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PIGMENTABLE ENGINEERED CEMENTITIOUS COMPOSITES

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Abstract

In this paper, pigmentable Engineered Cementitious Composites (ECC) incorporating white cement was developed for architectural applications. The adoption of white cement in ECC results in changes in micromechanical properties different from standard ECC. Material re-engineering of white ECC to improve its mechanical properties was demonstrated in this paper based on micromechanical principles.

1. INTRODUCTION

Large form-factor architectural elements, such as counter tops, walls, and floors, are generally made from natural stones or rocks. Recent development on pigmenting technology [1] has made it possible to make large form-factor architectural elements of mortar or concrete with the advantage in low cost, lightweight, and shape versatility. However, cracking and chipping during handling and transportation is of great concern for large form-factor architectural elements [2] due to the brittleness of mortar and concrete materials.

Engineered Cementitious Composites (ECC), a ductile concrete material with extreme tensile ductility exceeding 3%, serves as a potential material solution for preventing cracking and chipping of large form-factor architectural elements. Figure 1 shows a typical uniaxial tensile stress-strain curve of standard PVA-ECC M45, revealing the characteristic strain-hardening response when loaded beyond the elastic stage. The tensile strain capacity of ECC is several hundred times that of normal concrete

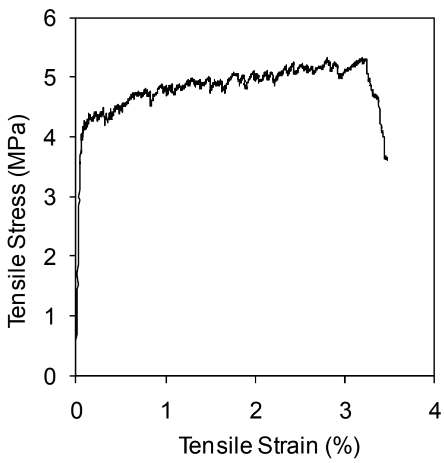

Figure 1: A typical uniaxial tensile stress-strain curve of standard PVA-ECC M45

and the fracture toughness of ECC is similar to that of aluminum alloys [3].

Development of ECC is guided by micromechanical principles [4], which provide quantitative links between composite mechanical behavior and the properties of the individual constituent, which are the fiber, matrix and interface. The design strategy of strain-hardening fiber reinforced brittle matrix composites lies in recognizing and tailoring the interaction of those constituents.

Current ECC uses Type I Portland cement and other mineral admixtures, such as fly ash, as binders. The resulting material is grayish and not pigmentable. Therefore, there is a need to develop a pigmentable ECC for architectural applications.

2. MATERIALS ENGINEERING OF PIGMENTABLE ECC

In the first attempt of pigmentable ECC development, Portland cement was replaced by white cement and fly ash was excluded in the mix design due to the dark color of these two ingredients. The mix design of the first version of white ECC (white ECC v1) can be found in Table 1. The white cement used was a type I white cement. F-110 fine silica sand with a maximum grain size of 250 μm and an average size of 110 μm was adopted in the mixture. The superplasticizer used was a polycarboxylate-based high range water reducer. Polyvinyl Alcohol (PVA) fiber REC-15 from Kuraray Co., Ltd., Japan, was used at a moderate volume fraction of 2% in this study. The dimensions of the PVA fiber were 8 mm in length and 39 μm in diameter on average. The nominal tensile strength of the fiber was 1600 MPa and the density of the fiber was 1300 kg/m^3. The fiber was surface-coated by oil (1.2% by weight) in order to reduce the fiber/matrix interfacial bond strength. This decision was made through ECC micromechanics material design theory for PVA-ECC M45 and has been experimentally validated in previous investigations [5].

