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Study on the Effect of Recycled Coarse Aggregate on the Shrinkage Performance of Green Recycled Concrete

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Abstract: Shrinkage property is a significant indicator of the durability of concrete, and the shrinkage of green recycled concrete is particularly problematic. In this paper, construction waste was crushed and screened to generate simple-crushed recycled coarse aggregate (SCRCA). The SCRCA was then subjected to particle shaping to create primary particle-shaped recycled coarse aggregate (PPRCA). On this basis, the PPRCA was particle-shaped again to obtain the secondary particle-shaped recycled coarse aggregate (SPRCA). Under conditions where the dosage of cementitious material is 300 kg/m^3 and the sand rate is 38%, a new high-belite sulphoaluminate cement (HBSAC) with low carbon emission and superior efficiency was used as the basic cementitious material. Taking the quality of recycled coarse aggregate (SCRCA, PPRCA, and SPRCA) and the replacement ratio (25%, 50%, 75%, and 100%) as the influencing factors to prepare the green recycled concrete, the workability and shrinkage property of the prepared concrete were analyzed. The results show that the water consumption of green recycled concrete decreases as the quality of the recycled coarse aggregate (RCA) increases and the replacement ratio decreases, provided that the green recycled concrete achieves the same workability. With the improvement of RCA quality and the decrease of replacement ratio, the shrinkage of recycled concrete decreases. The shrinkage performance of green recycled concrete configured with the SPRCA completely replacing the natural coarse aggregate (NCA) is basically the same as that of the natural aggregate concrete (NAC).

Keywords: green recycled concrete; recycled coarse aggregate; water consumption; shrinkage property; SEM analysis

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1. Introduction

With the rapid development of the economy and the rise of infrastructure construction, problems related to natural resource shortages and the disposal of construction waste are becoming more and more serious. The construction industry is recognized to be the main contributor to environmental degradation due to all stages of its process requiring the consumption of natural resources and the production of construction waste [1–3]. More than 10 billion tons of construction waste are generated globally each year, accounting for approximately 30% of total solid waste, and about 35% of construction waste is treated directly in landfills [4–6], which not only causes environmental pollution such as soil pollution and water pollution, but also seriously affects the living environment of inhabitants [7]. Therefore, achieving the use of the resources in construction waste has become an issue that needs to be addressed urgently. Many studies have proved that construction waste can be used as raw materials for preparing recycled coarse aggregate (RCA), which can replace natural coarse aggregate (NCA) [8–10]. It is worth noting that the performance of green recycled concrete prepared by RCA is usually far inferior to that of natural aggregate concrete (NAC) [11–13]. Some researchers have investigated the influencing factors and the micro mechanism of recycling concrete performance to make effective use of recycled materials. Y. Mao, A. BravoGerman and R. Wang et al. found that the main factor affecting the shrinkage of concrete is the performance of recycled aggregate [14–16]. To improve the performance of RCA, researchers have made a lot of attempts to strengthen RCA, such as through pulsed power treatment [17], mechanical grinding treatment [18], thermal treatment [19,20], acid treatment [21–23], polymer emulsions [24,25], accelerated carbonation curing [26–28], and bio-deposition [29,30]. It has been found that the strength and properties of recycled aggregate concrete (RAC) prepared by treated RCA can be almost the same as those of NAC [31].

Shrinkage is the root cause of concrete cracking [32]. At present, the research on recycled concrete is mainly focused on the two aspects of mechanical properties and durability, while relatively little research has been done on the more important property of shrinkage. Shrinkage can affect the overall performance of recycled concrete, which in turn can cause damage to the reinforced concrete. More seriously, large shrinkage can lead to changes in the structure of the concrete as well [33,34]. Lu et al. [35] found that the dry shrinkage of the concrete made of RCA increased by 30% to 94.9% compared with that of NAC. Sonagnon Medjigbodo et al. [36] used 0%, 30% and 100% RCA instead of NCA to prepare concrete. The results showed that in the long term, the maximum change in shrinkage caused by RCA was less than 15%. Cui et al. [37] directly tested the shrinkage strain of RCA by embedding the bonded strain gauge into the concrete. The results showed that the water release rate of RCA was linearly related to the shrinkage strain. Duan et al. [38] used an artificial neural network to model the characteristics of three RACs with a target compressive strength of 30–80 MPa. It was found that the properties of RACs from different sources differed significantly, and high-quality RACs could be used to produce high-strength concrete. Yue et al. [39] found that the multi-interface transition zones are the weak point of recycled aggregate concrete (RAC) performance. The bonded mortar attached to the aggregate surface makes the recycled concrete form three interfaces, i.e., original mortar and fresh cement paste, aggregate and fresh cement paste, and original mortar and aggregate. Shi-cong Kou et al. [40] studied the effect of recycled coarse aggregate prepared from base metal concrete with a strength grade of 30–100 MPa on the shrinkage performance of concrete. The results showed that the shrinkage of RCA prepared by base metal concrete with higher strength is relatively lower. D. Pedro et al. [41] prepared concrete from RCA after primary crushing and primary plus secondary crushing, respectively. The results indicated that the mixture prepared by RCA after primary plus secondary crushing exhibited better long-term shrinkage performance. V.W.Y. Tam et al. [42] drew the conclusion that mixing with the two-stage mixing approach can strengthen the shrinkage performance of concrete. Sun Daosheng showed the effects of the morphology and defects of RCA prepared by three different processes on the drying shrinkage of concrete [43]. A. Akbarnezhad et al. [44] investigated the combined effects of the intensity of the parent concrete, the number of crushing phases and the size of the NCAs used in the parent concrete on the properties of RCA. These studies quantified the effect of shrinkage on plain recycled concrete through various properties and size distribution of RCA, the strength of the parent concrete, the method of preparation of RCA and the mixing method.

