Study on Tensile Properties of TRU Plate under Conventional Environment and Acidic Environment

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Abstract. Ultra-high toughness cementitious composites (UHTCC) and textile have emerged as advanced composite materials in recent years. Combining these materials results in textile reinforced ultra-high toughness cementitious composites (TRU). In this paper, the tensile properties of TRU plates were studied. Both conventional and acidic test environments were set up, and the influencing factors, such as the number of textile layers and the matrix of the specimen were considered. The tensile stress-strain curve of the specimens were measured, revealing that both the ultimate tensile stress and ultimate tensile strain of TRU increase with the number of textile layers. It was also observed that UHTCC has higher tensile strength compared to mortar. Additionally, the acidic environment significantly affects the bearing capacity of the components. Based on the experimental data, auniaxial tensile stress-strain constitutive model suitable for TRU in both conventional and acidic environments was established. The theoretical values obtained from the model are in good agreement with the experimental results.

Keywords: TRU, Tensile properties, Constitutive model.

1 Introduction

With the rapid development of the civil engineering industry, there is a growing need to enhance the performance and durability of existing building materials. Textiles offer advantages such as light weight, high strength, and corrosion resistance[1], while ultra-high toughness cementitious composites (UHTCC) provide ultra-high toughness, high tensile strain, and exceptional durability[2,3]. Combining these materials results in textile reinforced ultra-high toughness cementitious composites (TRU), a new composite material that effectively controls crack formation and improves structural bearing capacity and durability[4,5]. These advantages make TRU a hot topic for scholars to study.

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In recent years, scholars have conducted extensive research on the tensile properties and durability of TRU. In terms of tensile properties, Li Chuanxiu[6] et al. carried out tensile and four-point bending tests on TRU plates, revealing that as the number of textile layers increases, the bearing capacity and ultimate tensile strain of the plates also increased. Halvaei[7] studied the effects of volume fraction on the bending properties of TRU plates, finding that the crack width of the specimen increases with the decrease in textile content. The bearing capacity of TRU increases with the increase in fiber volume content. Regarding the durability of TRU, Zhao Junling[8] studied the mechanical properties of TRU under a freeze-thaw environment. The tests show that although the ultimate tensile stress and bending resistance of the specimen have decreased, the overall curve trend remains favorable.

The range of acid corrosion affecting concrete has been increasing annually, with reposts indicating that one-third of China's area is now affected by acid rain[9]. It can be seen that it is particularly necessary to study acid corrosion-resistant materials with superior performance. While there has been research on the mechanical properties and durability of TRU, studies focusing specifically on its durability and mechanical properties in acidic environments are limited. Therefore, this paper set up two different test environments, conventional environment and acidic environment, to study the tensile properties of TRU plates under different conditions. Subsequently, a tensile constitutive model of TRU plates under both conventional and acidic environments is proposed, providing a theoretical basis for the sustainable development of the construction industry and infrastructure construction.

2 Test Overview

2.1 Test Materials

The TRU is composed of UHTCC and textile. The UHTCC component materials include quartz sand, cement, mineral powder, wollastonite, limestone powder, water-reducing agents, and polyethylene short fiber (PE fiber). According to the standard[10], the 28-day compressive strength of the UHTCC cube standard specimen was 60.2 MPa, the ultimate tensile strength was 7.75 MPa, the ultimate tensile strain was 3.1%, and the elastic modulus was 19374.0 MPa. The textile used is a carbon-glass mixed textile with a gird size of 20mm×20mm and a tensile strength of the 5516.0 MPa.

The textile reinforced concrete (TRM) is composed of mortar and textile. The Mortar consists of cement, fine river sand and quartz sand. The compressive strength of mortar is 54.0 MPa, which was similar to that of UHTCC and suitable for use as a comparison material in this test. The elastic modulus of the mortar was 23821.0 MPa. The textile used in TRM was similar to that used in TRU.

