

Research Flexural Test and Crack Development of PVA-steel Fiber Composite Reinforced Recycled Concrete Beams

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Abstract

Excessive crack width and numerous cracks in high-strength recycled concrete beams significantly impair their serviceability. To address this, steel fibers and polyvinyl alcohol (PVA) fibers-known for their excellent crack resistance-were incorporated into high-strength recycled concrete beams to effectively restrict crack development. Through flexural tests on six steel/PVA fiber-reinforced recycled concrete beams, one natural aggregate concrete beam, and one recycled concrete beam without fibers, the effects of PVA fiber volume ratio, steel fiber volume ratio, and PVA-steel hybrid fibers on the average crack width under serviceability limit state, maximum crack width under ultimate limit state, and the number of cracks during loading were investigated. The results demonstrate that the incorporation of hybrid steel and PVA fibers effectively inhibits cracking in recycled concrete beams, reducing the maximum crack width under ultimate load by 47.5%. The failure load of hybrid fiber-reinforced recycled concrete beams exceeded that of both single-fiber recycled beams and the natural concrete beam, while exhibiting crack resistance comparable to that of natural concrete.

Keywords

Recycled Aggregate Concrete Beam; PVA Fiber; Steel Fiber; Maximum Crack Width; The Number of Cracks.

1. Introduction

With societal development, numerous aging buildings are being demolished, generating substantial amounts of waste concrete. Recycling this waste concrete enhances resource utilization, reduces environmental pollution, and decreases the consumption of natural aggregates. Recycled aggregate concrete (RAC) is produced by crushing, grading, and sieving waste concrete to create recycled aggregates that replace natural aggregates^[1]. However, the adhered old mortar on recycled aggregates reduces the bond strength with new mortar, leading to significant degradation in the fundamental mechanical properties of RAC^[2-4]. Consequently, the crack resistance and load-bearing capacity of recycled concrete beams are inferior to those of natural aggregate concrete beams.

Extensive domestic and international studies indicate that the failure characteristics and crack development patterns of recycled aggregate concrete beams are similar to those of natural aggregate concrete beams^[5]. Under both serviceability limit states and ultimate limit states, the flexural performance of natural concrete beams surpasses that of recycled aggregate concrete beams, though their failure processes are analogous. Theoretical analyses confirm that the existing theoretical framework and design codes for concrete beams remain applicable to recycled aggregate concrete beams^[6]. Compared to recycled concrete beams, natural concrete beams exhibit higher flexural capacity but smaller crack widths and deflections^[7-8].

Relevant research demonstrates that incorporating steel fibers into recycled concrete beams can reduce crack width and effectively restrain concrete cracking^[9]. Studies by Cheng Donghui et al.^[10]

^{12]} show that adding steel fibers alone to recycled aggregate concrete beams reduces crack width and significantly improves cracking load. Karimipour et al. ^[13] investigated the effects of separately adding polypropylene and steel fibers to recycled aggregate concrete beams, revealing that fiber addition enhances flexural capacity and increases the cracking load of the beams.

Current research primarily focuses on singly incorporating polypropylene or steel fibers in recycled concrete beams. Different types of fibers exhibit distinct characteristics, and adding a single fiber type can only enhance performance within specific limits. Steel fibers offer limited toughening and crack resistance during the elastic stage, failing to inhibit microcrack initiation ^[14-15]. In contrast, polyvinyl alcohol (PVA) fibers possess high tensile strength and can restrain crack initiation and propagation ^[16-18], effectively mitigating early-age cracking ^[19]. However, single-fiber reinforcement has limited effectiveness in improving the ultimate crack resistance of recycled concrete ^[20]. Hybridizing different fiber types can create synergistic effects, enhancing the mechanical properties of RAC. Hybrid fibers demonstrate pronounced multi-stage crack resistance in concrete ^[21-23]. Nevertheless, few studies have explored the crack resistance of recycled concrete beams reinforced with solely PVA fibers or PVA-steel hybrid fibers.

