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Mechanical properties of hybrid short fibers reinforced oil well cement by polyester fiber and calcium carbonate whisker

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HIGHLIGHTS

- A novel fiber hybridization reinforced cementitious composite was prepared.
- Triaxial tests were performed on the hybrid fiber reinforced cementitious composite.
- The multiscale cracking resistance was improved by the fiber hybridization.
- The new cementious composite offers better strain capacity and toughness behavior.

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ABSTRACT

In the present work, a novel fiber hybridization containing PET fiber and $CaCO_3$ whisker is developed to improve the multiscale cracking resistance, as well as to boost the toughness and mechanical performance of cement pastes. The mechanical properties, microstructure, the uniaxial and triaxial compression of hybrid fiber reinforced oil well cement pastes are investigated. The results indicate that after the introduction of mono PET fiber, the flexible strength and tensile strength were increased by 19.4% and 40.1%, but the compressive strength was decreased by 11.5%. Therefore, the $CaCO_3$ whisker combined with the PET fiber is used to enhance the compressive strength of the cement matrix. Because PET fibers and $CaCO_3$ whiskers are different in size, elasticity modulus and length-diameter ratio, the hybrid fiber can effectively interact with micro to macro cracks at multiple load stages. Hence, the hybridization contributes to enhancing multiscale cracking resistance from the microscale to the macroscale level, and the capability coefficients index of the cementious material are improved by 450.7% and 284.5% compared with those of control samples, respectively, under confining pressure. Moreover, the strategy enables to reduce the production cost of the cementing sheath of oil and gas well, and other large-scale construction project applications.

1. Introduction

The function of oil well cement to offer the long-term zonal isolation depends on the mechanical properties of the cement sheath and other well conditions. Previous studies have shown that the requirements to tensile strength, Young's modulus and flexibility of the well cement material are crucial for a long-term zonal isolation [1]. Because the exterior conditions under the well are becoming increasingly complex, the application of normal oil well cement slurry system can hardly satisfy the cementing operation. The cracks and flaws in different dimensions used to appear in oil well sheath, especially at the high-temperature and high-pressure condition under the well [2–4]. It becomes much more difficult to achieve the desirable toughing effects of the cementing sheath and the improvement of wellbore integrity [5,6]. One of significant approaches is to improve mechanical properties of the cementing system with the final purpose of preventing the crack and flaw propagating and coalescing to damage the well integrity. Although loads of fibers can perfectly meet the requirement, the relative effectiveness of fibers is a fundamental factor associated with fiber size and their mechanical behaviors. The inorganic

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Table 1
Properties of different commercial fibers.

Fibers	Density (g/cm^3)	Mechanical property	Production cost
Steel fiber	7.8 g/cm^3	Tensile strength ≥ 2000 MPa	590–750 $/T
PVA fiber	1.29 g/cm^3	Tensile strength ≥ 1100 MPa, E = 41 GPa	800–1500 $/T
PP fiber	0.9 g/cm^3	Tensile strength ≥ 684 MPa, E = 3.7 GPa	1200–2500 $/T
Carbon fiber (CF)	1.76 g/cm^3	Tensile strength ≥ 3500 MPa, E ≥ 220 GPa	> 20,000 $/T
PET fiber	1.36 g/cm^3	Tensile strength ≥ 700 MPa, E = 5 GPa	300–400 $/T
$CaCO_3$ whisker	2.86 g/cm^3	Tensile strength = 3–6 GPa, 700 MPa, E = 410–710 GPa	200–230 $/T

crystal whiskers are excellent candidates for microscopic reinforcement in the cement based materials [7]. Among them, the application of calcium carbonate whisker is gradually developed as a hotspot in cement-based composite. Due to the reasonable price and excellent capability, the incorporation of calcium carbonate whisker as an admixture can effectively restrict the micro-crack propagating and coalescing [8]. However, employing only one species of fiber can merely strengthen one aspect of the cementious material. Numerous recent research has been focused on the application of hybrid fibers with various sizes and performances that can improve the physical properties of cement paste at an extensive scale. At the same time, the crack propagation in cement paste is a multiscale and multistage process. However, using single kind of micro-fiber such as calcium carbonate whisker in the cement composite cannot solve this problem perfectly. The employment of hybrid fibers with different sizes and mechanical behaviors can take full advantages of hybridization and enforce the performance of material in multiple aspects.

