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Experimental Study on The Mechanical Properties of High Territory-Steel Fiber-Rubber Concrete Under Multi-Component Coupling Effects

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Abstract

In this paper, the effects of multi-component coupled dosages on the compressive strength, splitting tensile strength, and flexural strength of concrete, a three-factor, three-level orthogonal experiment was employed, and the analysis of variance method was used to determine the primary and secondary order of the effects of materials on concrete properties. Results indicate that the single incorporation of rubber particles into traditional concrete optimizes impact resistance via elastic deformation but results in a significant reduction in strength. In contrast, high territory improves strength and durability by generating C-S-H gels through its pozzolanic activity, while steel fibers establish a three-dimensional supporting network that enhances crack resistance and toughness. The combined incorporation of high territory compensates for the strength loss by virtue of its filling effect and pozzolanic reaction, while steel fibers inhibit the propagation of micro-cracks at the rubber interface. SEM analysis results reveal that the hydration products of high territory–steel fiber-rubber concrete exhibit a smoother surface, fewer weak interfacial zones and better bonding between aggregates and cement mortar, which significantly improves the overall performance of the concrete.

Keywords

High territory; Steel fiber; Rubber particles; Mechanical properties; Orthogonal experiment.

1. INTRODUCTION

Behind the prosperity of the transportation industry, the quantity of waste rubber tires is increasing steadily.Developing cost-effective technologies for the recycling of waste rubber tires has become a significant research topic in the fields of circular economy and sustainable development. According to statistics, the annual production of waste rubber tires in China exceeds 300 million, equivalent to approximately 10 million tons in weight, and the number of scrapped tires is growing at a rate of 6% to 8% annually [1-2]. The large quantity of waste tires leads to massive accumulation, where bacteria are prone to breed, causing influenza and even fires [3]. Currently, processing scrapped tires into rubber powder can promote China's green and sustainable development strategy. Adding it to concrete can also optimize impact resistance and enhance durability and other properties [4-6]. However, research indicates that while using rubber powder to improve the durability of concrete, it significantly reduces the compressive strength, which has hindered its large-scale application [7].

However,the incorporation of rubber powder into concrete is accompanied by a significant reduction in compressive strength, some scholars have explored the addition of fibers [8-9]. Studies in references [10-14] on the mechanical properties of steel fiber-reinforced concrete

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show that steel fibers can play a role in toughening and crack resistance within concrete, delaying the propagation of micro-cracks propagation. This not only compensates for the negative effects of single-rubber incorporation on the mechanical properties of concrete but also significantly enhances the mechanical properties of concrete [15-16].

Using high territory as an equal-mass substitute admixture for cement is mainly based on its unique pozzolanic activity and micro-aggregate effect. It can effectively fill the pores between rubber and the matrix, optimize the distribution of hydration products, thereby improving the compactness of the concrete's microstructure and enhancing its mechanical properties [17].

In summary, using multi-component coupling as a reinforcing material for concrete, comparing and analyzing the effects on compressive strength, splitting tensile strength, and flexural strength, and analyzing the micro-morphology of the interface through SEM can provide references for the design of enhanced traditional concrete.

2. EXPERIMENT

2.1. Raw Materials

Cement: The cement produced by Shengyuan Co., Ltd. in Anshan City has a strength grade of 42.5R, with a 28d compressive strength of 43.5MPa and a flexural strength of 8.4MPa. Coarse aggregate: Continuously graded crushed stones with a size of 5-20mm from Xiuyan City, having an apparent density of 2630kg/m^3. Fine aggregate: Ordinary river sand from Xiuyan City is used as the fine aggregate, with a fineness modulus of 2.45 and an apparent density of 2615kg/m^3. Water-reducing agent: ZY-HPWR polycarboxylate superplasticizer with a water - reducing rate of ≥26%. Water: Tap water. Waste rubber powder: 60-mesh rubber powder produced by Yanxi Factory in Hebei Province. Its performance indicators are shown in Table 1, and its external characteristics are presented in Figure 1.Steel fiber: Milled corrugated steel fibers produced by Hunan Road and Bridge Company. Its performance indicators are shown in Table 2, and its external characteristics are presented in Figure 2. High territory: 1250-mesh high territory powder produced by a factory in Chengdu City, Sichuan Province. Its chemical composition and performance indicators are shown in Table 3, and its external characteristics are presented in Figure 3.



