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Study of the Properties of Full Component Recycled Dry-Mixed Masonry Mortar and Concrete Prepared from Construction Solid Waste

Zhenwen Hu [1], Zhe Kong [2], Guisheng Cai [3], Qiuyi Li [1,*], Yuanxin Guo [1,*], Dunlei Su [4], Junzhe Liu [1] and Shidong Zheng [5]

1 College of Architectural Engineering, Qingdao Agricultural University, Qingdao 266109, China; 20192214693@stu.qau.edu.cn (Z.H.); liujunzhe@qau.edu.cn (J.L.)
2 Qingdao Real Estate Vocational Secondary Specialized School, Qingdao 266034, China; kongzhe@qdfcxx.com
3 Shandong Academy of Building Research Co., Ltd., Jinan 255000, China; Caigs2008@126.com
4 School of Traffic Civil Engineering, Shandong Jiaotong University, Jinan 250357, China; sudunlei@163.com
5 Shandong Junhong Environmental Technology Co., Ltd., Zibo 255000, China; zsd@junhonghuanbao.com
* Correspondence: 201801001@qau.edu.cn (Q.L.); guoyuanxin@qau.edu.cn (Y.G.); Tel.: +86-185-6172-5051 (Q.L.); +86-139-6963-0648 (Y.G.)

Citation: Hu, Z.; Kong, Z.; Cai, G.; Li, Q.; Guo, Y.; Su, D.; Liu, J.; Zheng, S. Study of the Properties of Full Component Recycled Dry-Mixed Masonry Mortar and Concrete Prepared from Construction Solid Waste. *Sustainability* **2021**, *13*, 8385. https://doi.org/10.3390/su13158385

Academic Editors: José Ignacio Alvarez, Ruoyu Jin, Yidong Xu, Libo Yan and Zhenhua Duan

Received: 4 June 2021
Accepted: 21 July 2021
Published: 27 July 2021

Abstract: Solutions are needed to solve the problem of a large amount of construction solid waste and a shortage of natural aggregate (coarse and fine aggregates). In this paper, simple-crushed coarse aggregate (SCRCA) and simple-crushed fine aggregate (SCRFA) were obtained by simple-crushing of construction solid waste. On this basis, SCRCA and SCRFA were treated with particle-shaping to obtain particle-shaping coarse aggregate (PSRCA) and particle-shaping fine aggregate (PSRFA), and the recycled powder (RP) produced in the process of particle-shaping was collected. Under the condition of a 1:4 cement-sand ratio, RP was used to replace cement with four substitution rates of 0, 10%, 20%, and 30%, and dry-mixed masonry mortar was prepared with 100% SCRFA, PSRFA, and river sand (RS). The basic and mechanical properties and microstructure of hydration products of dry-mixed mortar were analyzed, and the maximum substitution rate of RP was determined. Under the condition that the amount of cementitious material is 400 kg/m^3 and the RP is at the maximum replacement rate, three different aggregate combinations to prepare concrete are the 100% use of SCRCA and SCRFA, PSRCA and PSRFA, and RS and natural aggregate (NCA); the workability, mechanical properties, and aggregate interface transition zone of the prepared concrete were analyzed. The results show that when the replacement rate of RP is less than 20%, it has little effect on the properties of products. The performance of PSRCA and PSRFA after treatment is better than that of SCRCA and SCRFA. Under different RP substitution rates, the performance of dry-mixed mortar prepared with PSRFA is very close to that prepared with RS. The performance of recycled concrete prepared with PSRCA and PSRFA is also very close to that of products prepared with NCA and RS. The failure morphology of PSRCA and RSRFA concrete is also similar to that of NCA and RS concrete.

Keywords: recycled aggregate; recycled powder (RP); recycled concrete; performance test; microstructure; interface transition zone

1. Introduction

With the development of human society and urban modernization, a large amount of construction waste is generated every year due to the demolition of buildings. The annual output of these construction wastes can reach 4 billion tons, and the output is increasing year by year [1–6]. Most of these construction wastes are directly dumped or landfilled, and the recycling rate is extremely low; pollution of the environment is increasingly serious [7–9]. In recent years, with the awakening of human environmental awareness, coupled with natural aggregates and cementing material in short supply, people have gradually turned their attention to this part of construction waste. Various technical means to prepare it into RCA, RFA, and RP, and recycled concrete [10–12]. However, the performance of these recycled materials is generally inferior to that of natural materials [13–15].

