Wet-mix Shotcreting Application of High Ductile Fiber Reinforced Mortar Designed by Optimizing Mix Proportion

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ABSTRACT

High ductile fiber reinforced mortar suitable for wet-mix shotcreting (sprayable ductile mortar) in the fresh state, while maintaining tensile strain-hardening behavior in the hardened state, has been developed based on micromechanics and workability control. In the development concept of sprayable ductile mortar, micromechanics is adopted to properly select the matrix, fiber, and interface properties to exhibit strain hardening and multiple cracking behaviors in the composites. Within the pre-determined micromechanical constraints, the workability is controlled by optimizing mix proportions. A series of spray tests show the excellent pumpability and sprayability of the sprayable ductile mortar. Subsequent direct tensile tests demonstrate that the tensile performance of sprayed mortar is comparable to that of cast mortar, for the same mix design.

1. INTRODUCTION

High ductility has been achieved by the use of micromechanical tool[1] which allows the composite to exhibit extreme tensile strain capacity while using a moderate amount of fiber. Sprayable ductile mortar can be defined as the fiber-reinforced mortar conveyed through a hose and pneumatically projected from a nozzle onto place. The fresh mix should be moderately deformable, i.e., pumpable under the pumping, so it would efficiently move through the hose to the nozzle. Once it is sprayed onto the substrates, however, it should be viscous enough to stay adhered to the substrate and to remain cohesive without composite ingredient segregation.

The objective of this study is to develop a sprayable ductile mortar to exhibit fluid properties suitable for spraying with comparable ductility to the fiber-reinforced mortar cast by ordinary processing. To attain such unique fresh properties, while embodying the ductile performance of fiber-reinforced mortar, we adopt the method to control the processing and micromechancial parameters in a parallel manner. Previous work[2] has confirmed that this approach is highly beneficial to achieving the desired properties of both fresh and hardened material.

2. DESIGN OF MIX PROPORTIONS

2.1. Micromechanical design

Micromechanical design utilized herein is mainly focused on achieving strain hardening in uniaxial tension since the tensile ductility can be representative of material ductility. A fundamental requirement for strain hardening is that steady state cracking occurs, which requires the crack tip toughness J_{tip} to be less than the complementary energy J_b' calculated from the bridging stress σ vs. crack opening δ curve, as illustrated in Fig. 1[2],

$$J_{tip} \le \sigma_o \delta_o - \int_0^{\delta_o} \sigma(\delta) d\delta \equiv J_b' \quad (1)$$

$$J_{tip} = \frac{K_m^2}{E_c} \quad (2)$$

where σ_o is the maximum bridging stress corresponding to the opening δ_o and E_c is the composite elastic modulus. Another condition for strain hardening is that the tensile first crack strength σ_{fc} must not exceed the maximum bridging stress σ_o,

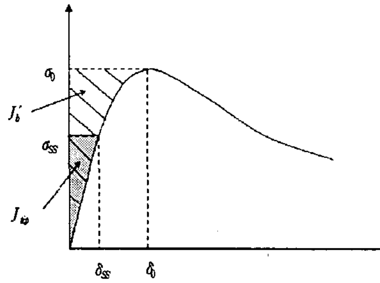

Fig. 1 A typical $\sigma(\delta)$ curve for strain-hardening composite

$$\sigma_{fc} < \sigma_o. \quad (3)$$

Details of these micromechanical analyses can be found in Li and co-workers. Satisfaction of Equation (1) and (3) is necessary to achieve high ductile behavior represented by strain-hardening behavior in uniaxial tension.

2.2. Materials

High ductile fiber reinforced mortar is composed of common mortar matrix and polymer fibers. In this study, a PVA fiber (Kuraray Co. Ltd., Japan) was used as the reinforcing fiber. KS Type I ordinary portland cement (C, Ssangyong Co.), silica sand (S, Saehan Silica Co.), ground granulated blast furnace slag (Slag, Basic Materials Co.), and alumina cement (CA, Union Co.) were used as the major ingredients in the matrix. Chemical admixtures comprised of high range water reducing admixture (HRW, Atex Co.) and hydroxypropylmethylcellulose (HPMC, Atex Co.), were used to modify the fluid properties.

2.3. Micromechanical constraints and Workability control

We determined appropriate range of ingredients loading from extensive micromechanical analyses and experiments[3]. It was disclosed that W/C of 0.50, S/C ratio of 0.8, Slag/C ratio of 0.25 would be appropriate to achieve satisfactory matrix properties as well as interfacial properties. These adjustments would set the fiber volume fraction (V_f) of 2.0%. Slag have been added to enhance workability and mortar strength, while satisfying strain-hardening requirements. The positive effects of Slag have been demonstrated by the authors[3]. They have also revealed that the optimized mix proportion for ordinary casting is as displayed in Table 1(Mix 11). To develop a satisfactory wet-mix shotcreting process, we focussed on modulating dosage of chemical admixtures with the assistance of reactive particles, which provides desirable adhesion and cohesion after spraying. First, to achieve a moderate workability suitable for pumping, a proper concentration of chemical admixtures to disperse cement particles was determined. To enhance viscosity of fresh mortar over time, reactive particles (CA) were also introduced. Based on the previous study[2], CA dosage was limited to 3% of cement weight since overdose of reactive particles can be detrimental to achieving satisfactory pumpability, leading to undesirable quick setting of the composite.