Figure 1. Waste rubber powder



Figure 2. Milled corrugated steel fibers



Figure 3. High territory

Table 1. Performance indicators of waste rubber powder

Particle size	Performance density	Fiber content	Moisture content	Ash content	Combustion residue
(mm)	(km/m^3)	(%)	(%)	(%)	(%)
0.25~0.3	1030	0	0.2	6.9	36.5

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Table 2. Steel fibers performance indicators

Fibers Types	Length (mm)	Width (mm)	Thickness (mm)	Density (km/m³)	Tensile strength (MPa)
Milled wave pattern	35	2	0.8	7.8	432

Table 3. Composition and performance indices of high territory

SiO2	Al2O3	Fe3O2	CaO	MgO	Na2O	Physical properties	
(%)	(%)	(%)	(%)	(%)	(%)	Fineness	Activity index
54.01	41.28	0.73	0.18	0.07	0.16	1250	≥110

2.2. Experimental Design

The designed strength grade of the concrete in this test is C40.The mix proportion of the reference concrete was calculated in accordance with the Code for Design of Concrete Mix Proportions (JGJ55-2011) [18] from which the reference mix proportion was determined as follows: cement 369.95kg/m³, sand 649.59kg/m³,gravel 1157.76kg/m³,water-reducing agent 7.03kg/m³.A three-factor, three-level orthogonal design was conducted with the influencing factors including high territory, steel fiber, and rubber, and they are marked as A, B, and C respectively. According to the dosage range of high-performance concrete components in the literature [19], the dosages of each factor are determined as follows: high territory 5%,9%,13%; steel fiber 1.0%,1.5%,2.0%; rubber powder 5%,10%,15%. The orthogonal test factor table is shown in Table 4, and the orthogonal test design table is shown in Table 5.

The influence on the mechanical properties of concrete is studied, and the influence of the incorporation of high territory, steel fiber, and rubber on the mechanical properties of concrete is analyzed through variance analysis.

Table 4. Orthogonal test factor table

Test levels	Test factors		
	A High territory (%)	B Steel fibers (%)	C Rubber powder (%)
1	5	1	5
2	9	1.5	10
3	13	2	15

Table 5. Orthogonal experimental design table

Identification number	Test factors		
	A High territory (%)	B Steel fibers (%)	C Rubber powder (%)
M1	5	1	5
M2	5	1.5	10
M3	5	2	15
M4	9	1	10
M5	9	1.5	15
M6	9	2	5
M7	13	1	15
M8	13	1.5	5
M9	13	2	10

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2.3. Sample Preparation

In the experiment, crushed stones, river sand, steel fibers, cement, high territory, and rubber powder are added and mixed in the stated sequence, and then water mixed with the water-reducing agent is added. After thorough mixing, rapid stirring is carried out. The mixture is then poured into molds coated with release oil, labeled, and cured. The prepared specimens are cured under standard conditions for 24 hours and then demolded. The demolded specimens are then moved to water at (20±2)°C for 28d curing.