In summary, this study investigates the effects of individually incorporating steel fibers, PVA fibers, and their hybrid combination on the crack resistance and ultimate load-bearing capacity of high-strength recycled aggregate concrete beams through four-point bending tests. A total of eight beam specimens were designed and tested to analyze the influence of fiber type, fiber volume fraction, and single/hybrid fiber reinforcement on the load–maximum crack width curves and load–number of cracks curves. The findings aim to provide practical guidance for the design of PVA-steel hybrid fiber-reinforced recycled concrete beams.

2. Experimental Overview

2.1 Materials

Concrete was prepared in accordance with the Chinese specification JGJ 55—2011 ^[24]. The binder used was P.O 42.5 ordinary Portland cement. Fine aggregates consisted of natural river sand with a fineness modulus of 2.78. Recycled coarse aggregates (RCA) were obtained by manually breaking waste concrete into large pieces, which were then crushed using a crusher. Particles with sizes ranging from 5 to 25 mm were selected, washed, and air-dried. Natural coarse aggregates (NCA) were continuous-graded crushed stones with the same particle size range. S95-grade mineral powder and Grade II fly ash were used as supplementary cementitious materials; their physical properties are listed in Table 1. Polyvinyl alcohol (PVA) fibers and steel fibers, shown in Fig. 1, were incorporated; their physical properties are provided in Table 2. A liquid polycarboxylate-based high-performance water reducer with a water reduction rate of 35% was used. The concrete mix proportions are presented in Table 3.



(a) Polyvinyl alcohol (PVA) fiber



(b) Steel fiber

Fig. 1 Types of fiber

Table 1. Physical properties of fly ash and mineral powder

Material Types	Density / (kg·m ⁻³)	Bulk Density / (kg·m ⁻³)	Specific Surface Area / (cm ² ·g ⁻¹)	Loss on ignition /%
fly ash	2180	1124	3400	1.78
mineral powder	2980	1440	3850	4.09

Table 2. Physical and mechanical properties of fibers

Material Types	fiber diameter /μm	Fiber length /mm	density / (g·m ⁻³)	Tensile strength of fiber /MPa	Elastic modulus of fiber /GPa	Elongation rate of fiber /%
PVA	15	27	1.27	1060	29	6.00
Steel fiber	600	19	7.80	1500	220	8.00

2.2 Specimen Design and Fabrication

All specimens had dimensions of 150 mm × 300 mm × 2600 mm. As shown in Table 4, the types and labels of the specimens were as follows: natural aggregate concrete beam (NACB), recycled aggregate concrete beam (RACB), PVA fiber-reinforced recycled beams (RP-1 and RP-2), steel fiber-reinforced recycled beams (RS-1 and RS-2), and PVA-steel hybrid fiber-reinforced recycled beams (RPS-1 and RPS-2). The concrete cover thickness was 20 mm. The beam dimensions are illustrated in Fig. 2.

The bottom tension zone and top compression zone of the beams were reinforced with 2Φ22 and 2Φ12 HRB400-grade steel bars, respectively. Stirrups were made of 6 mm diameter HPB300-grade plain round steel bars. Within the mid-span L/6 region, the stirrup spacing was 150 mm. To prevent shear-flexural failure during loading, the stirrup spacing was reduced to 100 mm within the L/3 range from both ends of the beam. The measured mechanical properties of the steel are provided in Table 5.

Mechanical property tests were conducted on standard concrete cubes in accordance with the Chinese standard GB/T 50081—2019 [25]. The 28-day cubic compressive strength and axial tensile strength of the concrete are summarized in Table 4.

Table 3. Mix ratio of concrete

RCA Replacement Ratio	Material / (kg·m ⁻³)							
	Cement	Sand	NCA	RCA	Water	Additional Water	Fly ash	Mineral powder
0	337	634	1126	0	154	0	48	96
100	337	634	0	1126	154	25	48	96