Table 1. Mix proportions for spray test.

Mix	C	W	S	BFS	HPMC	HRW	CA	V_f
11	1.00	0.5	0.80	0.25	0.0005	0.020	0	0.02
22	0.97	0.5	0.80	0.25	0.0005	0.020	0.03	0.02
33	0.95	0.5	0.80	0.25	0.0005	0.020	0.05	0.02

(C: cement; W: water; S: sand; BFS: blast furnace slag;
HPMC: hydroxy propyl methyl cellulose;
HRW: high range water reducing admixture;
CA: calcium aluminate cement; V_f: fiber volume fraction)
All numbers are mass ratios except for V_f.

Table 2. Results of spray tests.

Mix	Slump test		Pump-out test	Fill-up test	Spray-on test (thickness)	
	Γ_0	Γ_{rest}	Pumping pressure	Rest time*	Vertical surface	Overhead surface
22	3.1	2.0	< 1 MPa	15 min.	45 mm	-

(-: not available; *: rest time demanded for the fresh mix to attain a viscosity to meet the requirement of fill-up test)

3. EXPERIMENTS AND RESULTS

3.1. Spray Test

An N2V (PFT Gmbh & Co. KG, Iphofen, Germany) spiral pump was used for spraying process in this study. This system was known to be particularly suitable for premixed liquids and mortar with the maximum grain size of 3mm.

Several mortar mixes were designed (Table 1) and sprayed to determine suitable fresh properties for spraying process in terms of deformability Γ which can be obtained by using a slump cone test. A regular slump cone (diameter, D_0=20cm) for the conventional slump test was employed to measure the deformability Γ which were calculated by Equation (4) with the measured maximum diameter of the spread D_1 and the diameter perpendicular to it D_2,

$$\Gamma = \frac{(D_1 \times D_2) - D_0^2}{D_0^2} \qquad (4)$$

As displayed in Table 2, no excess pumping pressure was observed during spray tests, indicating superior pumpability when compared to that observed in the previous work[2]. This is because we have introduced Slag particles, which were expected to enhance workability and pumpability as well due to their spherical

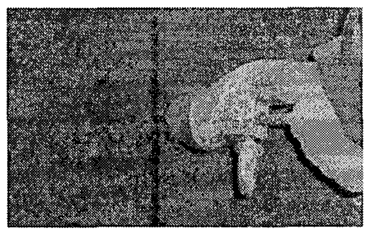

Fig. 2 Spray test onto vertical surface (Mix 22)

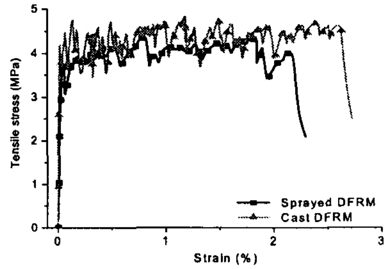

Fig. 3. Uniaxial tensile stress versus strain curves

geometry in shape.

The spray tests revealed that the suitable deformability when spraying, in terms of Γ, was estimated to be around 2.0. The maximum thicknesses of 45mm (Mix 22) was obtained spraying onto vertical surface in a continuous process. Mix 33 (CA/C=5%) was easily stuck inside hose and sprayed in lumps even when it came out. In constrat, Mix 11 (CA/C=0%) was too flowable to obtain sufficient viscosity after spraying while it was moderately deformable under pumping pressure. This is mainly due to the overdose/absence of CA particles.

3.2. Tensile performance of the sprayed mortar

To confirm the ductile strain-hardening behavior of the sprayed ductile mortar and to compare it with the test results of cast specimens, direct tensile tests were performed. As shown in Fig. 3, the strain capacity of the sprayed ductile mortar, which is around 2%, is comparable to that of the specimens cast with external consolidation.

4. CONCLUSIONS

(1) A high ductile fiber-reinforced mortar suitable for wet-mix shotcreting which exhibits proper pumpability and sprayability in the fresh state and strain hardening behavior in the hardened state has been successfully developed by using micromechanical design and workability control.
(2) W/C ratio of 0.50, S/C ratio of 0.8, Slag/C ratio of 0.25, and fiber volume fraction of 2% were employed based on micromechanics. Desired fresh properties within the limited range of loading of solid ingredients were achieved by optimizing concentrations of HRW, HPMC, and CA particles.
(3) Spray tests revealed that the mortar exhibited sufficient pumpability and sprayability. The maximum thicknesses of 45mm was obtained spraying onto vertical surface. Uniaxial tensile test results demonstrated strain-hardening behavior of sprayed ductile mortar.

ACKNOWLEDGEMENTS

Reaserch funding from kicttep to KAIST(A06-04) is gratefully acknowledged.

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