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Utilization of waste concrete recycling materials in self-compacting concrete

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ABSTRACT

This paper evaluates the feasibility of preparing self-compacting concrete (SCC) by incorporating waste concrete recycling materials (WCRMs). Some or all of the natural materials were substituted with WCRMs, such as recycled coarse aggregate (RCA), recycled fine aggregate (RFA) and recycled powder (RP). Nine SCC mixtures were produced, including eight self-compacting recycled concrete mixes and one control mix without WCRMs. The SCC mixes were designed with four different RCA replacement rates (0%, 25%, 50% and 100%) along with a constant amount of RFA (10%) and varying percentages of RP (10% and 20%). The water/binder ratio was designed as 0.4 for all the SCC mixtures. The workability properties (e.g., flowability, viscosity and passing ability) and mechanical properties (e.g., compressive, splitting tensile and flexural strengths) of self-compacting recycled concrete were investigated. The findings indicate that the substitution ratio of WCRMs will affect the workability and mechanical behavior of SCC. This study demonstrates that the decline in the workability and mechanical behavior of self-compacting recycled concrete results from the cooperation of WCRMs. When natural materials are substituted and the amount of WCRMs is limited, the workability of self-compacting recycled concrete can satisfy the European standard EFNARC (2005). Meanwhile, this study also finds that the self-compacting recycled concrete can achieve acceptable mechanical performance when compared to the ordinary SCC without WCRMs.

1. Introduction

In recent decades, the construction industry has faced a series of problems, from a shortage of resources, and energy to environmental pollution. These problems include the consumption of natural resources and energy, emission of greenhouse gas (CO_2) and the creation of construction and demolition waste (CDW). Recycling CDW is the most promising solution for reducing the adverse environmental impacts in landfills caused by the construction industry. In 2015, 3.9 billion tons of CDW were produced in China, nearly 30% of which was waste concrete (Fu, 2016; Xiao, 2018). Therefore, utilizing waste concrete recycling materials (WCRMs) in engineering will contribute to protecting the environment and capturing the residual value of waste concrete. The WCRMs include recycled coarse aggregate (RCA), recycled fine aggregate (RFA) and recycled powder (RP). Recycled aggregate (RA), consisting of RCA and RFA, refers to aggregate with a diameter of less than 31.5 mm manufactured by crushing waste concrete. RP is a fine particle produced by collecting dust or finely grinding the CDW (Zhu et al., 2019). In recent years, these WCRMs have become widely accepted as alternative recycled materials that can be used in the construction industry.

RA is widely recognized as a substitute material for natural aggregate (NA) in recycled aggregate concrete (RAC) (Rao et al., 2007; Ghorbani et al., 2019). Due to the attached old mortar, the physical properties of RA are inferior to those of NA, exhibiting lower compressive strength, higher water absorption rate and higher porosity (Thomas et al., 2020). Consequently, the mechanical properties of RAC (e.g., compressive strength, elastic modulus, etc.) are lower than those of conventional concrete (Xiao et al., 2005; Xiao et al., 2016; Pradhan et al., 2020). However, experimental studies have shown that modifying the gradation of RA, the mixing method and the quality of RCA can favorably enhance the mechanical behavior of RAC (Zhang et al., 2019; Lu et al., 2019; Bai et al., 2020; Duan et al., 2020). Research findings have shown that no obvious reduction in the compressive strength and elastic modulus is found for RAC with a limited substitution percentage of RFA (Evangelista and de Brito, 2007; Ju et al., 2019; Yu et al., 2019). RP is a by-product in the manufacturing process of RA that contains unhydrated cement particles. Studies of recycled concrete fines demonstrate that, by benefiting from the residual anhydrous clinker, those fines can be used to produce high-

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(a) RCA (b) RFA

Fig. 1. Recycled aggregates: a) RCA, b) RFA.

quality concrete (Nežerka et al., 2020; Prošek et al., 2020). Xiao et al. (2018) also concluded that, when the RP content is less than 30%, the mechanical properties of RAC are only slightly degraded.

Self-compacting concrete (SCC) is now widely used in the construction industry, which seeks to benefit from its high flowability. SCC can easily pass through the reinforcement frame and fill formwork without vibration, which accelerates the construction process and improves the construction quality and working environment (Senas et al., 2016; Tahar et al., 2016; Santos et al., 2017; Nili et al., 2019). However, to ensure the required workability, the amounts of cement and chemical admixtures are raised, which leads to an increase in the cost of SCC (Ramanathan et al., 2013; Kebaïli et al., 2015). Incorporating WCRMs in SCC is an environmentally friendly, cost-saving strategy (Pereira-de Oliveira et al., 2013; Tang et al., 2016; Omrane et al., 2017). Several studies have investigated the effect of RA on the performance of self-compacting recycled concrete. Owing to the high porosity and high water absorption rate of RA, the amount of high-performance water-reducing agents should be raised to modify the workability of self-compacting recycled concrete (Safiuddin et al., 2011a; Kebaïli et al., 2015). Experimental studies have pointed out that the workability and mechanical behavior of SCC are slightly affected by the increase in the replacement ratio of RA (both RCA and RFA) (Kou and Poon, 2009; Grdic et al., 2010). Meanwhile, experimental research conducted by Safiuddin et al. (2011b) found that the workability of SCC can be improved by limiting the substitution rate of RCA to less than 50%. Kasami et al. (2001) found that the compressive strength of SCC with RP was comparable to that of normal SCC. It is confirmed by Singh et al. (2019) that the flowability of SCC with 10% RP decreased, while a reduction in the compressive strength was relatively small.

A brief review of the studies shows that a single-scale WCRM (RCA, RFA or RP) can be used to produce SCC. Past studies have investigated the influence of a single-scale WCRM on the workability and mechanical behavior of SCC. Nevertheless, the performance of SCC with WCRMs has not been adequately investigated, especially when covering the three scales of the particle sizes: RCA ≥;4.75 mm, 0.15 mm ≤ RFA < 4.75 mm and RP ≤ 40 µm. The effects and cooperation of WCRMs on the workability and mechanical behavior of SCC remain vaguely understood.

To characterize the workability and mechanical behavior of SCC with WCRMs, nine SCC mixes were prepared using different ratios of RA (0%, 25%, 50% and 100%-RCA, 10%-RFA) incorporating different contents of RP (10% and 20%). To investigate the workability of self-compacting recycled concrete, experimental tests were conducted including the slump flow, V-funnel, L-box and J-ring tests. Additionally, the influences of WCRMs on the mechanical behavior of hardened SCC were analyzed at 7 days and 28 days. Furthermore, the microstructure of SCC was studied to analyze the effect of the WCRMs on the fresh and hardened properties of SCC. The investigation of the microstructure of SCC will be conducive to better understanding the workability and mechanical behavior of self-compacting recycled concrete.

Therefore, this investigation aims to contribute to facilitating the utilization of waste concrete recycling materials (WCRMs) in engineering. The workability and mechanical properties of SCC with WCRMs are of great significance for the application of self-compacting recycled concrete. This paper considers the duplicate effect of three different scales of WCRMs (RCA, RFA and RP) on the performance of SCC at varied substitution rates. The investigation of SCC with WCRMs is devoted to improving the substitution rate of WCRMs and provides an appropriate mix design reference for self-compacting recycled concrete. By identifying the maximum utilization ratios of WCRMs that can be used to maintain the quality of SCC, this study will further promote the reclamation of CDW and the use of self-compacting recycled concrete in the construction industry.

2. Experiment descriptions

2.1. Materials

The WCRMs in this study were as follows:

- Recycled coarse aggregate (RCA) with a water absorption rate of 4.07% in 24 h.
- Recycled fine aggregate (RFA) with a water absorption rate of 9.56% in 24 h and a fineness modulus of 2.33.
- The recycled powder (RP) used in this study was produced by grinding the RFA with a ball mill and collected by sieving the powder through a negative pressure sieve.

