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Investigations on mechanical performance of cementitious composites micro-engineered with poly vinyl alcohol fibers

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HIGHLIGHTS

- Engineering of cementitious composites using Polyvinyl alcohol (PVA) fibers.
- Influence of matrix constituents and fiber geometry on response of composite.
- Flexural strength shifts from the first crack to post crack with higher w/c.
- Higher flexural strength doesn't guarantee better ductility.
- Both the fracture energy and complementary play great role for ductility.
- Deformability could be increased by 10 times through PVA fibers incorporation.

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ABSTRACT

Polyvinyl alcohol fiber (PVA), being hydrophilic, has the capability to strongly bond with the cement matrix in the presence of water. Water which helps in developing the hydration product is also essential for the development of chemical bonding between the PVA fiber and the matrix. PVA fiber has two important characteristics when embedded in a cement matrix, viz. chemical bond and interface friction. The present study employs a micro-mechanics based approach and brings out a clear understanding on the behaviour of PVA fibers inside cement matrix. Flexure and fracture studies are carried out on the cementitious composites engineered with PVAs where the volume fraction and length of PVA fibers, the water-cement ratios (w/c) and sand to cement ratios (s/c) are the parameters. Results from flexural strength show that when water-cement ratio is varied from 0.3 to 0.4, gain of absolute strength shifts from the first crack to post crack. Lesser w/c ratio provides high strength but, the ductility could not be achieved whereas higher w/c ratio helps to activate chemical fibers, hence strain hardening phenomenon in PVA incorporated cement composite is achieved. The fracture studies depict that with clear understanding of mechanical behaviour and feasible tailoring thereafter, it is possible to develop the constituents to achieve the high fracture energy.

1. Introduction

Cement is a binding material mainly used for the construction purposes. The property of cement gets activated after addition of water, the process known as hydration. Many composites have been developed with cement as the primary binder. Cement mortar, plain and reinforced concrete, fiber reinforced concrete are some of the examples. The annual global consumption of concrete is about 12 billion metric tons [1]. With the usage of concrete being increased, its limitations are also more noticeable. The hardened cement composite is strong in compression, but it is ineffective when subjected to tensile load. This has made cement composites prone to brittle and catastrophic failure [2,3]. The brittleness of the composite is due to lack of energy dissipation mechanisms. Unlike metals, energy dissipation is not an inherent property in cement composites. Compressive strength being the most important material parameter of concrete, the focus of several research works is more inclined towards improving the compressive strength as a measure to improve the concrete performance. The improvement in compressive strength doesn't guarantee good structural performance as any failure occurs due to tension only. This is because even under compressive loading, concrete undergoes tensile fracture failure and compressive strength doesn't govern the failure

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mode at that point. Thus, a high compressive strength doesn't guarantee better performance of concrete structures, but a ductile concrete does [4].

Ductility is the measure of strain value (tensile strain capacity) under increasing tensile deformation until the material loses its load bearing capacity [5]. A ductile concrete can undergo volumetric inelastic deformation and can be resilient to severe loading while maintaining its load carrying capacity. The addition of reinforcement in proper locations and forms can improve the structural ductility whereas the improvement at material level is an additional, and perhaps, a better proposition. The addition of fibers in concrete is one of the ways in imparting ductility into concrete.

Fiber reinforced composites (FRC) can undergo inelastic deformations under severe loading and also maintain the load carrying capacity [6,7]. Fibers act as bridging members by holding the cracks together and become a source for dissipating the energy release at the crack tip as the crack grows with the increase in load. This will delay the failure resulting in a modified mode of failure from brittle to quasi-brittle post peak tension softening behaviour. Different types of failure modes are shown in Fig. 1. The increase in fracture toughness and change of failure mode from brittle to quasi-brittle is not sufficient enough to make the composite ductile, but the possession of strain hardening behaviour does.

Strain hardening is the ability of the material or composite to take load even after reaching the yield point. It is a characteristic property of the ductile materials. In brittle cement composites, the above property can be induced by judiciously introducing fibers in the matrix and is termed as pseudo-strain hardening [8,9]. Pseudo strain hardening in brittle composites is associated with the development of micro-cracks that develop normal to the loading direction. The brittleness of the composite is distinctly exposed when it is subjected to tension or bending. When cement composite is subjected to tensile loading, cracks start to develop once its tensile strength is reached and the composite will fail soon. Adding fibers enhances the fracture toughness of the composite, but improvement in strain hardening is required to attain ductility. Thus, all ductile concretes are inherently tough, but all tough concretes are not necessarily ductile. Hence, there is a distinctive difference between improving the fracture toughness of concrete versus imparting tensile ductility to it.

