The Application of ISMD in Development of White ECC

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Abstract
Integrated structural and materials design (ISMD) represents a new design approach that combines materials and structural engineering for the purpose of more effectively achieving targeted structural performance. Performance based design of structures provides flexibility and incentive to select composite materials with properties that efficiently meet the structural performance target. Currently, modern materials engineering provides tools for tailoring material ingredients for desired composite properties. Thus, the integration of structural and materials design is a natural joining of these technical fields. In this paper, the ISMD concept is applied to develop white Engineered Cementitious Composites (White ECC) thin panels for architectural applications. Finite Element Analysis (FEA) is carried out in order to transfer targeted structural performance to required material properties. Based on the simulation results, White ECC is developed to meet the desired mechanical properties.

Keywords: engineered cementitious composites; panel; ISMD; mechanical properties; micromechanics

1. Introduction
In structural engineering, materials are shaped into structural elements, which are assembled into structural systems in order to reach targeted structural functions and performance goals described in terms of ultimate limit states or serviceability limit states. Typically, design codes provide the structural design framework with respect to material selection, dimensioning, and in the case of reinforced concrete, reinforcement detailing. However, it is pointed out by Li1) that those design codes, developed from structural mechanisms analysis and verified by extensive experimental investigations and experience, do not allow flexibility in dimensioning and reinforcement detailing by structural engineers.

In the last decade, systematic engineering of ultra high ductility concrete containing short discontinuous fibers has proceeded at a rapid pace, to the point where such materials have been placed in full-scale structures, such as the ultra ductile concrete used in a super thin composite bridge deck in Hokkaido, Japan, and in a coupling of beams for a tall building in central Tokyo in Japan2). These materials and their tensile properties achieved based on micromechanics criteria are deployed to enhance the structural functions, thus requiring the application of performance based design concepts.

Performance based structural design and micromechanics based concrete material design offer the opportunity for structural engineers and material engineers to integrate their knowledge in order to attain structural performance not feasible heretofore3).

Integrated structural and materials design (ISMD) combines materials and structural engineering for the purpose of more effectively achieving targeted structural performance. As can be seen in the upper triangle in Fig.1., the world of structural engineering shapes materials into structural elements and joins them to form the structural system, with structural performance as target. The world of materials design, which is represented by the lower triangle shapes raw ingredients into a composite through processing in order to achieve targeted composite properties. As can be seen, the common link between structural and materials engineering is the material properties.

While performance based design of structures provides flexibility and incentive to select composite materials with properties that efficiently meet the structural performance target, modern materials engineering provides tools for tailoring material ingredients for desired composite properties. The integration of structural and materials design is a natural joining of these technical fields.

However, for ISMD to be successful, materials engineers need to view structural performance as an
ultimate goal. Structural engineers need to recognize that beyond dimensioning and reinforcement type and detailing, concrete materials properties are designable, and in many instances the global performance can be strongly governed by properties other than compressive strength of concrete materials.

Nowadays Poly Vinyl Alcohol (PVA) ECC represents an innovation in concrete technology. Durability, water-impermeability and fire-resistance are improved while weight is dramatically reduced by combining PVA fibers with an engineered cement mortar. The durability of PVA ECC has been proven over twenty years of field and laboratory tests, including freeze/thaw and accelerated deterioration. In particular, white PVA ECC is a special version which can be utilized to cast thin panels for curtain walls in buildings without the procedure of painting. PVA ECC provides 2 to 5 times the tensile and bending strength, and 10 to 20 times the toughness and elongation of normal pre-cast concrete. This increased strength allows a reduction in panel thickness and a weight saving of 50 to 66% over traditional pre-cast concrete. The fine, ductile fibers allow intricate castings, freeing the architect to use PVA ECC which is compatible with a variety of finish types, including embedded colors, tile or stone surface treatments or resin-based paints for highly decorative panels. ECC panels are typically cast one half to two thirds thinner than traditional panels, while offering dramatically higher tensile and flexural strength. This, in turn, reduces the building’s seismic moment, total weight, and foundation requirements. In addition, the lighter weight makes installation easier.