In this test, two types of coarse aggregate (NCA and RCA) with 4.75~12.5 mm continuous grading were used. Fig. 1 presents the RCA (maximum particle size of 12.5 mm) and RFA (under 4.75 mm) used in this experiment. The sieve analysis curves of the RCA and RFA are illustrated in Fig. 2. The grain size of the RP was smaller than 45 microns.

The ordinary Portland cement in this study was grade P. O 42.5 (GB 175-2007, 2007). Fly ash (FA) and Metakaolin (MK) have proven to be useful in improving the workability and mechanical behavior of self-compacting recycled concrete (Poon et al., 2001; Kim et al., 2007; Kong et al., 2010), so locally manufactured FA and MK were used in this study. The superplasticizer (SP) was polycarboxylic ether (PCE) powder with a solid content > 90%. The amount of SP was 0.08%-0.1% of the total cementitious material. To modify the cohesion of the SCC and reduce the sensitivity caused by variations in the composition, a

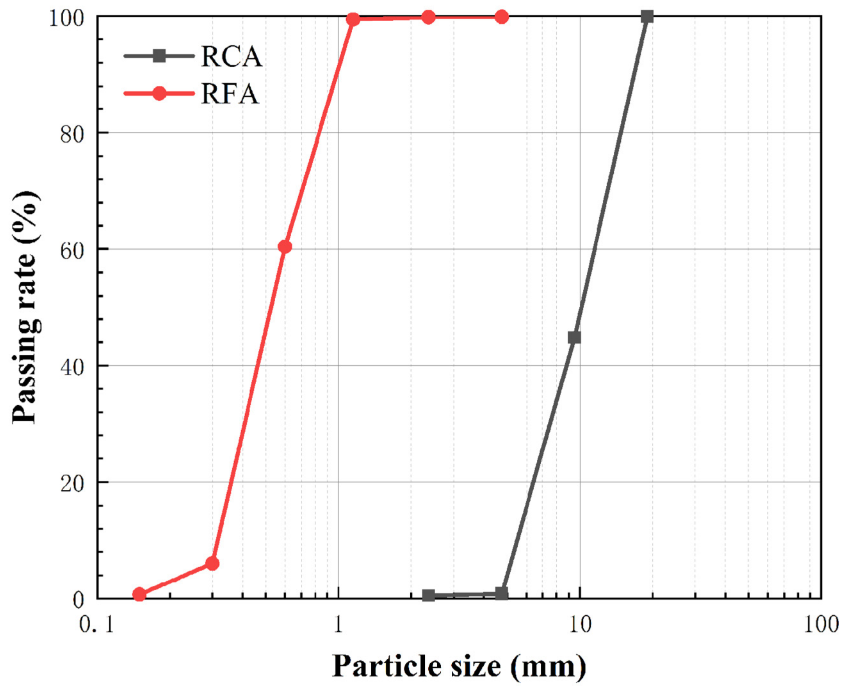


Fig. 2. Sieve analysis curves of the RCA and RFA.

Table 1.
Chemical compositions of cementitious materials.

Material	Chemical compositions (%)												
	SiO_2	CaO	Al_2O_3	Fe_2O_3	K_2O	SO_3	TiO_2	Na_2O	SrO	MnO	P_2O_5	ZnO	ZrO_2
OPC	17.61	61.82	6.59	4.76	0.96	1.70	0.39	0.26	0.22	0.13	0.09	0.06	0.00
FA	34.56	17.11	17.95	19.64	1.81	1.34	1.22	1.36	0.23	0.21	0.17	0.00	0.00
MK	51.15	0.51	46.13	0.57	0.13	0.00	1.10	0.09	0.04	0.00	0.06	0.00	0.09
RP	37.01	24.22	13.09	9.86	2.75	1.41	1.03	0.71	0.08	0.18	0.17	0.04	0.04

Abbreviations: OPC: Ordinary Portland cement; FA: Fly ash; MK: Metakaolin; RP: Recycled powder

viscosity-modifying admixture (VMA) was used in this test. The proportion of VMA was between 0.05% and 0.08%. The oxide components of all the cementitious materials in this study are provided in Table 1.

2.2. Mix design

In this experiment, nine SCC mixtures were designed, including eight self-compacting recycled concrete mixtures and one control mix. Table 2 presents the SCC mix proportions.

The RCA replacement rate and the composition of the cementitious materials were considered in the SCC mix design. In this study, FA, MK, RP were used to substitute some of the Portland cement. The total amount of FA, MK and RP was 30% of the binder material by mass. The cementitious materials of mix CON were composed of 70% cement and 30% FA. The self-compacting recycled concrete mixtures were scheduled as two series. M1-M4 were designed as Series I, representing the mix proportion with 10% FA + 10% MK + 10% RP and different RCA replacement rates. M5-M8 were classified as Series II with 10% MK and 20% RP. NCA was substituted by the proportions of 0%, 25%, 50% and 100% of the RCA by mass, represented as C0, C25, C50 and C100 in the mix ID. The water/binder ratio for all the mixtures was designed as 0.4. The actual dosages of the SP and VMA were adjusted to achieve a satisfactory condition for SCC in the fresh state.

Table 2.
Mix proportions of SCC.

Mix No.	Mix ID	W/B	Cement (kg/m^3)	FA (kg/m^3)	MK (kg/m^3)	RP (kg/m^3)	NFA (kg/m^3)	RFA (kg/m^3)	NCA (kg/m^3)	RCA (kg/m^3)
CON	C0 MK0 RP0	0.4	413	103	0	0	805	0	858	0
M1	C0 MK10 RP10	0.4	413	34	34	34	724.5	80.5	858	0
M2	C25 MK10 RP10	0.4	413	34	34	34	724.5	80.5	643.5	214.5
M3	C50 MK10 RP10	0.4	413	34	34	34	724.5	80.5	429	429
M4	C100 MK10 RP10	0.4	413	34	34	34	724.5	80.5	0	858
M5	C0 MK10 RP20	0.4	413	0	34	68	724.5	80.5	858	0
M6	C25 MK10 RP20	0.4	413	0	34	68	724.5	80.5	643.5	214.5
M7	C50 MK10 RP20	0.4	413	0	34	68	724.5	80.5	429	429
M8	C100 MK10 RP20	0.4	413	0	34	68	724.5	80.5	0	858

Abbreviations: FA: Fly ash; MK: Metakaolin; RP: Recycled powder

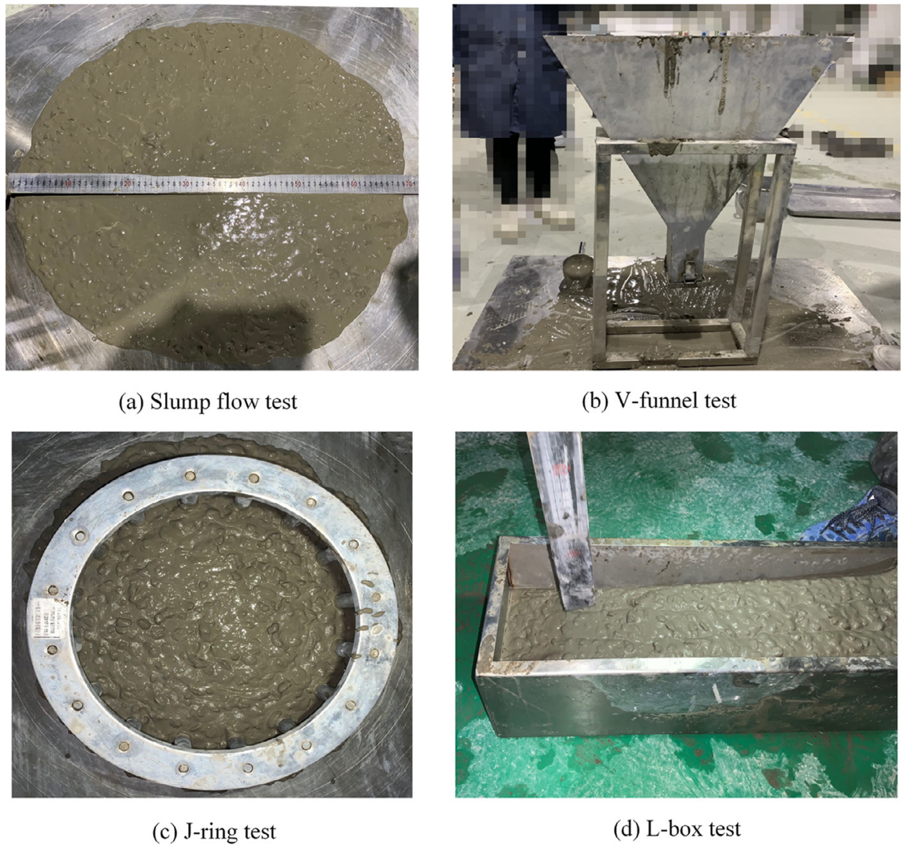


Fig. 3. Processes for the workability property tests.

