Visual Abstract

Analysis of the bond-slip performance of steel bars and steel fiber recycled concrete based on the constitutive relationship model

Xia Zhengbing, Duan Xiaofang
College of Architecture and Civil Engineering, Jiangsu City Vocational College Nantong Campus, Nantong, 226006, China
zhengbxia@163.com

ABSTRACT. In order to promote the application of steel fiber recycled concrete in road and bridge construction, 25 groups of steel fiber recycled concrete with different mix proportions were designed, taking the replacement rate of recycled aggregates and the volume fraction of steel fibers as experimental parameters, and 77 steel bars and steel fiber recycled concrete bonded specimens were made and pasted with strain gauges for the pull-out test. The research results showed that the greater the replacement rate of recycled aggregates was, the lower the bond strength between steel bars and steel fiber recycled concrete was; in the range of 0~1.2%, the higher the mixing amount of steel fibers was, the greater the bond strength of the specimen was; in the range of 0~1.6%, the higher the mixing amount of steel fibers was, the greater the slip value of the specimen under the peak load was; the addition of steel fibers improved the failure behavior of the recycled concrete pull-out specimens; the test specimens mainly had pull-out failure when the mixing amount of steel fibers was 1.2% and 1.6%. Finally, this study modified the bond-slip constitutive relationship model of steel and steel fiber recycled concrete, analyzed the influence of the replacement rate of recycled aggregates and the mix proportion of steel fibers on its bonding performance, and compared the results with the test results. The results demonstrate that the test curve is in good agreement with the fitted curve, which can provide theoretical support for engineering applications.

KEYWORDS. Steel bar; Steel fiber recycled concrete; Bonding performance; Constitutive model.

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INTRODUCTION

With the rapid development of highway construction in China, the demolition, maintenance and reinforcement of existing roads and bridges have produced an astonishing amount of abandoned concrete construction waste, causing extremely serious damages to the environment [1]. Therefore, it is imperative to realize the green and sustainable development of the construction industry, and the processing of waste concrete into recycled aggregates is an important trend in the development of civil engineering materials today, which is of great significance for saving sand aggregate resources and maintaining ecological balance [2]. Due to the presence of defects such as initial microcracks and micropores in recycled aggregates, the performance of recycled aggregate concrete is poor than natural aggregate concrete. Studies have shown that the addition of steel fibers to recycled concrete can optimize the internal defects of recycled concrete, improve its various properties, further enhance its ductility and strength, and inhibit the development of cracks [3, 4]. The above studies provide new ideas for the promotion and application of recycled concrete in reinforced concrete structures. In recent years, steel fiber recycled concrete has developed extremely fast and has been widely used in high-rise building engineering, bridge engineering, pipeline engineering, and maintenance and reinforcement engineering [5].

In the reinforced concrete structure, the good bonding between steel bars and concrete ensures that they can work normally and bear the load; thus, it is of great significance to study the bonding between steel bars and concrete. The bonding of steel bars and concrete is affected by many factors, such as the composition of concrete, the performance of steel bars, the restraint effect of steel bars or concrete, and the anchorage length. In recent years, Chinese and foreign scholars have analyzed the influence of factors such as the replacement rate and size of recycled aggregates, direction and position of steel bars, and concrete age on the bonding performance of steel bars and recycled concrete through a series of experiments [6]. Jau et al. [7] conducted a bond test and found that the bond strength between recycled concrete and steel bars varied greatly, but was lower than that between steel bars and ordinary concrete. Cao et al. [8] found that when the concrete coarse aggregate was 100% recycled aggregates, the bond strength between steel bars and concrete decreased significantly, which was significantly lower than that when the replacement rate of recycled coarse aggregate was 33% ~ 66%, and the bond strength when using deformed steel bars was higher than when using plain round steel bars. The test results of Li et al. [9] showed that when the relative anchorage length was five times the diameter of steel bars, the bond strength between deformed steel bars and high-strength ceramsite concrete was about 25% higher than that of ordinary concrete of the same strength level.

The core issue of the current bond-anchorage experimental research is the bond-slip constitutive relationship between steel bars and concrete. The slip here refers to the relative displacement between steel bars and concrete interface under the action of external force. In reinforced concrete structures, the bond-slip constitutive relationship curve is an indispensable basis in nonlinear calculations, and it is as important as the stress-strain relationship curve of concrete. So far, the research on the bond characteristics and bond-slip constitutive model between steel bars and ordinary concrete and between steel bars and steel fiber concrete have been relatively sufficient. Li et al. [10] have studied the bond-anchorage performance of high-strength steel bars and concrete. Through the pull-out experiment, the basic bond-slip relationship and position function have been established, and the bond-slip constitutive relationship of high-strength steel bars in concrete structures has been determined. The bonding between medium- and high-strength recycled concrete and reinforcement [8], the bonding between rusted reinforcement and recycled concrete [11] and the stress distribution in the bonded section of reinforcement and recycled concrete [12] have also been discussed. However, scholars in China and abroad studied little about the bond-slip performance of steel bars and steel fiber recycled concrete. In this paper, the center pull-out test was conducted to systematically study the bond-slip properties of steel and steel-fiber recycled concrete under the influence factors, including the replacement rate of recycled aggregates and the volume fraction of steel fibers, and the constitutive relationship model of bond-slip was modified. The objective of this study is to confirm that changing the replacement rate of recycled aggregates and the mix proportion of steel fibers can affect the bonding and slipping performance of steel bars and steel fiber recycled concrete through experiments. However, through the experimental analysis and summary, it was found that there were still shortcomings in the experimental process to be improved. The bond-slip performance of steel bars and concrete is usually studied through the center pull-out test. Due to the limited test conditions, there are errors in the measurement process; therefore, the test equipment has an important influence on the study of the bond-slip performance of steel bars and concrete.