In this study, a green recycled concrete was prepared using a new low-carbon-emission and high-performance high-belite sulphoaluminate cement (HBSAC) as the basic cementitious material, the quality and replacement ratio of RCA as the important influencing factors of shrinkage performance, and the shrinkage performance of green recycled concrete was compared with that of NAC. Simple-crushed recycled coarse aggregate (SCRCA) is obtained by the jaw crusher simple crushing of construction waste. Primary particle shaping recycled coarse aggregate (PPRCA) and secondary particle-shaped recycled coarse aggregate (SPRCA) are obtained by particle shaping equipment, which is a new type of physical strengthening equipment. Under the conditions of 300 kg/m^3 of cementitious material and 38% sand ratio, the green recycled concrete was prepared by replacing NCA with SCRCA, PPRCA and SPRCA at the replacement ratios of 0%, 25%, 50%, 75% and 100%, respectively. The workability and shrinkage properties of different recycled concrete were analyzed comprehensively. The choice of green cement with excellent anti-cracking properties is environmentally friendly and energy efficient. It can also solve the problems of poor shrinkage performance and easy cracking of traditional recycled concrete. At the same time, high-quality RCAs are used to replace NCA. While narrowing the performance gap with NAC, green recycled concrete with stable performance is prepared.

2. Experimental Materials and Methods

2.1. Materials

(1) Cement: HBSAC with a strength of 42.5 R was produced by Tangshan Polar Bear Building Material Co., Ltd. in Tangshan, China, which met the requirements of "PRC standards for Portland cement and ordinary Portland cement" (GB 175-2007). The chemical and mineral compositions are shown in Table 1.

Table 1. The chemical and mineral composition of HBSAC (mass fraction/%).

Chemical Composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	SO_3	TiO_2	Loss
	45.34	12.56	20.78	2.32	3.04	13.67	0.68	0.38
Mineral Composition	$C_4A_3\overline{S}$	β-C_2S	$C_4A_{2.85}Fe_{1.5}\overline{S}$	$C\overline{S}$	C_m			
	35.77	36.05	8.07	14.05	1.01			

(2) Water-reducing agent: Polycarboxylic acid high-efficiency water-reducing agent with 30% water reduction rate was provided by Qingdao Construction New Material Co., Ltd., the dosage of water-reducing agent was 2% dosage of cementitious material.

(3) Fine aggregate: natural river medium sand from Qingdao Construction New Material Co., Ltd. in Qingdao, China. The basic properties of fine aggregate are shown in Table 2.

Table 2. Natural fine aggregate properties.

Bulk Density/ (kg/m^3)	Apparent Density /(kg/m^3)	Porosity /%	Harmful Substance Content	Powder Content /%	Clay Lump /%	Crushing Index /%	Robustness /%	Fineness Modulus
1450	2600	40	Qualified	1.1	0.7	12.5	4.6	2.6

(4) NCA: Natural granite crushed stone from Laoshan, Qingdao, supplied by Qingdao Construction New Materials Co., Ltd. in Qingdao, China. The basic properties are shown in Table 3.

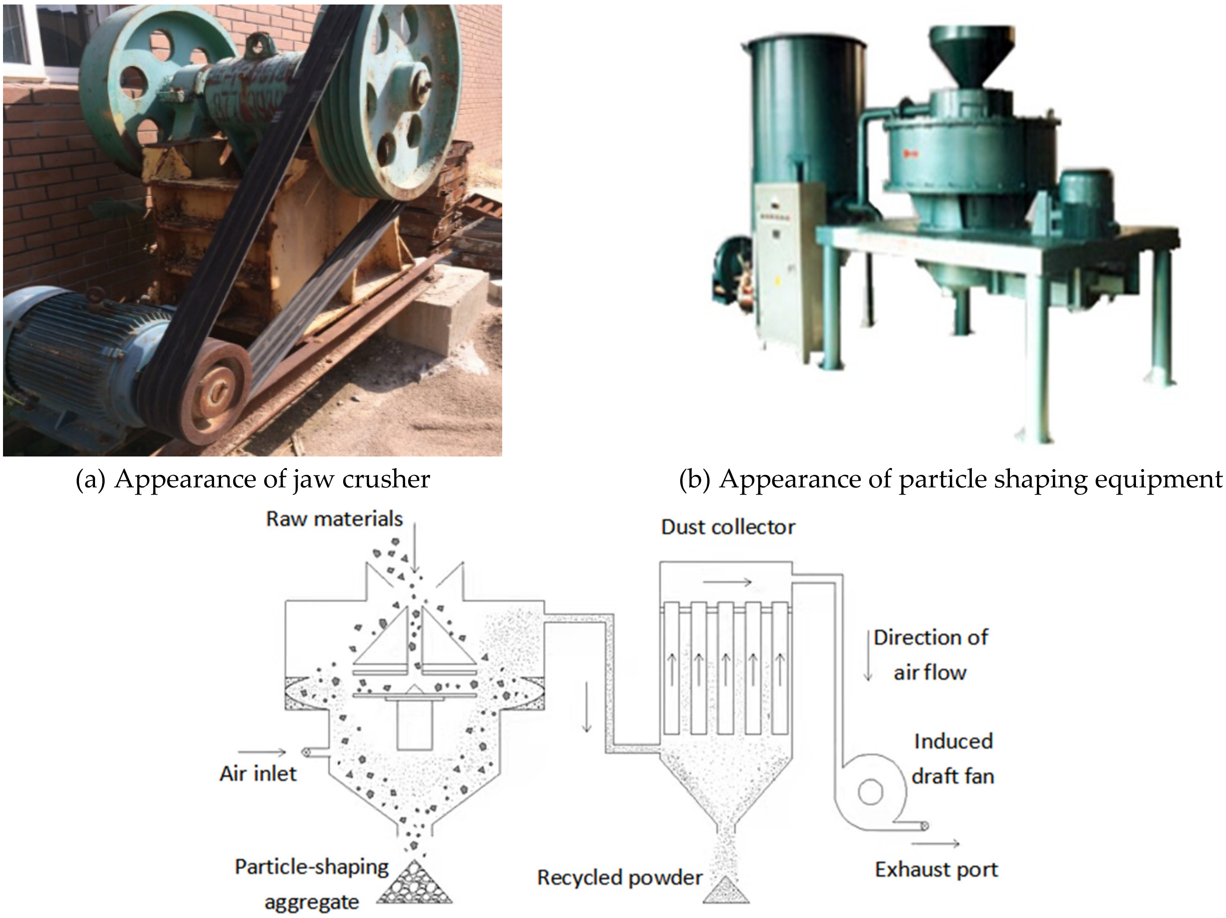
Table 3. Natural coarse aggregate properties.