2.3. Test methods

The workability properties of the SCC, including the flowability, viscosity and passing ability, were tested under the SCC criteria defined by the European standard EFNARC (2005). To carry out the tests on concrete in its fresh state, these experiments were performed within 15 minutes after the concrete was mixed. The flowability was estimated by the slump flow values. The T_{500} flow time (the time needed to reach a flow diameter of 500 mm) and V-funnel time (the time taken to flow out of the funnel) were used to assess the viscosity of fresh concrete. The passing ability was measured by the height ratio ($PA = H_2/H_1$) and the slump flow diameter with J-ring, respectively tested by the L-box test and J-ring test. Fig. 3 illustrates the operation process of each test.

After all the workability property tests, for each mix, twelve 100 × 100 × 100 mm cubes and six 40 × 40 × 160 mm prisms were cast. The cubes and prisms were de-molded after 24 h. All the specimens were placed in water, some of them were cured for 7 days and the rest for 28 days. After curing, all the cubes and prisms were air-dried. The compressive and splitting tensile strengths at 7 and 28 days were tested on the cubes. The flexural strength at 7 and 28 days was obtained by tests on the prisms. To assist in the microstructure analysis of the self-compacting recycled concrete, the hydration products and the microstructure of the interfacial transition zone (ITZ) were explored by the scanning electron microscopy (SEM) in this study.

3. Results and discussions

3.1. Workability results

Table 3 gives the workability results for all the SCC mixes. The value of the slump flow diameter is the primary criterion to estimate the fresh properties of the SCC. From Table 3, the values of the slump flow diameter range from 510 mm to 755 mm. In EFNARC (2005), the consistency classification for SCC is listed in Table 4. According to the EFNARC (2005) requirements, M1-M7 can be categorized as an SCC. M4, M6 and M7 are identified as SF1, and M1-M3 and M5 are identified as SF2. M8 is the only mix that does not satisfy the criteria for SCC because of the high content of WCRMs.

3.1.1. Flowability

Some studies have shown that the substitution ratio of RCA affects the flowability of SCC only to a light degree (Kou and Poon, 2009; Grdic et al., 2010). In this test, Series I and Series II were designed to further study the influence of the RCA and RP replacement rates on the flowability of self-compacting recycled concrete. Fig. 4 shows the influence of RCA and RP. Fig. 4(a) states that with the same RP content, the increasing RCA replacement rate leads to a decline in the slump flow diameter. For Series I, the slump flow value decreases by 13.4% as the RCA replacement rate is increased from 0% to 100%, while for Series II, the value decreases by 28.7%. Comparing the SCC mixtures containing 10% RP and 20% RP, the effect of RP on the flowability is shown in Fig. 4(b). As the RP content is increased, a substantial reduction in the slump flow diameter is found. From Fig. 4, the slump flow diameter of M8 (C100 MK10 RP20) is the smallest of all the mixes. Compared to the value of mix CON, the slump flow diameter of M8 decreases by 32.5%. The decrease in the flowability is due to the inferior properties of WCRMs. As NCA was substituted by some or all of the RCA by mass, the low density of RCA would increase the volume of coarse aggregate in the concrete. Meanwhile, owing to the high water absorption ratio and high porosity of the WCRMs (RCA, RFA and RP), the free water in fresh concrete would be absorbed by WCRMs during the mixing process. The increase in particle volume and the decrease in the content of free water lead to a reduction in the flowability of SCC. Also the rough surface and angular shape of RCA aggravate the decrease in the flowability of fresh concrete. Those factors also adversely affect the viscosity and passing ability of self-compacting recycled

Table 3.
Workability properties of the test results for all the mixes.

Group	Mix No.	Mix ID	Slump flow Diameter (mm)	T_{500} flow time (s)	V-funnel (s)	L-box (PA)	J-ring (mm)
	CON	C0 MK0 RP0	755.00	1.96	3.12	0.96	750.00
Series I	M1	C0 MK10 RP10	747.50	1.87	3.23	0.96	745.00
	M2	C25 MK10 RP10	735.00	1.80	3.45	0.96	731.00
	M3	C50 MK10 RP10	685.00	2.00	3.56	0.93	685.00
	M4	C100 MK10 RP10	647.50	2.67	3.73	0.90	645.00
Series II	M5	C0 MK10 RP20	715.00	1.80	3.49	0.96	711.00
	M6	C25 MK10 RP20	647.50	2.80	4.12	0.96	644.00
	M7	C50 MK10 RP20	605.00	3.20	4.65	0.87	590.00
	M8	C100 MK10 RP20	510.00	5.80	5.12	0.75	506.00

Table 4.
Classification used for the specification of the SCC.

	SF1	SF2	SF3		VS1/VF1	VS2/VF2		PA1	PA2
Slump flow (mm)	550-650	660-750	760-850	T_{500} (s) V-funnel (s)	≤ 2 ≤8	> 2 9-25	L-box (H_2/H_1)	≥ 0.8 with 2 rebars	≥ 0.8 with 3 rebars

concrete.

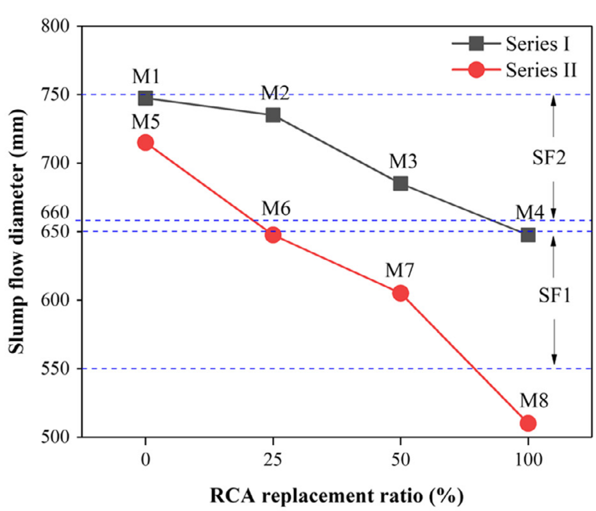
3.1.2. Viscosity

The viscosity can be evaluated in this test by the T_{500} flow time and V-funnel time. The T_{500} flow time values for all the mixtures are from 1.80 s to 5.80 s, shown in Table 3. According to standard EFNARC (2005) in Table 4, M1-M3 and M5 are identified as classes VS1, M4 and M6-M8 are classified as VS2. Fig. 5(a) shows the influence of the RCA substitution rate on the viscosity of SCC. As the RCA replacement rate increases from 0% to 100%, the value of T_{500} flow time for Series I and Series II increases by 0.43 times and 2.2 times, respectively. Comparing the T_{500} flow time in Series I and II, it is found that the RCA content has a more significant influence on the T_{500} flow time when the SCC mix incorporates a high RP content as 20%. Fig. 5(b) shows that the RP content negatively affects the value of T_{500} flow time for SCC mix with RCA. As the RP content increases from 10% to 20%, the value of T_{500} flow time increases by 0. 56 times, 0.6 times and 1.17 times, respectively. Among all the mixes, the value of T_{500} flow time for M8 is the highest. Due to the cooperation of a high RP content of 20% and a high RCA replacement rate of 100%, an obvious decline in the viscosity performance for M8 is noticed in this test.

