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ORIGINAL ARTICLE

Development of pigmentable engineered cementitious composites for architectural elements through integrated structures and materials design

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Abstract Integrated structures and materials design (ISMD) represents a new design approach that combines materials and structural engineering for the purpose of more effectively achieving targeted performance. Performance based design of structures provides flexibility and incentive to select composite materials with properties that efficiently meet the structural performance target. In this paper, ISMD concept was applied to develop pigmentable engineered cementitious composites (ECC) for architectural applications. Finite element analysis was carried out to relate structural performance (load capacity and energy absorption) to composite mechanical properties (tensile and compressive) under live and dead loads. Subsequently, white (and therefore highly pigmentable) ECC was developed to meet the desired composite properties. This paper details the structural performance—composite properties analyses, and test data on white ECC designed for the large form-factor panels. Through this research, the effectiveness of ISMD is revealed.

Keywords Engineered cementitious composites (ECC) · Integrated structures and materials design (ISMD) · White cement · Architectural panels

1 Introduction

Large form-factor architectural panels, such as counter tops, walls, and floors, are generally made from natural stones or rocks. Recent development on pigmenting technology has made it possible to make large form-factor thin architectural panels of high strength mortar or high strength concrete with the advantage in low cost, lightweight, and shape versatility [1]. This type of concrete is generally known as the architectural and decorative concrete [2]. Architectural and decorative concrete has become an enormously popular product for both building interiors and exteriors, combining an aesthetic finish with structural capabilities [3]. However, cracking and chipping during handling and transportation is of great concern for large form-factor architectural concrete panels due to the brittleness of high strength mortar or high strength concrete (personal communication with Austin and Speciale 2007).

White cement is a key ingredient in developing architectural and decorative concrete. It enables the

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resulting concrete to be pigmentable for a broad spectrum of colors [4]. White clinker is produced by carefully selecting the raw materials, i.e. iron-free clay and white limestone, in the clinkering process. The content of ferrous composites and other heavy metal composites in the raw materials must not exceed 0.15% to give the distinctive white color [5].

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 panels. 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 and the fracture toughness of ECC is similar to that of aluminum alloys [6].

Development of ECC is guided by micromechanical principles [7], 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.

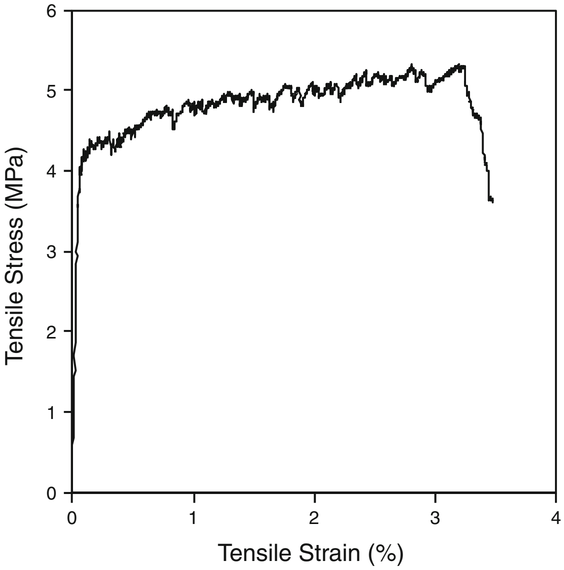


Fig. 1 A typical uniaxial tensile stress–strain curve of standard PVA-ECC M45

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. In addition, there is a need to determine the required material mechanical properties for applications in large form-factor thin architectural panels. These considerations form the objectives of this paper, namely to determine the required mechanical properties for typical worse scenario loading, and to develop a new pigmentable ECC to meet these properties requirement in large form-factor thin architectural panels.

2 Integrated structures and materials design

Prescriptive-based design approach gives structural engineers minimum degree of freedom to specify desired material properties other than the compressive strength of concrete. With recent advances in modern materials engineering, it is now possible to design concrete materials to meet specified properties beyond the compressive strength requirement.

The concept of ISMD was proposed by Li [8] by recognizing that beyond dimensioning and reinforcement type and detailing, concrete materials properties are designable, and in many instances the global structural performance can be strongly governed by properties other than compressive strength of concrete materials. ISMD combines materials engineering and structural engineering by adopting material properties as the shared link as depicted in Fig. 2.

