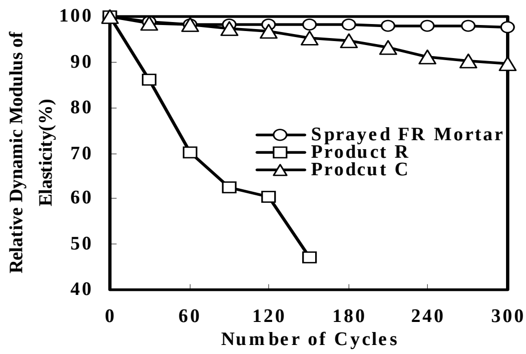


Fig. 7 Results of relative dynamic modulus of elasticity

Figure 8 plots the variation of the flexural strength before and after the freezing-thawing test. Even if the existing products satisfied the criteria of KS F 4042 before the test, their flexural strength appeared to drop below 6MPa after the completion of the test. However, the sprayed fiber-reinforced mortar presented insignificant variation of the flexural strength before and after the freezing-thawing test, and satisfied thus 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 cracks of the repair layer, while the sprayed fiber-reinforced mortar appears to be immune to the action of freezing and thawing.

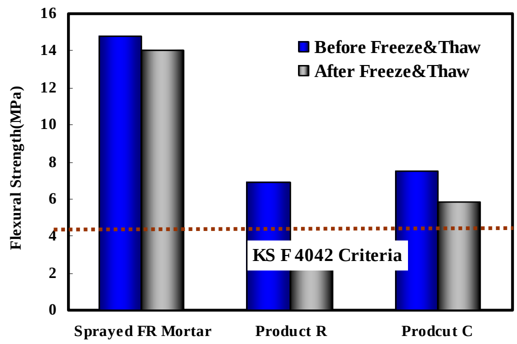


Fig. 8 Change of the flexural strength before and after freezing-thawing test

Figure 9 is the experimental results of bond strength before and after freezing-thawing cycles. The test was repeated by 300 cycles. Before freezing and thawing cycles, all the materials satisfied the criteria KS F 4042 which regulate that the repair material should be over than 1 MPa in bond strength and especially the sprayed fiber-reinforced mortar exhibited higher bond strength by 1.35 times than the compared materials. But after cycles, product R showed the deceased bond strength under the criteria at 150 cycles and nearly no bond strength at 300 cycles. And also Product C showed a little noticeable decrease in bond strength even though it satisfied the criteria both at 150 and 300 cycles. On the other hand, the sprayed fiber-reinforced mortar hardly had a difference between before and after cycles.

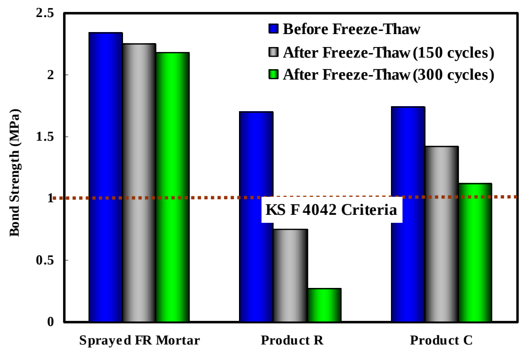


Fig. 9 Comparison of Bond Strength before and after Freezing Thawing Cycles

3.4 Flexural Performance

Table 5 summarizes the results of the load-displacement relationship of the beam specimen and the strain of the tension rebar. Figure 10 and Figure 11 plot the corresponding curves. Assuming that a yield strength of f_y = 350MPa 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_ε = 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) and the non-reinforced specimen.

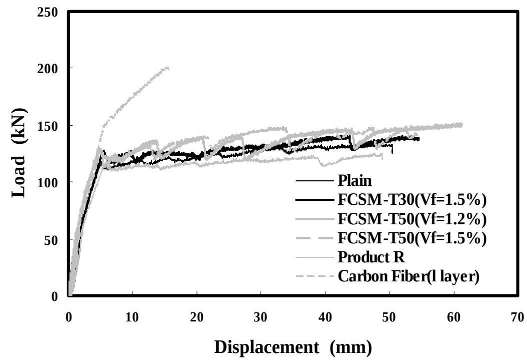


Fig. 10 Load-displacement relationships

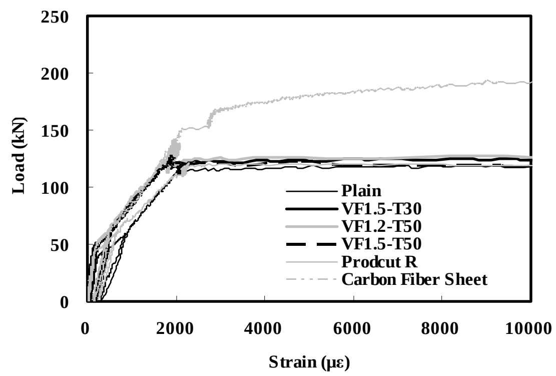


Fig. 11 Relationships of Load versus strain of rebar

For the specimens using existing repair materials, since both strength and stiffness are not exhibiting any increase compared to the reference

Table 5 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

non-reinforced specimen, it is likely that no reinforcement effect should be expected. The specimen bonded with 1 layer of carbon fiber sheet, which corresponds to a reinforcement methods widely adopted recently, is showing reinforcement effect with an increase of 50.7% of the maximum strength compared to the reference specimen. However, debonding of the sheet occurs suddenly at a displacement of 15.6mm, which reveals significant reduction of the ductility. Accordingly, even if the carbon fiber sheet reinforcement technique is providing reinforcement effect regard to the load bearing capacity at early construction, attention shall be paid to the sudden failure at the interface between the sheet and concrete that is the eventual brittle fracture at failure.

Increase of the maximum strength and stiffness was verified for all of the 3 specimens adopting the sprayed fiber-reinforced mortar. Among these specimens, the one with admixing of 1.5% of fiber in the 50mm reinforcement thickness presented the largest increase of the maximum strength corresponding to an augmentation of about 15% compared to the reference specimen, and an increase of approximately 17% of the yield strength. In addition, the yield strain increased by 1.2 times compared to the reference specimen regardless of the proportion of fiber and reinforcement thickness and without clear difference between the types of specimen. Consequently, regard to the fact that the sprayed fiber-reinforced mortar also exhibits reinforcement effect, and considering globally the durability and load bearing capacity, the sprayed fiber-reinforce mortar can be seen to be sufficiently applicable as a material combining both rehabilitation and reinforcement effects.

4. CONCLUSIONS

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

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

(2) The sprayed fiber-reinforced mortar did not initiate crack under plastic shrinkage, and presented reduction of the autogenous and drying shrinkages by approximately 30% compared to existing repair materials. It also exhibited remarkable dimensional stability like exceptional crack control performance.

(3) The sprayed fiber-reinforced mortar presented no quite difference in flexural and bond strength between before and after freezing-thawing cycles while the existing repair materials experienced considerable drop of their bond and flexural strength.

(4) The sprayed fiber-reinforced mortar exhibited not only significant improvement of the load bearing capacity compared to exiting restorative materials but also enhanced ductility without occurrence of interface failure or brittle fracture. The sprayed fiber-reinforced mortar also presented reinforcement effect nearly similar to existing reinforcement method (95% of the reinforcement effect of 1 layer of carbon fiber sheet).

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