In this paper, the ISMD concept is applied to develop white Engineered Cementitious Composites (White ECC) panels for architectural applications. In the first phase, finite element analysis (FEA) is carried out in order to determine required material mechanical properties for production of White ECC wet cast thin panels. In the second phase, White ECC material is developed to meet the desired mechanical properties, based on micromechanics models.

2. Engineered Cementitious Composites

Engineered Cementitious Composite (ECC) is a special type of high performance fiber-reinforced cementitious composite featuring significant tensile ductility with small crack width. The stress-strain curve is shown in Fig.2. The design of ECC is guided by micromechanical principles, which provide quantitative links between composite mechanical behavior and the properties of the individual constituent, which are fiber, matrix and interface. The design strategy of strain-hardening fiber reinforced brittle matrix composites lies in realizing and tailoring the interaction of these constituents.

![Fig.1. Concept of ISMD](image1)

![Fig.2. Typical Tensile Stress-strain-crack Width Relationship of PVA-ECC](image2)

The pseudo strain hardening is achieved by sequential development of matrix multiple cracking. The fundamental requirement for multiple cracking is that steady-state crack extension prevails under tension, which requires the crack tip toughness \( J_{tip} \) to be less than the complementary energy \( J^c \) calculated from the bridging stress \( \sigma \) versus crack opening \( \delta \) curve, as illustrated in Fig.3.

\[
J_{tip} \leq \sigma_0 \delta_0 - \int_0^\delta_0 \sigma(\delta)d\delta = J^c
\]

where \( J_{tip} = K_m^2 / E_m \), \( \sigma_0 \), is the maximum bridging stress corresponding to the opening \( \delta_0 \). \( K_m \) is the matrix toughness and \( E_m \) is the matrix Young's modulus. The concept of energy balance during flat crack extension through matrix breakdown and fiber-matrix interface debonding and sliding are employed in Eq. 1. This energy-based criterion determines the crack propagation mode (steady-state flat crack or modified Griffith crack). The predominance of flat crack over modified Griffith crack propagation is important since the crack width can be constrained to below \( \delta_0 \), and the stress level is always maintained below the bridging capacity of the fibers. Otherwise, fracture will be localized, resulting in tension-softening and large opening of a single-crack.

Another condition for the pseudo strain-hardening is that the matrix first crack strength \( \sigma_{fc} \) must not exceed the maximum fiber bridging strength \( \sigma_0 \).

\[
\sigma_{fc} < \sigma_0
\]

where \( \sigma_{fc} \) is determined by the matrix fracture toughness \( K_{mc} \), pre-existing internal flaw size and the
While the energy criterion (Equation 1) governs the crack propagation mode, the strength criterion (Equation 2) controls the initiation of cracks. Satisfying both equations is necessary to achieve ductile strain-hardening behavior, otherwise normal tension-softening fiber reinforced concrete behavior results. Due to the random nature of pre-existing flaw size and fiber distribution in cement composites, a large margin between $J_{\text{b}}$ and $J_{\text{tip}}$ as well as $\sigma_{fc}$ and $\sigma_0$ is preferred.

3. Determination of Required Material Properties
3.1 Material constitutive models and property

In order to determine the required material properties of White-ECC thin panels, finite element analysis is carried out by using the software MLS module of FEMMASSETM version 8.5. This finite element program is able to simulate the physical and structural behavior of composed structures in varying environmental conditions. The 3 dimensional finite element model is based on the application of dead load and 3-point-bending live load in a simply supported panel (Fig.4.). The panel dimensions are (203.2x101.6x.9.5mm).