How to effectively use this part of recycled materials to turn waste into treasure has become a hot topic for researchers in many countries and regions in the world. First, some scholars have studied the principle of performance loss of recycled products caused by recycled materials. C. Thomas, S. Pradhan, and R. Wang found that the mortar attached to the recycled aggregate is the main factor affecting the performance degradation of the aggregate, and when the recycled aggregate is prepared as recycled concrete, the mortar adhesion rate of the secondary recycled aggregate recovered from the recycled concrete can be more than twice that of the primary recycled aggregate [16–18]. At present, the main use of recycled or treated recycled aggregate is to replace natural aggregate at a certain rate. To ensure the performance of recycled concrete products, a large number of scholars have explored the performance of concrete mixed with recycled aggregate. M. C. Shah used RCA instead of NCA to prepare recycled concrete with a gradient of 7%, 14%, 21%, and 28% and studied the mechanical properties of recycled concrete. It was found that the mechanical properties of recycled concrete could still meet the design requirements [19]. Ruaa Yousif Hassan used RCA to replace NCA at 100%, and RFA to replace RS with 25%, 50%, 75%, and 100% replacement rates to prepare recycled self-compacting concrete with different mix ratios and study its mechanical properties. It was found that the use of RFA instead of RS had little effect on the performance of recycled self-compacting concrete [20]. D. Gao prepared SFRFA by using steel fiber to process RFA, and using RFA and SFRFA to prepare recycled concrete, and explored the mechanical properties of recycled concrete. The results demonstrated that the concrete prepared with SFRFA had a significant performance improvement compared with the concrete prepared with RFA [21]. M. Kaarthik used RFA to replace RS at different substitution rates to prepare recycled concrete. By studying the mechanical properties of recycled concrete, it was found that when the RFA substitution rate was 60%, the strength of recycled concrete reached its peak [22]. J. Pacheco found that the higher the strength grade of concrete prepared with recycled aggregate, the higher the strength loss rate [23]. In addition, to save the amount of cement, some scholars use RP, a by-product produced in the process of recycled aggregate treatment, to partially replace cementitious materials in RP concrete preparation. Through their research on the performance of RP concrete, these scholars found that the performance of RP is similar to that of fly ash, which can provide certain hydration activity [23–29]; this provides a theoretical basis for the application of RP in concrete.

It is necessary to alleviate the pressure of construction solid waste on the environment and improve the resource utilization level of construction solid waste. In this paper, different kinds of RCA, RFA, and RP are combined to prepare full component recycled dry-mixed mortar and full component recycled concrete, and their performance is compared with pure natural aggregate mortar and concrete. SCRCA and SCRFA are obtained by simple-crushing the solid waste from construction; SCRCA and SCRFA are then processed by particle-shaping to obtain PSRCA, PSRFA, and by-product RP. After testing and analyzing the physical properties of products in different treatment stages, under the condition of a 1:4 cement-sand ratio and 100% use of SCRFA, PSRFA, and RS as fine aggregate, the dry mixed masonry mortar was prepared, using RP instead of cement with four replacement rates of 0%, 10%, 20%, and 30%, respectively. The basic and mechanical properties and microstructure of hydration products of dry-mixed mortar were analyzed, and the maximum substitution rate of RP was determined. Under the condition that the amount of cementing material is 400 kg/m^3 and the RP substitution rate is the largest, three different aggregate combinations to prepare concrete, the 100% use of SCRCA and SCRFA, PSRCA and PSRFA, RS and NCA, are used to analyze working and mechanical performance, and the transition zone of the aggregate interface of the prepared concrete.

2. Materials and Methods

2.1. Materials

Construction solid waste: waste concrete from a construction site in Qingdao, its main components are waste clay bricks and waste concrete fragments with strength grades C20 to C30; Cement: P·O 42.5 cement produced by a cement factory in Shandong, its chemical composition is displayed in Table 1; Water reducing agent: naphthalene series superplasticizer, the water reduction efficiency is 30%, and the chemical composition is displayed in Table 1; NCA: granite gravel, continuous gradation of 4.75–31.5 mm, performance indicators are displayed in Table 2; RS: continuous gradation of 0.075–4.75 mm, performance indicators are displayed in Table 3; Water: tap water.

Table 1. Chemical composition analysis of water reducing agent and cement (%).

Component	CaO	CO_2	Al_2O_3	SO_3	SiO_2	Fe_2O_3	MgO	K_2O	Na_2O	LOSS	Moisture Content
Water reducing agent	2.94	65.19	0.17	24.71	0.32	0.05	0.13	0.03	6.44	0.02	0.05
Cement	65.71	-	4.33	1.92	19.75	3.79	0.34	0.55	0.90	2.18	0.09

Table 2. Physical properties of natural coarse aggregate.