In this design approach, the ultimate goal is to achieve the targeted structural performance. Based on

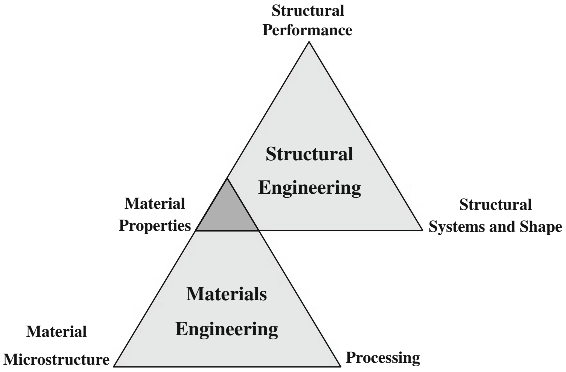


Fig. 2 Integrated structures and materials design

the structural performance requirement, structural engineers design structural systems by specifying structural element dimensioning, reinforcement detailing, and desired materials properties. Knowing the required material properties, materials engineers can tailor material microstructure and processing details to meet the targeted materials properties. Having the materials, structural engineers then can design structures based on the actual attainable materials properties. This multi-scale design approach from material microstructure to structural macroscale is holistic and is meant for a more efficient, economical, and sustainable design.

In this paper, ISMD was used for the development of pigmentable ECC for architectural panel applications. These panels are expected to experience flexural loading, both live loads and dead weight, and are designed for use without steel reinforcement. As a first step within the ISMD scheme, structural analysis by means of finite element analyses (FEA) were carried out to determine the required material mechanical properties for the thin panels of specified large format dimensions. This information was then deployed for development of white (colorable) ECC with the desired material properties, based on micromechanics modeling tools. The new ECC allows coloring that employs a proprietary digitally controlled technology, that can be applied full thickness and repeatable in the manufacturing process [9].

3 Structural engineering: relating material properties to panel capacities

FEA were carried out to relate material properties to panel capacities. A 2-D finite element model was based on the application of dead load and 3-point-bent live load in a simply supported panel, as shown in Fig. 3. The simply supported boundary conditions were used to simulate the most common and severe supporting conditions during construction handling and transportation. The panel dimensions are 2.44 m × 1.22 m × 9.5 mm (length × width × thickness). The large form-factor thin panel meets the requisites for architectural applications such as floors and walls.

The thin panels must be designed against the possibility of cracking or brittle fracturing during production, handling and transportation. For this reason, the live-load carrying capacity and impact resistance represented by the energy absorption capacity become two important structural performance indicators. No steel reinforcement is intended, so that any tensile stresses must be managed by the tensile properties of the ECC material.

A linear elastic model was used to describe the compressive behavior. The compressive strength f'_c and the elastic modulus E were specified in the model. A compressive failure is defined as when the compressive stress in the panel exceeds the material compressive strength. A bi-linear stress–strain curve was used to describe the tensile strain-hardening behavior as shown in Fig. 4. A linear descending line was used to describe the post-peak tension softening behavior. The tensile strength σ_{ult}, the tensile strain capacity ε_{ult} and the elastic modulus E were specified in the tensile model. The first cracking strength was defined as 80% of the tensile strength based on experimental observation.

An elastic modulus of 20 GPa was specified in both tension and compression in this study. The elastic modulus of ECC is generally lower than that of concrete due to the absence of coarse aggregates.

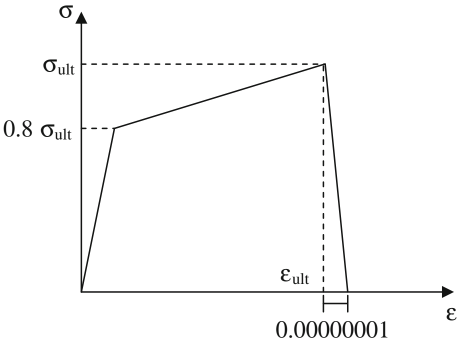
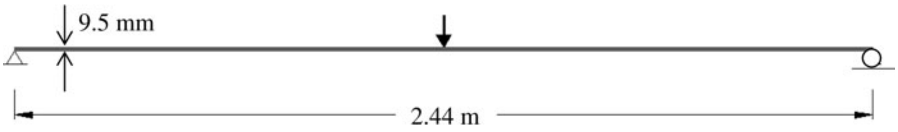