TEST OVERVIEW

Test materials

The materials used in the experiment mainly included cement, natural coarse aggregate, natural fine aggregate, recycled coarse aggregate, mixing water, water reducing agent, steel fiber, etc.

P.O 42.5 grade ordinary Portland cement (Zhengzhou Tianrui Group, China) with a density of 3.02 g/cm^3, a specific surface area of 328 m^2/kg, a mortar fluidity of 192 mm, a normal consistency water demand of 29.8%, an initial setting time of 126 min, and a final setting time of 208 min was used. The raw material of recycled coarse aggregate was waste concrete (Xuchang Jinke Resource Recycling Co., Ltd., China), and its performance indicators are shown in Tab. 1. The fine aggregate was natural river sand, and the coarse aggregate was natural gravel. SiKa ViscoCrete 530 PC high-efficiency water-reducing agent (Nanjing Sitai Trading Co., Ltd., China) with high water-reducing rate and high plasticity retention was used. The milled shaped wave-steel fiber (Shengze Building Materials Co., Ltd., China) was used, and its performance indicators are shown in Tab. 2. HRB400 hot-rolled ribbed steel bars with a diameter of 18 mm were used.

Particle size/mm	Apparent density/(kg/m^3)	Bulk density/(kg/m^3)	Water absorption/%	Moisture content/%
5~25	2550	1460	4.1	1.8

Table 1: The performance indicators of coarse aggregate

Equivalent diameter/mm	Aspect ratio	Tensile strength/MPa	Density (g/cm^3)
0.600	45	≥ 600	7.86

Table 2: The performance indicators of steel fibers

Design of the mix proportion

The basic mix proportion of C40 concrete was used, as shown in Tab. 3. ϱ represents the replacement rate of recycled aggregates.

ϱ/%	Cement/(kg/m^3)	Sand/(kg/m^3)	Water/(kg/m^3)		Coarse aggregate/(kg/m^3)	
			Free water	Added water	Natural	Recycled
0	430	675	194	0	1102.1	0
30	430	675	194	7.61	771.3	330.5
50	430	675	194	12.68	551.0	551.0
70	430	675	194	17.73	330.5	771.3
100	430	675	194	25.35	0	1102.1

Table 3: The mix proportion of recycled concrete

Specimen design and production

A total of 25 sets of pull-out specimens were designed for the center pull-out test, and each set included three specimens. The design parameters of the test specimens are shown in Tab. 4, and N-0-0 was defined as the baseline group. The test specimen was a concrete test cube with a side length of 150 mm, and a 18 mm HRB400 steel bar with a diameter of d was inserted in the middle of the cube. The effective bonding length of the steel bars was 5 d. The non-bonding section was embedded with a polyvinyl chloride (PVC) casing with a length of 60 mm and painted with glass glue to prevent the relative sliding of the steel bar. The design dimensions of the test specimens are shown in Fig. 1.

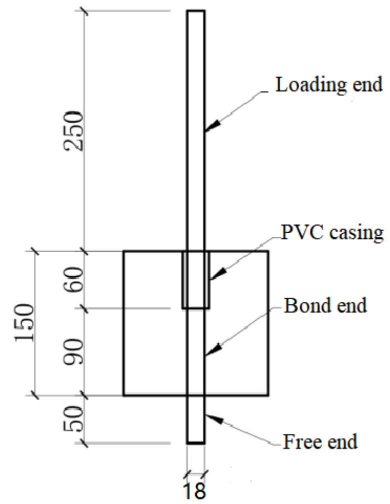


Figure 1. The design dimensions of the test specimen (unit: mm)

No. of test specimen	ρ/%	Volume fraction of steel fibers/%	Splitting tensile strength/MPa	Compressive strength/MPa
N-0-0	0	0	2.27	43.21
DC-30	30	0	2.00	40.81
DC-50	50	0	1.94	35.70
DC-70	70	0	1.43	36.52
DC-100	100	0	1.31	32.33
SFC-0.4	0	0.4	2.40	50.98
SFC-0.8	0	0.8	2.65	54.82
SFC-1.2	0	1.2	2.96	55.70
SFC-.16	0	1.6	3.25	57.18
SFDC-30-0.4	30	0.4	2.08	45.23
SFDC-30-0.8	30	0.8	2.15	47.40
SFDC-30-1.2	30	1.2	2.54	51.70
SFDC-30-1.6	30	1.6	2.58	53.22
SFDC-50-0.4	50	0.4	1.80	44.01
SFDC-50-0.8	50	0.8	1.93	44.69
SFDC-50-1.2	50	1.2	2.20	49.31
SFDC-50-1.6	50	1.6	2.25	47.14
SFDC-70-0.4	70	0.4	1.45	40.36
SFDC-70-0.8	70	0.8	1.81	40.18
SFDC-70-1.2	70	1.2	2.02	41.29
SFDC-70-1.6	70	1.6	1.99	39.69
SFDC-100-0.4	100	0.4	1.40	32.68
SFDC-100-0.8	100	0.8	1.68	34.73
SFDC-100-1.2	100	1.2	1.29	39.70
SFDC-100-1.6	100	1.6	1.71	38.85

Table 4: The design parameters of the test specimen (DC: recycled concrete; SFC: steel fiber concrete; SFDC: steel fiber recycled concrete)

Loading system in the pull-out test

A WAW-600C electro-hydraulic servo universal testing machine was used for loading. The loading speed was controlled no more than 0.4 kN/s. The loading device is shown in Fig. 2.