Table 1: Mix design of white ECC v1

	Cement	Sand	Water	Superplasticizer	PVA Fiber [by volume]
White ECC v1	1	1	0.34	0.004	0.02

The 28 days compression test was carried out on cylinders measuring 75 mm in diameter and 150 mm in length following ASTM C39 standard. The cylinder ends were capped with a sulfur compound to ensure a flat and parallel surface and better contact with the loading device. The tensile stress-strain behavior at the age of 28 days was determined from direct uniaxial tensile tests in coupon specimens measuring 152 mm by 76 mm by 13 mm following procedures described in [6]. A servo hydraulic testing system was used in displacement control mode to conduct the tensile test. The loading rate used was 0.0025 mm/s to simulate a quasi-static loading condition.

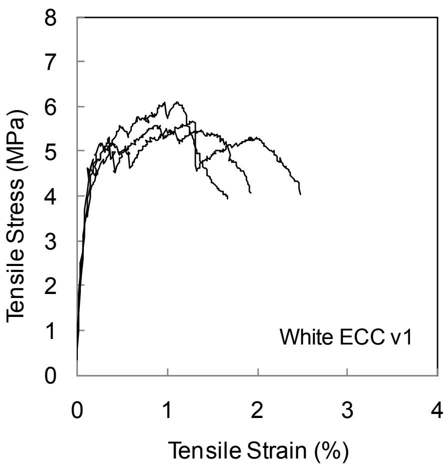

Figure 2: Uniaxial tensile stress-strain curves of white ECC v1

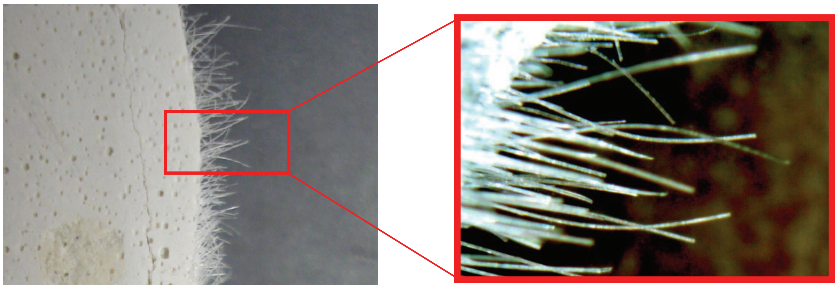

Figure 3: Microscopic observation of fracture surface of white ECC v1

Figure 2 shows the uniaxial tensile stress-strain curves of the white ECC v1. This first version exhibits tensile strain hardening behavior with an average tensile ductility of 1.3±2 % and an average tensile strength of 5.7±0.3 MPa. The 28 day compressive strength of white ECC v1 is 60 MPa. It was found that the tensile strain capacity is substantially lower than that of the standard ECC M45. A microscopic observation of the fracture surface of white ECC v1 reveals that most of the PVA fibers were pulled out instead of rupture (Figure 3). This suggests that the interfacial bond of white ECC v1 is lower than that in regular ECC. Single fiber pullout tests were conducted to quantify the bond properties of white ECC v1. Details of the test setup of single fiber pullout test can be found in [7]. The fiber/matrix interfacial bond properties can be characterized by three parameters, namely interface chemical bond G_d, interface frictional bond τ_0, and slip hardening coefficient β. Table 2 shows the test results from single fiber pullout tests. As can be seen, white ECC v1 has lower interface frictional bond when compared with PVA-ECC M45. The result suggests that the PVA fiber strength in white ECC v1 has not been fully utilized. Improving the fiber bridging capacity of white ECC by tailoring fiber, matrix and interfacial properties, as guided by micromechanics principles, should further enhance white ECC performance, in particular tensile properties.

Table 2: Fiber/matrix interface properties of standard ECC and white ECC v1

	G_d [N/m^2]	τ_0 [Mpa]	β
PVA-ECC M45	1.08	2.27	0.58
White ECC v1	1.06	1.18	0.56

To improve the fiber-bridging capacity in white ECC, three different strategies may be incorporated. These are (1) incorporating high dosage of fiber, (2) adopting longer fiber, and/or (3) increasing fiber/matrix interface frictional bond strength [8]. To increase the fiber/matrix interface frictional bond strength, a lower oiling content may be used. Figure 4 shows the interfacial frictional bond as a function of oiling content [5]. It was found that the interface frictional bond decreases with the oiling content. Following these strategies, white ECC version 2 (white ECC v2) incorporated 2.5 vol.% of PVA fiber, version 3 (white ECC v3) used a longer (12 mm) fiber, and version 4 (white ECC v4) adopted a longer fiber (12 mm) with a lower (0.5% by weight) surface oiling content. Table 3 summarizes the fiber characteristics for the four versions of white ECC tested.