2.2 Preparation of Specimens

In this paper, rectangular plates were used for tensile tests, with specimen dimensions of 400mm×100mm×15mm. The plate pattern is shown in Figure 1. During specimen preparation, the UHTCC was evenly smoothed to the appropriate thickness of the matrix layer, and the textile was laid onto the matrix layer. Then a U-shaped hook was inserted into the matrix every three grids vertically[11], as shown in Figure 2, and finally, the upper matrix layer was filled.

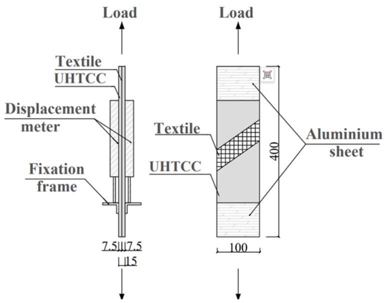


Fig. 1. Pattern and drawing diagram of TRU

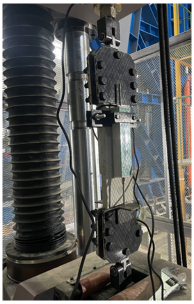


Fig. 2. Tensile loading test diagram

2.3 Grouping of Specimens

The test environment in this paper was divided into conventional and acidic environment. In the conventional environment, the number of layers of carbon textile and the matrix of specimens are considered. The test groups are shown in Table 1, with two specimens in each group.

Table 1. Tensile test group of TRU plate.

Specimen number	Number of layers of textile	Thickness of protective layer	Test environment	Type of substrate
CTX5	1	7.5 mm	conventional environment	UHTCC
CTX6	2	5mm	conventional environment	UHTCC
CTX8	1	7.5 mm	conventional environment	Mortar
CTX-ac8	1	7.5 mm	corroded 90d under acidic environment	UHTCC

2.4 Test Methods

In this paper, a uniaxial tensile test method was employed. To eliminate the adverse effects of eccentric force, a universal hinge was used to apply tension at both ends of the specimen. The loading machine is a 200-ton electro-hydraulic servo universal testing machine, utilizing displacement control loading. Two displacement meters were placed on both sides of the specimen, with a loading rate set to 0.6mm/min. The diagram of the tensile test is shown in Figure 1, and the experimental setup is shown in Figure 2.

To accelerate the corrosion rate, the concentration of hydrogen ions in the solution was increased. TRU plates were soaked in an acidic solution for 90 days, after which the specimens were removed and allowed to dry indoors for 2 days. The tensile mechanical properties were then tested to analyze the degree of mechanical property degradation.

3 Results and Analysis of Tensile Test of TRU Plate

3.1 Failure Patterns of Specimens

It was observed that during the entire process from crack formation to failure, the TRM specimen exhibited only one crack with a large width. In contrast, the TRU specimen developed many fine cracks on its surface. Microscopic observation revealed that the maximum width of these cracks was only 40 μm . This indicates that TRU has excellent corrosion resistance.

3.2 Analysis of Stress-Strain Curve of TRU Plate

The results of the uniaxial tensile test are shown in Table 2.

Table 2. Uniaxial tensile test results.

Specimen number	Cracking strain (%)	Cracking stress (MPa)	Ultimate strain (%)	Ultimate stress (MPa)
CTX5	0.03	2.01	2.15	18.07
CTX6	0.03	2.63	2.36	19.58
CTX8	0.08	1.28	1.38	5.94
CTX-ac8	0.02	0.92	1.27	11.52

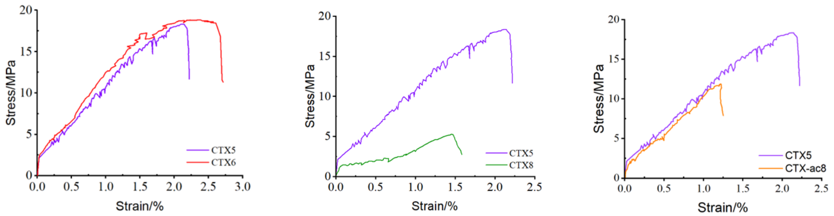
3.2.1 Stress-Strain Curve Analysis of TRU Plate under Conventional Environment.

