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Shear Behavior of Recycled Concrete Beam from Building Wastes

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There are six beams made from recycled concrete and one from common concrete in the test. We conduct a shear test on them to analyze how the fracture morphologies, shear capacity and oblique crack width of beams are subjected to change with the replacement rate and shear-span ratio of recycled aggregates. The results reveal that the two fracture morphologies, i.e. shear stress and oblique tension, occur on the recycled concrete beams. Shear span ratio is still the dominant factor that affects the failure mode and load capacity of recycled concrete beams. In the end, this paper proposes the computation formula for the ultimate flexural and shear capacities of recycled concrete beams, which provides a reference for further exploration and application of recycled concrete in structures.

1. Introduction

Recycled Aggregate Concrete (RAC) is prepared by the following method: the crushed and classified waster concretes are mixed by a certain ratio whereby to form the recycled aggregate, all or part of which as natural aggregate are added with cement mortar to prepare a new kind a concrete, referred to as recycled concreter (Liu et al., 2018). In recent years, scholars have made extensive studies on the physical properties of recycled coarse aggregates (Li and Zhang, 2017; Xing et al., 1999; Liang et al., 2017).
In particular, given that recycled concrete will apply to structural components, scholars from many countries focused on developing the shear behaviors of recycled concrete beams in relatively early days (Zhou and Jiang, 2009; Zhang et al., 2006). Etxeberria et al. (2007) explored the shear properties of 12 recycled concrete beams poured with 4 types of concretes which differ at replacement rates of recycled coarse aggregates (0 %, 25 %, 50 % and 100 %) but have a similar compression strength. How the stirrup ratio affects the shear properties is also considered. Studies show that the bond strength of concrete and steel bars and the bite strength of aggregates are dominant stress mechanisms for recycled aggregate concrete beams. González et al. (2004) adopted 4 types of recycled concretes available from different formulae to make 16 beams to probe into their shear behaviors. All beams use similarly longitudinal reinforcement ratio and 4 sets of different stirrup ratios. The test results reveal that the concrete prepared by different formulae has a great impact on the crack propagation and development of the shear beam, but plays a little on the mid-span deflection and the shear ultimate capacity of the beams. The above studies all consider what impact the shear span ratio plays on the shear behaviors of recycled concrete beams. Here we work on the study of shear behaviors of recycled concrete beams with different replacement rates and shear span ratios by the test.

2. Test materials

2.1 Fine aggregate and cement

The test uses fine aggregate as common river sands. In accordance with the Standard and Test Method of Sands for Ordinary Concrete (JGJ52-92), it is measured that its bulk density is 1550 kg/m^3 and moisture content is 7.0 %. After sieve test, the fineness modulus is 2.72, which suggests the sand is medium.
The Qinling PC32.5R composite Portland cement produced by Shaanxi Yaoxian Cement Co., Ltd is used and the mixing water comes from Xi'an city tap water.

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2.2 Coarse aggregate

Natural aggregate and recycled aggregate are used as coarse aggregate in the test. The recycled coarse aggregates are provided by Xi'an Xinsheng Yuan Construction Muck Recycling Co., Ltd. The aggregates are available in such a way that the concrete blocks abandoned after the demolition of buildings are broken up, cleaned and classified by the jaw crusher. Natural aggregates are common gravels, and have particle size range and granular composition equivalent to recycled aggregates. The test measures the apparent density, moisture content, water absorption, and crush index of the coarse aggregates.

Table 1: Physical properties of coarse aggregates

Aggregate type	Apparent density (kg/m^3)	Crush index	Moisture content	Water absorption		Particle size range (mm)		
				10min	30min	5～10	10～20	20～30
Natural	2658	10.6%	4.21%	0.69%	0.14%	14%	57%	29%
Recycled	2601	18.3%	0.65	0.34%	0.46%	13%	53%	34%

2.3 Mix ratio of recycled concrete

The concrete strength is prepared as grade C30 in the test. Here designs the mix ratio of recycled concrete based on free water cement ratio. Determine the water absorption rate of regenerated and natural mix aggregates in a certain time at different aggregate replacement rates. Then soakage is calculated based on the measured water absorption, and this part of water is used as the suction water; the other part is mixed water. The water consumption of this part is determined in accordance with the Specification for Mix Proportion Design of Ordinary Concrete (JGJ55-2000). The ratio of free water to cement, i.e. water cement ratio (w/c) determines the strength of recycled concrete. The detailed match ratio is shown in table 2.

