Mechanical Performance of HTCC Subjected to Elevated Temperatures

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Abstract: High toughness cementitious composite (HTCC) with high cracking resistance, high extensibility and high durability is widely applied in the field of civil engineering infrastructure, but in extreme environments such as elevated temperatures/fire due to the volatilization of organic fiber vulnerable to HTCC burst and mechanical performance degradation, structural damage and security problem. In this paper, the research status of post-high temperature mechanical properties is deeply analyzed. On this basis, suggestions for the optimization design of mechanical properties of HTCC to elevated temperature are put forward to provide technical support for the engineering application of this material.

1. Introduction
Since the beginning of the 19th century, cement composite material has been gradually adopted in the field of infrastructure engineering. ECC is fiber reinforced cement matrix composites, which is designed based on micro mechanics of material theory. Its fiber mixture ratio is generally 2% (Volume Percentage) [1-3]. The mixing and shaping process is same as the concrete or mortar. Its tensile strength can reach more than 10 MPa when the flowability could be guaranteed, the ultimate tensile strain can reach 0.5% ~8.0% [4-7]. It has been applied in the field of structural strengthening and rehabilitation.

High toughness cementitious composite (HTCC) exhibits energy-dissipating capacity and ductility under fatigue life [8-10]. Currently scholars had a lot of experimental research and theoretical analysis about its mechanical properties and applications. This paper summarizes the research of HTCC exposed to high temperature. In addition, the development trend and research suggestions of HTCC are prospected.

2. Mechanical properties of HTCC at room temperature
Victor Li firstly based on the fracture mechanics and micromechanics principles, adjusted the microstructure of materials and designed ECC with excellent mechanical properties at room temperature [11-14]. The ECC tensile stress-strain curve and fracture width development chart is shown in Fig.1 and the mix proportion in Table 1. The high ductility and toughness of ECC are beneficial to improve the ductility and energy-dissipating capacity of the structure. Compared with concrete, HTCC has higher tensile ductility. And its tensile strain hardening behavior and energy-dissipating are both superior to ordinary concrete [15,16]. Hu conducted experimental studies about the compression performance of
UHTCC cylinder and cube specimens with different ages and fiber properties. The results showed that the compressive strength of cube specimens was higher than that of cylinder specimens with the same ages. The geometric size and shape of the specimens played a greater impact on the compression performance [17].

![ECC tensile stress-strain curve and fracture width development chart](image)

Table.1 The mix proportion of ECC

| Type of fiber | Cement | Sand | Fly ash | Water | Preparation | Thickening | Defoamer | Fiber volume percentage |
|---------------|--------|------|---------|-------|-------------|------------|----------|-------------------------|
| PVA-ECC       | 1      | 1    | 0.11    | 0.42  | 0.012       | 0.049%     | 0.048%   | 2%                     |

HTCC is the research hotspots of fiber concrete. Its excellent mechanical properties have been demonstrated at room temperature.

3. Mechanical properties of HTCC at elevated temperature

3.1. Effect on HTCC with single kind of fiber
It has been reported in previous literature that with the increase of specimen size, temperature and heating time, the compressive strength, stiffness and residual strength will decrease. Elevated temperature is one of the most unfavorable conditions for HTCC. In order to improve the properties of composites, interface optimization is applied to polymer fibers [18]. According to the microstructural characterization, Yin suggested that the lower load-bearing capacity behavior of ECC components and structures should be analyzed according to the elevated temperature deterioration law and characteristics of ECC. So as to provide theoretical and technical support for improving the fire resistance design of ECC structures [19]. Zhang found that when the temperature was between 20°C and 200°C, with the increase of the temperature, the compressive strength of HTCC specimens with different fly ash contents all increased. They all showed tensile high ductility under tension [20].

![ECC tensile stress-strain curve and fracture width development chart](image)

According to the literature report it has been observed that the strengthening and toughening effects of steel fiber were weakened because of the effect of elevated temperature [21]. Zhang found that the decrease of ECC compressive strength was the result of melting and phase decomposition of fiber and matrix under elevated temperature [22]. Yu used scanning electron microscopy (SEM) and mercury porosities (MIP) to characterize the microstructure of HTCC samples to elevated temperature exposure, which effectively explained the observed mechanical properties [23].