Water Absorption (%)	Moisture Content (%)	Content of Needle-Like Particles (%)	Crushing Index (%)	Bulk Density (kg/m^3)	Apparent Density (kg/m^3)
1.6	0.45	4.25	11.9	1458	2480

2.2. Preparation of Recycled Coarse Aggregates

In this paper, three types of physically strengthened recycled coarse aggregates, SCRCA, PPRCA and SPRCA, were prepared using a jaw crusher and a particle shaping equipment.

SCRCA: The construction waste provided by Qingdao Construction New Material Co., Ltd. located in Qingdao, China was simply crushed and screened using a jaw crusher (Figure 1a) to obtain SCRCA. The resulting aggregate had a wide range of particle shapes, uneven quality, and mostly contained prominent angles.



(a) Appearance of jaw crusher

(b) Appearance of particle shaping equipment

(c) Structure and principle of particle shaping equipment

Figure 1. (**a**) Appearance of jaw crusher, (**b**) appearance of particle shaping equipment, and (**c**) structure and principle of particle shaping equipment.

PPRCA: After putting SCRCA into the particle shaping equipment [45] for primary particle shaping, the product is sieved to get PPRCA with the particle size of 4.75–31.5 mm. The granular shaping process is a new process for physically strengthening recycled aggregates, first proposed by Professor Li Qiuyi. It works by relying on the repeated impact and friction of recycled aggregate moving at high speed (linear speed $\geq$ 80 m/s) to effectively break off the more prominent edges and remove the mortar and cement stone adhering to the surface of the granules [10]. The aggregate collision time in the machine body is about 20–25 s. The appearance of the particle shaping machine is depicted in Figure 1b. The structure and principle of the particle shaping machine are shown in Figure 1c, and it can significantly improve the properties of recycled coarse aggregate.

SPRCA: PPRCA is put into the particle shaping equipment again for secondary particle shaping, and the product is sieved to obtain SPRCA with the particle size of 4.75–31.5 mm. The performance of the recycled coarse aggregate is more stable after secondary particle shaping treatment.

The basic properties of the different grades of RCA in Chinese National Standard GB/T 25177-2010 [46] and the basic properties of the three types of RCA are shown in Table 4. In addition, the images of the three different qualities of RCA and NCA are shown in Figure 2, respectively.

Table 4. Performance indicators for RCA.

Projects	Standard Provisions			Recycled Coarse Ggregates for Trials		
	Class I	**Class II**	**Class III**	**SPRCA**	**PPRCA**	**SCRCA**
Grain Gradation	Qualified	Qualified	Qualified	Qualified	Qualified	Qualified
Powder Content/%	<1.0	<2.0	<3.0	0.7	0.9	2.2
Water Absorption/%	<3.0	<5.0	<8.0	1.6	2.4	3.5
Content of Needle-Like Particles/%		<10.0		1.0	4.0	7.0
Impurity Content/%		<1.0		0.2	0.5	0.9
Ruggednesss/%	<5.0	<10.0	<15.0	3.9	4.9	9.8
Crushing Index/%	<12.0	<20.0	<30.0	9.0	14.0	17.0
Apparent Density/(kg/m^3)	>2450	>2350	>2250	2475	2470	2436
Void ratio/%	<47.0	<50.0	<53.0	43.0	46.0	48.0

(a) Appearance of SCRCA

(b) Appearance of PPRCA

(c) Appearance of SPRCA

(d) Appearance of NAC

Figure 2. (**a**) Appearance of SCRCA, (**b**) appearance of PPRCA, (**c**) appearance of SPRCA, and (**d**) appearance of NAC.