Water Absorption/%	Moisture Content/%	Content of Needle-Like Particles/%	Crushing Index/%	Bulk Density/(kg/m^3)	Apparent Density/(kg/m^3)	Moisture Content/%
1.7	0.42	4.05	11.2	1460	2510	0.42

Table 3. Physical properties of river sand.

Fineness Modulus	Bulk Density/(kg/m^3)	Apparent Density/(kg/m^3)	Porosity/%	Powder Content/%	Clay Lump/%	Crushing Index/%	Moisture Content/%
2.4	1450	2590	40	1.0	0.7	13	0.23

2.2. Treatment of Construction Solid Waste

The specific processing flow is demonstrated in Figure 1. The details are as follows: (1) Use a jaw crusher to simply crush the waste concrete. (2) Sieve the crushed products with a shaker, and return the particles >31.5 mm to the jaw crusher for crushing again. Repeat operation (2) until the particle size of all products is <31.5 mm. (3) SCRFA with particle sizes of 0.075–4.75 mm and SCRCA with particle sizes of 4.75–31.5 mm were obtained by sieving simple-crushing products with a shaker. (4) The simple-crushing products were placed in the particle-shaping machine for treatment, and the particle-shaping products at the discharge port of the particle-shaping equipment were collected. The particle-shaping products were screened and graded by a vibrating screen. RP with a particle size <0.075 mm, PSRFA with a particle size of 0.075–4.75 mm, and PSRCA with a particle size of 4.75–31.5 mm, were obtained.

Some of the operating principles are as follows:

Simple-crushing: put the construction solid waste into a jaw crusher and crush the construction solid waste by extrusion force.

Particle-shaping: put the products crushed and screened by the jaw crusher in the particle-shaping equipment. Under the high-speed movement of online speeds ≥80 m/s, use the repeated impact and mutual friction between recycled aggregate to polish off the old mortar and cement stone attached to the surface of recycled aggregate.

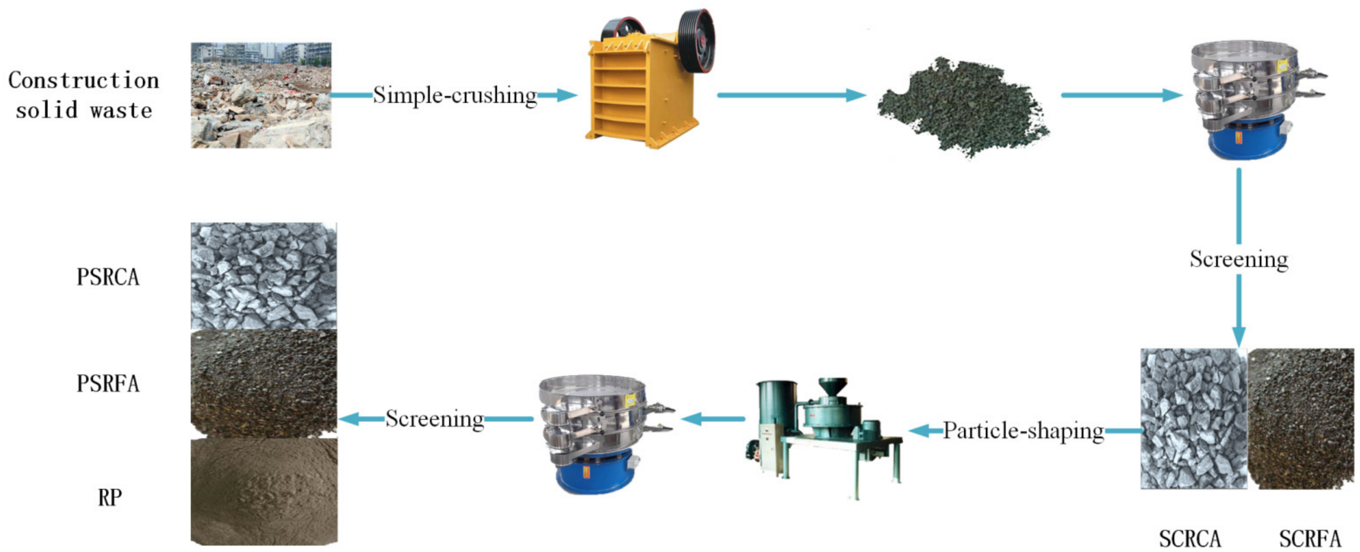


Figure 1. Flow chart of construction solid waste treatment.