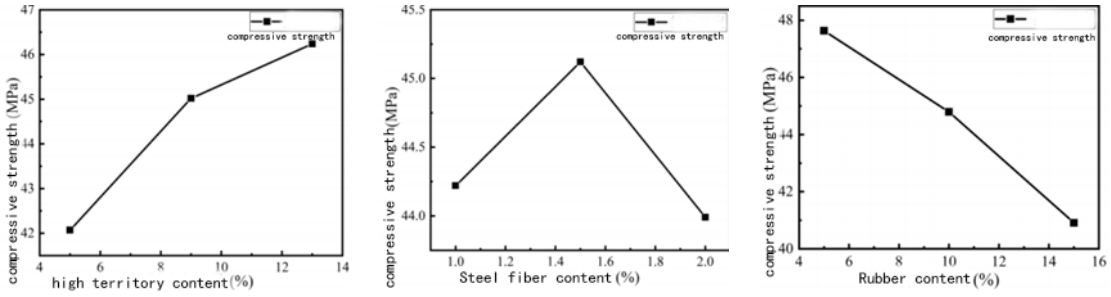
According to the Standard Test Methods for Physical and Mechanical Properties of Concrete (GB/T 50081-2019), specimens for testing the 28d compressive, splitting tensile,and flexural properties of concrete are prepared. The compressive and tensile specimens have dimensions of 100mm×100mm×100mm, and the flexural specimens have dimensions of 100mm×100mm×400mm.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength of High Territory-Steel Fiber-Rubber Concrete

Table 6. 28d Compressive strength values of high territory-steel fiber-rubber concrete

Test identification number	Factor levels			28d Compressive strength (MPa)
	A	B	C	
	High territory (%)	Steel fibers (%)	Rubber powder (%)	
P1	0	0	0	38.80
M1	5	1	5	45.70
M2	5	1.5	10	42.65
M3	5	2	15	37.31
M4	9	1	10	44.50
M5	9	1.5	15	42.83
M6	9	2	5	47.52
M7	13	1	15	42.03
M8	13	1.5	5	49.55
M9	13	2	10	46.43



A Factor influence B Factor influence C Factor influence

Figure 4. A, B, C Relationship between factors and compressive strength

As indicated in Table 6 and Figure 4:

The 28d compressive strength of high territory-steel fiber-rubber concrete is jointly affected by the three factors. Overall, the compressive strength varied in the range of 37.31-49.55MPa, and the compressive strength of M8 reached the maximum at a high territory content of 13%, steel fiber content of 1.5% and rubber powder content of 5%, reaching 49.55MPa. The strength

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of the ordinary concrete P1 without admixtures is the lowest, being 38.80MPa. This indicates that a reasonable admixture ratio can significantly improve the compressive performance of concrete.

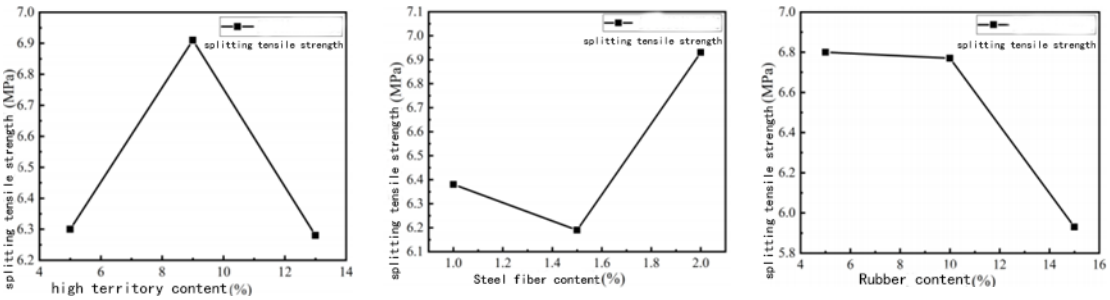
High territory was used as a highly reactive mineral admixture. high territory can fill pores and improve compactness through its pozzolanic effect. Steel fibers enhance the toughness of the matrix and inhibit crack propagation through bridging and crack-arresting effects. Although rubber powder may weaken the stiffness due to its relatively low elastic modulus, an appropriate amount of it can improve the impact resistance and deformation ability. When the three act synergistically, high territory and steel fibers jointly enhance the strength and toughness of the matrix, and rubber powder adjusts the brittleness of the material within a certain dosage range. However, an excessive amount of rubber powder will significantly reduce the compressive strength (e.g. the strengths of M3 and M5 are significantly lower than that of M8).