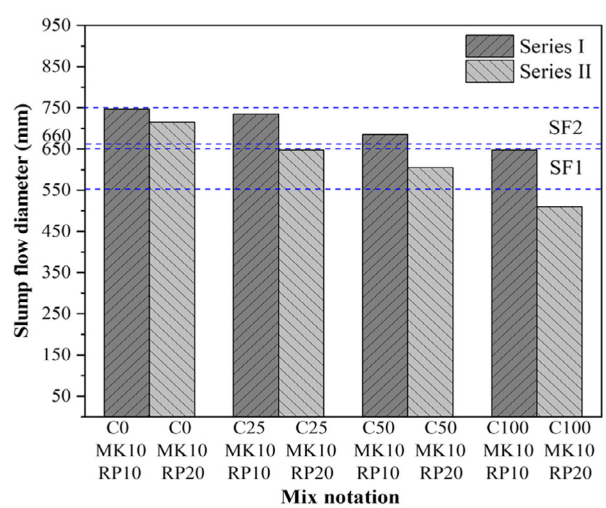
Similar to the T_{500} flow time, the V-funnel time is another parameter used to assess the viscosity of the SCC. As referred to in Table 4, the values of the V-funnel time are categorized into two classes by the standard EFNARC (2005). As listed in Table 3, the V-funnel time for all mixes can satisfy the criteria for VF1 (0-8 s). SCC categorized at VF1 has a good filling ability. Fig. 6 shows that the effect of the WCRMs substitution ratio on the V-funnel time is similar to that on T_{500} flow time. Consequently, the replacement ratio of WCRMs negatively affects the viscosity of the SCC, and the total amount of WCRMs in SCC should be limited.

3.1.3. Passing ability

The PA value measured by the L-box test is a parameter that can estimate the passing ability of SCC in EFNARC (2005). The PA values for all mixtures are between 0.75 and 0.96, as presented in Table 3. The minimum limit for the PA value is 0.8 in the standard, listed in Table 4. In this test, the PA value of M8 is lower than the minimum limit. The passing ability of M1-M7 can meet the criteria for flowing through confined spaces. Fig. 7(a) proves that as the RCA replacement rate increases from 0% to 100%, the PA value for Series I decreases by 6.25% and the value for Series II decreases by 21.9%. The effect of RP on the passing ability varies according to different RCA replacement rates. The RP content barely affects the PA value when the RCA replacement rate is limited (<50%), as shown in Fig. 7(b). For SCC mixes with higher RCA replacement percentages (up to 50%), the increasing RP content

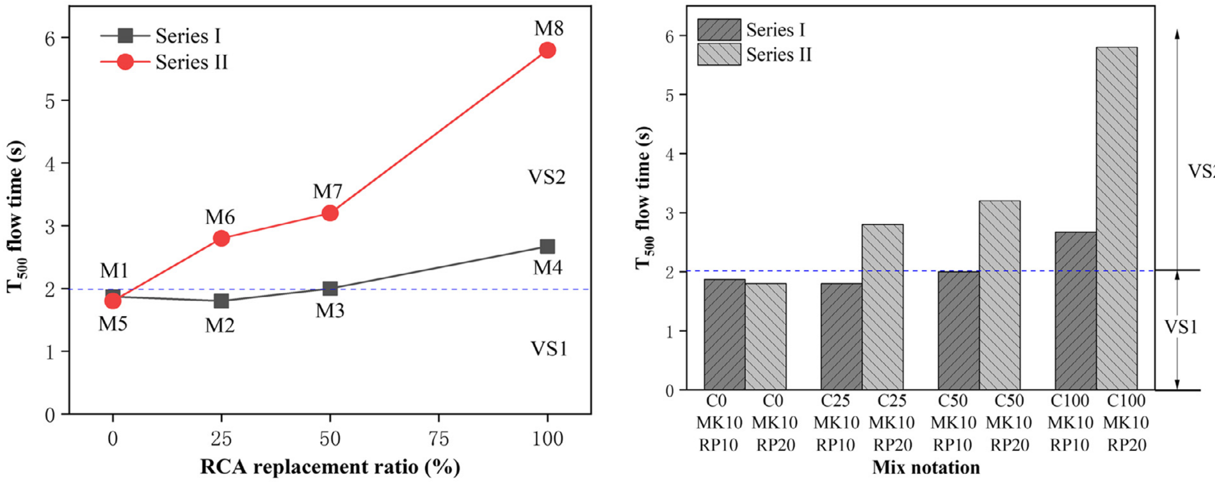


(a) Effect of RCA content on the slump flow diameter



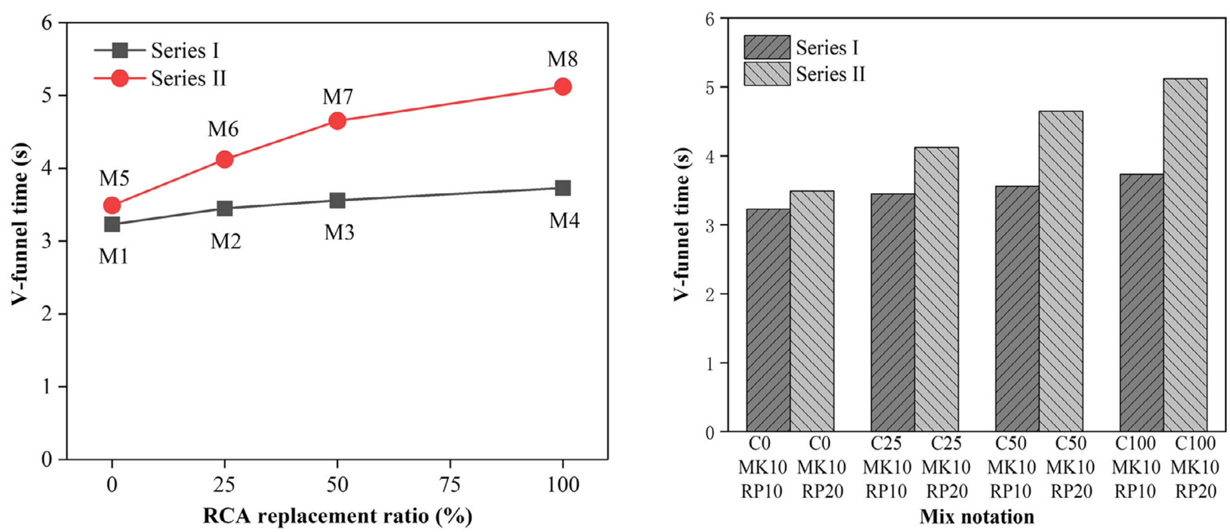
(b) Effect of RP content on the slump flow diameter

Fig. 4. Slump flow diameter of the SCC mixes.



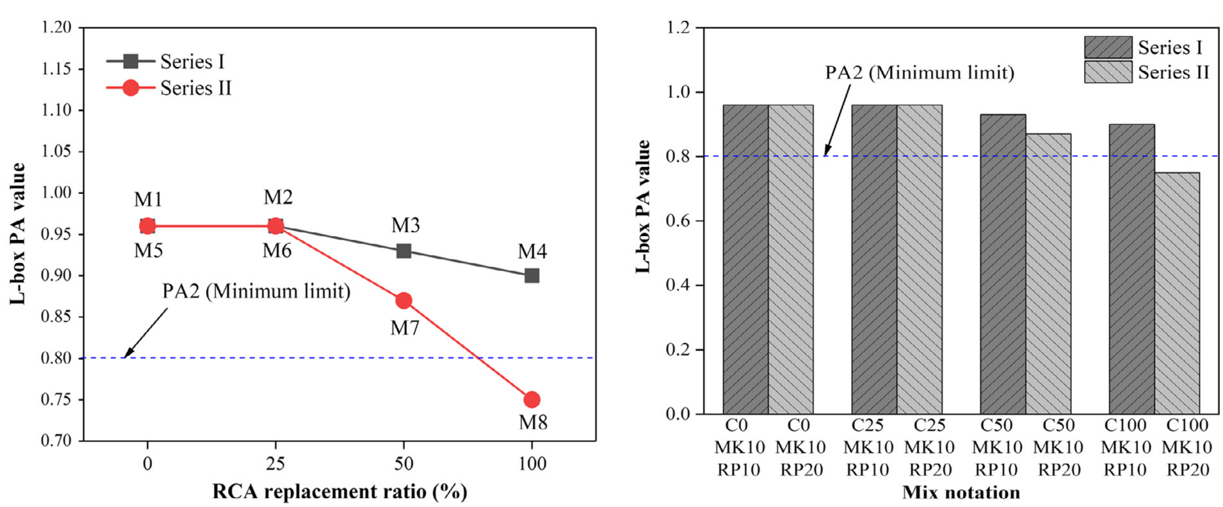
(a) Effect of RCA content on T_{500} flow time   (b) Effect of RP content on T_{500} flow time

Fig. 5. T_{500} flow time of the SCC mixes.



