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# Matrix tailoring of Engineered Cementitious Composites (ECC) with non-oil-coated, low tensile strength PVA fiber

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## HIGHLIGHTS

- High ductile ECC with non-oil-coated, low tensile strength PVA fiber could be developed by re-tailoring matrix.
- Viscosity modifying admixture improves the dispersion of fibers in ECC, and increase its ductility.
- Incorporating crumb rubber in ECC has the most effectiveness on ductility.
- Lower matrix toughness benefits to decrease the variability of ECC's mechanical properties.

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## ABSTRACT

Engineered Cementitious Composites (ECC) with ductile strain-hardening behavior has been recognized as a high performance and durable alternative to conventional concrete material. However, relative high initial material cost, mainly associated with high cost of PVA fibers commonly used in ECC mixtures, has limited broader field application of ECC in the construction, especially in Chinese market. In this study, new ECC mixture designs have been developed incorporating a type of lower-cost PVA fibers. Unlike the PVA fibers normally used, this low-cost PVA fiber has no surface oil coating and exhibit lower tensile strength, which are undesirable in basis of micromechanics underlying ECC design. High fly ash content, viscosity modifying admixture (VMA), fly ash cenosphere (FAC), and crumb rubber were incorporated into the mixture design to tailor the ECC matrix so as to compensate the micromechanical change associated with using the low-cost PVA fibers and to further enhance the performance of the resultant ECC mixture. It is found that the newly designed ECC mixtures with low-cost PVA fibers can achieve similar tensile strain capacity (up to 5.2%) with lower compressive and tensile strength when compared with previous ECC mixtures in literatures. The successful development of ECC with low-cost PVA fiber is expected to greatly promote the field application of ECC in China and give the references for the professionals to develop ECC with the local PVA fibers.



## 1. Introduction

For concrete infrastructure, it undergoes the combined effects of mechanical and environmental loading (such as restrained shrinkage, freezing-and-thawing cycles, temperature changes, et al.) during its service life, hence the crack in concrete is inevitable to appear due to its intrinsic property of brittleness which result in the loss of mechanical properties of concrete and corrosion of re-bar embedded inside, thus shorten the service life of structures. The frequent maintenance and repeatable repair to the concrete structure throughout the service life cause significant negative life-cycle economic, social, and environmental impacts, bring inconvenience to people's daily lives. In order to enhance the durability and sustainability of the concrete infrastructure, to extend its service life, and reduce the maintenance work, a kind of "crack-free" concrete material with high ductility is desired.

Engineered Cementitious Composites (ECC) belong to the family of high-performance fiber-reinforced cementitious composites (HPFRCC), which is developed by Victor Li in 1990 s as a ductile alternative to conventional concrete [1]. It is designed based on the micro-mechanics theory through optimizing three phases:

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matrix, fiber, and matrix/fiber interface [2–7]. Unlike the brittleness of normal concrete, ECC exhibits a metal-like pseudo strain-hardening behavior with high tensile strain capacity up to 3–5%, which is 300–500 times that of conventional concrete [3–8]. In contrast to the brittle fracture failure mode under tension commonly observed in normal concrete, multiple fine cracks (typically less than 100 μm in width [9–13]) develop in ECC under tension before final fracture, therefore resulting in the highly ductile behavior. With high tensile ductility and tight crack widths, ECC overcomes many challenges faced by concrete material associated with brittleness and cracking damage, significantly improving the structural and durability performance of the infrastructure [14–18].

Apart from material performances, the cost of the material also takes a very important role for large-scale applications of ECC in the construction. The history of ECC development also reflects the continuous endeavor of finding more economical polymer fibers. ECC was originally developed using polyethylene (PE) fibers [19]. However, PE fiber is almost prohibitively expensive to be used in large-scale construction applications in the 1990s. In search for a cheaper alternative, Polyvinyl Alcohol (PVA) fiber was selected to produce PVA-ECC [20–23]. The price of PVA fiber in US is about 1/8 of that of PE fiber, thus greatly reducing the cost of ECC material. However, at original stage, the PVA fiber is not treated by oil-coating, thus it possess very strong bond with surrounding hydration products because of the hydrophilic property of this kind of fiber. The most PVA fibers in ECC are ruptured during the propagation of crack when ECC are under tension; as a result, the strain capacity of ECC with PVA fibers is only around 1% meanwhile shows high variation of mechanical properties [4]. To better adopt PVA fibers into ECC design, collaborating with a Japanese fiber manufacturer, researchers at University of Michigan found that oil coating the surface (typically 1.2% oiling coating by fiber weight) of PVA fiber lead to better tensile behavior of ECC [4], since the tensile strain capacity of ECC with the oil-coated PVA fiber achieves to 5%. The oil coating treatment on the surface of PVA fiber reduces excessive interfacial bond between the hydrophilic PVA fibers and the surrounding cementitious matrix, which helps the pull-out phenomenon of fibers, consequently, results in desired tensile behavior of the PVA-ECC. Since then, the oil-coated PVA fibers have then been used extensively in the development of ECC materials.