3.2. Effect of hybrid fibers on HTCC
In recent years, the research on HTCC to elevated temperature has attracted worldwide attention. At the same time, a large number of scholars tried to use hybrid fiber to solve the problems. The Ultra High
Toughness Cementitious Composite (UHTCC) adding nano-SiO₂ and steel fiber has excellent mechanical properties and high temperature performance [24].

The performance of hybrid fiber is better than those with single kind of fiber. The hybrid fiber is made with 1.0% steel fiber and 0.10% PVA fiber is the best. In addition, as the increase of fiber volume fraction, the compressive strength and splitting tensile strength are on the increase [25]. The PVA and steel fibers have a synergistic crack blocking effect which may change the propagating path of cracks [24]. Quan through compared PVA-ECC with hybrid steel-PVA fiber to elevated temperature tensile properties, found that the tensile strain hardening ability of PVA-ECC was degraded by replacing PVA fiber with steel fiber in equal amount at room temperature, and the mixed steel fiber can slow tensile toughness of tensile strength and the attenuation rate [26].

3.3. Effect of elevated temperature on HTCC

Damage degradation and final failure to elevated temperature (fire) environment is a common problem of cement-based materials. Sahmaran found that the mechanical properties of fire-deteriorated ECC mixtures were similar or better than those of conventional concrete with polypropylene or steel fiber. Then, the influence of fly ash content and PVA fiber to elevated temperature compressive performance of ECC was studied, and it was found that the increase of fly ash content could effectively improve the residual compressive strength of the material in the range from 200 to 600°C, and the melting mechanism of PVA fiber could effectively avoid the substrate bursting [27,28].

Fu studied the UHTCC which mixed steel fiber with PVA fiber to elevated temperature and found that the compressive strength has increased before 400°C, while the flexural strength decreased to the elevated temperature exceeded 200°C, mainly due to the secondary hydration of the substrate and the melting of PVA fiber [29,30]. Wang tested the compressive and bending mechanical properties of hybrid basalt-PVA fiber and single PVA fiber ECC at room temperature to 400°C, and observed the microstructure changes of the material with scanning electron microscopy at different temperatures. The results showed that the compressive strength of hybrid fiber HTCC to elevated temperature is improved compared with the room temperature, and the compressive toughness of hybrid fiber HTCC to elevated temperature is better than that of single fiber system [31]. ZHAO found that the bonding stress reduces with experienced temperature increases and a considerable steel bar slippage occurs when UHTCC softened and deformation capacity strengthened because of the increase of interspace after high temperature [32].

HTCC can meet the demand of building applications. Under the static tensile load, it shows excellent deformation ability, and can generate multiple small cracks and crack development. In the meantime, it showed better ductile failure characteristics. HTCC have excellent ductility and micro-crack width control properties to meet the requirements of next-generation infrastructure. But the mechanical properties under elevated temperature (fire) condition, the tensile ductility characteristics and the control ability of crack width are related to the safety of HTCC structure under elevated temperature (fire) condition, which needs to be broken.

4. Conclusions

Based on the existing research results of HTCC and centering on the mechanical properties of fibers to elevated temperature, this paper reviewed the research progress and research results of single fiber and hybrid fiber at home and abroad respectively, and came to the following conclusions:

1) High melting point and high strength fiber of hybrid fiber can undertake bridging between cracks to elevated temperature and effectively improve HTCC’s elevated temperature mechanical properties.

2) The HTCC to elevated temperature are greatly improved compared with that of single fiber, and the addition of steel fiber can slow down the decay rate of tensile strength and tensile toughness.

In order to optimize the performance of HTCC, scholars have carried out experimental studies on different types of hybrid fibers, in order to obtain cement-based materials with more economic raw materials, better performance and better applicability. However, according to the above interpretation and analysis, there are still problems that need to be further studied in the research of HTCC at the
present stage:

1) The study on the optimization of HTCC mix ratio takes full account of the change of material properties to elevated temperature, in order to obtain the optimal mix ratio to improve the engineering application value of HTCC;

2) To develop a detection and monitoring method for HTCC material structural components, so as to ensure that they conform to the construction application quality and health monitoring of long-term service status.

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