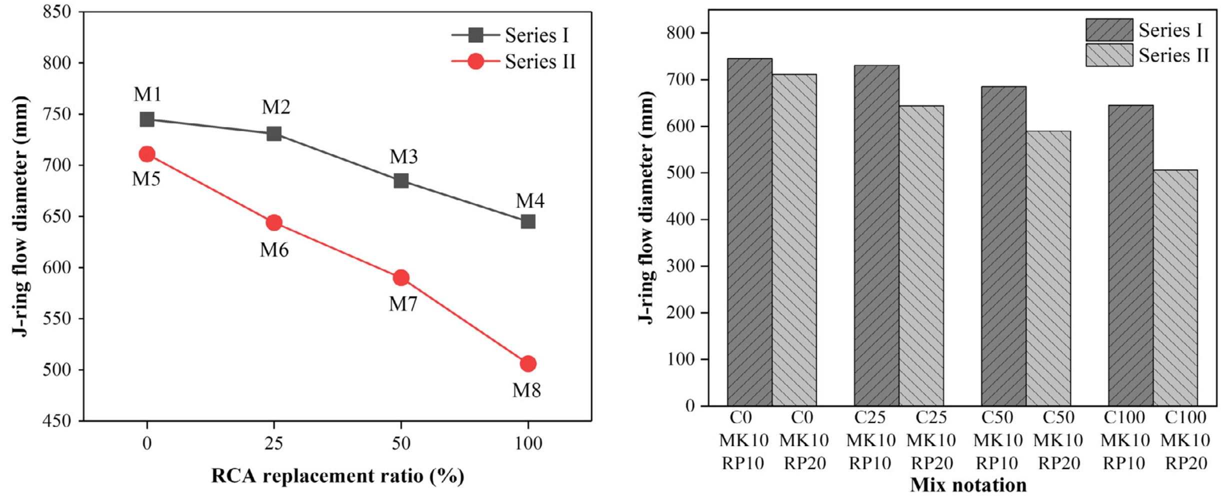
(a) Effect of RCA content on the V-funnel time   (b) Effect of RP content on the V-funnel time

Fig. 6. V-funnel time of the SCC mixes.



(a) Effect of RCA content on the PA value   (b) Effect of RP content on the PA value

Fig. 7. L-box PA values of the SCC mixes.



(a) Effect of RCA content on the J-ring flow diameter (b) Effect of RP content on the J-ring flow diameter

Fig. 8. J-ring flow diameter of the SCC mixes.

leads to a decrease in the PA value. As the RP content increases from 10% to 20%, the PA value decreases by 6.5% and 16.7%, respectively.

Table 3 gives the J-ring flow diameter of all the SCC mixtures. The results of the J-ring flow test range from 506 mm to 750 mm. In EFNARC (2005), the limit value required for J-ring flow diameter is not given, as the PA value of the L-box test is the main parameter defining the passing ability of SCC. Referring to the experimental work conducted by Brameshuber and Uebachs (2001), for SCC mix with acceptable passing ability, the difference between the slump flow diameter and the J-ring flow diameter cannot be greater than 50 mm. From Table 3, the difference between the two test results for all the mixtures is smaller than 15 mm. Hence, the value of J-ring flow for all the mixes can satisfy the minimum requirements for passing ability. Fig. 8 illustrates the influence of the RCA and RP replacement percentage on the J-ring flow diameter. Consistent with the analysis on the PA value, the cooperation of the RCA and RP accelerates the decrease in the passing ability of the SCC.

3.2. Mechanical properties results

In this investigation, the compressive strength, splitting tensile strength and flexural strength were measured at 7 and 28 days to analyze the mechanical behavior of SCC. Table 5 gives the mechanical properties of all the mixes.

3.2.1. Compressive strength analysis

From Fig. 9, it can be seen that the RCA content adversely influences the compressive strength at both 7 days and 28 days. As the RCA replacement percentage increases from 0% to 100%, for Series I, the compressive strength decreases by 6.9% and 14.6% at 7 days and 28 days respectively; for Series II, the compressive strength decreases by 7.6% and 8.4% at 7 days and 28 days. For SCC mixes with a low substitution percentage of WCRMs (C0 MK10 RP10 and C25 MK10 RP10), the compressive strength at 28 days is relatively high, achieving almost 95% of the concrete strength for mix CON. Comparing the test results of Series I with the results of Series II, the influence of the RP substitution percentage on the compressive strength is demonstrated. As the content of RP is relatively high at 20% in Series II, the compressive strength at 28 days for all the mixes in Series II remains low, reaching only 80%-88% of the value for mix CON. Meanwhile, the findings show that the high substitution percentage of WCRMs (RCA, RP) limits the growth rate of the compressive strength with increasing curing time. For Series I, when the curing time increases from 7 days to 28 days, the compressive strength for M1-M4 increases by 15.9%, 20.7%, 12.8% and 6.3% respectively. Whereas, for Series II, the increase in compressive strength for M5-M8 is about 3.1%, 9.7%, 3.6% and 2.2%, respectively.

Recycled aggregates (RCA and RFA) are manufactured by crushing waste concrete. Due to the production process, there are some initial defects such as microcracks and old mortar attached to the aggregate particle. The decline in the compressive strength can be attributed to the poor quality of the RA (Aslani et al., 2018). The old mortar attached to the RCA weakens the ITZ bonding strength, and further reduces the compressive strength of the concrete. The initial defects in RCA lead to the low compressive strength of RCA, and also adversely affect the compressive strength of hardened concrete. In this study, the RP content also negatively affects the compressive strength of self-compacting recycled concrete. The RP with a high water absorption rate and high porosity absorbs a large amount of water from the mortar phase,

Table 5.
Mechanical properties of SCC.

Group	Mix No.	Mix ID	Compressive strength (MPa)		Splitting tensile strength (MPa)		Flexural strength (MPa)	
			7 Days	28 Days	7 Days	28 Days	7 Days	28 Days
	CON	C0 MK0 RP0	34.45	40.26	3.26	4.03	4.87	6.08
Series I	M1	C0 MK10 RP10	33.69	39.05	3.06	3.28	5.48	6.54
	M2	C25 MK10 RP10	31.51	38.04	3.00	3.32	5.30	6.52
	M3	C50 MK10 RP10	31.45	35.46	2.47	3.37	4.88	5.77
	M4	C100 MK10 RP10	31.37	33.35	2.66	3.28	5.51	5.61
Series II	M5	C0 MK10 RP20	34.31	35.36	2.68	3.41	4.63	4.85
	M6	C25 MK10 RP20	32.43	35.58	2.64	3.53	4.58	4.84
	M7	C50 MK10 RP20	31.51	32.63	2.60	3.17	4.24	4.37
	M8	C100 MK10 RP20	31.70	32.39	1.59	2.81	3.72	4.34