When the high territory dosage is moderately high, the steel fiber dosage is between 1.5%-2%, and the rubber powder dosage is low, the compressive strength performs best. This indicates that the positive enhancement effects of high territory and steel fibers are dominant, and the rubber powder dosage is preferably controlled at a low level to avoid excessive weakening of the compressive strength. The three need to be optimized in proportion to achieve the synergistic improvement of mechanical properties.

3.2. Splitting Tensile Strength of High Territory-Steel Fiber-Rubber Concrete

Table 7. 28d Splitting tensile strength values of high territory-steel fiber-rubber concrete

Identification number	Factor levels			28d Splitting tensile strength (MPa)
	A	B	C	
	High territory (%)	Steel fibers (%)	Rubber powder (%)	
P1	0	0	0	3.05
M1	5	1	5	7.01
M2	5	1.5	10	6.48
M3	5	2	15	5.51
M4	9	1	10	6.40
M5	9	1.5	15	6.49
M6	9	2	5	7.85
M7	13	1	15	5.82
M8	13	1.5	5	5.55
M9	13	2	10	7.53



A Factor influence B Factor influence C Factor influence

Figure 5. A, B, C Relationship between factors and splitting tensile strength

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As indicated in Table 7 and Figure 5:

The 28d splitting tensile strength of high territory-steel fiber-rubber concrete is jointly affected by the three factors. The overall strength varies between 5.51-7.85MPa. Among them, the strength of Group M6 is the highest, reaching 7.85MPa when the high territory dosage is 9%, the steel fiber dosage is 2%, and the rubber powder dosage is 5%. Compared with the benchmark group P1, the improvement is significant, indicating that the composite admixtures have an obvious effect on improving the tensile performance of concrete.

Steel fibers contribute the most significantly to the tensile strength. Their bridging effect can effectively transfer tensile forces and inhibit crack development. High territory improves the interfacial transition zone through the filling effect and pozzolanic reaction, enhancing the compactness and bond strength of the matrix. Rubber powder particles have high elasticity. Although they may slightly reduce the tensile strength, they can absorb energy and improve the toughness and crack resistance of the material. Under a reasonable ratio, the synergistic effect of steel fibers and high territory can significantly improve the tensile strength, and the incorporation of rubber powder helps to balance strength and toughness.

When the high territory dosage is at a medium level, the steel fiber dosage is high, and the rubber powder dosage is low, the splitting tensile strength performs optimally. This indicates that steel fibers are the dominant factor in improving the tensile performance, high territory can further optimize the matrix performance, and the rubber powder dosage needs to be controlled. An excessively high dosage may lead to a decrease in strength, indicating that the proportion coordination of the three is crucial for the tensile performance.

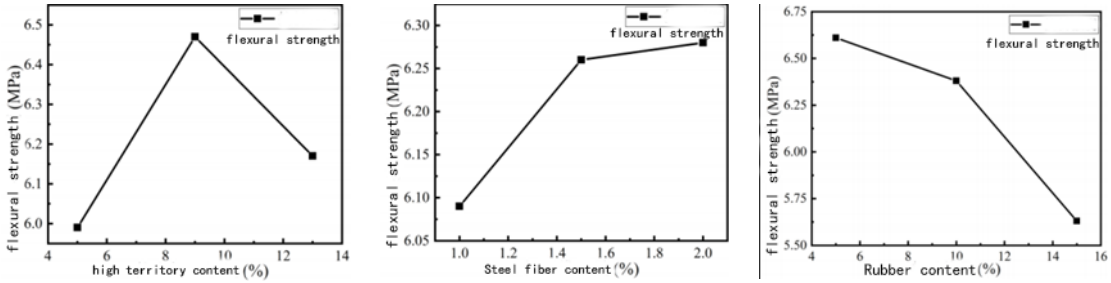
3.3. Flexural Strength of High Territory-Steel Fiber-Rubber Concrete