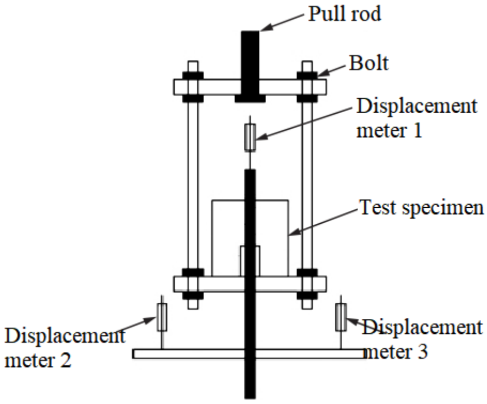


Figure 2. The layout drawing of the loading device

A displacement meter with a measuring range of 50 mm was set at the free end of the steel bar to measure the free-end slip. The slip at the loading end was measured by two displacement meters with a measuring range of 50 mm, which was the difference between the mean value of the two displacement meters and the elastic elongation of the steel bar. The free-end slip was defined as the relative slip between the steel bar and the concrete. The calculation method of the average bond stress between the steel bar and the concrete is:

$$\kappa = \frac{1000P}{\pi d l_e} \tag{1}$$

where κ stands for the average bonding stress between the steel bar and the concrete, P stands for the pull-out load value, d stands for the diameter of the steel bar, and l_e stands for the effective bonding length of the steel bar.

ANALYSIS OF TEST RESULTS

Failure behavior

After analysis of the test phenomenon, the failure behaviors of the test specimens in the bond-slip performance test mainly included splitting failure, splitting pull-out failure, and pull-out failure, as shown in Fig. 3.

(a) Splitting failure (b) Splitting pull-out failure (c) Pull-out failure

Figure 3. The failure behaviors of the test specimens

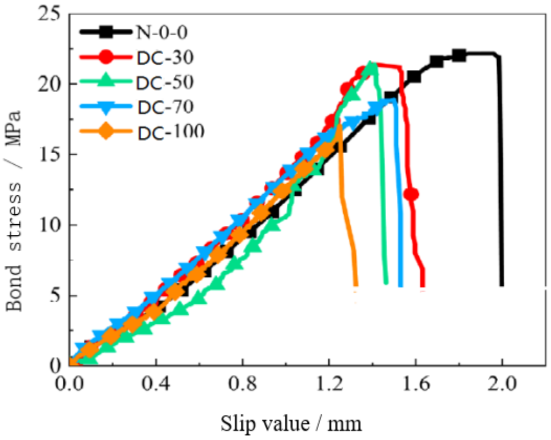
Splitting failure mainly occurs in the pull-out specimen without steel fibers, and its failure behavior is shown in Fig. 3(a). At the beginning of the test, when the pull-out load was small, the relative slip between the steel bar and the concrete mainly occurred at the loading end; at that time, the free end had no obvious slip, and the specimen had no obvious cracks. With the further increase of the load, the slip of the loading end gradually expanded to the free end, and the main cracks that penetrated the surface of the specimen began to appear. When the load rose to the limit, the specimen suddenly cracked, the load dropped sharply, the slip values of the free end and the loading end no longer increased, the steel bar completely separated from the main body of the concrete specimen, the specimen split into two or three pieces, and it was seen from the split surface that the concrete was sheared by the steel bar rib.

Splitting pull-out failure mainly occurred in the pull-out specimen with a low content of steel fibers. The failure behavior is shown in Fig. 3(b). There was no obvious slip at the free end of the specimen at the beginning of loading. With the further increase of the load, when the bonding stress reached the split bond strength of the specimen, the internal cracks of the specimen developed slowly because of the cracking resistance effect of steel fibers. When the cracks further increased, the relative slip between the steel bar and the concrete gradually expanded to the free end, and the concrete on the surface of the steel bar was sheared by the ribs. After the failure, there were obvious transverse cracks on the surface of the test specimen, and the steel bar and the concrete were partially separated, but the test specimen was not completely split; there was a friction resistance and mechanical interaction between the steel bar and the concrete.

