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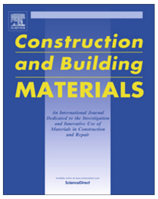

# The influence of mineral additive type and water/binder ratio on matrix phase rheology and multiple cracking potential of HTPP-ECC

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## HIGHLIGHTS

- W/B ratio significantly influenced the fiber-matrix interaction.
- GBFS incorporation modified the matrix rheology of composites.
- Matrix rheology affected the tensile performance of HTPP-ECCs.
- Tensile ductility of GBFS incorporated composites were 2–3%.
- Crack width distribution is measured by Digital Image Correlation Method.

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## ABSTRACT

Engineered Cementitious Composites (ECC) exhibit pseudo strain-hardening behavior by fine multiple cracking with controlled tight crack width mechanism. The optimization of interaction between fiber and matrix is the main design strategy of ECC. Mineral additives are preferable in the design of ECC due to technical and economic advantages. In this study, the influence of mineral additives on normal strength grade ECC (compressive strength range: 20–50 MPa) procured with a recently developed fiber known as high tenacity poly-propylene (HTPP) have been experimentally studied. Composites incorporating ground granulated blast furnace slag (GBFS) and fly ash (FA) were prepared at three different Water/Binder (W/B) ratios (0.31, 0.34, 0.37). Matrix phase rheology of composites characterized. The tensile stress-strain relationship, crack width distribution, fiber bridging stress – crack opening relation, matrix fracture toughness and compressive strength values have been experimentally determined. The role of mineral additives on multiple cracking has been discussed. Furthermore, energy and strength based pseudo–strain hardening indices of composites have been calculated by using ECC micromechanical theory.

## 1. Introduction

The optimization of interaction between fiber and matrix in terms of interface bond properties is the main design strategy of Engineered Cementitious Composites (ECCs). Despite their brittle matrices, ECCs exhibit pseudo strain-hardening behavior with tensile ductility more than 1% and as high as 8% [1]. If a proper combination of matrix and fiber is selected, fine multiple cracking with tight crack width (less than 100 μm) can be observed, which is the main source of pseudo strain-hardening concept [2]. Recent studies showed that in addition to structural applications, ECC is a promising candidate material in terms of solving durability problems of reinforced concrete structures due to this tight micro-cracking ability [3–5].

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*Abbreviations:* ECC, Engineered Cementitious Composites; HTPP, High tenacity poly-propylene; GBFS, Granulated Blast Furnace Slag; FA, Fly Ash; W/B, Water/Binder; $J_b'$, Complementary energy; $\sigma$, Fiber bridging stress; $\delta$, Crack opening; $\sigma_o$, Maximum bridging stress; $\delta_0$, Crack width; $J_{tip}$, Matrix crack tip fracture energy; $K_m$, Matrix fracture toughness; $E_m$, Matrix Young's modulus; $\sigma_{cr}$, Matrix cracking strength; PSH, Pseudo–strain hardening; $\mathrm{PSH}_{\mathrm{energy}}$, Pseudo strain hardening energy indices; $\mathrm{PSH}_{\mathrm{strength}}$, Pseudo strain hardening strength indices; PE, Polyethylene; PVA, Polyvinyl alcohol; PP, Poly-propylene; PC, Portland Cement; BMS, Ball Measuring System; $a = \tau_o$, , Yield value; $b$, Consistency index; $\dot{\gamma}$, shear rate; $p$, Power coefficient; $R$, Correlation coefficient; $\eta_{15s}{}^{-1}$, Viscosity values at 15 $s^{-1}$ shear rate.

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Micromechanics-based theory of ECC provides a basis for composite design exhibiting pseudo strain-hardening behavior with saturated multiple cracking [6–8]. A fundamental requirement of pseudo strain-hardening is that steady state cracking occurs. Steady state cracking of composite can be provided by the satisfaction of two conditions based on energy and strength criteria [9,10]. According to first criterion (Eq. (1)), complementary energy ($J_b'$), calculated from the fiber bridging stress ($\sigma$) – crack opening ($\delta$) curve of composite must exceed the matrix crack tip fracture energy ($J_{tip}$) (Fig. 1). This curve describes the relationship between the averaged stress carried by the fibers bridging across a matrix crack (known as fiber bridging law). In most fiber reinforced cementitious composites with less than 5% fiber volume fraction, $J_{tip}$ can be calculated by Eq. (1) where $K_m$ and $E_m$ are matrix fracture toughness and matrix Young's modulus, respectively. For steady state cracking, the second criterion that is matrix cracking strength ($\sigma_{cr}$) must be less than the maximum bridging stress ($\sigma_o$) should also be satisfied (Eq. (2)) [6,11]. If Eqs. (1) and (2) are not satisfied, composite exhibits strain softening behavior with a single Griffith type localized widening crack [9]. On the basis of previous researchers' experience on polyethylene (PE) fibers, lower limit values for robust energy and strength based pseudo strain hardening indices have been proposed as $\text{PSH}_{\text{energy}}$ ($J_b'/J_{tip}$) > 3 and $\text{PSH}_{\text{strength}}$ ($\sigma_o/\sigma_{cr}$) > 1.2, respectively [12,13]. According to Yang [14], these index values should be minimum 3 and 1.45 for polyvinyl alcohol (PVA) fiber, 3 and 2 for ordinary polypropylene (PP) fibers respectively. It can be summarized that for a successful combination of proper fiber and matrix, it is necessary to determine the fiber bridging law for a given specific fiber-matrix system.

$$J_{tip} = \frac{K_m^2}{E_m} \leqslant \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J_b' \tag{1}$$

$$\sigma_{cr} < \sigma_0 \tag{2}$$

Polymeric fibers based on high molecular weight PE and PVA less than 2% by volume have been frequently employed in ECC design [15,16]. In recent years, high tenacity polypropylene (HTPP) fibers with 10–12 μm diameter have been employed in the design of ECC as a low-cost alternative [14,17]. However, the bond characteristics of this hydrophobic fiber needs to be improved by selecting proper matrix design with mineral and chemical admixtures [18,19]. Another major concern on the applicability of HTPP fibers in ECC design is the workability problems associated with the composite matrix rheology. Workability problems usually result with poor fiber distribution that has a significant influence on tensile performance of composite.