Table 8. 28d Flexural strength values of high territory-steel fiber-rubber concrete

Identification number	Factor levels			28d Flexural strength (MPa)
	A	B	C	
	High territory (%)	Steel fibers (%)	Rubber powder (%)	
P1	0	0	0	5.83
M1	5	1	5	6.39
M2	5	1.5	10	5.90
M3	5	2	15	5.74
M4	9	1	10	6.82
M5	9	1.5	15	6.01
M6	9	2	5	6.63
M7	13	1	15	5.09
M8	13	1.5	5	6.91
M9	13	2	10	6.54

The 28d flexural strength of high territory-steel fiber-rubber concrete varies between 5.09-6.91MPa. Overall, it shows a certain degree of improvement or fluctuation compared with the benchmark group P1. Among them, the flexural strength of Group M8 is the highest, reaching 6.91MPa, indicating that a reasonable material ratio can effectively improve the flexural performance of concrete. However, when the rubber dosage is high (e.g. M3, M5, M7), the flexural strength is generally low, indicating that rubber powder may have a certain weakening effect on the flexural strength.

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A Factor influence B Factor influence C Factor influence

Figure 6. A, B, C Relationship between factors and flexural strength

Steel fibers play a key bridging and crack - arresting role in the flexural strength, significantly delaying crack propagation and enhancing toughness. High territory improves the cement stone structure through the pozzolanic effect, enhancing the compactness of the matrix and the interfacial bond strength, thereby indirectly enhancing the flexural ability. Due to its low modulus, rubber powder forms elastic weak points in the matrix. Excessive incorporation will weaken the overall stiffness, leading to a decrease in flexural strength. However, it has a positive effect on improving the impact resistance and deformation coordination of the material.

Steel fibers and high territory can improve the flexural strength at appropriate dosages, especially the role of steel fibers is more crucial. The rubber powder dosage needs to be strictly controlled. At a low dosage, it can synergistically improve the toughness with high territory and steel fibers, but when the dosage exceeds 10%, it is unfavorable to the flexural strength. The optimal ratio for flexural strength usually occurs when the steel fiber dosage is moderate, the high territory dosage is high, and the rubber powder dosage is low, indicating that the synergistic ratio of the three is crucial for achieving both high strength and high toughness in flexural performance.

3.4. Analysis Of Variance

In this test, the variance analysis method is used to evaluate the influence of the incorporation of high territory, steel fiber, and rubber on the test results. If the significance level F<F0.010 of a factor, it indicates that the factor has a particularly significant influence on the results; if F0.010<F<F0.50, it indicates that the factor has a significant influence on the results; otherwise, it indicates that the factor has a small influence on the results. The variance analysis results of the concrete mechanical properties are shown in Table 9.

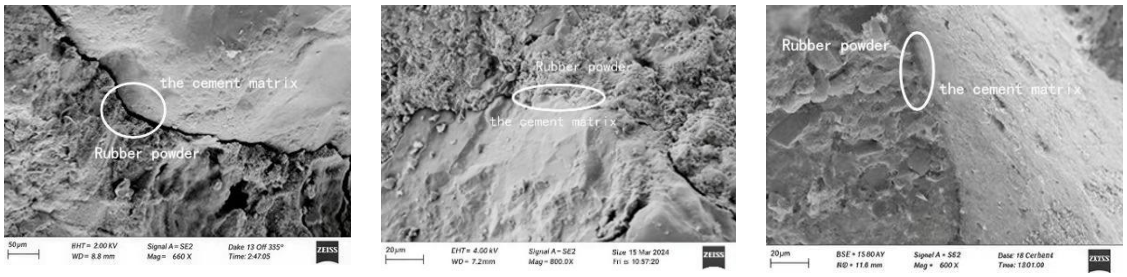
Table 9. Analysis of variance of mechanical properties of high territory-steel fiber-rubber concrete