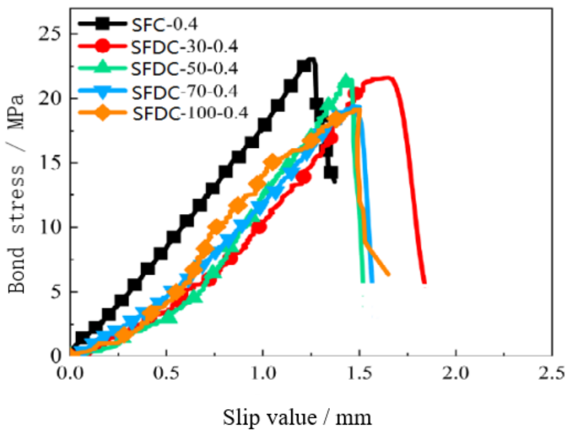
No. of test specimen	Ultimate load P_u/kN)	Ultimate strength κ_u /MPa	The slip value S_{ui} of the free end/mm	The slip value S_{uz} of the loading end/mm	Average slip value S_u/mm	Failure behavior
N-0-0	112.85	22.19	1.95	3.39	2.67	Splitting failure
DC-30	109.05	21.41	1.38	2.36	1.87	Splitting failure
DC-50	108.97	21.40	1.39	2.11	1.75	Splitting failure
DC-70	96.08	18.87	1.50	1.92	1.71	Splitting failure
DC-100	86.87	17.08	1.25	2.23	3.48	Splitting failure
SFC-0.4	117.18	23.01	1.26	3.40	2.33	Splitting pull-out failure
SFC-0.8	117.90	23.15	1.45	2.69	2.07	Splitting pull-out failure
SFC-1.2	121.28	23.84	1.54	2.92	2.43	Pull-out failure
SFC-.16	117.32	23.05	1.91	2.99	2.45	Pull-out failure
SFDC-30-0.4	109.43	21.50	1.58	2.18	1.88	Splitting pull-out failure
SFDC-30-0.8	111.05	21.81	1.26	2.70	3.96	Splitting pull-out failure
SFDC-30-1.2	113.17	22.23	0.94	3.12	2.03	Pull-out failure
SFDC-30-1.6	116.45	22.87	1.16	3.50	2.33	Pull-out failure
SFDC-50-0.4	108.95	21.40	1.42	1.50	1.46	Splitting pull-out failure
SFDC-50-0.8	109.33	21.49	1.08	2.68	1.88	Splitting pull-out failure
SFDC-50-1.2	112.28	22.05	1.21	2.33	1.77	Pull-out failure
SFDC-50-1.6	113.13	22.23	1.28	2.90	2.09	Pull-out failure
SFDC-70-0.4	98.36	19.31	1.48	1.66	1.57	Splitting pull-out failure
SFDC-70-0.8	102.75	20.20	1.63	1.75	1.69	Splitting pull-out failure
SFDC-70-1.2	101.18	19.88	1.62	1.84	1.73	Splitting pull-out failure
SFDC-70-1.6	101.43	19.92	2.04	2.86	2.45	Pull-out failure
SFDC-100-0.4	97.30	19.13	1.50	2.10	1.80	Splitting pull-out failure
SFDC-100-0.8	102.41	20.11	0.78	3.02	1.90	Splitting pull-out failure
SFDC-100-1.2	106.33	20.89	1.55	2.49	2.02	Splitting pull-out failure
SFDC-100-1.6	101.22	19.88	0.73	4.95	2.84	Pull-out failure

Table 5: The results of the pull-out test

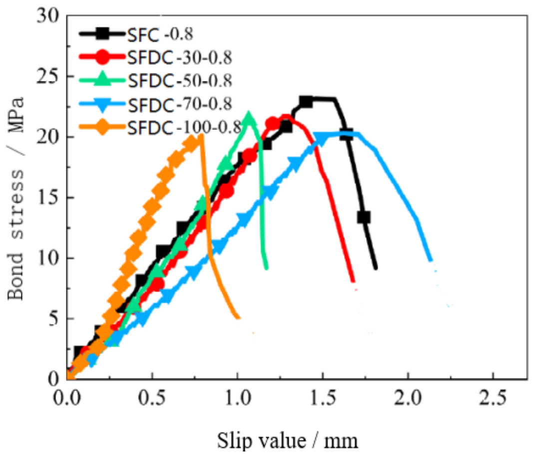
Pull-out failure mainly occurred in the pull-out specimen with a large content of steel fibers. The failure behavior is shown in Fig. 3(c). With the increase of the load, the slip value of the steel bar continued to increase, and there were micro cracks penetrating the surface of the test specimen at the loading site. As the load increased further, the steel bar slowly separated from the main body of the concrete specimen, and the specimen began to fail; at that time, the slip value continued to rise and the load gradually decreased. Due to the crack resistance of the steel fibers, there were only fine and concentrated cracks on the surface of the specimen when it was destroyed; at that moment, the integrity of the specimen was good, and there was a degree of bonding ductility.



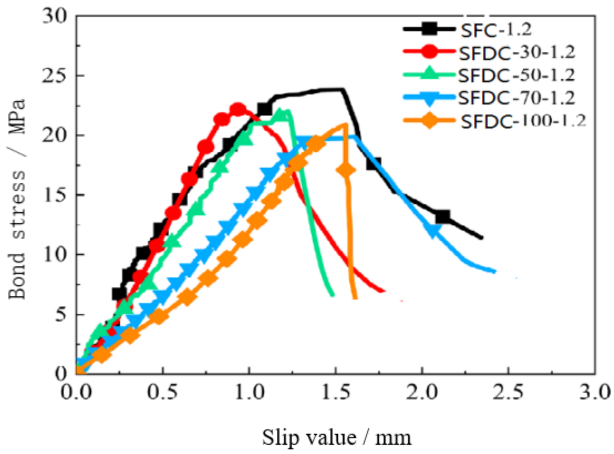
a) The mix proportion of steel fibers is 0%.



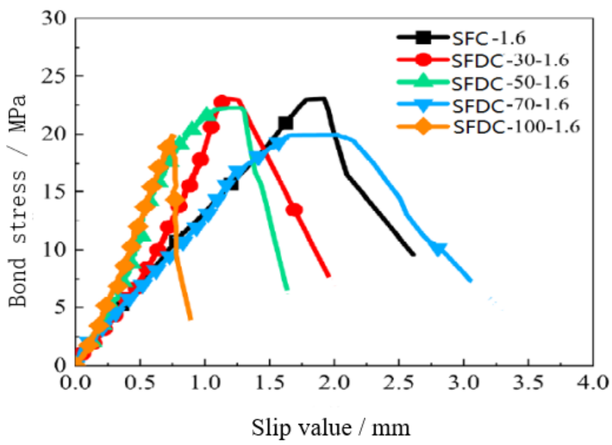
b)The mix proportion of steel fibers is 0.4%.



c) The mix proportion of steel fibers is 0.8%.



d) The mix proportion of steel fibers is 1.2%.



e) The mix proportion of steel fibers is 1.6%

Figure 4: The bond stress-slip relationship curve under different replacement rates of recycled aggregates.