Fig. 4 ECC materials tensile constitutive model

Fig. 3 Geometry and boundary conditions of thin panel model

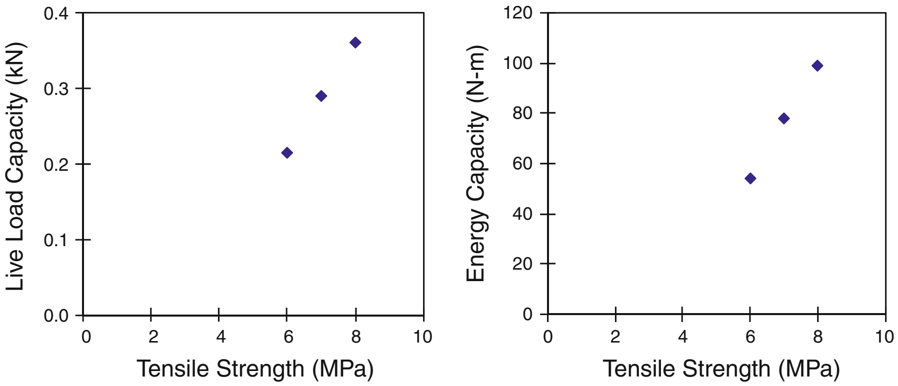


A brittle post-tension behavior was assumed in the tensile model ($\varepsilon_{post} = 0.00000001$). Compared with concrete or mortar, ECC has much better crack opening resistance after damage localization due to fiber reinforcement. This has been observed experimentally. Although this is a rather conservative assumption for ECC, it helps to clarify the contribution of the unique ECC tensile ductility to the performance enhancement of ECC panel compared with normal concrete/mortar panel. The compressive strength, the tensile strength, and the tensile strain capacity were treated as variables, i.e. designable material properties, in this study.

Parametric studies on the effects of material tensile strength on panel load and energy absorption capacities were carried out through the FEA. It was observed that panel load and energy capacities increase linearly with material tensile strength as illustrated in Fig. 5.

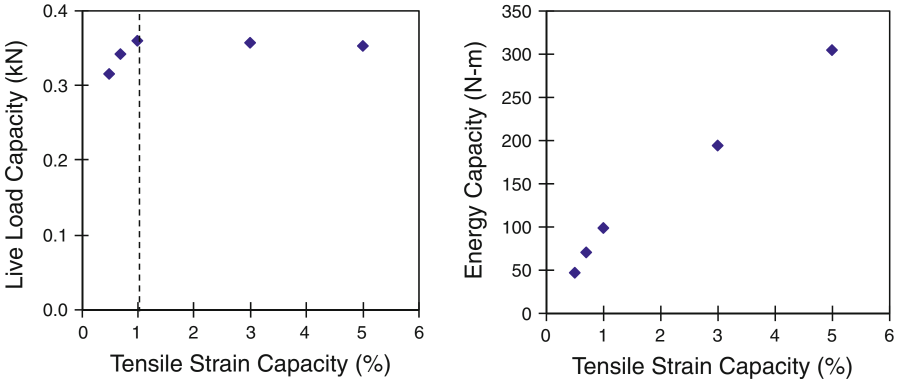
Parametric studies on the effects of material tensile strain capacity on panel load and energy absorption capacities were carried out through the FEA. As shown in Fig. 6, it was found that panel load capacity increases with material tensile strain capacity and reaches a plateau after a certain limit—around 1%. This implies that a 1% tensile ductility material is able to prevent brittle failure and elevates panel load capacity in the present study. This critical tensile strain capacity is likely dependent on structural geometry (panel thickness) and loading configuration [10]. Panel energy capacity, however, increases linearly with material tensile strain capacity.

Unreinforced concrete panels usually tend to fail in tension rather than in compression when subjected to bending. The tensile strength of concrete is typically an order of magnitude lower than its compressive strength, and therefore tensile properties of concrete usually limit the panel performance. It was found, however, that failure in compression could occur (Fig. 7) due to high material tensile ductility, which introduces large panel deformation and forcing the compression side of the panel to reach



(a) (b)