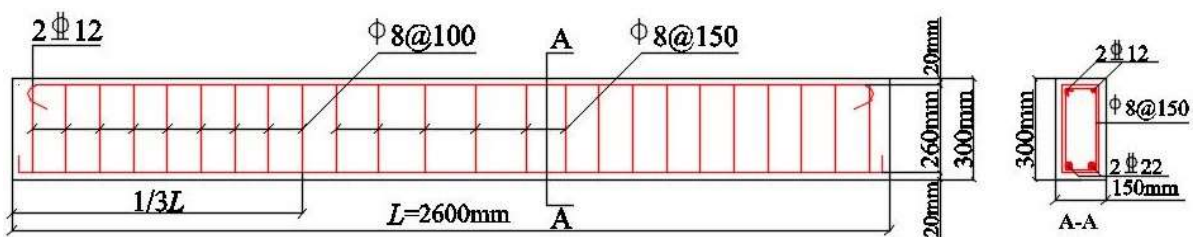


Fig. 2 Dimensions of fiber reinforced high-strength recycled aggregate concrete beams (mm)

Table 4. Specimen design and test parameters

Specimen Designation	RCA Replacement Ratio /%	Fiber Volume Fraction /%		$f_{cu}/\text{Mpa}^{[26]}$	$f_{tk}/\text{MPa}^{[26]}$	P_p/kN	P_r/kN
		PVA	Steel				
NACB	0	0	0	69.0	6.2	215	35
RACB	100	0	0	66.4	4.8	212	25
RP-1	100	0.2	0	57.1	7.6	214	35
RP-2	100	0.3	0	57.4	7.0	213	35
RS-1	100	0	0.5	66.2	5.3	219	35
RS-2	100	0	1.0	69.2	7.2	221	40
RPS-1	100	0.3	0.5	61.4	5.8	220	35
RPS-2	100	0.2	1.0	62.6	7.9	223	40

Note: P_p : Ultimate failure load; P_r : Cracking load.

Table 5. Material properties of steel bars

Reinforcing bar grade	d/mm	f_y/MPa	f_u/MPa	E_c/MPa
HRB400	22	401	530	2.1×10^5
	12	443	584	2.1×10^5
HPB300	6	332	456	2.2×10^5

Note: d nominal rebar diameter; f_y , steel yield strength; f_u , steel ultimate tensile strength; E_c , concrete elastic modulus.

3. Results and Analysis

3.1 Experimental Observations

At a load level of $0.12P_p$ (where P_p denotes the ultimate load), no cracks were observed in any specimen. As loading increased, cracks initiated in the tensile zone at mid-span. With further load escalation, the width of mid-span cracks expanded, and crack propagation intensified near the mid-span region, extending longitudinally along the beam. Simultaneously, cracks developed in the shear-flexural zone.

When the load reached $0.66P_p$ (corresponding to the serviceability limit state), the number of cracks in the pure bending zone stabilized, while existing cracks propagated rapidly. In the shear-flexural zone, cracks extended toward the loading points, forming inclined cracks, indicating that the specimens entered a cracked working state.

At approximately $0.90P_p$, the tensile steel reinforcement reached its yield strength, accompanied by significant widening of cracks and cracking in the compressive zone concrete. Upon attaining the ultimate load P_p , partial crushing of compressive concrete occurred, accompanied by pronounced beam deformation. The post-test condition of selected specimens is shown in Fig. 3.

During the entire loading process, the recycled aggregate concrete beams exhibited a larger number of cracks and earlier crack initiation compared to natural aggregate concrete beams. The incorporation of PVA fibers alone delayed crack appearance and increased the initial cracking load. However, in the mid-to-late loading stages, the crack width in recycled beams was larger than that in ordinary beams. Although specimens with a higher PVA fiber volume fraction showed a reduction in the number of cracks during the early loading phase, both the number and width of cracks increased under ultimate load conditions.

For recycled beams with steel fibers only, the time of crack initiation and the number of cracks in the early loading stage were similar to those of fiber-free recycled beams. As the load gradually increased until near failure, both crack width and number were smaller than those in fiber-free recycled beams. Nevertheless, with higher steel fiber content, crack width and number increased under ultimate load conditions.

Recycled beams with hybrid PVA-steel fibers showed significantly reduced crack number and width in the early loading stage compared to those with only one type of fiber, performing similarly to ordinary beams. Under ultimate load conditions, their crack resistance was notably superior to that of singly reinforced beams, though crack number and width were still greater than those of natural aggregate concrete beams.