Material constitutive models are displayed in Fig.5. A bilinear, elastic and perfectly plastic model is used to describe the compressive behavior of both mortar and ECC materials. The compressive strength $f_c$ and elastic modulus $E$ can be specified in the model. The middle plot indicates the tensile model used for mortar material with elastic modulus of 30GPa. A descending line is used to describe the tension softening post-peak behavior of mortar. For ECC material, a tension strain-hardening model is used. The ultimate tensile strength $\sigma_{ult}$ can be specified and the first cracking strength $\sigma_{fc}$ is defined as 80% that of the ultimate tensile strength based on experimental observation.

The elastic modulus of ECC is generally lower than concrete or mortar due to the absence of coarse aggregate and is specified as 20GPa based on experimental measurements. The post-peak curve in the tensile model (both concrete and ECC) describes the resistance of crack opening after damage localization. It is observed experimentally that ECC has much better crack opening resistance after damage localization than concrete or mortar due to fiber reinforcement. In this study, this parameter is fixed and it is assumed that both mortar and ECC have the same post-peak crack opening resistance. Although this is rather a conservative assumption for the ECC panel, it helps to clarify the contribution of ECC tensile ductility to the performance enhancement of the ECC panel compared with a normal concrete/mortar panel.

The ECC panel performance is evaluated first and ECC properties are summarized in Table 1. To demonstrate the contributions of material tensile ductility to structural capacities, an imaginary mortar (Mortar_coupon) with ultra high compressive strength 600Mpa and tensile strength 10 Mpa but normal brittleness is used for comparison. The tensile strain of mortar is only 0.03%. Here the ECC (ECC $f_c$=50 strength5–strain3) has compressive and tensile strength equal to 50Mpa and 5Mpa respectively, and tensile strain equals 3%. The computational comparison between the ECC and mortar panel under dead weight and 3-point-bend loading is shown in Fig.6.

Table 1. Properties of ECC and Imaginary Mortar

| Material                  | $f_c$ (MPa) | $\sigma_{ult}$ (MPa) | $\epsilon_t$ |
|---------------------------|------------|----------------------|--------------|
| ECC $f_c$=50 strength5–strain3 | 50         | 5                    | 3            |
| Mortar_Coupon             | 600        | 10                   | 0.03         |

As can be seen, an initial deformation offset is present. This pre-deformation introduced by the dead weight has lowered the panel live load and energy capacities. Despite a much lower compressive and tensile strength, the ECC panel shows much higher load and energy capacities compared with the ultra high strength mortar panel. The load and energy capacities are 6 and 3500 times that of the imaginary mortar panel, respectively. This is attributed to the extreme tensile ductility of the ECC material that suppresses brittle failure and raises panel load and...
energy capacities.

Despite the lower compressive and tensile strength of the ECC material, its tensile ductility can suppress the brittle failure, which is observed in mortar panels. Based on the preliminary studies, it is clear that the panel performance under bending load is a result of compressive strength, tensile strength and tensile ductility interaction. ECC possessing balanced tensile and compressive properties is desirable for the thin panel application subjected to three-point-bend loading.

Based on the study above, it is clearly shown that ECC with its extreme tensile ductility can be a potential material solution for large-scale thin panels.

3.2 Effect of ECC compressive Strength on panel load and energy capacities

Simulations are conducted to evaluate the effect of ECC compressive strength, tensile strain capacity and ultimate tensile strength on load and energy capacities of the panel under 3-point-bending load.

Five ECCs with different compressive strength ranging from 20 to 200Mpa are investigated. Besides compressive strength, the five ECCs have the same material properties. The same imaginary mortar studied in the previous section is also used in this study for comparison. In Fig.7, the simulation results can be seen. It is found that the ECC panel fails as the maximum principle compressive stress in the panel reaches the compressive strength of ECC ranging from 20 to 50MPa.