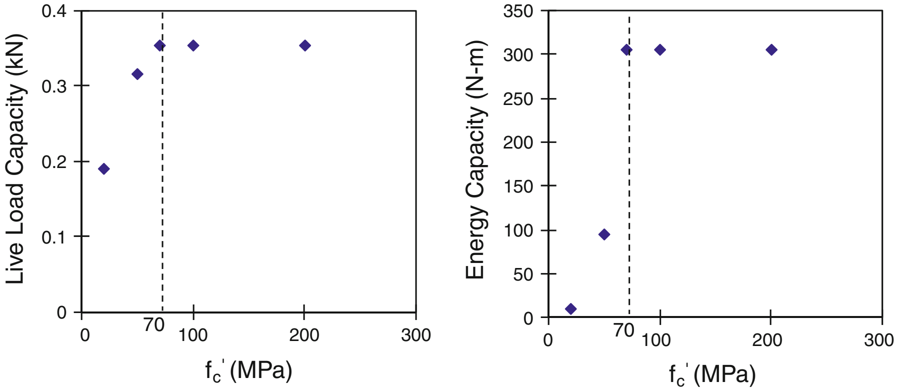
Fig. 5 **a** Load capacity and **b** energy absorption capacity as a function of tensile strength (All other parameters were fixed. A high compressive strength was used in calculations to prevent compressive failure)



(a) (b)

Fig. 6 **a** Load capacity and **b** energy absorption capacity as a function of tensile strain capacity (All other parameters were fixed. A high compressive strength was used in calculations to prevent compressive failure)

Fig. 7 **a** load capacity and **b** energy absorption capacity as a function of compressive strength (All other parameters were fixed)



(a) **(b)**

the compressive strength limit. Therefore, to fully utilize the tensile ductility, an adequate compressive strength is necessary to prevent panel compressive failure. It can also be seen from Fig. 7, after a certain compressive strength, around 70 MPa, the panel load and energy capacities reach a plateau. This would be the minimum required compressive strength to prevent compressive failure.

The required material compressive strength varies and depends on material tensile strength and tensile strain capacity as well as structural geometry and loading configuration. Thus, for the given thin panel loaded in a three-point-bend configuration, the required compressive strength to prevent compressive failure has been computed as a function of material tensile strength and tensile strain capacity as shown in Fig. 8. The general trend shows that the required compressive strength to prevent compressive failure of panel increases with the material tensile strength and tensile strain capacity.

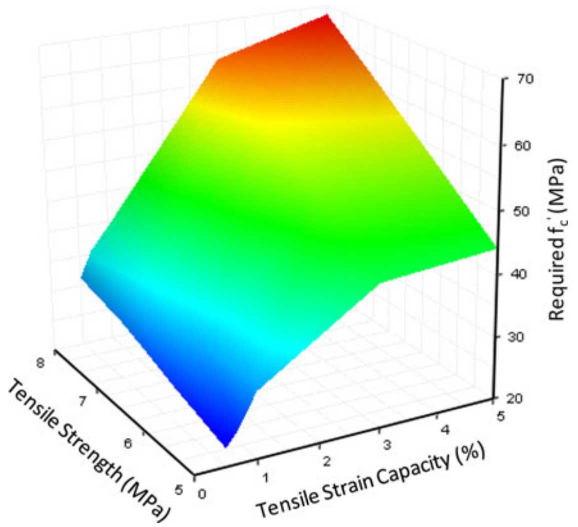
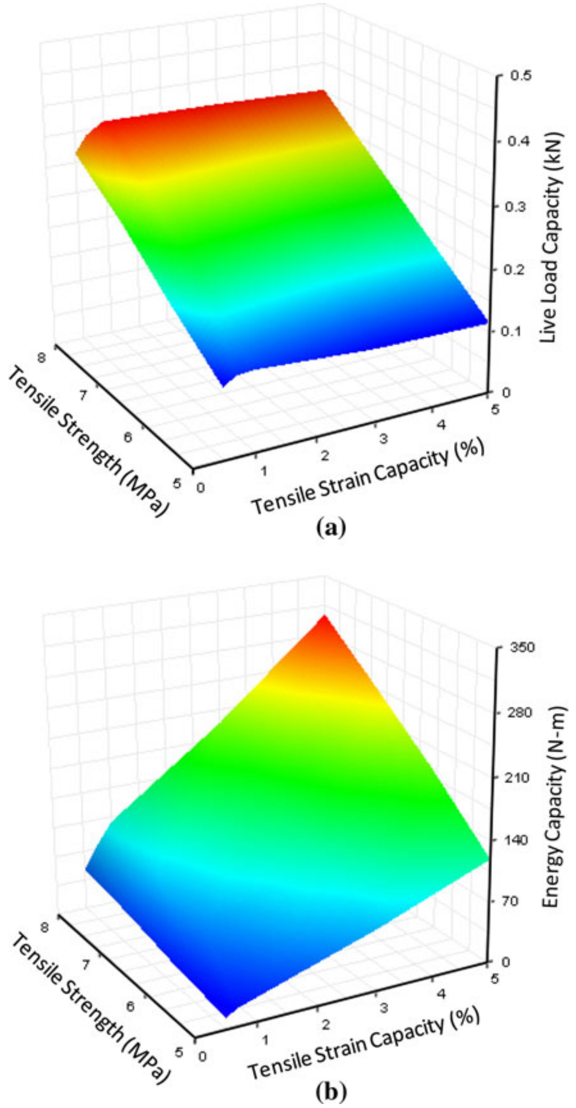