Bond-slip performance: characteristic value

The bond-slip performance test was performed using a WAW-600C universal testing machine and Donghua strain testing system. The measured characteristic values are shown in Tab. 5.

It was seen from Tab. 5 that the pull-out specimens mainly underwent splitting failure when steel fibers were not mixed, the specimens mainly underwent splitting failure when the content of steel fibers was 0.4% and 0.8%, and the specimens mainly underwent pull-out failure when the content of steel fibers was 1.2% and 1.6%.

Effects of the replacement rate of recycled aggregates on the bond-slip performance

When the mix proportion of steel fibers was 0, 0.4%, 0.8%, 1.2%, and 1.6%, the bond stress-slip relationship under different replacement rates of recycled aggregates is shown in Fig. 4.

The following results were seen from Fig. 4.

(1) When the mix proportion of the steel fiber content was 0%, the pull-out specimens and recycled concrete pull-out specimens in the baseline group immediately were destroyed immediately after reaching the ultimate strength because of the lack of the restraining effect of steel fibers, and the bond stress dropped rapidly. The slip value further increased in the initial stage of loading, and the curve had an obvious linear rising relationship. When the load reached the limit, the slip value increased slowly, and there was only a small slip.

(2) When the mix proportion of steel fibers was not 0%, the peak bond stress of the curve decreased with the increase of the replacement rate of recycled aggregates under different mix proportions of steel fibers, i.e., recycled aggregates weakened the bond strength of the pull-out specimens. When the mix proportion of steel fibers was fixed, the slope of the curve had no obvious change law under different replacement rates of recycled aggregates, i.e., although the change of the replacement rate of recycled aggregates had a significant influence on the bond strength of the specimens, it had no significant influence on the bond stress-slip relationship.

(3) When the replacement rate of recycled aggregates was 100%, the strength in the descending section of the bond stress-slip curve under different mix proportions of steel fibers changed rapidly, but the slip value did not change significantly. The reason for the above result was because the internal mechanical properties of the specimen had relatively large defects when the replacement rate of recycled aggregates was 100%, and the incorporation of steel fibers had a weak effect in improving the bond-slip performance of the specimen.

Effects of the mix proportion of steel fibers on the bond-slip performance

When the replacement rate of recycled aggregates was 0%, 30%, 50%, 70%, and 100%, the bond stress-slip relationship under different mix proportions of steel fibers is shown in Fig. 5.

The following results were seen from Fig. 5.

(1) The bond stress-slip curve of the pull-out specimens under the influence of the mix proportion of steel fibers was mainly divided into an ascending section, a slip failure section, and a descending section.

(2) In the initial stage of loading, the bond stress-slip curve was nearly in a linear rising relationship. When the replacement rate of recycled aggregates was 0%, 30%, 50%, and 70%, within the range of 0.4% ~ 1.2%, the larger the mix proportion of steel fibers was, the steeper the bond stress-slip curve was, and the larger the ultimate bond strength of the specimen was. The reasons for the above result was that the cracking resistance and energy dissipation effects of steel fibers further restrain the relative displacement of steel bars, and the larger the mix proportion of steel fibers, the more significant the restraint effect was, the smaller the change of the slip value was, and the faster the development of the bond strength was.

(3) When the load reached about 95% of the ultimate load, the bond stress-slip curve entered the slip failure section. In this period, the load rose slowly, the slip values of the free end and the loading end continued to increase, microcracks began to appear on the surface of the specimen, and the specimen began to fail.

(4) When the load reached the limit, the bond stress-slip curve began to enter the descending section. As the steel fibers formed a fiber space network structure inside the test specimen, the descending section of the bond stress-slip curve of the pull-out specimen was more complete, and the descending speed of the bond strength was smaller than that of the pull-out specimen without steel fibers. Steel fibers improved the bond-slip failure process of the pull-out specimen and made the bond stress-slip curve more complete when the specimen failed.

(5) The comparison of the bonding strength between SFDC-100-1.6 and SFDC-100-1.2 found that the bonding strength declined when the mix proportion of steel fibers was 1.2% and 1.6%, which was because the steel fibers dispersed unevenly in the mixing process of the concrete with the increase of the mix proportion of the steel fibers, forming weak layers.