FRC are now increasingly being used in construction industry. Steel fibers [10–13], carbon fibers [14,15], glass fibers [16], polyvinyl-alcohol fibers [17,18], polyethylene fibers [19], polypropylene fibers [20], natural fibers [21] like coconut husk, sisal, sugar cane bagasse, bamboo, akara, plantain and musamba are some of the fibers that can be used with concrete. The choice of the fiber depends on the application and requirement of the user. Amongst the fibers mentioned above, polymeric fibers (polypropylene, polyethylene, polyvinyl alcohol) are gaining more attention in the recent years because they are easy to handle and cost effective. Due to cost considerations, polyvinyl alcohol fibers are preferred over other polymeric fibers [5]. The cost of PVA fibers is lower than that of steel fibers in terms of volume basis.

Polyvinyl alcohol (PVA) fibers possess high strength, high aspect ratio, high modulus and good resistance to alkali. They cause no harm to the environment. Hence, they have become an ideal material for usage with cement for developing concrete. They are hydrophilic in nature resulting in a strong bond with the surrounding cementitious matrix, this bond effectively prevents and suppresses the crack formation and development, improves bending strength, impact strength and crack strength, improves permeability, impact and seismic resistance of concrete. The fiber structure of PVA is shown in Fig. 2. The hydroxyl group (OH) has the potential to form hydrogen bond between the molecules. This results in a phenomenal change in surface bond strength between the PVA and the matrix [22,23].

The economic aspects and preferred microstructural (chemical bond, interface friction, aspect ratio, high modulus) properties of PVA have promoted its usage beyond normal fibers and a new class of ductile concrete called "Engineered Cementitious Composites (ECC)" was developed by Li et al. by using PVA as a primary reinforcing material [5]. Engineered cementitious composites are similar to fiber reinforced composites except for the absence of coarse aggregates. The salient feature of ECC is its ability to undergo pseudo-strain hardening behaviour under tensile loading. The strain capacity of the ECC is also estimated to be several times more than normal concrete. The distinct feature of ECC is that, unlike high strength concrete or normal FRC where the failure occurs after initiation and propagation of the single macro-crack, a large number of micro-cracks is developed in ECC resulting in ability to take load even after initiation of the crack. This pseudo-strain hardening behaviour improves the ductility and tensile strain capacity of the composite. Development of such an ECC is possible by means micromechanics based composite optimization [5].

Micro-mechanics based models were first proposed in early 90s [9,24,25]. These models provide a link between material microstructure and mechanical properties, taking into account the interacting effects of fiber, matrix and interface properties on the composite response. Due to the lack of knowledge of the Designers' on the material microstructure and its response, the prediction of the performance of the structure using the necessary materials is grossly done using thumb rule or over simplified calculations. But, with the judicious employment of micromechanics, it is possible to determine the response of engineered materials with a strong scientific basis.

The present study aims at understanding the behaviour of PVA fibers inside cement matrix with different water to cement ratios. Flexure and fracture studies using fibers of different lengths and different volume fractions are carried out. The study helps to understand the influence of fiber, matrix and interface parameters (micro level) on the composite mechanical properties (macro level). This study provides to route to design the microfiber based cement composites with desired response parameters.

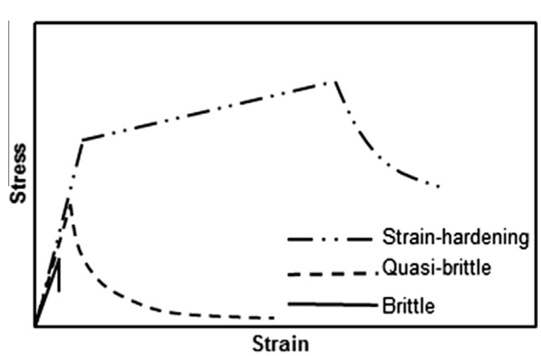

Fig. 1. Types of failure modes in concrete [5].

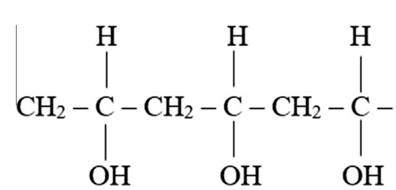

Fig. 2. Fiber structure of PVA.