Table 2: Mix ratio of concrete under test

recycled aggregate replacement rate (%)	Water cement ratio	Water absorption of mix aggregate(%)	Slumps (mm)	Consumption of materials per m^3 concrete(kg)				
				Water	Cement	Sands	Natural aggregate	Recycled aggregate
0	0.46	1.5	67	190	380	633	1232	-
30	0.46	2	62	202	380	633	862	370
50	0.46	3.5	48	239	380	633	616	616
80	0.46	4.5	44	264	380	633	370	370
100	0.46	5	39	276	380	633	-	1232

2.4 Steel drawing test

HRB335 grade hot-rolled steel bars are used for tensile steel bars, and HPB235 grade hot-rolled bars are used for support bars and stirrups. The diameter of the support bar is 8 mm; the longitudinal tensile steel bar of the shear specimens is 18 mm in diameter, and the stirrup is 6 mm in diameter. The pullout test is conducted for steel bars, and the measured results are shown in Table 3.

Table 3: Mechanical properties measured for steel bars

Types of steel bars	Diameter (mm)	Yield strength fy (N/mm^2)	Ultimate strength fu (N/mm^2)	Elasticity modulus (N/mm^2)
HPB235	φ6	334	502	2.1×10^5
	φ8	321	486	
HRB335	Φ12	406	574	2.0×10^5
	Φ14	408	592	
	Φ18	393	582	

3. Profile of shear test

For the purpose of the test, specimen design allows for several variable factors such as replacement rate and shear span ratio of recycled aggregates. There are the total of 7 beams made in the test, which are all 200 mm x 300 mm in section dimensions, rectangular, and 2300 mm in length. All specimens use the identical reinforcement bars, and the stirrup rate is 0.22 %. In order to prevent flexion and failure of the beams under test, 3 Φ 18 reinforcement bars in longitudinal stress are set in the tensile area of the beam, and the longitudinal reinforcement ratio is 1.39 %. The pressure zone is equipped with 2 φ8 support bars in vertical stress and the stirrup is φ6@150. The thickness of the concrete protection layer is 25 mm, see Fig. 1 for member reinforcement.

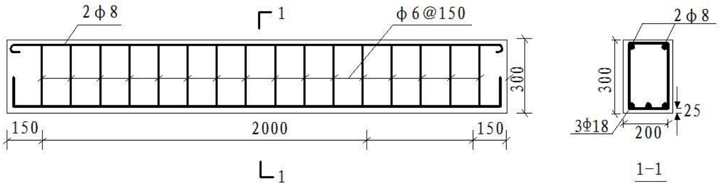


Figure 1: Reinforcement and section size of specimen (mm)

Concerning the effect of the replacement ratio of recycled aggregate and the shear span ratio in the test, the specimens are divided into two groups: the beams with the shear span ratios when λ=1.5, λ=2 and λ=3 are 1, respectively, the replacement rates of recycled aggregates are all 30%; when the shear span ratio λ=2 in the test, there are 5 beams, for 4 of which, the replacement rates of recycled aggregates are 30 %, 50 %, 80 %, 100 %, respectively, and the other 1 are ordinary concrete beams. 3 cubic test blocks (150 mm×150 mm×150 mm) are reserved for each specimen when casting the beams, cured with test beams so that the concrete strength can be measured in the test. The detailed parameters of the oblique section test beam are shown in Table 4, where the RBS in RBS-λ-A represents the oblique section shear test beam; λ represents the shear span ratio (3 types, i.e. 1.5, 2, 3); A represents the replacement ratio of the recycled aggregate (5 types, i.e. 0, 30 %, 50 %, 80 %, 100 %).

Table 4: Specific parameters of the test beam

SN	No.	Replacement rate of recycled aggregate (%)	Stirrups	Stirrup Ratio (%)	Shear span ratio(λ)	Cube compression strength $f_{cu,k}$ (MPa)	Concrete slump(mm)
1	RBS-2-0	0	φ6@150	0.22	2	37.29	67
2	RBS-2-50	50	φ6@150	0.22	2	39.84	46
3	RBS-2-80	80	φ6@150	0.22	2	34.77	43
4	RBS-2-100	100	φ6@150	0.22	2	34.42	41
5	RBS-2-30	30	φ6@150	0.22	2	33.25	60
6	RBS-1-30	30	φ6@150	0.22	1.5	33.25	63
7	RBS-3-30	30	φ6@150	0.22	3	33.25	59

4. Test results and analysis

4.1 Analysis of the failure mode of the regenerated concrete beam in the oblique section

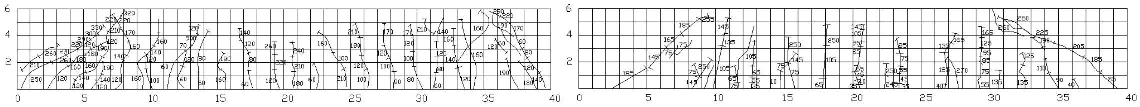
The analysis is made on the crack distribution and development of the test beam, as well as its failure behaviors. It is concluded that the oblique tension failure occurs on the RBS-3-30 specimens with the shear span ratio of 3, while the shear compression failure occurs on the RBS-1-30 with shear span ratio of 1.5 and the RBS-2-A with the shear span ratio of 2.