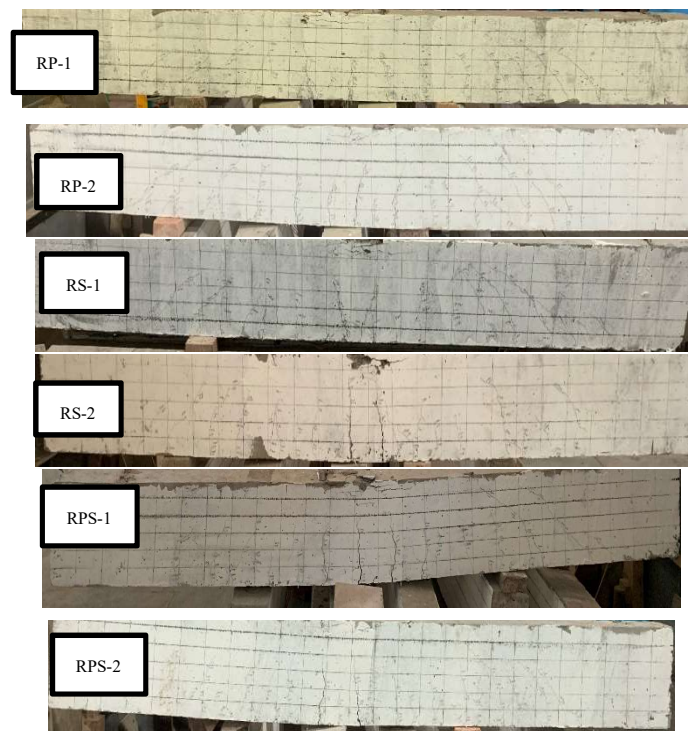


Fig. 3 Typical failure modes of beam

3.2 Analysis of Factors Influencing Crack Width and Number

3.2.1 Load–Maximum Crack Width at Mid-Span Curves

As shown in Fig. 4(a), compared with the recycled aggregate concrete beam RACB, the specimens RP-1 and RP-2 with PVA fibers exhibited similar crack widths and nearly overlapping $P-\omega_{max}$ curves during the initial loading stage. The crack widths were smaller than those of RACB, and the maximum crack width of RP-1 was even smaller than that of the natural aggregate concrete beam NACB, reflecting the effectiveness of PVA fibers in controlling early-age crack development without forming wide cracks. As the load approached the peak load, the crack width decreased significantly. For specimen RP-1 with a PVA fiber volume ratios of 0.2%, the maximum crack width was reduced by 62.9% under the same load level; for specimen RP-2 with volume ratios of 0.3%, the reduction was 40.7%. This indicates that the incorporation of PVA fibers effectively restrained the initiation and propagation of cracks. However, increasing the PVA fiber content did not enhance the crack control capacity under ultimate load conditions but rather reduced it. The main reason is that in the ultimate state, crack width is primarily governed by the synergy between steel reinforcement and concrete. PVA fibers contribute limited stress resistance at this stage. The failure of PVA fiber-reinforced beams was not brittle as in under-reinforced beams; instead, these specimens underwent considerable deformation before reaching the ultimate load. Visible local crushing in the compression zone of the pure bending segment indicated a ductile failure mode.

As illustrated in Fig. 4(b), increasing the steel fiber volume ratio did not significantly affect the crack width during loading. The crack widths of specimens RS-1 and RS-2 were slightly smaller than those of RACB. However, at the failure load of RACB, the maximum crack width was markedly reduced. For specimens RS-1 and RS-2 with steel fiber volume ratios of 0.5% and 1.0%, the maximum crack widths were reduced by 45.7% and 16.6%, respectively, indicating that steel fibers also effectively inhibited crack development. The specimens did not exhibit multiple fine cracks or densely distributed microcracks. This is mainly because the addition of steel fibers increased the matrix cracking load. After cracking, the steel fibers bore more bridging stress. Due to their small deformation, they could transfer stress while restraining further matrix cracking until fiber pull-out occurred, leading to a sudden increase in crack width. Many interfacial failures propagating upward from the cast concrete layer were observed on the side of the beams, and the crack distribution in steel fiber-reinforced recycled beams was denser than that in fiber-free recycled beams. With higher steel fiber content, the crack width of specimen RS-2 under the same load was smaller than that of RACB without fibers, primarily because the steel fibers acted as bridges across cracks, restraining further crack propagation.