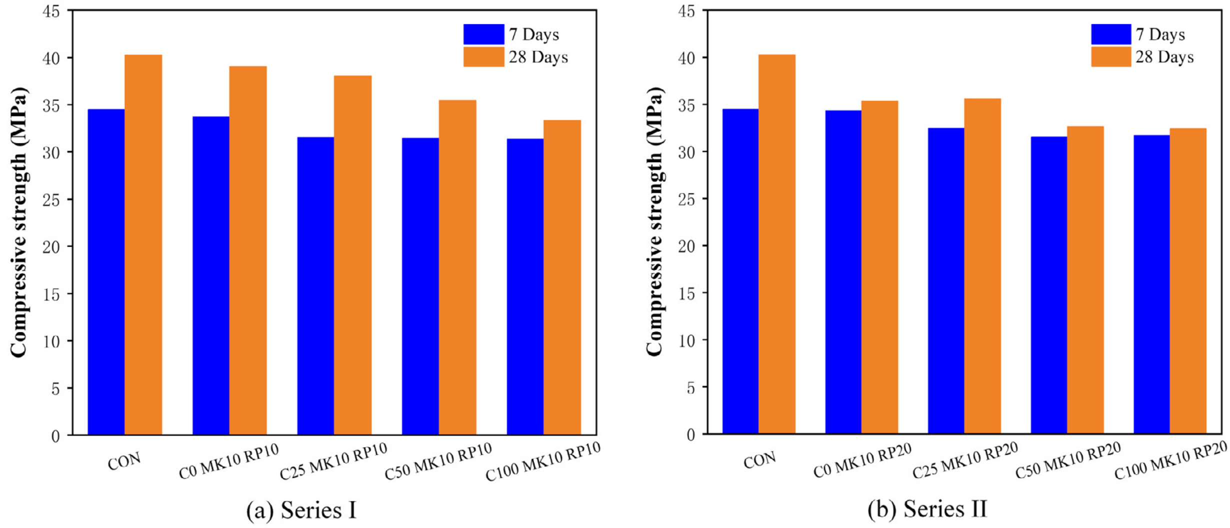


Fig. 9. Compressive strength of SCC mixes with different WCRMs content.

leading to insufficient water content and poor hydration in the concrete, which further weakens the compressive strength. Those factors also lead to a decrease in the splitting tensile strength and flexural strength.

3.2.2. *Splitting tensile strength analysis*

Table 5 presents the average splitting tensile strength (at 7 days and 28 days) of all the mixes. The splitting tensile strength values at 7 days vary between 1.59-3.26 MPa. The splitting tensile strength at 28 days varies between 2.81-4.03 MPa. The test values for all self-compacting recycled concrete mixtures are lower than for the mix CON at both 7 days and 28 days. Due to the substitution of natural materials with WCRMs, the splitting tensile strength decreases for all the self-compacting recycled concrete mixtures. From Fig. 10, it is found that the RCA replacement rate will negatively affect the splitting tensile strength of the SCC, only when the RP content exceeds 20%. A similar trend is noticed for the influence of RP on the splitting tensile strength. Comparing Fig. 10(a) with Fig. 10(b), it is found that for mixes with an RCA replacement rate up to 50%, the content of RP will negatively affect the splitting tensile strength at 28 days. Overall, the total amount of WCRMs should be limited to achieve a greater splitting tensile strength of the SCC.

3.2.3. *Flexural strength analysis*

Table 5 gives the flexural strength values from this study. The flexural strength values of all the mixtures at 7 days range from 3.72 MPa to 5.51 MPa. The flexural strength values at 28 days range from 4.34 MPa to 6.54 MPa. Fig. 11 illustrates that the flexural strength at 28 days is slightly improved for the SCC mixtures containing a low content of WCRMs (0%, 25%-RCA, 10%-RP). For other mixtures (M3-M8), when the amount of WCRMs is high, a decrease in the flexural strength can be observed. Due to the synergetic effect of the RCA and RP, the value of the mixtures in Series II decreases by 20.2%, 20.4%, 28.1% and 28.6% respectively, compared to the flexural strength of the mix CON.

3.3. *Microstructural analysis*

The weakest part in concrete is widely regarded as the interface transition zone (ITZ) (Zheng et al., 2005). There are two kinds of ITZ in RAC, the zone between the old mortar and the NA is named as the old ITZ, and the one between the new mortar and the RCA named as the new ITZ. The bonding strength of the new ITZ is superior to that of the old ITZ, and the cracks easily propagate through the old ITZ, consequently the compressive strength of RAC decreases (Otsuki et al., 2003; Leite and Monteiro, 2016). The mechanical properties on the macro-scale are certainly influenced by the microstructure of the ITZ in

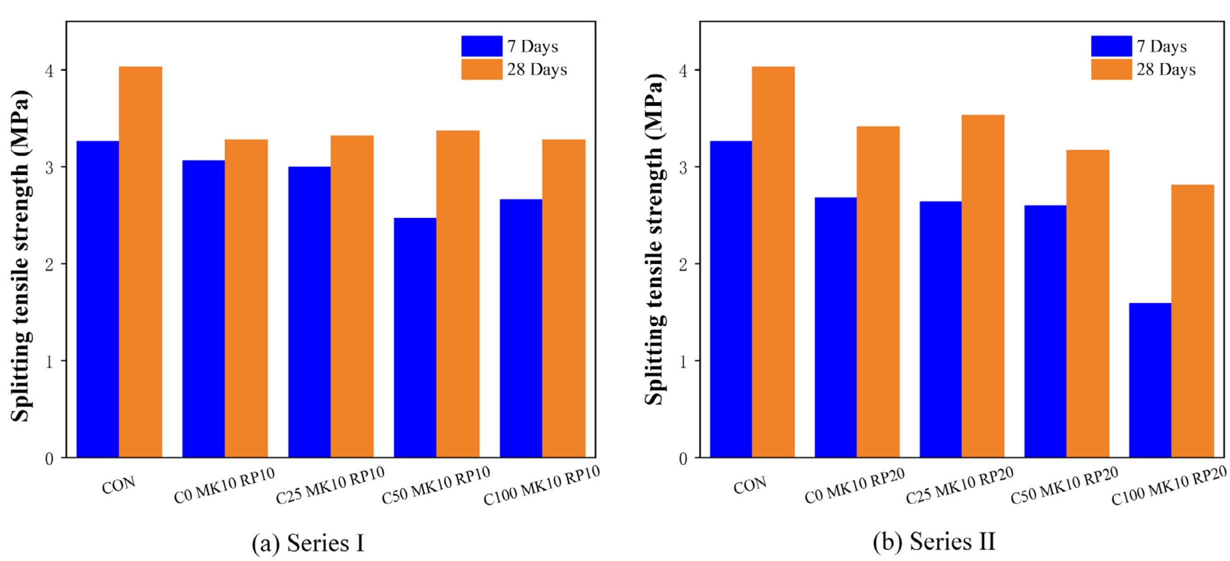


Fig. 10. Splitting tensile strength of SCC mixes with different WCRMs content.

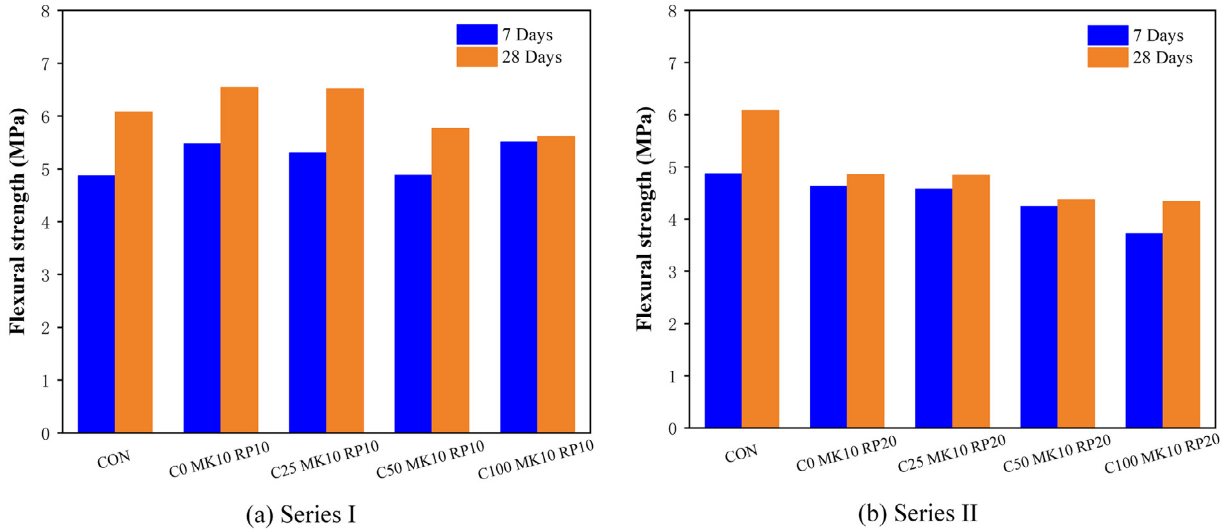


Fig. 11. Flexural strength of SCC mixes with different WCRMs content.

recycled concrete. In this paper, the hydration products of the self-compacting recycled concrete and the microstructure of the new and old ITZ were investigated by the SEM.