As can be seen from Table 4, the RCAs treated by different treatment methods (SCRCA, PPRCA and SPRCA) can successfully meet the requirements of the Chinese National Standard GB/T 25177-2010 for Type I, Type II and Type III recycled aggregate, respectively. SCRCA only has powder content within the range of the Type III recycled coarse aggregate index; the other indexes are within the range of the Type II recycled coarse aggregate index; PPRCA only has a crushing index within the range of the Type II recycled coarse aggregate index, and SPRCA all meet the requirements of the Type I recycled coarse aggregate index. Compared to SCRCA, SPRCA and PPRCA have 6% and 3% lower needle-like particle content, 1.9% and 0.8% lower water absorption, and 8% and 5% lower crushing index, respectively. Combined with the appearance of the different coarse aggregates in Figure 2, this might mainly be because the "old mortar" adhering to the surface of the RCA is effectively removed after treatment with the particle shaping equipment, and the removal degree of the "old mortar" increases with the number of particle shaping. In addition to this, Figure 2 also shows that the shape of the RCA at different stages of treatment changes in the same way as the "old mortar" removal law. In other words, as the number of times the particles are shaped increases, the shape of the RCA particles becomes more and more smooth. The synergistic effect of the two causes the performance of recycled aggregate to improve with increasing particle shaping time.

2.3. Experimental Methods

2.3.1. Concrete Slump

The slump is an essential index to measure the workability of the concrete mixture. If too large, the slump will cause the fresh concrete to separate, while if it is too small, the construction difficulty of the concrete will increase. The test was carried out under the requirements of the Chinese National Standard GB/T 50080-2002.

2.3.2. Concrete Shrinkage

The shrinkage variation values are lower due to the micro-expansion and crack resistance properties of HBSAC. Therefore, the drying shrinkage of green recycled concrete was determined by using a fixed vertical shrinkage and expansion apparatus (Figure 3). The size of the test blocks is 100 mm × 100 mm × 515 mm. The drying shrinkage performance of HBSAC-based recycled concrete applicable to the actual project was investigated by controlling the slump in the range of 160–200 mm, and the data were obtained by using the shrinkage rate calculation formula. The arithmetic average of the three results, taken to an accuracy of 1.0×10^{-6} is the shrinkage of green recycled concrete. The shrinkage of green recycled concrete at different ages is according to the following formula:

$$\varepsilon_{st} = \frac{L_0 - L_t}{L_b},$$

where ε_{st} is the shrinkage rate of the green recycled concrete specimen at t(day). L_0 is the initial length reading of the green recycled concrete specimen, mm. L_t is the measured reading at t(day) of the green recycled concrete specimen, mm. L_b is the measured distance of the green recycled concrete specimen, mm, i.e., the total length of the specimen minus the sum of the length of the iron plate anchor nail at the bottom of the specimen and the length of the internal torsion screw at the top.

Figure 3. Fixed vertical shrinkage and expansion meter.

The test procedure is as follows: the specimens with the mold were placed in the standard maintenance room for 1 day, and then the film was removed and put into the constant temperature and humidity room with a temperature of 20 ± 2 °C and a relative humidity of 60% ± 5%. Make a note of the initial length values. The shrinkage changes are measured at intervals of 1 day, 3 day, 7 day, 28 day, 45 day, 60 day, 90 day, 120 day, 150 day and 180 day, respectively.

2.3.3. SEM Analysis

The specimens were taken from the whole fragment after the compression damage and were taken at random. The specimen size was less than 1 cm, and the surface was required to be flat. The specimens were sprayed with gold before the test, and the thickness was 200–300 A. The green recycled concrete was studied and analyzed under a JSM-7500F03040702 scanning electron microscope made by JEOL. The magnification of the test was 2000 times.

2.4. Mix Proportion Design

The mixed proportions of RAC in this study are as follows: The replacement ratio of RCA to NCA was from 0% to 100%, with a gradient of 50%. The quality of RCA is SPRCA, PPRCA and SCRCA; the sand ratio was 38%, the cementitious material content was 300 kg/m^3, and water-reducing agent dosage was 1.2% of the cementitious material. In this experiment, the water consumption of the mixes was determined by controlling the workability of the concrete to be the same. The experiment was conducted by controlling the slump between 160 mm and 200 mm to study the drying shrinkage performance of HBSAC-based recycled concrete, as it applies to practical work. The test mix proportion is shown in Table 5.

Table 5. Mix proportions of HBSAC-based recycled concrete.

No.	RCA		Natural Coarse Aggregate/(kg/m^3)
	Replacement Ratio/%	**Consumption /(kg/m^3)**	
TR	0	0	1166
SC-25	25	291.5	874.5
SC-50	50	583	583
SC-75	75	874.5	291.5
SC-100	100	1166	0
PP-25	25	291.5	874.5
PP-50	50	583	583
PP-75	75	874.5	291.5
PP-100	100	1166	0
SP-25	25	291.5	874.5
SP-50	50	583	583
SP-75	75	874.5	291.5
SP-100	100	1166	0

3. Results and Discussion

This study focuses on the effect law of RCA on the shrinkage properties of green recycled concrete. Recycled aggregate concrete made by JDRCA is abbreviated as JD-RAC. Recycled aggregate concrete made by KLRCA is abbreviated as KL-RAC. Recycled aggregate concrete made by EKLRCA is abbreviated as EKL-RAC.

3.1. Effect of RCA on Concrete Water Consumption at Different Replacement Ratios

Figure 4 shows the relationship curve between the water consumption of green recycled concrete and the replacement ratio of RCA. It can be known that the water consumption of concrete increases with the increase in the replacement ratio of RCA, and decreases with the improvement of the quality of RCA. The water consumption of concrete has a good positive correlation with the replacement rate of RCA. Every 25% increase in SCRAC replacement rate increases green recycled concrete water consumption by approximately 4.3 kg/m^3; every 25% increase in PPRCA replacement rate increases green recycled concrete water consumption by approximately 2.8 kg/m^3; and every 25% increase in SPRCA replacement rate increases green recycled concrete water consumption by approximately 2.0 kg/m^3. Compared to PPRCA and SCRCA, the increase in water use for SPRCA is less than half that of SCRCA and less than 70% of the increase for PPRCA. It is clear that the better the quality of the RCA, the smaller the effect of the RCA replacement rate on the water consumption of green recycled concrete.