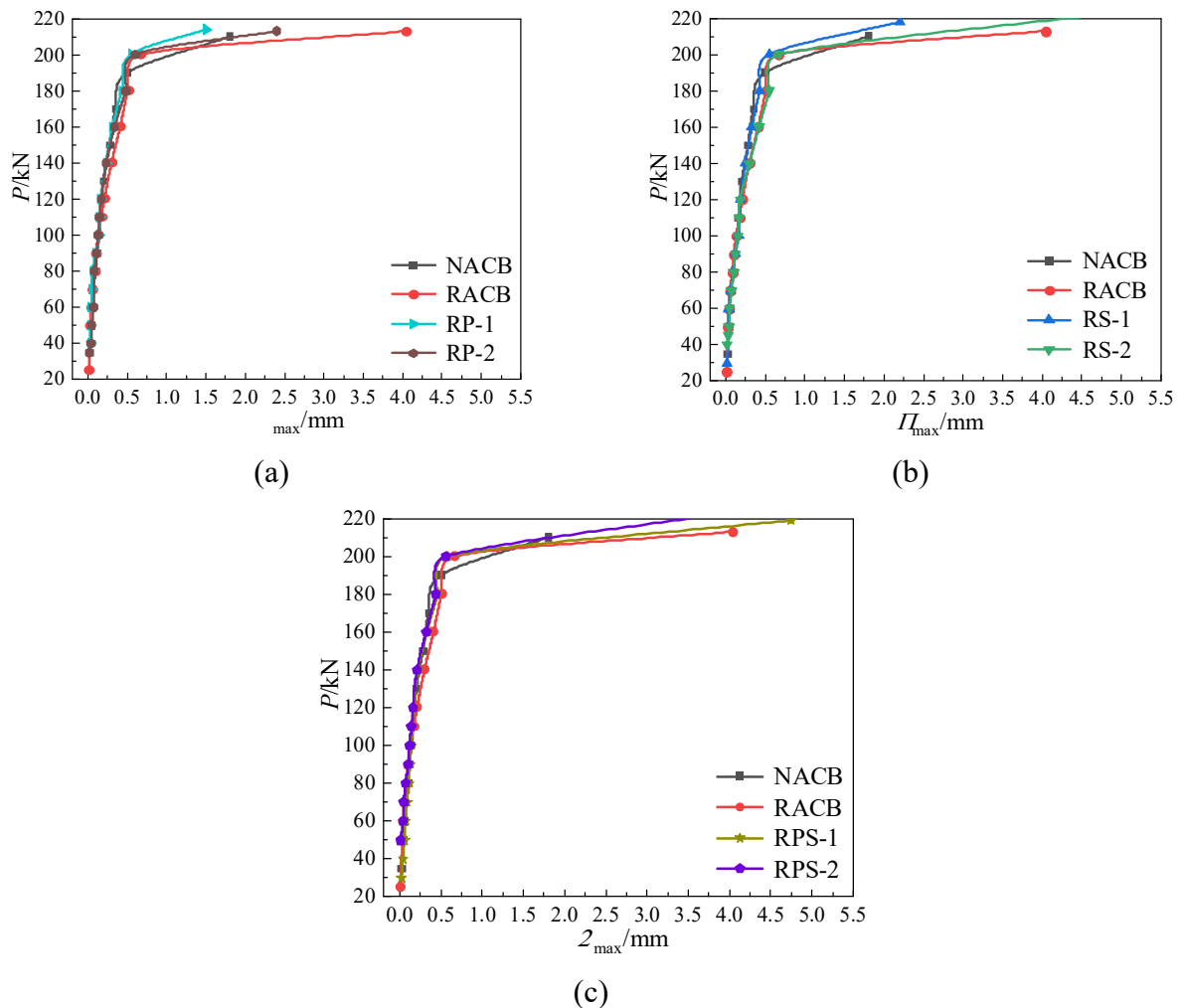


Fig. 4 Load-maximum crack width curves of specimens with different fiber and volume ratios