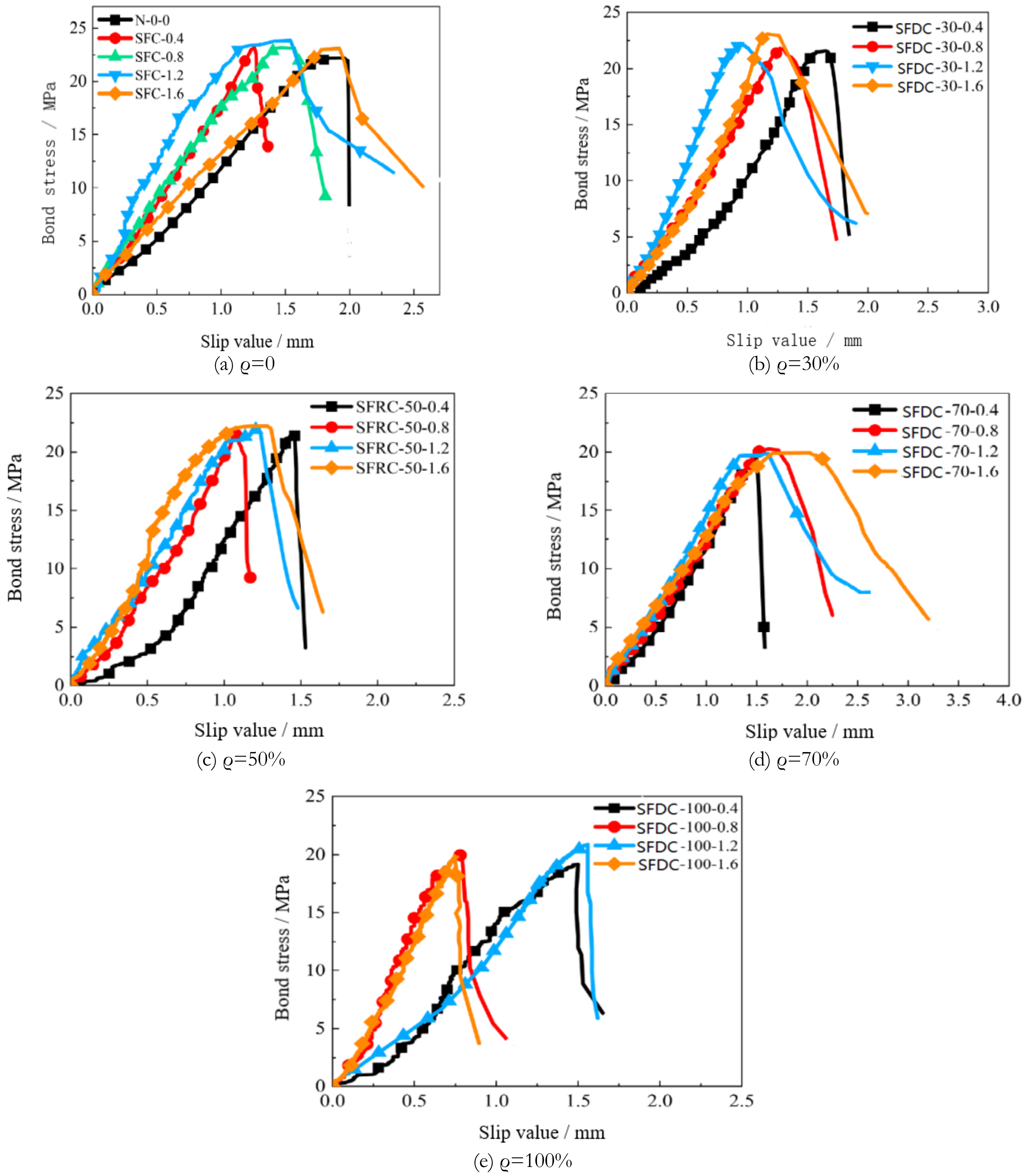


Figure 5: The bond stress-slip curve under different mix proportions of steel fibers.

DESIGN OF THE BOND-SLIP CONSTITUTIVE MODEL FOR STEEL AND STEEL FIBER RECYCLED CONCRETE

Commonly used bond-slip constitutive relationship models

At present, a large number of studies have been carried out on the bond-slip constitutive relationship between steel bars and concrete in China and abroad, and some research results have been obtained. This article summarizes the bond-slip constitutive relationship models for steel bars and concrete.

(1) Houde model

Through a pull-out test, Houde [13] proposed an expression for the bond stress-slip constitutive relationship that considers compressive strength of concrete:

$$\kappa = (5.29\times10^{2}s - 2.51\times10^{4}s^{2} + 5.84s^{3} - 5.46\times10^{6}s^{4})\sqrt{\frac{f_c}{40.7}} \quad (2)$$

where f_c stands for the compressive strength of concrete and s stands for a slip value.

(2) Nilson model

Nilson [14] further studied the pull-out test results of some scholars and proposed a constitutive relationship expression of the average bond stress and the slip at the end of steel bars:

$$\kappa = 9.78\times10^{2}s - 5.72\times10^{4}s^{2} + 8.35\times10^{5}s^{3} \quad (3)$$

(3) Haraji model

Haraji [15] obtained the bond-slip constitutive relationship through study. The ascending section is expressed as:

$$\frac{\kappa}{\kappa_u} = (\frac{s}{s_u})^{a} \quad (4)$$

where a is a constant and κ_u and s_u represent the maximum bond strength and corresponding slip respectively.

(4) Teng Zhiming's model

Teng Zhiming [16] proposed an equation of bond-slip relationship after comprehensively studying the influence of the tensile strength of concrete, the thickness of protective layer of steel bars, the diameter of anchor bars, and anchor position on the bond stress:

$$\kappa = (61.5s - 693s^{3} + 3.14\times10^{3}s^{3} - 0.478\times10^{4}s^{4})f_{ts}\sqrt{\frac{c}{d}}\cdot\sqrt{4\cdot\frac{x}{l}(1-\frac{x}{l})} \quad (5)$$

where f_{ts} stands for the tensile strength of concrete, $\frac{c}{d}$ stands for the relative thickness of the protective layer of concrete, x stands for the transverse distance to the nearest crack, and l stands for the spacing of cracks.