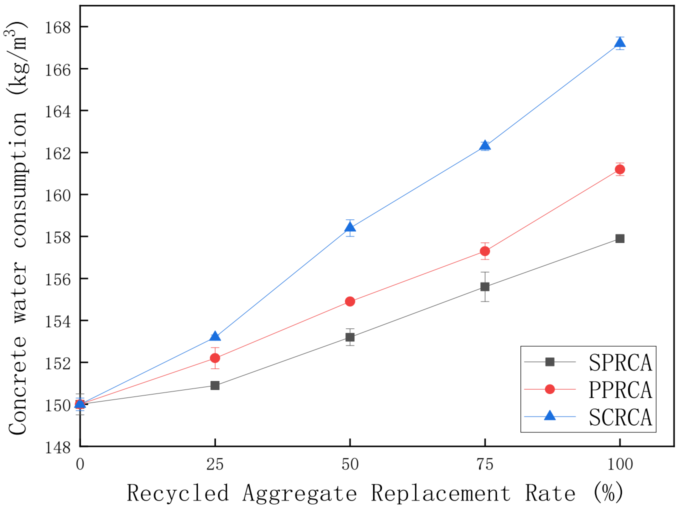


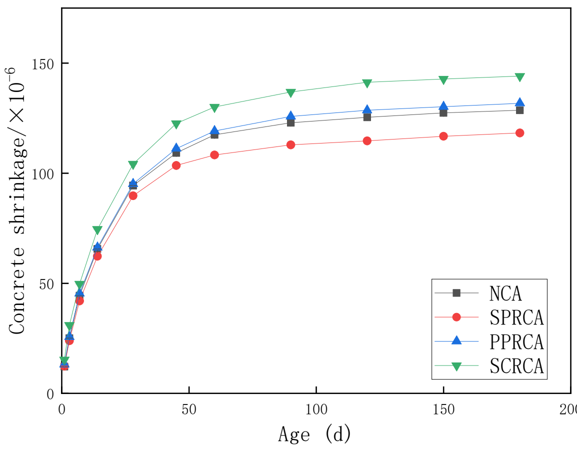
Figure 4. Effect of RCA on water consumption.

The underlying reason for the difference in water absorption between the different qualities of RCA and NCA is the mortar adhering to the RCA [47,48]. Compared to the other aggregates, SCRCA is only subject to simple crushing treatment, its particle shape has more edges and corners, and the amount of old mortar and micro powder attached to the surface is much higher than the other two kinds of RCA. The hardened old mortar attached to the surface of SCRCA has high water absorption, resulting in increased water consumption and reduced workability of green recycled concrete. However, SPRCA underwent secondary particle shaping, which effectively improved the particle shape and gradation of the aggregate and reduced the amount of old mortar adhered to the surface of the aggregate, causing its water absorption rate to be significantly reduced compared to the other two types of RCA, and its impact on the water consumption of green recycled concrete is relatively less. In addition, compared with NCA, SCRCA has a higher needle and flake particle content and crushing index, and PPRCA also has a higher crushing index. Therefore, at a certain replacement rate, the water consumption of green recycled concrete is still not lower than NAC.

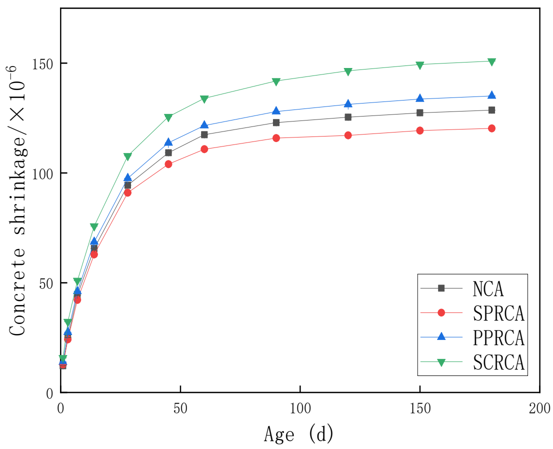
3.2. Effect of RCA Quality on Concrete Shrinkage

The variation curve of shrinkage of green recycled concrete with RCA quality is shown in Figure 5. The shrinkage development trend of green recycled concrete is that the shrinkage rate increases rapidly in the first 28 days, the growth rate gradually slows down over the next 28 to 90 days, and the growth slows down and tends to be stable after 90 days. In the early stages of contraction, considering the rapid hydration reaction of cement and the large water absorption of RCA, the time interval for shrinkage measurement is short, and it can be seen that the shrinkage of green recycled concrete is obvious from 1 to 28 d. Taking SP-RAC with a 100% replacement ratio as an example, the shrinkage rate ($\times 10^{-6}$) from 1 d to 28 d increased from 13.1 to 94.4, and the shrinkage rate in 28 days shrinkage increased by 81.3 within 28 days, reaching approximately 70% of the total 180 d shrinkage.