As shown in Fig. 4(c), the crack widths of recycled beams with different hybrid fiber ratios were close to those of RACB during initial loading. Cracks appeared later in the hybrid PVA-steel fiber specimens (RPS). When the load increased to approximately $0.66P_p$, the maximum crack width of the fiber-reinforced RPS specimens under the same load level was smaller than that of the fiber-free

RACB specimen. At the peak load of RACB, the maximum crack width of RPS-1 was reduced by 33.3%, and that of RPS-2 was reduced by 47.5%. As shown in Fig. 4, the failure load of RPS-2 was higher than those of RS-2 and RP-1, and the crack width under the same load was significantly smaller. This indicates that the combination of PVA and steel fibers effectively inhibits crack development. The crack resistance and ultimate load-bearing capacity of hybrid fiber-reinforced recycled beams are superior to those of beams with a single fiber type and even better than those of natural aggregate concrete beams.

3.2.2 Load–Number of Cracks Curves

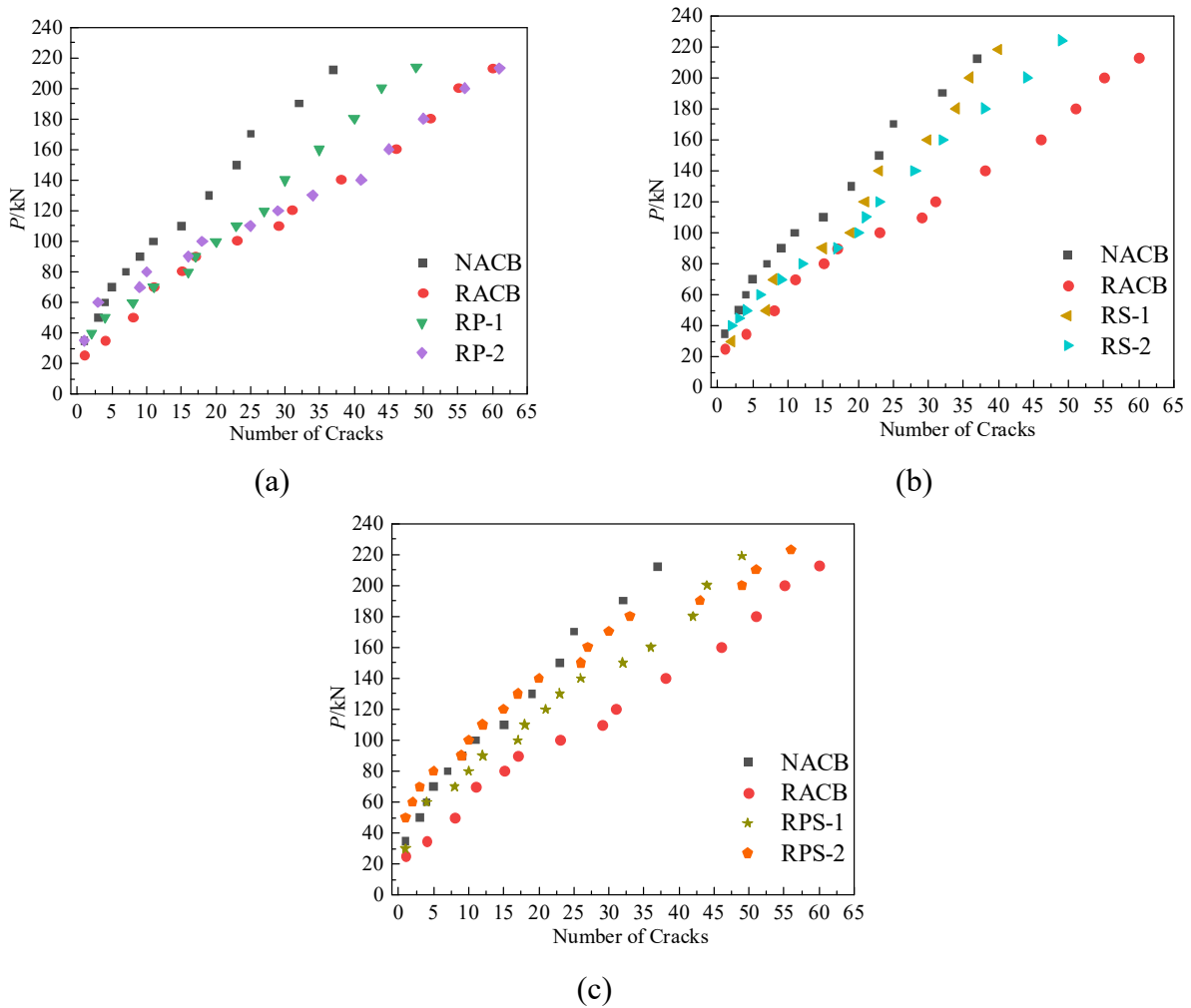


Fig. 5 Load-crack number curves of specimens with different fiber and volume ratios

As shown in Fig. 5(a), during the initial loading stage, the addition of PVA fibers alone had a limited effect on the number of cracks in the recycled beams. As the load increased beyond 120 kN, the number of cracks in specimen RP-1 decreased significantly. At the same load level, the number of cracks in specimen RP-2 was similar to that of the fiber-free recycled beam but higher than that of RP-1. The primary reason is that the increased PVA fiber volume fraction has limited crack resistance under ultimate load conditions, leading to a higher number of cracks.

As illustrated in Fig. 5(b), the number of cracks in the steel fiber-reinforced recycled beams was lower than that in the fiber-free recycled beams throughout the loading process. For specimen RS-1 with a steel fiber volume fraction of 0.5%, the number of cracks during the early and mid-loading stages was higher than that in the NACB specimen. However, under ultimate load conditions, the number of cracks was nearly identical to that of the ordinary beam. This is because the steel fibers did not

yield under low to moderate loads, and the bond between the steel fibers and concrete under ultimate load conditions resulted in fewer cracks. Nevertheless, when the steel fiber volume fraction increased to 1.0% (specimen RS-2), the number of cracks under ultimate load conditions increased. This may be attributed to the uneven distribution of steel fibers in regions with stress concentration, leading to a higher number of cracks.