Failure in compression occurs due to the tensile ductility of the ECC material with large panel deformation. It is concluded that tensile ductility of ECC prevents premature failure of the panel in tension, but pushes the failure mode to the compression side of the panel under flexure. In mortar panels, this is not the case due to the premature failure by the limited tensile ductility. Therefore, an adequate ECC compressive strength is necessary to prevent panel compressive failure. It is also found that after a certain compressive strength (around 70Mpa), the panel load and energy capacities reach a plateau. This should be the minimum desirable compressive strength for ECC material. The required compressive strength $f_c'$ of ECC material varies and depends on tensile properties (ultimate tensile strength $\sigma_{ult}$ and tensile strain capacity $\varepsilon_{ult}$) as well as structural geometry and loading configuration. Thus, for the given thin panel loaded in a three-point-bending configuration as depicted in Fig.4., the required ECC compressive strength to prevent compressive failure can be described as a function of ECC tensile strain capacity and ultimate tensile strength (Fig. 8).

3.3 Effect of ECC tensile strain capacity on panel load and energy capacities

Simulations are conducted to evaluate the effect of ECC tensile strain capacity on panel load and energy capacities. Five different ECCs with different tensile strain capacities ranging from 0.5 to 5% are investigated. Besides strain capacity, the five ECCs have the same material properties. A high compressive strength of 200MPa is assumed to the five ECCs to prevent compressive failure. The same imaginary mortar studied in the previous section was also used in this study for comparison. The simulation results can be observed in Fig.9. It is found that the panel load capacity increases with ECC ductility, but after a certain limit – around 1% - reaches a plateau. This means that 1% ECC tensile ductility can prevent brittle failure in compression.
failure of the plate configuration considered in this study. Regarding the panel energy capacity, it increases linearly with ECC tensile ductility. Thus, higher tensile strain capacity means higher panel energy absorption capacity.

3.4 Effect of ECC ultimate tensile strength on panel load and energy capacities

To evaluate the effect of ECC tensile strength on panel load and energy capacities, three ECCs with different ultimate tensile strength (6MPa, 7MPa, and 8MPa) are investigated. The three ECC have the same material properties other than ultimate tensile strength. A high compressive strength of 200MPa is again assumed to the three ECCs to prevent compressive failure. The tensile strain capacity of all ECCs is chosen to be 1% to suppress the brittle tensile failure completely. The same imaginary mortar is also used in this study for comparison. The results can be found in Fig.10. As can be seen, the ultimate tensile strength of ECC governs panel load and energy capacities as long as brittle failure is prevented. Panel load and energy capacities increase linearly with ECC tensile strength.

4. Design Charts for Development of ECC Thin Panel

Based on the previous numerical results, design charts for thin panels under 3-point-bend loading are developed. These charts represent the integration between material and structural engineering, as discussed in the integrated structural and materials design section.

Assuming no premature compressive failure of the panel, the load and energy capacities of the thin panel can be calculated as a function of ECC tensile strain capacity and ultimate tensile strength, as shown in Fig.11.

Based on the discussion above, ECC with 1% strain capacity can suppress the brittle failure. The general trend shows that higher ultimate tensile strength results in higher panel load and energy capacities.

The corresponding compressive strength can be identified from Fig.8. High compressive strength may become necessary for better wear resistance, which is important for flooring application. Therefore, white ECC with high ultimate tensile strength and compressive strength is always desirable. In the following sections, white ECC is developed based on the required material properties summarized in Table 2. ECC materials that satisfy the combination of compressive strength, tensile strength and tensile ductility as described above will be considered meeting the load performance target of the large-scale panels under flexural loads. Naturally, if the compressive strength is made still higher due to aesthetic reasons, the resulting ECC will still meet the load performance target, but the capacity will not be increased.

Although this calculation is conducted for the large-scale panel subjected to dead weight and three-point-bend loading, the general trend is expected to apply to other loading conditions as well.

Table 2: Required Material Properties of White ECC

| Material property | $\varepsilon$ (%) | $\sigma_{ut}$ (MPa) | $f_c$ (MPa) |
|-------------------|-----------------|-----------------|-------------|
| White ECC         | >1              | >6              | >32         |
bend loading, the design strategy can be deployed to other applications as well. Through the collaboration of structural engineering and materials engineering, desired structural performance can be achieved more effectively.