Hybridization containing whisker fibers and commercial fibers is capturing more and more interest due to the excellent physical performance of crack restraining at different scales during the loading process. Mingli Cao [9] has studied a new kind of fiber hybridization containing steel fiber, PVA (polyvinyl alcohol) fiber and cheap calcium carbonate whisker. The interaction of different fibers and multi-scale cracks contributes to enhancing the mechanical properties of cementious composite, which is also reflected in its deflection hardening performance and multiple anti-cracking behaviors. Jianqiang Wei [10] showed that the strength of whiskers and PPF (polypropylene fiber) reinforced concrete is obviously improved compared with that of pure concrete, whisker concrete and PPF concrete. These increases could be correlated to the synergism of PPF and $CaCO_3$ whisker, which have different size, aspect ratio, elastic modulus and reinforcing role in concrete. Hang Yao [11,12] has investigated the cement pastes with hybrid fiber of calcium carbonate whisker and basalt fibers. The result shows that this hybridization of fibers is employed in the cement pastes, and the mechanical property of the cement pastes is further improved than that using single kind fiber. Simultaneously, the calcium carbonate whisker was a kind of desirable filling material with excellent performances of high strength, high elasticity modulus, excellent heat-resisting, economic efficiency and heat insulation. Calcium carbonate whisker can sufficiently fit the requests of the cementing and geological engineering in petroleum industry [13]. Ming Li [3,14] has explored the workability of cement slurry with calcium carbonate whisker and CF (carbon fiber). The mechanical performance and the microstructure of the oil well cement paste with hybrid fibers were also studied. Simultaneously, the strengthening mechanism of this hybrid fiber reinforced cement pastes was elaborated as hybrid reinforcement mode.

From above, steel fiber, PVA fiber, PP fiber, $CaCO_3$ whisker and carbon fiber reinforced cement-based materials were documented. Furthermore, PET fiber is a kind of stable chemical, heat-resistant, moderate strength and low elastic modulus fibrous material, and it has been applied in asphaltic concrete. Due to its low stiffness, the PET fiber is a potential candidate to improve the tensile strength and deformation ability of cementious materials. The mechanical properties and production cost of those fibrous materials are compared in Table 1 from previous studies. We can see that steel fiber, PVA fiber, CF and $CaCO_3$ whisker have higher tensile strength and elasticity modulus than those of the PP and PET fibers. Moreover, the production cost of PET fiber and $CaCO_3$ whisker are much lower than the other fibers. Therefore, the PET fiber and $CaCO_3$ whisker are considered to replace the expensive commercial fibers such as PVA, PP and CF. The application of both fibers not only increases the deformation performance but also promotes the economic efficiency. In the case of too low tensile properties and/or volumetric instability, the cement sheaths fail to perform the desirable performance under the well [1]. Thus, in this manuscript a new kind of fiber hybridization containing PET fiber and $CaCO_3$ whisker is designed to improve the multiscale cracking resistance from the microscale to the macroscale level, and to increase the toughness and deformation ability of the cement pastes. Furthermore, though elaborating the mechanical properties, microstructure and uniaxial and triaxial compression, the utilization of the designed hybrid fiber reinforced oil well cement paste will become possible, which contributes to reducing the production cost of the oil and gas well cementing sheath.

2. Materials and methods

The raw materials applied in this manuscript were cement (G high sulfur resistant oil-well cement), $CaCO_3$ whisker, PET fiber, cement dispersant (phenol and formaldehyde condensation polymer), de-foaming agent (HDBP), methylcellulose (MC), sodium carboxymethylcellulose (CMC), hydroxyethyl cellulose (HEC) and the tap water. The basic introductions and physical properties of $CaCO_3$ whisker and PET fiber were shown in Table 2.

The hybrid fiber cement slurry was produced based on the Chinese standard "GB 10238-2005: Oil-well cement" and "GB/T 19139-2012: The application performance and test methods of oil-well cement".

The mixing procedures were illustrated in Fig. 1. The $CaCO_3$ whisker was mixed with the cement powder for 5 min as pre-dispersing. The PET fiber was mixed and ultrasonic treated in the dispersant (MC or CMC) aqueous solution till the fibers could be dispersed well. Thereafter, the hybrid fibers were incorporated into the cement slurry. In this manuscript, the test specimens were prepared according to the proportions in Table 3.

Simultaneously, the cement additives and the $CaCO_3$ whisker used in this manuscript were mixed with the cement powder according to the quality fraction of cement. For further test, six parallel specimens were employed for each group and batch to provide the average and standard deviation. The curing condition of the cement slurry was under the relative humidity of 95% and temperature of 30 °C for 7 days. The compressive strength, flexible strength and split tensile strength of the cement pastes were tested according to Chinese standard "GB/T50081-2002: The standard of concrete mechanics performance test method". The triaxial compressive experiments of the fibrous cement pastes were examined