The modified bond-slip constitutive relationship model

The failure behaviors of the test specimens in this test mainly included splitting failure, splitting pull-out failure, and pull-out failure. For the pull-out specimens whose failure behavior was splitting failure, the bond-slip curve only had an ascending section but had no obvious descending section. For the specimens with splitting pull-out failure and pull-out failure, the bond-slip curves had complete ascending and descending sections. Therefore, this paper divided the bond-slip constitutive relationship into an ascending section and a descending section. As the main research subject of this experiment was the steel fiber recycled concrete, and the bond-slip relationship of recycled concrete was similar to that of ordinary concrete, the ascending section of bond-slip can be fitted with Eqn. (4) proposed by Haraji. The descending section was fitted by the curve model of the concrete tension descending section proposed by Guo Zhenhai. The stress and strain of the concrete under tension were respectively equivalent to the bond stress and slip value between the steel bar and the concrete, and the peak stress and strain were equivalent to the peak bond strength and the corresponding peak slip. See Eqn. 6 for details:

$$\frac{\kappa}{\kappa_u} = \frac{s/s_u}{b(s/s_u - 1)^{2} + s/s_u} \quad (6)$$

According to the test data, 1stopt software was used for curve fitting, and the parameter a of the ascending section and the parameter b of the descending section of the bond-slip constitutive relationship were obtained.

The constitutive relationship model when ρ = 30%

The comparison between the test results and fitted curves and the test results when the replacement rate of recycled aggregates was 30% are shown in Fig. 6 and Tab. 6.

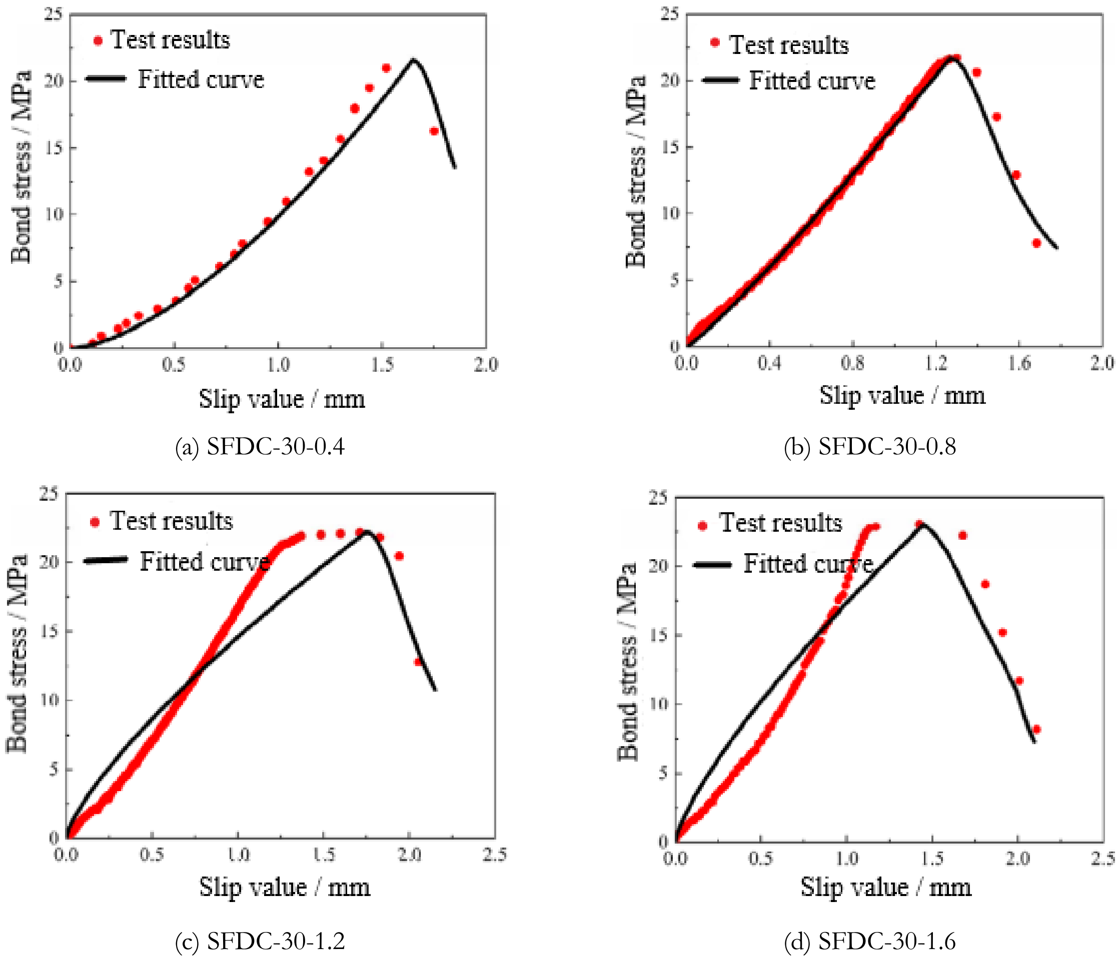


Figure 6: The test curves and fitted curves.

Number of test specimen	Parameter of ascent stage a	Correlation coefficient	Parameter of descent stage b	Correlation coefficient
SFDC-30-0.4	1.57	0.998	44.68	0.999
SFDC-30-0.8	1.11	0.999	16.73	0.999
SFDC-30-1.2	0.75	0.998	24.88	0.997
SFDC-30-1.6	0.76	0.974	34.65	0.998