Fig. 12 shows the old ITZ in specimen M4 (C100 MK10 RP10). The photo of the transition area of the old ITZ was taken with an optical microscope. Fig. 12 (a) shows that the old mortar can be seen attached to the outside of the NA, which appears slightly lighter in color than the new mortar. Fig. 12 (c)-(d) shows the SEM image of the RCA and the cement mortar, and microcracks can be observed on the surface of the cement mortar. Due to the relatively high content of RP and RCA in M4, rapid hydration caused by the fine size of the RP leads to micro stresses in the concrete, resulting in microcracks in the cement matrix. Due to the defects of the RA, the accumulation of damage between the aggregate and attached mortar will lead to different degrees of damage in the old ITZ.

Fig. 13 presents the new ITZ in M2. A clearly distinct ITZ can be observed in the image. In further investigations using SEM, hydration compounds are observed at the interface between the new mortar and

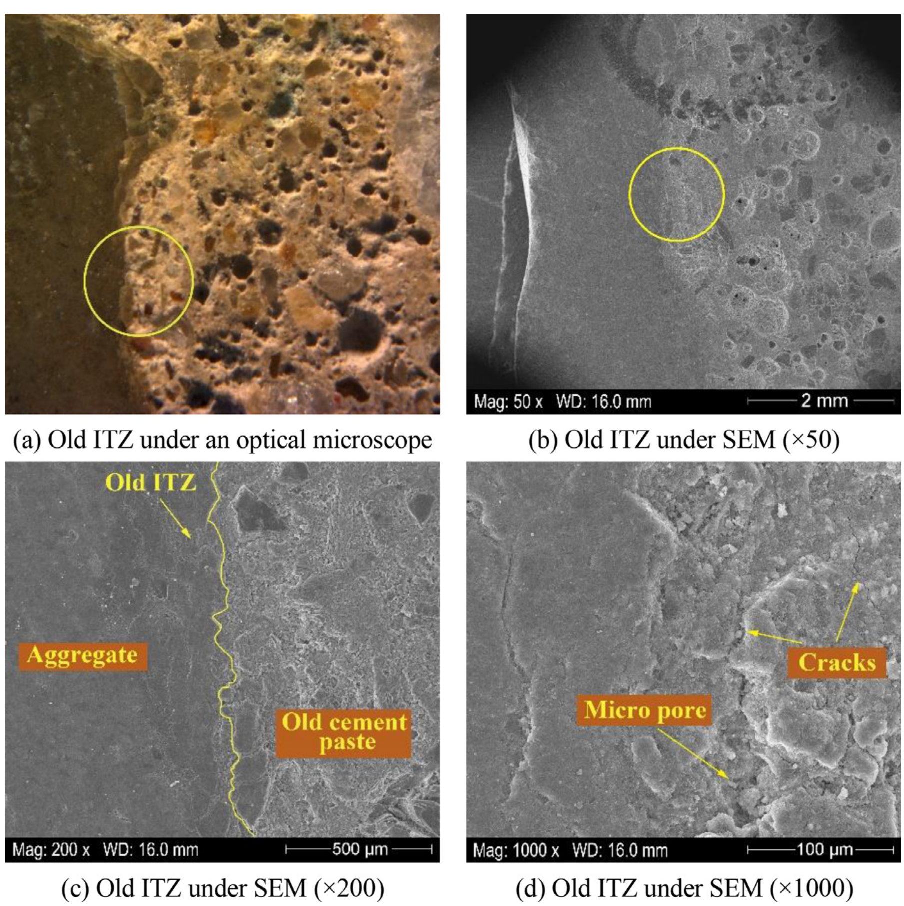
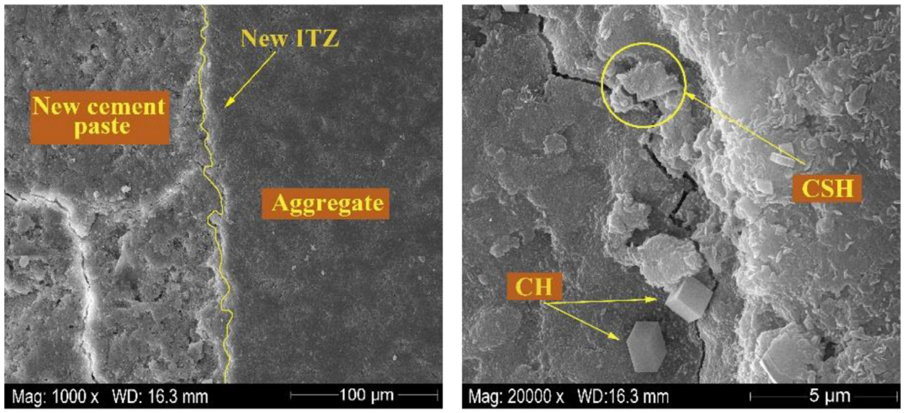


Fig. 12. Microstructure of the old ITZ in M4 (C100 MK10 RP10).



(a) New ITZ (b) Hydration products

Fig. 13. Microstructure of the new ITZ in M2 (C25 MK10 RP10).

aggregates. Moreover, additional hydration products, CH, are also found. The small particle size of the RP contributes to the reaction of CH, and then increases the production amount of CSH, leading to relatively higher strength in some cases.

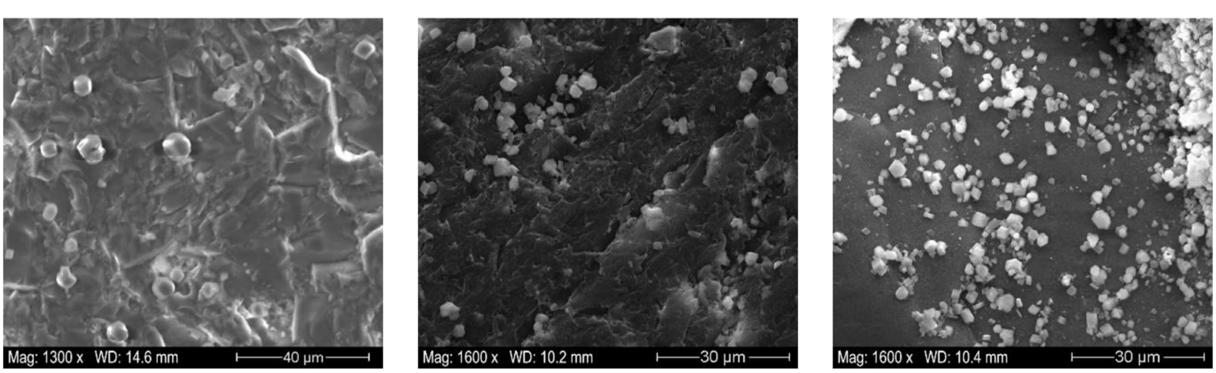
Fig. 14 shows the change in the unhydrated particles on the surface of the concrete and around it. The hydration degree of the SCC corresponds to its mechanical properties. It can be observed that the content of the unhydrated particles on the surface of Series II with 20% RP is significantly higher than that of the group with 10% RP (Series I). To study the chemical composition of unhydrated particles, an EDS energy spectrum analysis was made on the surface of the sample M8 that contained the highest WCRMs replacement ratio. Fig. 15 proves that Ca, Si and O are the main components of the unhydrated particles, which may be part of the unhydrated RP and cement. In the mix CON containing no WCRMs, cement hydration is relatively sufficient, and there are almost no unhydrated particles on the surface. Due to the agglomeration of RP in the cement matrix, the high amount of RP may adversely affect the degree of hydration and lead to an increase in the content of unhydrated particles.