Fig. 8 Computed required material compressive strength to prevent compressive failure of panel as a function of material tensile strength and tensile strain capacity

Assuming no premature compressive failure of the panel, the load and energy capacities of the thin panel were calculated as a function of material tensile strength and tensile strain capacity, as shown in Fig. 9. The general trend shows that higher material tensile strength results in higher panel load and energy capacities while higher material tensile strain capacity contributes more to the panel energy capacity. However, a 1% tensile strain capacity is necessary to prevent brittle failure in this panel application. Based on the discussion above, a pigmentable ECC with 1% in tensile strain capacity and 6 MPa in tensile strength were specified as minimum targeted material properties. The corresponding compressive strength of the pigmentable ECC was 32 MPa, which was identified from Fig. 8. This would be the minimum required compressive strength for the pigmentable ECC in this panel application. For ECC, failure in tension is more desirable as this is a more ductile failure mode. This preference is analogous to that in R/C structural design where tensile ductility is provided by the steel reinforcements. High compressive strength may become necessary for better wear resistance which is important for flooring applications. Therefore, pigmentable ECC with high tensile strength and compressive strength is always desirable.



(a)

(b)

Fig. 9 **a** Load capacity and **b** energy absorption capacity as a function of material tensile strength and tensile strain capacity

Comparisons of panel load and energy capacities were carried out between panels made of ECC ($f'_c = 32\,\mathrm{MPa}$, $\sigma_{\mathrm{ult}} = 6$ MPa, $\varepsilon_{\mathrm{ult}} = 1\%$) and high strength mortar (HSM) as control ($f'_c = 120\,\mathrm{MPa}$, $\sigma_{\mathrm{ult}} = 4.2$ MPa, $\varepsilon_{\mathrm{ult}} = 0.01\%$). It should be pointed out that large form-factor panel (2.44 m × 1.22 m × 9.5 mm) made of HSM cannot even sustain its own weight (dead load), and therefore a smaller form-factor HSM panel (1.52 m × 0.91 m × 12.7 mm) was simulated and compared with the large form-factor ECC panel. Compared with the smaller form-factor HSM panel, the load capacity of large form-factor ECC panel is improved by 300%, from 70 to 210 N, and the energy capacity is improved by 135,750%, from 0.04 to 54.3 N-m. It should be pointed out that this is a very conservative estimation of load and energy capacities improvement of ECC panel due to the larger size as compared to the HSM panel. The actual improvement of load and energy capacities of the same size ECC panel to the HSM panel should be much higher than the valued indicated here.

In the following sections, a pigmentable ECC was developed based on these required properties ($f'_c = 32\,\mathrm{MPa}$, $\sigma_{\mathrm{ult}} = 6$ MPa, $\varepsilon_{\mathrm{ult}} = 1\%$). ECC material that satisfy the combination of compressive strength, tensile strength and tensile ductility will be considered meeting the load performance target of the large format panels under flexural loads. Naturally, if the compressive strength is made still higher, the resulting ECC would still meet the load performance target, but the capacity will not increase further.

While this calculation was conducted for the large form-factor thin panel subjected to dead weight and three-point-bend loading, the design strategy can be deployed for other applications as well. Figures 8 and 9 serve as a quantitative link between structural performance and material properties for panel design, as illustrated schematically and generally in Fig. 2.