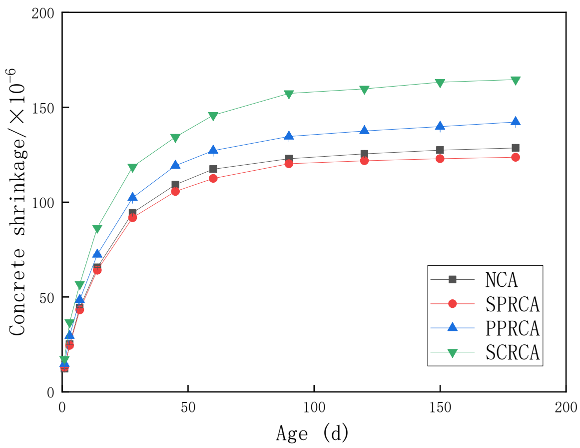
In contrast, the change in shrinkage of green recycled concrete was more moderate after 28 d. For RAC prepared with different qualities of RCA, the shrinkage after 28 d varied significantly. When the RCA replacement ratio was 25%, the shrinkage increased by 11.4% for PP-RAC and 21.8% for SC-RAC compared to SP-RAC. When the RCA replacement ratio was 50%, the shrinkage rate increased by 12.3% for PP-RAC and 25.5% for SC-RAC compared to SP-RAC. When the RCA replacement ratio was 75%, the shrinkage rate increased by 15% for PP-RAC and 33.2% for SC-RAC compared to SP-RAC. The shrinkage of SC-RAC reached a maximum of 178.2×10^{-6} when the SCRCA replacement ratio was 100%, which is about 40% higher than the shrinkage of NAC. When the PPRCA replacement ratio was 100%, the shrinkage of PP-RAC was about 15% higher than that of NAC. When the SPRCA replacement ratio reached 100%, the shrinkage of SP-RAC was approximately the same as that of NAC. It can be seen that the shrinkage of green recycled concrete decreases significantly with the improvement of RCA quality, and the greater the replacement ratio of RCA, the greater the effect of RCA quality on the shrinkage of green recycled concrete. The shrinkage performance of green recycled concrete configured with SPRCA completely replacing NCA is basically the same as that of NAC.



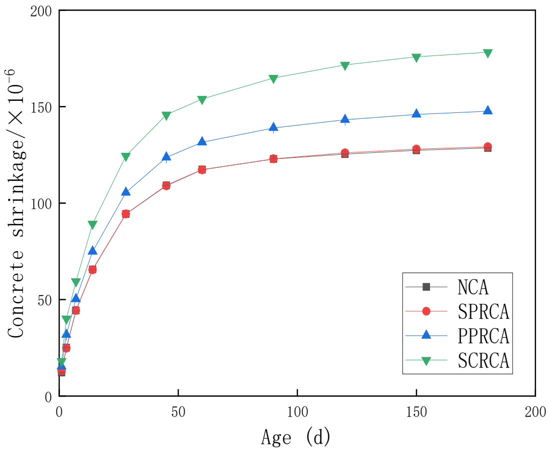
(a) Shrinkage of different qualities of RCA at a replacement ratio of 25%



(b) Shrinkage of different qualities of RCA at a replacement ratio of 50%



(c) Shrinkage of different qualities of RCA at a replacement ratio of 75%



(d) Shrinkage of different qualities of RCA at a replacement ratio of 100%

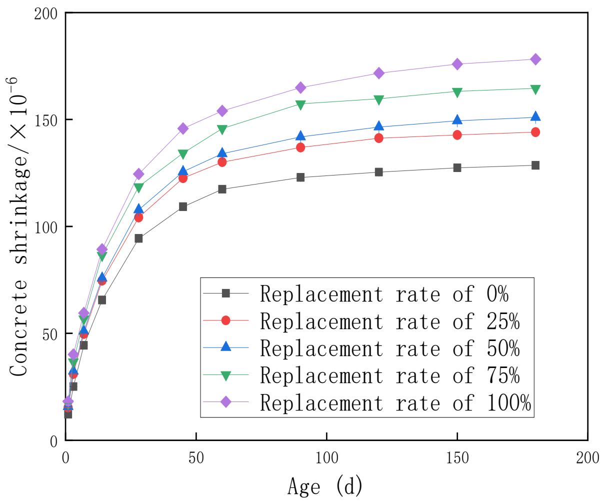
Figure 5. (**a**) Shrinkage of different qualities of RCA at a replacement ratio of 25%, (**b**) shrinkage of different qualities of RCA at a replacement ratio of 50%, (**c**) shrinkage of different qualities of RCA at a replacement ratio of 75%, and (**d**) shrinkage of different qualities of RCA at a replacement ratio of 100%.

This is because the use of RCA to replace part of the NCA reduces the overall stiffness of the aggregate, making the aggregate less resistant to deformation [49]. The modulus of elasticity of RCA is less than that of NCA due to the old mortar adhering to the RCA [50,51]. The decrease in elastic modulus reduces the constraint of aggregate and increases the shrinkage of green recycled concrete. In addition to this, the higher porosity means that green recycled concrete has a higher water absorption than NAC, which does not help to suppress drying shrinkage.

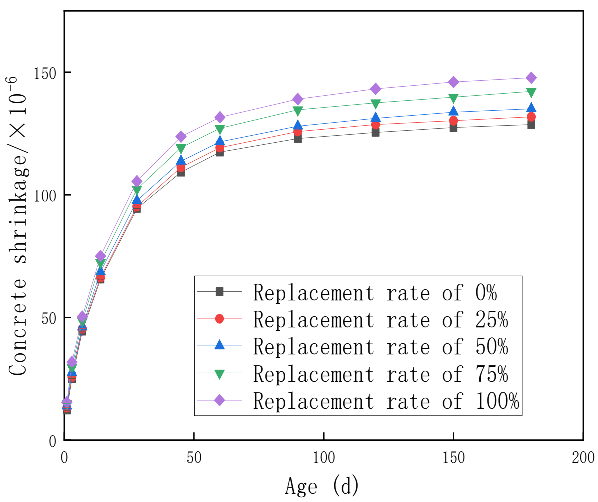
The drying shrinkage of green recycled concrete is highly dependent on the performance of the RCA, which in turn is largely related to the amount of mortar it adheres to [40]. Particle shaping removes the old mortar adhering to the surface of the aggregate and ameliorates the problem of new–old interface damage caused by old mortar adhesion. It can increase the overall modulus of elasticity while significantly reducing the difference in shrinkage properties with NAC. Therefore, the shrinkage of green recycled concrete is SP-RAC < PP-RAC < SC-RAC.