To further understand the surface characterization of the self-compacting recycled concrete, an analysis of the influence of WCRMs on the material morphology was conducted on mix M8 (C100 MK10 RP20). From Fig. 16, as WCRMs content of M8 is the highest among all the SCC mixtures, an increasing number of pores are found in the microstructure of the concrete surface. The diameter of the pores ranges from 0.1 mm to 0.3 mm. Fig. 16 (b) shows that the surface of the mortar in the pore is smooth, the hydration products can be seen, and the particles are closely arranged. The high amount of WCRMs (100% RCA, 10% RFA, 20% RP) will increase the porosity of the concrete, which will lead to a more brittle surface of the concrete and result in a further reduction of the mechanical properties.

4. Conclusions

In this paper, the analysis on the workability and mechanical behavior of SCC confirms the feasibility of using WCRMs to prepare SCC. The main conclusions are as follows:

(1) Owing to the high porosity and high water absorption rate of WCRMs, the slump flow value decreases with the rise in the WCRMs (RCA, RFA, RP) content. The flowability of the self-compacting recycled concrete can meet SCC standards by limiting the amounts of WCRMs (RP = 10%, RCA ≤ 100%; RP = 20%, RCA ≤ 50%).
(2) The negative effect of WCRMs on the viscosity and passing ability of SCC follows a similar trend as that for the flowability. Excluding M8 with the highest total amount of WCRMs (100% RCA, 10% RFA, 20% RP), the other SCC mixtures in this paper achieve acceptable performance standards in terms of viscosity and passing ability.
(3) The compressive strength of the SCC decreases as the RCA and RP replacement percentage increases. When producing SCC mixtures with a low substitution percentage of WCRMs (≤ 25% RCA, ≤ 10% RFA, ≤ 10% RP), the compressive strength at 28 days can reach 95% of the value achieved by normal SCC using natural materials.
(4) The synergetic effect of WCRMs (RCA and RP) on the splitting tensile strength and flexural strength in this paper, is consistent with that of the compressive strength. To achieve the acceptable mechanical properties of the SCC, the total amount of WCRMs should be limited to a certain range (≤ 25% RCA, ≤ 10% RFA, ≤ 10% RP).
(5) SEM analysis confirms that the initial defects and high water



(a) C0 MK0 RP0 (b) C100 MK10 RP10 (c) C100 MK10 RP20

Fig. 14. Microstructure of the surface hydration of the concrete.

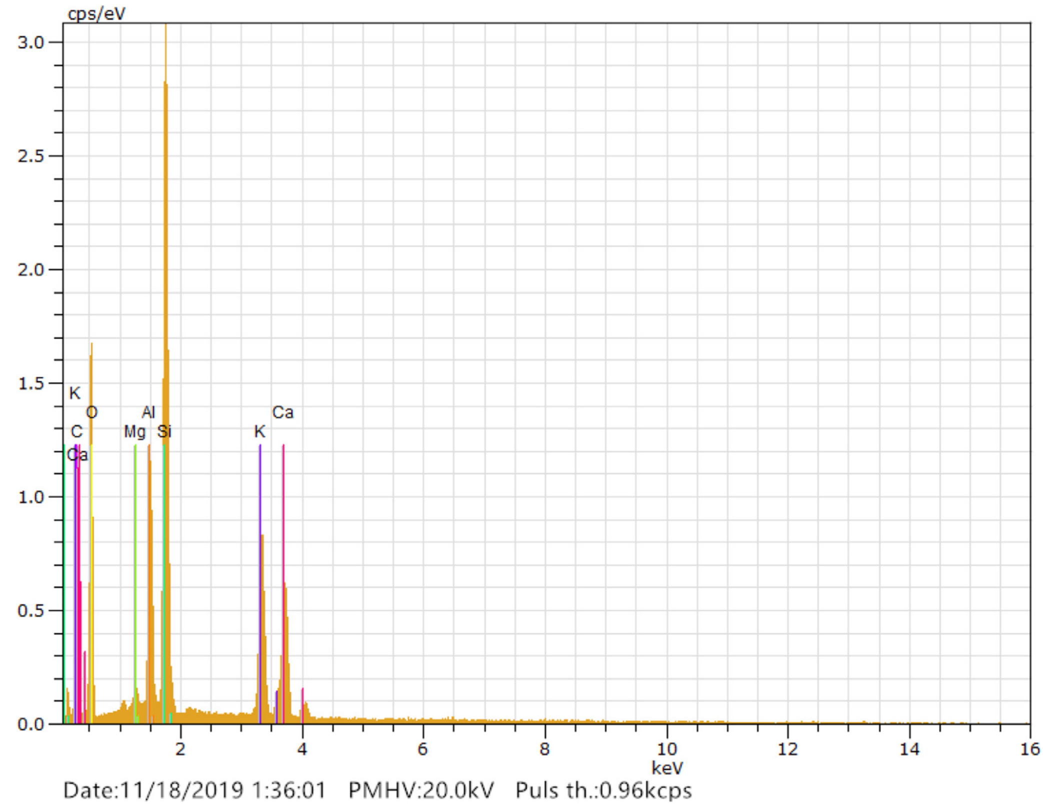


Fig. 15. EDS elemental analysis on the surface of M8.

absorption rate of WCRMs lead to an increase in the porosity and microcracks in the microstructure of the self-compacting recycled concrete, which further result in inferior mechanical properties for SCC mixtures with high amounts of WCRMs.

(6) This study demonstrates that incorporating WCRMs in SCC is an eco-friendly method for recycling CDW. Due to the inferior properties of WCRMs, the maximum substitution rate of WCRMs is limited. Further studies on modifying the properties of WCRMs and environmental impacts as well as economic cost will contribute to improving the utilization rate of WCRMs.

CRediT authorship contribution statement

Chang Sun: Conceptualization, Methodology, Formal analysis, Resources, Writing - review & editing, Project administration, Funding acquisition. **Qiuyi Chen:** Investigation, Writing - original draft, Visualization. **Jianzhuang Xiao:** Conceptualization, Resources, Supervision, Writing - review & editing. **Weidong Liu:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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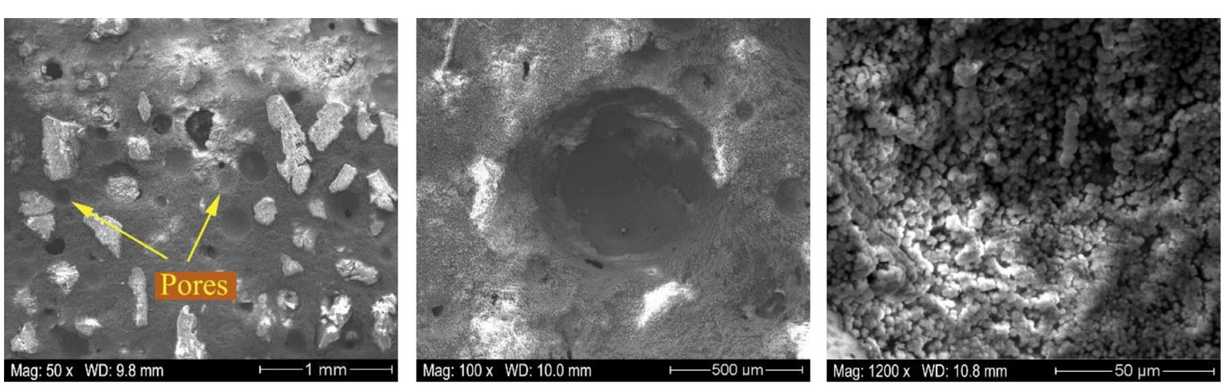

(a) Pores under SEM (×50) (b) Pore under SEM (×100) (c) Pore under SEM (×1200)

Fig. 16. Pores on the surface of M8 (C100 MK10 RP20).

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