4 Materials engineering: development of pigmentable ECC

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. In this study, 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 white ECC 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

Table 1 Mix design of white ECC

Material	Cement	Sand	Water	Superplasticizer	PVA Fiber (by volume)
White ECC	1	1	0.34	0.004	0.02

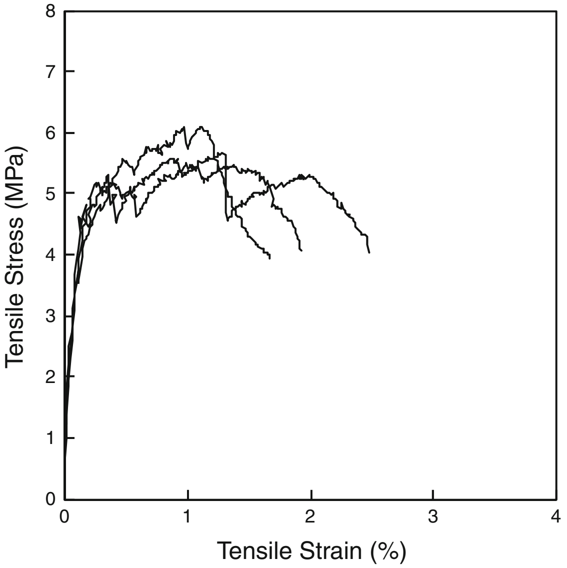


Fig. 10 Uniaxial tensile stress–strain curves of white ECC

the fiber was 1600 MPa and the density of the fiber was 1300 kg/m^3. The fiber was surface-coated by an oiling agent (1.2% by weight) in order to reduce the fiber/matrix interfacial bond strength. This decision was made through ECC micromechanics material design theory and has been experimentally demonstrated to be effective from previous investigations [11].

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 cylinders ends were capped with a sulfur compound to ensure a flat and parallel surface and a 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 Yang et al. [12]. 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.

Table 2 Actual attainable tensile and compressive properties of white ECCs (high strength mortar as control)

Material properties	White ECC	High strength mortar
$\varepsilon_{\mathrm{ult}}$ (%)	1.3	0.01
σ_{ult} (MPa)	5.7	4.2
f_c' (MPa)	60	120
Required f_c' (MPa)	32	N/A

Figure 10 shows the uniaxial tensile stress–strain curves of the white ECC and Table 2 summarizes its compressive and tensile properties. As can be seen, white ECC 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 is 60 MPa, higher than the required compressive strength (32 MPa) indicated in Fig. 8. It is concluded that the newly developed white ECC possesses mechanical properties that satisfy the structural performance for the large form-factor panels.

Compared to standard ECC M45 (Fig. 1), the white ECC shows a lower tensile ductility. An initial microscopic observation of the fracture surface of white ECC reveals that most of the PVA fibers were pulled out instead of rupture. This suggests that the interfacial bond of white ECC is lower than that of standard ECC M45 as a result of replacement of ordinary Portland cement and fly ash by white cement. Ongoing research is carried out to quantify the interfacial properties of white ECC and to re-engineer new versions of white ECC through micromechanics model to further improve its properties.

Table 3 summarizes the load and energy capacities of panels made of actual attainable white ECC and of HSM. Again, large form-factor HSM panels cannot sustain its own dead weight and a smaller form-factor was calculated for comparison. As shown in Table 3, the panel made of white ECC gives much improved energy capacity. Compare with high strength mortar, an improvement of 135,000%, from 0.04 to 54 N-m, was observed. The panel made of white ECC also

Table 3 Load and energy capacities of 2.44 m × 1.22 m × 9.5 mm white ECC panel (1.52 m × 0.91 m × 12.7 mm high strength mortar panel as control)

Panel capacity	White ECC (2.44 m × 1.22 m × 9.5 mm)	High strength mortar (2.44 m × 1.22 m × 9.5 mm)	High strength mortar (1.52 m × 0.91 m × 12.7 mm)
Load cap. (N)	189	N/A	70
Energy cap. (N-m)	54	N/A	0.04

shows a high live load carrying capacity. Compare with high strength mortar, an improvement of 270%, from 70 to 189 N, was observed.

5 Discussion and conclusions

This paper describes an Integrated Structures and Materials Design approach in the development of white ECC for thin architectural panel application. As can be seen, combining structural analyses and materials engineering is a powerful tool to provide an effective design. The effectiveness comes from the full utilization of material properties to prevent premature failure and to elevate structural performance. In the present study, for example, white ECC with balanced material properties not only satisfy the aesthetic requirements but also provide an improvement of at least 270% in panel load capacity and an improvement of at least 135,000% in panel energy capacity.

White ECC possesses mechanical properties that satisfy the load capacity performance for the large form-factor thin panels, following the simulations presented in this study. This means that white cement can be successfully utilized in the production of white ECC with desirable tensile ductility properties.

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