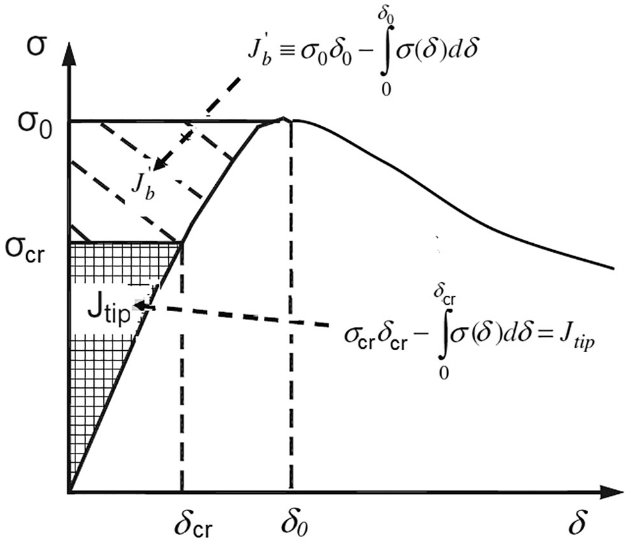

**Fig. 1.** Typical $\sigma(\delta)$ curve for tensile pseudo strain-hardening composite. Hatched area represents maximum complimentary energy $J_b'$. Shaded area represents crack tip toughness $J_{tip}$ [10].

The role of mineral additives such as silica fume, fly ash, granulated ground blast furnace slag, metakaolin, limestone powder or palm oil fuel ash on workability and hardened properties of PVA fiber reinforced ECC have been previously studied [20–26]. The water/binder (W/B) ratio on the performance of PVA-ECC was also studied in detail [27–29]. Li and Li [26] reported that the fiber distribution and related composite tensile performance significantly affected from matrix phase viscosity. However, the number of studies dealing with the role of W/B and mineral additives on matrix rheology and the linkage between matrix rheology and tensile performance of HTPP fiber reinforced ECC is very limited [30,31].

The influence of mineral additive type and W/B ratio on the matrix phase rheology and multiple cracking potential of HTPP-ECC have been investigated within the scope of this study. For this purpose, normal strength grade HTPP-ECCs incorporating granulated blast furnace slag (GBFS) and fly ash (FA) prepared at three different W/B ratios (0.31, 0.34, 0.37) have been prepared. Superplasticizer demand have been determined by keeping the mini-slump flow spreads value of each mixture constant (125 ± 10 mm). Rheological characterization of matrix phase of composites have been performed by using flow and viscosity curves. Hershel Bulkley Equation has been used to model the fresh state rheological data of matrices. The detailed tensile characterization including stress-strain relationship, fiber bridging stress – crack opening relation and compressive strength values have been experimentally performed. Furthermore, energy and strength based pseudo–strain hardening (PSH) indices of composites have been determined by using ECC micromechanical theory. Matrix fracture toughness and elastic modulus have been determined on notched beams. Crack number and width distribution of composites have been measured at peak tensile load via Digital Image Correlation Method. The potential of composites in terms of multiple cracking and strain hardening ability have been determined and related with their tensile ductility. Finally, the influence of mineral additive type and W/B ratio on matrix phase rheology and composite tensile performance have been discussed.

## 2. Experimental study

### 2.1. Materials

CEM I 42.5 R type Portland cement (PC), ground granulated blast furnace slag (GBFS) and C-type fly ash according to ASTM C618 [32] were used to prepare the binder phase of composites. The chemical composition and physical properties have been listed in Table 1. A polycarboxylate based F-type superplasticizer according to ASTM C494 [33] having 1.08 g/cm$^3$ density, was used to modify the workability of composites. The physical and mechanical properties of HTPP fiber has been presented in Table 2.

### 2.2. Composite mix proportions, mixing and specimen preparation method

The theoretical mixture ingredients of six HTPP-ECC for one cubic meter volume has been presented in Table 3. Each mineral additive studied at three different Water/Binder (W/B) ratios as 0.31, 0.34 and 0.37, respectively. The W/B ratios above 0.37 caused segregation and below 0.31 significantly increased the superplasticizer demand, which reduces the economic feasibility of the mix. Due to these reasons W/B ratios between 0.31 and 0.37 have been used. The PC/GBFS and PC/FA is kept constant as 2.5 for all mixes. High volumes of mineral additives have been used in ECC matrix in order to improve the economical feasibility and to reduce environmental impact. HTPP fiber dosage is also similar for all mixes as 2% by total volume. Superplasticizer demand has been determined by keeping the mini-slump flow spreads value of each mixture constant (125 ± 10 mm). Superplasticizer demand tended to decrease with increasing W/B ratio and no superplasticizer is required for GBFS-0.37 composite to achieve target spread flow value. Superplasticizer dosage of each mix has been inserted to its' code labels as "percent of cement by weight". For example, FA-0.34–0.6% indicates the fly ash incorporated composite prepared with a W/B ratio of 0.34 and superplasticizer dosage of 0.6% respectively.