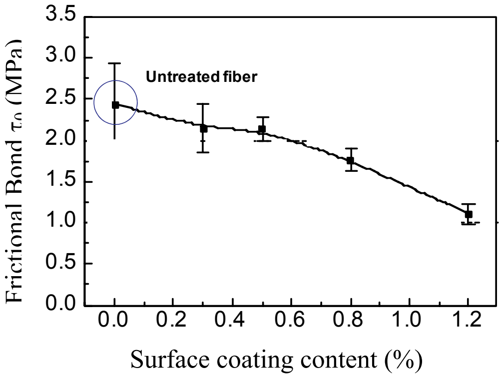

Figure 4: Fiber/matrix interface frictional bond as a function of surface coating content [5]

Table 3: Fiber characteristics and content for four versions

White ECC mix	Fiber type	Fiber diameter [μm]	Fiber length [mm]	Fiber oil coating [wt.%]	Fiber content [vol.%]
v1	PVA	39	8	1.2	2
v2	PVA	39	8	1.2	2.5
v3	PVA	39	12	1.2	2
v4	PVA	39	12	0.5	2

Figure 5 shows the uniaxial tensile stress-strain curves of white ECC v2, v3, v4, and v4-cured and Table 4 summarizes their compressive and tensile properties As can be seen, version 2 exhibits tensile strain-hardening behavior with an average tensile ductility of 0.7±0.1% and an average tensile strength of 6.0±0.9 MPa. The 28 day compressive strength is 55 MPa. Despite adopting high volumes of fiber, the mechanical properties of version 2 do not surpass those of the first version. This may be attributed to the difficulty of processing when adopting higher dosage of fibers, resulting in poor fiber dispersion and inefficient use of fibers.

White ECC v3 that incorporates longer fiber exhibits tensile strain hardening behavior with an average tensile ductility of 1.4±0.7% and an average tensile strength of 6.3±0.4 MPa. The 28 day compressive strength is 59 MPa. Compared with version 1, the tensile strength and tensile strain capacity of version 3 were improved.

White ECC v4 that incorporates longer fiber with lower surface oiling coating exhibits tensile strain hardening behavior with an average tensile ductility of 2.0±0.8% and an average tensile strength of 6.7±0.2 MPa. The 28 day compressive strength of white ECC v4 is 65 MPa. Compared with version 1, version 3 and version 4 show improved tensile strength and tensile strain capacity. This illustrates the application of micromechanics principles in the