The stress-strain curve of TRU plate under conventional environment is shown in Figure 3(a) (b).

According to the test results, the ultimate tensile stress of a single-layer textile (CTX5) can reach 18.07 MPa, and the ultimate tensile strain can reach 2.15%. The ultimate tensile stress of a double-layer textile (CTX6) is 19.55 MPa, and the ultimate tensile strain reaches 2.31%. As the number of textile layers increases, both the ultimate tensile stress and ultimate tensile strain increase incrementally.

Comparing the TRU and TRM specimens, it can be concluded that the ultimate tensile stress of the UHTCC-based specimen (CTX5) was approximately three times that of the mortar-based specimen (CTX8). The test curve indicates that the mortar specimen's curve is very gentle, showing no significant upward trend, and the stress does not increase with the strain.

The tensile test results of TRU plate under acidic environment are shown in Figure 3 (c). After 90 days of acid corrosion, the cracking strain and cracking stress of CTX-ac8 are 0.02% and 0.92 MPa, respectively, while the ultimate strain and ultimate stress are 1.27% and 11.5 MPa, respectively. Compared to the conventional environment, the degradation rate of ultimate stress after acidic corrosion reaches 35% to 37%. This demonstrates that acidic corrosion significantly impacts the tensile strength of TRU plates.



(a) Comparison of different layers (b) Comparison of matrix (c) Comparison of environment

Fig. 3. Tensile stress-strain curve of TRU plate Stress-strain curve analysis of TRU plate under conventional environment.

4 TRU Tensile Constitutive Model

4.1 TRU Tensile Constitutive Model under Conventional Environment

This section proposes a TRU tensile constitutive model under conventional environment, dividing the tensile stress-strain curve obtained from TRU plate into three stages, as shown in Figure 4.

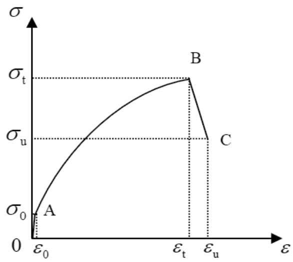


Fig. 4. Tensile constitutive model of TRU

The first stage (O-A) is the linear elastic stage, during which the textile and UHTCC work together as a unified whole. The second stage (A-B) is the tensile stage. Although the matrix is cracked, the stress continues to increase because the fibers in the UHTCC matrix have not yet broken and can still bear part of the tension. The third stage (B-C) is the failure stage, where the fibers in the matrix are in a state of fracture and pull-out, and the textile experiences either fracture failure or slipping-out failure. This stage results in a ductile failure.

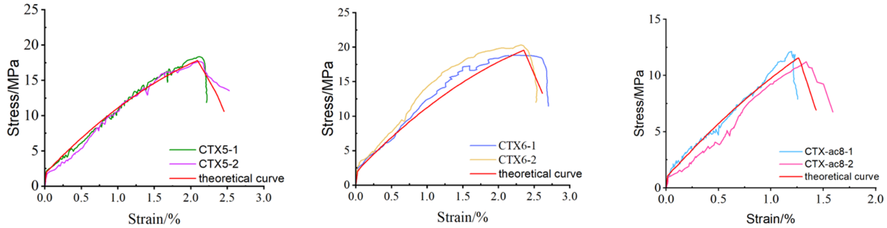
In this section, based on the stress-strain curve of the TRU plate measured in the experiment, the tensile constitutive model of TRU under a conventional environment is proposed, as shown in formulas (1)-(3):

$$\text{OA section: } \sigma = \sigma_t \frac{9.6\varepsilon}{\varepsilon_t} \left(\varepsilon \le \varepsilon_0\right) \tag{1}$$

$$\text{OB section: } \sigma = \sigma_t \left[\frac{1.29\varepsilon}{\varepsilon_t} - 0.38\left(\frac{\varepsilon}{\varepsilon_t}\right)^2 + 0.1\right] (\varepsilon_0 < \varepsilon < \varepsilon_t) \tag{2}$$

$$\text{OC section: } \sigma = 3.9\sigma_t - \frac{2.9\sigma_t}{\varepsilon_t} (\varepsilon_t < \varepsilon \le \varepsilon_u) \tag{3}$$