As shown in Fig. 5(c), under the combined action of PVA and steel fibers, the number of cracks in specimen RPS-2 was lower than that in the NACB natural concrete specimen before reaching 200 kN. However, beyond 200 kN, the number of cracks increased significantly. The main reason is the significant difference in the properties of steel and PVA fibers, which led to uneven stress distribution and varying tensile stress contributions under ultimate load conditions, resulting in a sudden increase in the number of cracks. Despite this, the ultimate load-bearing capacity improved. Compared to specimen RPS-1, specimen RPS-2 had a reduced PVA fiber content and an increased steel fiber content. Based on Fig5(a), 5(b), and 5(c), it can be concluded that an increase in PVA fiber volume fraction has a minor effect on the number of cracks during early loading but causes a sudden increase in crack numbers beyond 120 kN. In contrast, an increase in steel fiber content reduces the number of cracks under ultimate load conditions. Therefore, the fiber volume fractions in specimen RPS-2 are optimal, as the synergistic action of both fiber types enables crack resistance performance comparable to that of natural concrete.

4. Conclusion

- (1) The development process of recycled aggregate concrete beams, including those incorporating steel fibers and polyvinyl alcohol (PVA) fibers, is similar, progressing through the linear elastic stage, the cracked working stage, and the failure stage.
- (2) Compared to natural concrete beams, recycled concrete beams are more prone to cracking and exhibit larger crack widths and greater steel reinforcement strain.
- (3) The addition of steel fibers or PVA fibers can effectively inhibit the initiation and propagation of cracks, reduce the number and width of cracks, and enhance the flexural capacity of recycled aggregate concrete beams. Under serviceability conditions, the inhibitory effect of steel fibers on crack propagation is less pronounced than that of PVA fibers.
- (4) The hybrid fiber-reinforced specimen RPS-2, with 0.2 vol% PVA and 1.0 vol% steel fibers, demonstrated optimal performance by leveraging the complementary characteristics of both fiber types. Its crack resistance and ultimate load-bearing capacity exceeded those of single-fiber specimens (RP-1 and RS-2) and were superior to those of the natural concrete beam.

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