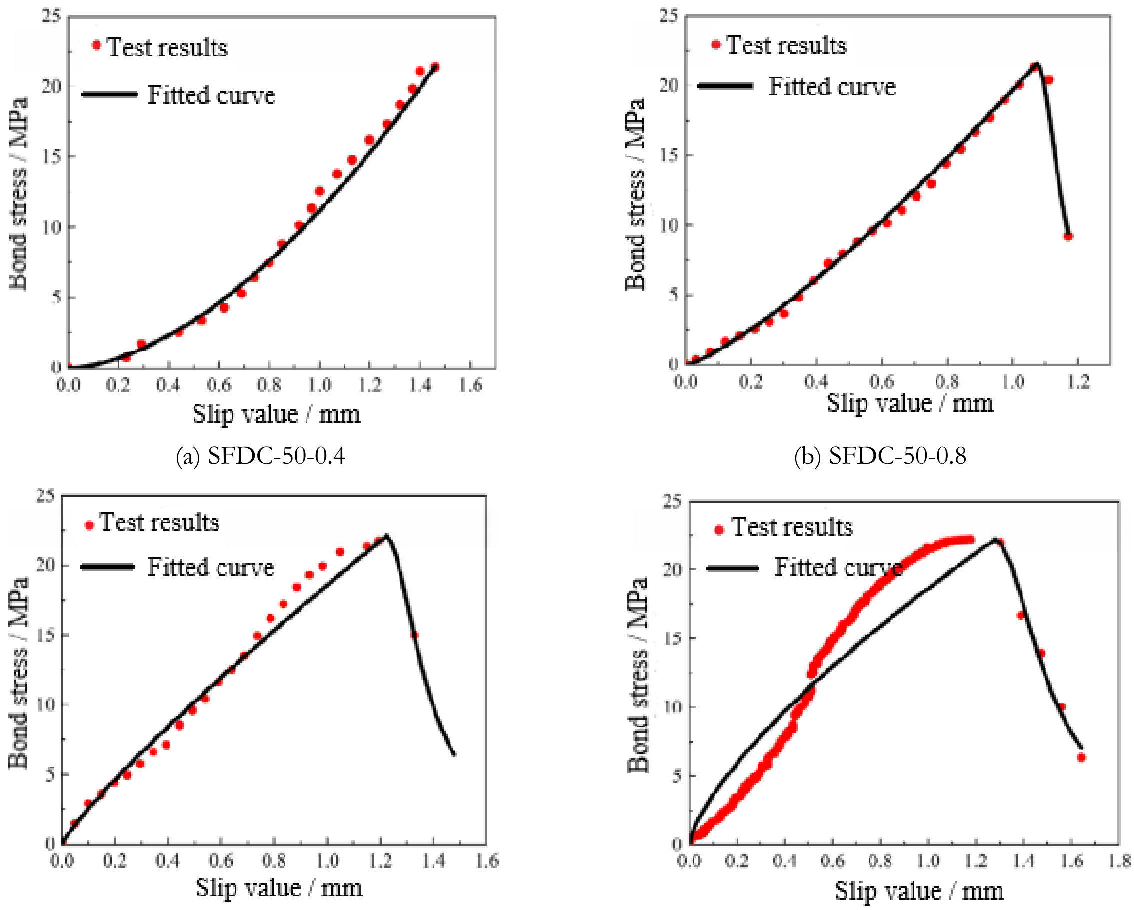
Table 6: Comparison of values obtained from fitting.

The constitutive relationship model when $\rho = 50\%$

The comparison between the test results and fitted curves and the test results when the replacement rate of recycled aggregates was 50% is shown in Fig. 7 and Tab. 7.

Number of test specimen	Parameter of ascent stage a	Correlation coefficient	Parameter of descent stage b	Correlation coefficient
SFDC-50-0.4	1.72	0.997	/	/
SFDC-50-0.8	1.27	0.999	176.2	0.999
SFDC-50-1.2	0.86	0.984	65.54	0.999

Table 7: Comparison of values obtained from fitting.



(a) SFDC-50-0.4 (b) SFDC-50-0.8

(c) SFDC-50-1.2 (d) SFDC-50-1.6

Figure 7. The test curves and fitted curves.

It was seen from Fig. 7 and Tab. 7 that when the replacement rate of recycled aggregates was 30% and 50%, the measured bond stress-slip curve of the pull-out specimens was fitted well with the fitted curve under different volume fractions of steel fibers, and the correlation coefficient was kept between 0.974 and 0.999. The relevant parameters obtained from the fitting could be regarded as a good reference basis of the bond-slip constitutive relationship.

Conclusions

The purpose of this paper is to study the bond-slip performance between steel bars and steel fiber recycled concrete. By varying two factors, namely recycled aggregate replacement rate and the mix proportion of steel fibers, the data analysis was carried out on the steel fiber recycled concrete center pull-out test. The following conclusions were obtained.

(1) The addition of steel fibers improved the failure state of the pull-out specimens. The main failure form of ordinary concrete pull-out specimens and recycled concrete pull-out specimens was splitting damage. Splitting pull-out failure and pull-out failure mainly occurred in steel fiber recycled concrete specimens. The cracks of concrete pull-out specimens without addition of steel fibers developed rapidly and damaged abruptly. In the steel fiber-added pull-out specimens, the cracks developed relatively slowly, the amount of cracks was large, the width of cracks was small, and the integrity of the specimens was good.

(2) Based on the measured bond-slip test results, the influence of two factors, namely, the replacement rate of recycled aggregates and the mix proportion of steel fibers, on the bond-slip performance was summarized: with the increase of the replacement rate of recycled aggregates, the bond strength of the pull-out specimens showed a decreasing trend, and the maximum decrease reached 36.64%; the steel fiber improved the bond-slip performance of the recycled concrete; after the steel fiber was incorporated, the maximum increase of the bond strength of the pull-out specimens was 16.52%, and the slip value under the peak load also increased; the bond-slip performance was

better when the mix proportion of steel fibers was 1.2%.
(3) Based on the measured bond stress-slip curve and the existing bond-slip constitutive relations, the actual curve and the fitted curve were compared and analyzed, and the results showed that the test curve and the fitted curve were in good agreement.

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