The oblique tension failure. Test results show that the recycled concrete beam with the recycled aggregate replacement rate of 30 % and the shear span ratio of 3 is subjected to oblique tension failure. The oblique crack develops rapidly accompanied by acute failure process with the increasing of test loads. The recycled concrete beam before failure deforms a little, which belongs to the typical brittle failure, basically consistent to that of the oblique section of the ordinary concrete beam. RBS-3-30 oblique failure surface is shown in Fig. 2.

Figure 2: Oblique failure mode (E-surface)

Shear compression failure. When shear span ratios λ=1.5 and λ=2, shear compression failure occurs on the test beams. When loaded later, the oblique cracks gradually extend to the load point, and the height of concrete shear press zone decreases continuously. The concrete at the top of the oblique crack near the load point is crushed under the combined action of shear stress and pressure stress, so that the specimen gets failed due to loss of bearing capacity. Compared with the balanced-reinforced beam, the normal section failure still belong to brittle failure in the beams of λ=1.5 and λ=2.

The crack development and distribution of some beams during the load process is shown in Fig. 3.



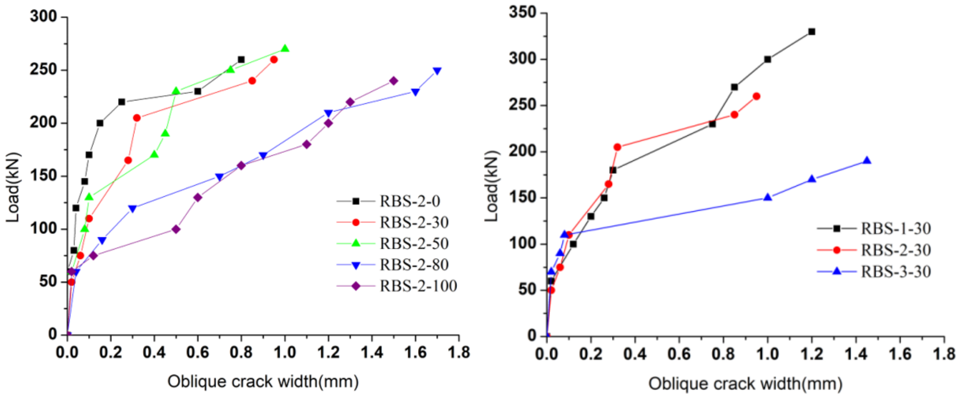
(a) Extension of RBS-1-30 crack (E-surface) *(b) Extension of RBS-2-30 crack (W-surface)*

Figure 3: Crack development and distribution of test beams

4.2 Average width curve of load-oblique crack

In Fig. 4, there is a curve of maximum oblique crack width of the test beam with four different recycled aggregate replacement rate and a shear span ratio of 2 when the load is applied, compare it with that of the common concrete beams. The loads from oblique cracks of specimens are greater than that of bend cracks. During the whole loading process, the width of the oblique crack of recycled concrete beams is generally greater than that of common concrete beams as load is constant.

For the recycled concrete beams with different shear-span ratios, as shown in Fig. 5, when the replacement rate of recycled aggregates reaches 30 %, RBS-1-30 (λ=1.5) and RBS-2-30 (λ=2) that shear compression failure occurs develops steadily within a certain loading time after the occurrence of oblique cracks, and widen in oblique crack at the time of near failure. For the RBS-3-30 (λ=3) beam with oblique tension failure, the oblique crack widens quickly once it appears. Its cracking load approaches to the failure load, which is very similar to common concrete beams.



(a) RBS-2-A *(b) RBS-λ-30*

Figure 4: Curve of oblique crack width

5. Regression analysis on shear capacity of recycled concrete beams

The cracking load, oblique crack load, ultimate load, maximum deflection, and maximum crack width of each beam will be available from the test, refer to Table 5 for data measured in practice.

Table 5: Summary of test results

Specimen No.	Crack load (kN)	Oblique crack load (kN)	Ultimate load (kN)	Maximum deflection (mm)	Max crack width (mm)
RBS-1-30	39.73	58.90	308.16	8.52	1.2
RBS-2-30	36.30	74.66	263.42	7.52	1.0
RBS-3-30	32.88	71.23	188.36	6.84	1.5
RBS-2-0	44.52	71.92	279.45	10.73	0.8
RBS-2-50	39.73	50.68	268.63	8.22	1
RBS-2-80	41.78	90.41	242.14	8.71	1.7
RBS-2-100	38.36	91.10	234.36	9.98	1.5