Factors	Compressive strength		Splitting tensile strength		Flexural strength		Critical F value
	F value	Significance value	F value	Significance	F value	Significance	
High territory	20.82	*	1.00	-	2.29	-	F0.01=99.01
Steel fibers	1.00	-	3.28	-	1.00	-	F0.05=19.00
Rubber powder	192.33	**	6.19	-	4.82	-	F0.10=9.00
Note: “**”indicates a particularly significant impact; “*”indicates a notable impact; “—”suggests a marginal effect							

As can be seen from Table 9, rubber has a particularly significant influence on the compressive strength of concrete, high territory has a significant influence on the compressive strength of concrete, and steel fiber has a small influence on the compressive strength of concrete. Rubber, steel fiber, and high territory all have small influences on the splitting tensile strength and flexural strength of concrete.

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3.5. Sem Analysis



3d Specimen 7d Specimen 28d Specimen

Figure 7. SEM morphology of the ITZ in high territory-steel fiber-rubber concrete

As shown in Figure 7, the microscopic morphology of the interface transition zone reveals that the ITZ between the paste and aggregates within concrete has a significant impact on the mechanical properties of concrete. In the case of rubberized concrete, due to the poor hydrophilicity of rubber, its bonding with the paste is weaker compared to ordinary aggregates. Therefore, improving the performance of the ITZ plays a crucial role in enhancing the overall integrity of concrete.After the combined addition of steel fibers and high territory, there are obvious differences in the morphology of the ITZ between rubber and the cement-mortar matrix at different ages.At the age of 3 days, the rubber surface is almost bare, there are continuous wide cracks in the ITZ, and the enrichment of $Ca(OH)_2$ crystals leads to interface debonding. At the age of 7 days, the hydration products increase, the pores and cracks are significantly refined, the rubber and the matrix are initially bonded, and the bonding performance of the ITZ is improved. By the age of 28 days, the pozzolanic effect of high territory [20] is fully activated, which consumes $Ca(OH)_2$ and promotes the formation of C-S-H gel and Aft crystals to densely fill the interface area, refines the pore structure of the ITZ. The randomly distributed steel fibers within the same system form a supportive framework,which fills the cracks in the matrix,enhances the performance of the ITZ in concrete, and inhibits the enrichment of $Ca(OH)_2$ crystals in the ITZ. The C-S-H gel plays a role in dense packing, and the structure of the cement stone at the interface gradually becomes compact.

4. CONCLUSION

(1) Through orthogonal tests and combined with variance analysis of the 28d mechanical properties of concrete, it is determined that the optimal mix of high territory-steel fiber-rubber concrete is superior to the reference group of traditional concrete. The optimal mix ratio is as follows: high territory content is 9%, steel fiber content is 2%, and rubber content is 5%. Under the optimal mix ratio, the 28d compressive strength of high territory-steel fiber-rubber concrete reaches 47.52MPa, the 28d splitting tensile strength is 7.85MPa, and the 28d flexural strength is 6.63MPa.

(2) Through experiments, the optimal mix ratio of high territory-steel fiber-rubber concrete is determined as follows: cement: sand: gravel: high territory: rubber powder: water:steel fiber:water-reducing agent dosage=336.65:637.2:1157.76: 33.3:12.8:152:156:7.03.

(3) SEM images show that with the increase of curing age, the ITZ between rubber and the cement matrix is improved, the surface of the hydration products becomes gradually smooth, and there are fewer weak areas inside. At 28 days, the hydration reaction is complete. The high territory and the randomly distributed steel fibers in the system cooperate with each other, enabling the rubber to be tightly wrapped by the cement mortar, restricting the formation of large-sized cracks, strengthening the performance of the ITZ in concrete, and optimizing the mechanical properties of concrete.

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