Where σ is tensile stress, σ_t is peak stress, ε is tensile strain, ε_0 is cracking strain, ε_t is peak strain, ε_u is failure strain.



(a) Single layer of textile (b) Double layers of textile (c) Under acidic environment

Fig. 5. Comparison between TRU tensile test and theoretical curve of textile with different layers

Table 3. Comparative analysis of TRU tensile test values and theoretical values under conventional and acidic environments.

Specimen number	Tensile test value (MPa)	Tensile theoretical value (MPa)	Theoretical value/test value
CTX5-1	18.33	18.07	0.986
CTX5-2	17.81		1.015
CTX6-1	18.84	19.58	1.039
CTX6-2	20.32		0.963
CTX-ac8-1	11.82	11.52	0.974
CTX-ac8-2	11.22		1.027

In this paper, the constitutive model is compared with the test data, as shown in Figure 5(a) (b) and Table 3, it can be concluded that the error between the theoretical value and the test value is less than 4%, and the results of the two are in good agreement.

4.2 TRU Tensile Constitutive Model under Acidic Environment

The behavior of the TRU tensile constitutive model under an acidic environment is consistent with that under a conventional environment, also comprising three stages. However, the peak stress and peak strain of the TRU tensile constitutive model under acidic environment decrease significantly. Based on the stress-strain curve of TRU measured in the acidic environment, the TRU constitutive model under acidic environment is proposed, as shown in formulas (4)-(6):

$$\text{OA section: } \sigma' = \sigma_t' \frac{8.0\varepsilon'}{\varepsilon_t'} \left(\varepsilon' \leq \varepsilon_0'\right) \tag{4}$$

$$\text{OB section: } \sigma' = \sigma_t' \left[\frac{1.14\varepsilon'}{\varepsilon_t'} - 0.21\left(\frac{\varepsilon'}{\varepsilon_t'}\right)^2 + 0.08 \right] (\varepsilon_0' < \varepsilon' < \varepsilon_t') \tag{5}$$

$$\text{OC section: } \sigma' = 4.17\sigma_t' - \frac{3.17\sigma_t'}{\varepsilon_t'} (\varepsilon_t' < \varepsilon' \leq \varepsilon_u') \tag{6}$$

Where σ' is the tensile stress of the specimen under acidic environment, σ_t' is the peak stress of the specimen under acidic environment, ε' is the strain of the specimen under acidic environment, ε_0' is the cracking strain of the specimen under acidic environment, ε_t' is the peak strain of the specimen under acidic environment, and ε_u' is the failure stress of the specimen under acidic environment.

By comparing the constitutive model with the experimental data, as shown in Figure 5 (c) and Table 3, it can be concluded that the error between the theoretical value and the experimental value is less than 3%, and the two results are in good agreement.

5 Conclusion

In this paper, uniaxial tensile tests of TRU plate were conducted under both conventional environment and acidic environment. The main conclusions are as follows:

(1) The tensile stress-strain curve for TRU plates was obtained from the tensile tests, and a tensile constitutive model for TRU under conventional conditions was presented. The comparison between theoretical and experimental values showed good agreement, providing a theoretical basis for predicting the ultimate tensile strength of TRU plates under tensile conditions.

(2) The experiment demonstrated that an acidic environment significantly impacts the bearing capacity of TRU component. The theoretical values align well with the experimental results, offering a theoretical basis for predicting the tensile properties of TRU under acidic environment. This provides a strong scientific foundation for the future application of TRU structures under acidic environment.

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