3.3. Effect of RCA Replacement Ratio on Concrete Shrinkage

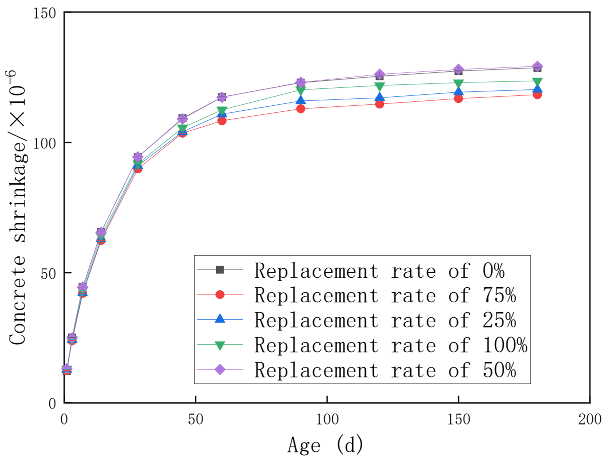
The content of RCA is one of the most important factors influencing the drying shrinkage of green recycled concrete. The variation curve of shrinkage of green recycled concrete with RCA substitution is shown in Figure 6.



(a) Shrinkage of SCRCA at different replacement ratios



(b) Shrinkage of PPRCA at different replacement ratios



(c) Shrinkage of SPRCA at different replacement ratios

Figure 6. (**a**) Shrinkage of SCRCA at different replacement ratios, (**b**) shrinkage of PPRCA at different replacement ratios, and (**c**) shrinkage of SPRCA at different replacement ratios.

For SC-RAC, the shrinkage of RCA when the replacement ratio is 50% is about 4.8% higher than that when the replacement ratio is 25%, the shrinkage of RCA when the replacement ratio is 75% is about 14.2% higher than that of 25% replacement ratio, and the shrinkage of RCA when the replacement ratio is 100% is about 23.7% higher than that of 25% replacement ratio. For PP-RAC, the shrinkage of RCA when the replacement ratio is 50% is about 2.5% higher than that when the replacement ratio is 25%, the shrinkage of RCA when the replacement ratio is 75% is about 7.9% higher than that when the replacement ratio is 25%, and the shrinkage of RCA when the replacement ratio is 100% is about 12.1% higher than that when the replacement ratio is 25%. For SP-RAC, the shrinkage of RCA when the replacement ratio is 50% is about 1.7% higher than that of 25% replacement ratio, the shrinkage of RCA when the replacement ratio is 75% is about 4.5% higher than that of 25% replacement ratio, and the shrinkage of RCA when the replacement ratio is 100% is about 9.2% higher thanthat of 25% replacement ratio. It can be seen that the shrinkage of green recycled concrete increases with increasing replacement ratio when the quality of RCA is the same and that the shrinkage stabilizes sooner when the replacement ratio is lower. In addition, the change in the shrinkage of green recycled concrete with the replacement ratio of RCA is related to the quality of the RCA. When the quality of the RCA is better, the increase in shrinkage of the green recycled concrete is smaller.

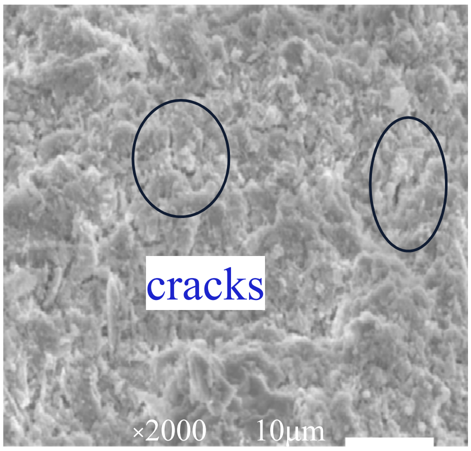
This is because the water absorption of RCA is higher than that of NCA. The greater the replacement rate of RCA, the more water is required by green recycled concrete to achieve the required slump to meet the workability requirements. With the increase of water consumption, more and more capillary channels are formed in the concrete due to the continuous evaporation of water, and the negative pressure in the hole also increases. Therefore, the drying shrinkage of green recycled concrete is increased. In the case of SPRCA; however, the surface mortar with a high water absorption rate is stripped off after two-particle shaping operations, and the more obvious angularity of the aggregate particles is removed, resulting in a near-spherical aggregate shape and a more reasonable gradation, both of which together result in SPRCA working roughly in line with NCA. Therefore, the shrinkage of green recycled concrete is approximately the same as that of green recycled concrete when the SPRCA replacement ratio is 100%.

The high water absorption enables RCA to store and release a certain amount of water during the hydration of the cement as a means of compensating for the self-drying of the matrix caused by the hydration of the cement, reducing the self-shrinkage of green recycled concrete and improving the internal curing effect. When the replacement rate of SPRCA is less than 100%, the water consumption of green recycled concrete is lower at this time than when the replacement rate is 100%, and SPRCA has an internal maintenance effect compared with natural coarse aggregate. Compared with natural coarse aggregate, SPRCA not only has the same working performance, but also has the effect of internal maintenance, so the shrinkage of green recycled concrete is lower than that of green recycled concrete when the replacement rate is 25% to 75%.