5. Development of white ECC

The numerical simulations developed in the previous sections are guides for the development of white ECC. The mechanical properties of this new material should satisfy the combinations prescribed in the numerical analysis. In the first attempt of white ECC, Portland cement has been replaced by white cement, and fly ash was excluded in the mix design due to the dark color of these two ingredients (Fig.12.).

Type I white cement is used. F-110 fine silica sand with a maximum grain size of 250µm and an average size of 110µm is adopted in the mixture. The superplasticizer used is a polycarboxylate-based high range water reducer. Polyvinyl Alcohol (PVA) fiber REC-15 from Kuraray Co. is used at a moderate volume fraction of 2% in this study. The dimensions of the PVA fiber are 8 mm in length and 39µm in diameter on average. The nominal tensile strength of the fiber is 1600 MPa and the density of the fiber is 1300 kg/m³. The fiber is surface-coated by oil (1.2% by weight) in order to reduce the fiber/matrix interfacial bond strength. This decision is made through ECC micromechanics material design theory for ECC Mix 45 and has been experimentally demonstrated from previous investigations. A Hobart mixer with 13L capacity was used in preparing all ECC mixtures. The mix design of white ECC is illustrated in Table 3.

A compressive test is carried out at the age of 28 days (Fig.13.a). Cylinders measuring 75 mm in diameter and 150 mm in length are used as compressive specimen moulds in this study. The ends of the cylinders are capped with a sulfur compound to ensure a flat and parallel surface and better contact with the loading device.

Tensile stress-strain behavior is determined from direct uniaxial tensile tests in specimens measuring 152mm by 76mm by 13mm at the age of 28 days (Fig.13b.). A servohydraulic testing system is used in displacement control mode to conduct the tensile test. The loading rate used is 0.0025 mm/s to simulate a quasi-static loading condition.

The regular and white ECC specimens and also crack pattern of white-ECC (Crack width: 30 - 110µm) is also presented in Fig.15. The 28-day compressive strength of white ECC is 60MPa, which is larger than the required compressive strength (32MPa) as depicted in Fig.8. As can be seen, the mechanical properties of white ECC satisfy the load capacity performance for (203.2x101.6 x.9.5mm) thin panels.

A microscopic observation of the fracture surface of white ECC reveals that most of the PVA fibers are pulled out instead of rupturing (Fig.16.). This observation suggests that the interfacial bonding of white ECC is lower than the ECC Mix 45 produced previously by Yu. It is indicated that interfacial frictional bonding increases with fly ash content in ECC. The lower frictional bond in white ECC may be attributed to the absence of fly ash in white ECC.
mix design. This result suggests that the PVA fiber strength in white ECC has not yet been fully utilized and exhausted. Improving the fiber bridging capacity of white-ECC should further enhance white ECC performance, tensile properties in particular.

6. Conclusions

The application of integrated structures and materials design (ISMD) concept in the development of white ECC for thin panel application is presented in this paper. It is demonstrated that a combination of structural engineering and materials engineering is a powerful tool to provide an effective material design approach.

Finite element analysis (FEA) of thin plates under 3-point-bend loading indicates that high material compressive strength may not lead to high structural load and energy capacities, although adequate compressive strength of ECC material is necessary to prevent compressive failure. The load and energy capacity of thin panels are instead generally governed by tensile properties. ECC tensile ductility helps suppress the brittle failure mode and therefore enhances structural load and energy capacities. Panel load capacity reaches a plateau when ECC strain capacity is higher than 1%, but the panel energy capacity increases linearly with strain capacity. However, ECC tensile strength is the material property that governs structural load and energy capacities as long as brittle failure is prevented. Under this condition, panel load and energy capacities increase linearly with ECC tensile strength.

Regarding the material development phase, white ECC produced in this study possesses mechanical properties – strain capacity (1-2%), tensile strength (6-7MPa) and compressive strength (70MPa) - that satisfy the load capacity performance for 203.2x101.6 x 9.5mm 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 for the production of panels to be utilized in civil and building engineering.

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