Based on the above analysis and basic assumptions, the parameters and test data are constituted into the computation formula for the shear capacity of the beams in accordance with the Code for Design of Concrete Structures (GB50010-2002), and the ultimate shear capacity of recycled concrete beams can be obtained. For the RBS-3-30 test beam with oblique tension failure, this standard does not apply, so that it is not discussed herein. The experimental and calculated values for the remaining test beams are listed in Table 6. The relationship between the axial tensile strength and the cube compression strength of concrete is calculated as follows in accordance with the Code for Design of Concrete Structures:

$$f_{tk} = 0.88 \times 0.395 f_{cu,k}^{0.55} (1-1.645\delta)^{0.45} \times \alpha_2 \quad (1)$$

Table 6: Comparative analysis of the theoretical results and measurements of test beams

Specimen No.	Replacement rate of RA (%)	Shear span ratio(λ)	Tensile strength f_{tk} (MPa)	Ultimate capacity calculated (kN)	Ultimate capacity measured (kN)	Calculated / measured values
RBS-1-30	30	1.5	2.27	242.05	308.16	1.2731
RBS-2-30	30	2	2.27	211.4	263.42	1.2461
RBS-2-0	0	2	2.54	221.28	279.49	1.2629
RBS-2-50	50	2	2.64	227.43	268.63	1.1812
RBS-2-80	80	2	2.44	215.22	242.14	1.1251
RBS-2-100	100	2	2.43	214.34	234.36	1.0934

From data in the table, the theoretical shear ultimate capacity of the test beam is less than the appropriate values specified in the Code for Design of Concrete Structures (GB50010-2002), and the ultimate shear capacity of the recycled concrete beam can be estimated. However, as compared with common concrete beams, the safety reserve of the test beam gradually decreases as the replacement rate of recycled aggregates increases. Given that the calculation formula is available, it is suggested that the ultimate shear capacity of recycled concrete beams with any recycled aggregate replacement rate can be calculated as follows:

$$V_u^r = (1-\alpha r)V_u^1 = (1-\alpha r)\left(\frac{1.75}{\lambda+1.0} f_t b h_0 + f_{yv}\frac{A_{sv}}{s} h_0\right) \quad (21)$$

Where, α is an adjustment coefficient, the measurement of the ultimate capacity of the recycled concrete beam in the test is substituted for the regression calculation. For the safe α=0.15; r is the replacement rate of the recycled coarse aggregate, and the remaining parameters are chosen in accordance with the current specifications. The comparison of the ultimate capacity of the beam calculated from formula (2) with the measured values is given in Table 7.

Table 7: Comparative analysis of calculated values from suggested formula and measured values of test beam

Specimen No.	Calculated value from proposed formula, V_u^r (kN)	Calculated value from specified formula, V_u^1 (kN)	Ultimate capacity measured (kN)	Measured/ calculated Values from proposed Formula, V_u^c / V_u	Measured/calculated values from specified formula, V_u^c / V_u^r
RBS-1-30	231.16	242.05	308.16	1.3331	1.2731
RBS-2-30	201.89	211.4	263.42	1.3048	1.2461
RBS-2-0	221.28	221.28	279.49	1.2629	1.2629
RBS-2-50	210.37	227.43	268.63	1.2769	1.1812
RBS-2-80	189.39	215.22	242.14	1.2785	1.1251
RBS-2-100	182.39	214.34	234.36	1.2864	1.0934

Based on data in the table, the calculated values from proposed formula are less than the measurements. The ratio of the measured to the calculated values from the proposed formula is taken as a statistical sample with a mean value of 1.290433, a standard deviation of 0.025007, and a variable coefficient of 0.019379. The calculated value obtained by the formula 5-2 fits well with the measured value. Compared with the common concrete beam, the ratio of the measured value and the calculated value of the shear capacity of the recycled concrete beam is slightly higher. The shear ultimate capacity evaluated by formula (2) for the recycled aggregate beams with different replacement rates is somewhat unsafe.

6. Conclusions

(1) From the fracture morphologies in the test of oblique section shear behaviors, the shear failure mode occurs on recovered concrete beams with shear ratio of 1.5 and 2 under symmetrically concentrated load, while oblique tension failure appears on those with shear span ratio of 3. The failure mode and shear mechanism of recycled concrete beams seem similar to that of common concrete beams.
(2) Like ordinary reinforced concrete beams, the shear-span ratio is still one of the dominant factors that affect the shear capacity and failure modes of recycled concrete beams. The stirrup strain and the mid-span deflection increase against the greater shear-span ratio of recycled concrete beams under the equal load. When replacement rate of recycled aggregates is constant, the shear capacity of beams lessens with the increase of shear-span ratio.
(3) The bending and shear mechanisms of recycled concrete beams seem similar to that of ordinary concrete. There is a small safety reserves for calculating the ultimate capacity of recycled concrete beams based on the current approaches. The proposed formula is given here for computing ultimate bend and shear capacities of recycled concrete beams.

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