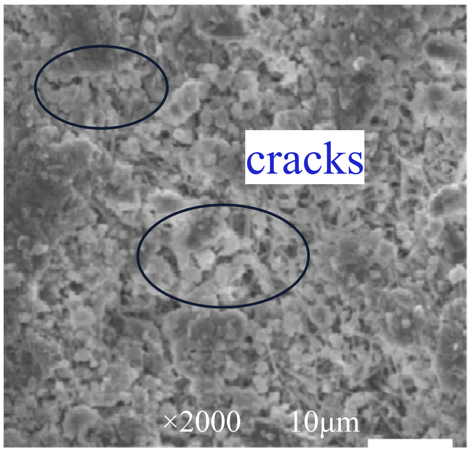
3.4. Micro-Analysis

Dry shrinkage is the most significant form of shrinkage affecting concrete, which is caused by the loss of water within the concrete resulting in shrinkage deformation, and then dry shrinkage cracks. To investigate the effect of RCA quality on the shrinkage performance of concrete, the SEM microscopic morphology of the hydration products of green recycled concrete prepared from different qualities of RCA at 100% replacement ratio at 28 day was analyzed, as shown in Figure 7.

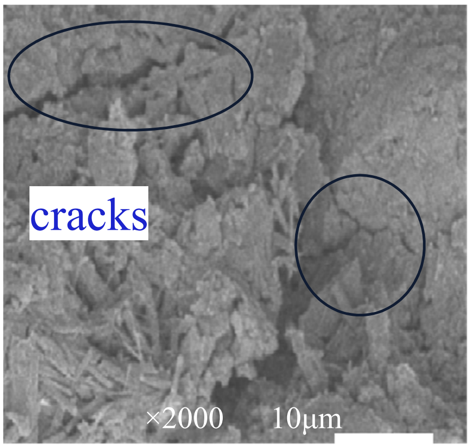
From the SEM images in Figure 7, it can be observed that the NAC paste structure has only small pores and almost no obvious cracks. The paste structure is relatively dense and has good volumetric stability. The SC-RAC paste structure has larger pores and a large number of interconnected deeper and wider cracks. The overall structure is loose and less stable. The PP-RAC paste structure has more cracks, and the overall structure is loose and less stable. The SP-RAC slurry structure has only small pores and minor cracks. The structure is dense, and the volume stability is relatively good. It can be seen that the structural compactness of the green recycled concrete hydration product paste is NAC > SP-RAC > PP-RAC > SC-RAC.



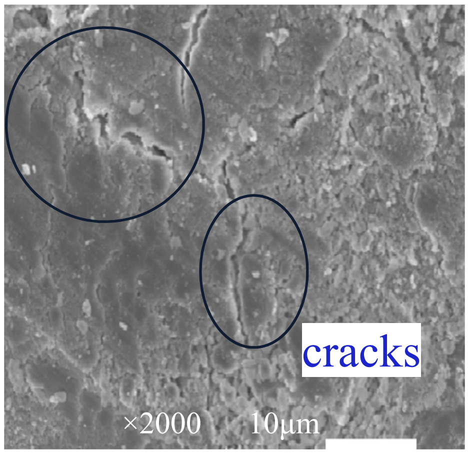
(a) Microscopic morphology of hydration products from NAC



(b) Microscopic morphology of hydration products from SP-RAC



(c) Microscopic morphology of hydration products from PP-RAC



(d) Microscopic morphology of hydration products from SC-RAC

Figure 7. (**a**) Microscopic morphology of hydration products from NAC, (**b**) microscopic morphology of hydration products from SP-RAC, (**c**) microscopic morphology of hydration products from PP-RAC, and (**d**) microscopic morphology of hydration products from SC-RAC.

Because when the paste is structurally dense and has few cracks, it can resist the drying shrinkage caused by water dissipation; whereas when the paste has more pores and cracks, the number of water loss channels and capillaries increases, resulting in greater shrinkage.

4. Conclusions

This study mainly focuses on the effect of RCA quality and replacement ratio on the shrinkage properties of green recycled concrete and the microscopic analysis of green recycled concrete. The following conclusions are as follows.

1. The water consumption of recycled concrete increases with increasing replacement ratio of RCA, and decreases with increasing quality of RCA. The better the quality of the RCA, the smaller the effect of the replacement ratio of RCA on concrete water consumption.
2. With the improvement of RCA quality, the shrinkage of the green recycled concrete decreases significantly, and the effect of RCA quality on the shrinkage of green

recycled concrete became greater with increasing replacement ratio of RCA. The shrinkage property of green the recycled concrete configured with SPRCA completely replacing NCA was basically the same as that of NAC.

3. For RCA of the same quality, the shrinkage of green recycled concrete increases with the replacement ratio, and the smaller the replacement ratio, the sooner the shrinkage rate stabilizes. In addition, the change in the shrinkage of green recycled concrete with the replacement ratio of RCA is related to the quality of green recycled concrete. When the quality of the RCA is better, the increase in shrinkage of the green recycled concrete is smaller.
4. From the SEM images analysis, the structure compactness of hydration product of different green recycled concrete is NAC > SP-RAC > PP-RAC > SC-RAC in sequence.
5. The test has not yet established a model for calculating the drying shrinkage of green recycled concrete which could more accurately capture the value of drying shrinkage at each age and the magnitude of the influence of various factors. The drying shrinkage is more related to the pore structure, and the mercury compression and other methods would be conducted further to perfect the drying shrinkage law.

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