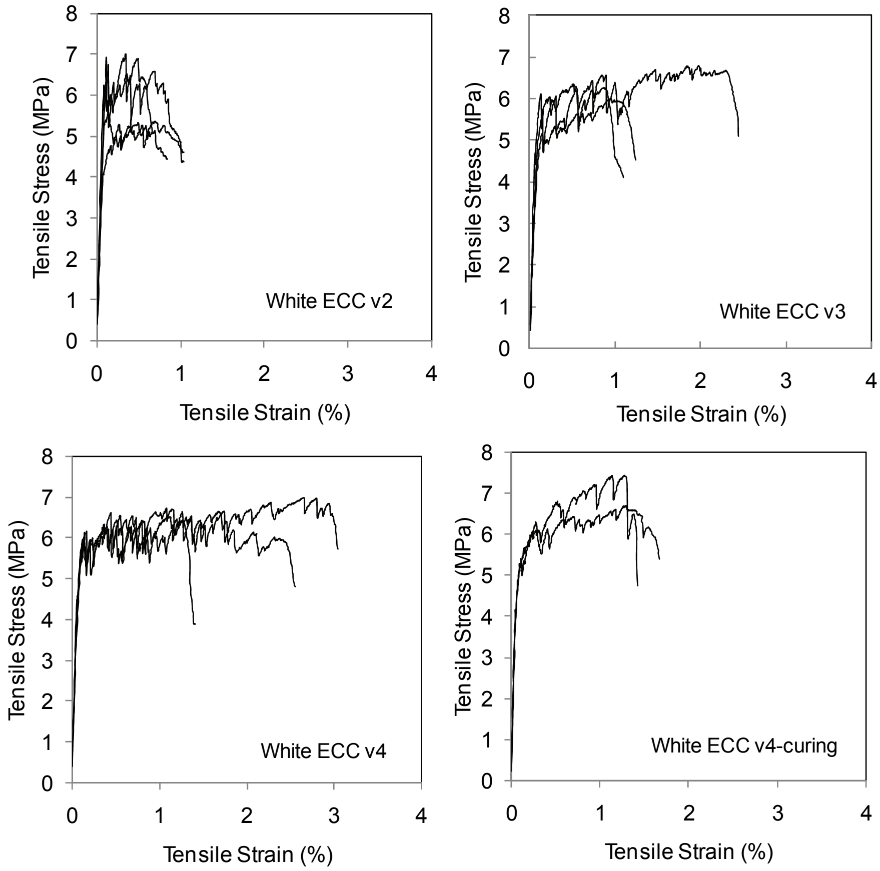

Figure 5: Uniaxial tensile stress-strain curves of white ECC v2 to v4

Table 4: Measured tensile and compressive properties of white ECCs

Material Properties	White ECC				
	v1	v2	v3	v4	v4-curing
ε_{ult} (%)	1.3	0.7	1.4	2.0	1.3
σ_{ult} (MPa)	5.7	6.0	6.3	6.7	7.1
f_c' (MPa)	60	55	59	65	70

development of white ECC by increasing fiber length and lowering surface oiling content in enhancing the fiber bridging capacity.

Large form-factor architectural elements are usually precast and steam curing is preferred to increase productivity by a more rapid turnover of molds and formwork, shorter curing periods before shipment to save time and space. White ECC v4 was cured in 38°C and 100% relative humidity for the first three days to simulate steam curing. This white ECC v4-curing exhibits tensile strain hardening behavior with an average tensile ductility of 1.3±0.1 % and an average tensile strength of 7.1±0.5 MPa (Figure 5). The 28 day compressive strength is 70 MPa. Compared to white ECC v4, white ECC v4-curing shows higher tensile strength but lower tensile strain capacity. The increase of tensile strength in v4-curing is attributed to fiber/matrix interfacial bond strength increase due to steam curing, resulting in a higher fiber bridging strength. The reduction of tensile strain capacity is attributed to 1) increase in matrix toughness, and 2) a lowered complimentary energy associated with an increase in fiber bridging stiffness. Both micromechanical changes due to steam curing are unfavorable to the multiple cracking of ECC and result in lower strain capacity [8]. However, it should be noted that the 1.3% tensile strain capacity of White ECC v4-curing represents about two orders of magnitude higher than that of normal concrete/mortar.

3. DISCUSSION AND CONCLUSIONS

This paper describes the development of white ECC for architectural applications. Pigmentable ECC allows color dyeing but imposes constraints on material ingredients that results in changes in micromechanical properties different from standard ECC. Specifically, white cement must be used while fly ash cannot be employed in the mix as in typical ECC formulation. This change in the matrix ingredient alters a number of micromechanical parameters, including the matrix toughness and fiber/matrix interface properties that have strong bearing on the composite tensile properties.

White cement can be successfully utilized in the production of pigmentable ECC with desirable tensile ductility properties. Further improvement of white ECC mechanical properties is possible and demonstrated in this paper based on micromechanical principles.

ACKNOWLEDGEMENTS

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