With recent rapid economic growth in China, China has seen a huge construction boom. With such background, scholars and professionals have also been working on introducing ECC technology to China in the past decade [24–26].

One of the major obstacles for widely adopting ECC in China is the high cost of the PVA fiber (type-K) normally used in previous literatures (on Chinese market). This kind of PVA fiber is very expensive in China (around 210 RMB (30 US$)/kg), significantly higher than that in US (6.6 US$/kg). Such price significantly increases the initial material cost of ECC (in China), given that the fiber typically makes up more than 50% of the total material cost. Therefore the high material cost greatly limited the broader applications of ECC in China. As a matter of fact, there are several PVA fiber manufactories in China with much lower cost (around 40 RMB (6 US$)/kg) for the PVA fiber. So it is desired to produce high ductile ECC using the local PVA fiber in China.

To reduce ECC cost in China, a kind of low-cost PVA fiber (type-C) manufactured in China is used in attempt to produce ECC in this study. In the present stage, both the tensile strength and elastic modulus of this PVA fiber are notable lower than those of type-K PVA fiber. Due to the lower tensile strength, the low-cost PVA fiber is prone to be ruptured instead of pull-out behavior during the propagation of micro-crack. That is unbeneficial to the fiber bridging capacity linking crack surfaces, which in turn, cause the energy criterion fail, therefore does negative impact on the development of multiple micro-cracks which is the source of high tensile strain capacity of ECC. Furthermore, unlike the type-K PVA fiber typically used in current ECC mixtures, this type-C PVA fiber has no oil-coating on the surface, which could potentially lead to the excessive chemical bond between the fiber and surrounding matrix. Both are considered undesirable according to micromechanics underlying ECC design [21–23]. With these different fiber properties, re-tailoring of the ECC mixtures might be needed to achieve mechanical behavior comparable to that with type-K PVA-ECC.

To compensate the disadvantages brought by adopting this non-oil-coated, low tensile strength PVA fiber to produce ECC, lower the matrix fracture toughness, which involves the matrix re-tailoring, is proposed to in this study. The detailed theory foundations of this propose will be discussed in the following Section 2. The industrial waste materials acting as the inert filler in ECC are considered to be incorporated in ECC matrix. The addition of inert fillers in ECC could disturb the continuity of matrix accordingly, thus allow the matrix trigger micro-cracks easier [9,10]. Besides the potential of increasing ductility of ECC, the reuse of the industrial waste materials could also improve the greenness and sustainability of ECC material, since it avoids the energy consumption during the disposal process and reduces the proportion of the energy-consumed raw materials used in ECC [27].

Additionally, the dispersion of this low-cost type-C PVA fiber in fresh cementitious paste is found to be worse than that of type-K PVA fiber, and tends to agglomerate during mixing, resulting in large variability of composite material properties. In previous studies, Yang and Li [28,29] attempted to improve the dispersion of fibers in ECC using the rheology control methodology. They found that the increase of plastic viscosity of the fresh matrix paste, which can be correlated with marsh cone flow time, helps to better distribute PVA fibers in the paste, thus improve the ductility of ECC mixture and reduce the variability of ECC material properties.

In this paper, new ECC mixtures have been developed using the low-cost type-C PVA fibers with no surface coating and low tensile strength. The viscosity modifying admixture (VMA) was added into the ECC mixture to adjust the plastic viscosity of the fresh mortar paste to improve the dispersion of PVA fibers, thus in turn to help its mechanical properties. High fly ash content, crumb rubber and fly ash cenosphere (FAC) were also incorporated to further enhance the tensile ductility of the mixtures by reducing the matrix fracture toughness and modifying the interface properties between fiber and matrix. The compressive and tensile behaviors of the newly developed mixtures were experimentally investigated. The variability analysis of test results and long-term tensile performance of ECCs with non-oil-coated PVA fiber (type-C) are also discussed in this paper. The underlying micromechanics were also discussed in this paper. All experimental procedures and findings were documented in the following sections. The successful development of ECC with low-cost type-C PVA fiber in this paper has the potential to give the references for the professionals to develop ECC with the local PVA fibers.

## 2. ECC design considerations

Unlike the typical trial-and-error material development methodology, ECC is designed based on micromechanics theory. The micromechanics-based design theory links the microstructural and micromechanical properties (matrix toughness, fiber property, matrix/fiber interfacial property, etc.) to the macro-level material properties (tensile strength, tensile ductility, cracks width, etc.). In this section, the ECC design theory is briefly reviewed. This will help the readers to understand the discussion in the later sections.