After the classification, three kinds of recycled products were evaluated according to the national standards of "recycled coarse aggregate for concrete" (GB/T 25177-2010), "recycled fine aggregate for concrete and mortar" (GB/T 25176-2010), and "recycled fine powder for concrete and mortar" (JG/T 573-2020).

Some test performances are defined as follows:

Water demand ratio: the fluidity of mortar reaches 130 mm ± 5 mm, the ratio of water consumption of mortar prepared with RFA to that of standard mortar.

Strength ratio: meet the fluidity of 130 mm ± 5 mm, 28 day strength ratio of recycled mortar and standard mortar.

2.3. Preparation and Performance Research of Dry-Mixed Masonry Mortar

Under the condition of a 1:4 cement-sand ratio, RP is used to replace cement with four substitution rates of 0, 10%, 20%, and 30%, respectively, and SCRFA, PSRFA, and RS are used as fine aggregate at 100% to prepare dry concrete mortar. The dosage of the water reducing agent is determined as 0.6% of the total amount of cementitious materials. The consistency of dry concrete masonry mortar is controlled within 70–80 mm by adjusting the water consumption. The specific test mix proportion is displayed in Table 4.

Table 4. Test mix ratio of dry-mixed masonry mortar.

Number	Types of Fine Aggregate	Cement/(kg/m^3)	RP		Fine Aggregate/(kg/m^3)	Water Reducing Agent
			Substitution Rate/%	Consumption/(kg/m^3)		
a-1	RS	340.0	0	0.0	1360	2.04
a-2	RS	306.0	10	34.0	1360	2.04
a-3	RS	272.0	20	68.0	1360	2.04
a-4	RS	238.0	30	102.0	1360	2.04
b-1	PSRFA	340.0	0	0.0	1360	2.04
b-2	PSRFA	306.0	10	34.0	1360	2.04
b-3	PSRFA	272.0	20	68.0	1360	2.04
b-4	PSRFA	238.0	30	102.0	1360	2.04
c-1	SCRFA	340.0	0	0.0	1360	2.04
c-2	SCRFA	306.0	10	34.0	1360	2.04
c-3	SCRFA	272.0	20	68.0	1360	2.04
c-4	SCRFA	238.0	30	102.0	1360	2.04

After formulation, the preparation, consistency, stratification degree, air content, apparent density, and cube compressive strength of dry-mixed masonry mortar were tested, according to the national industry standard test method for basic performance of building mortar (JGJ/T 70-2009); SEM technology was used to observe the micromorphology of dry-mixed masonry mortar.

The specific test steps are as follows:

Preparation: weigh all materials according to Table 4, add them into the planetary mortar mixer in the order of mixing water-powder-fine aggregate-water reducing agent, and mix them according to the automatic program.

Consistency test: after the automatic program of the mixer is completed, the mixed mortar is immediately put into the mold of the mortar consistency meter for a consistency test; the water consumption when the mortar consistency reaches 70–80 mm is the standard water consumption.

Stratification degree test: put the mortar mixed under standard water consumption into the stratification cylinder, stand for 30 min, remove the mortar 200 mm above, put the remaining mortar in the mortar mixer, and mix it with the automatic mixing procedure. Immediately carry out the consistency test after mixing and subtract the consistency of the standard water consumption from the consistency measured at this time; take the absolute value as the mortar stratification.

Air content test: put the mortar mixed under standard water consumption into the mortar air content tester; operate according to the regulations, and read the pressure gauge value, which is the air content value.

Apparent density test: put the mortar mixed under standard water consumption into the capacity bucket, weigh its weight, and calculate the apparent density.

Cube compressive strength test: put the mortar mixed under standard water consumption into a 70.7 mm × 70.7 mm × In the 70.7 mm cube test mold, curing to the specified age; the compressive strength was tested on the press at the loading speed of 0.25 KN/s.

SEM test: the hydration products of dry-mixed mortar were observed by high vacuum, GB-H mode, 2 KV voltage, and a 10 mA probe current scanning electron microscope.

2.4. Preparation and Performance Research of Fully Recycled Concrete

Under the condition that the amount of cementing material is 400 kg/m^3 and the RP substitution rate is the largest, with 100% use of the three different aggregates to prepare concrete, SCRCA and SCRFA, PSRCA and PSRFA, and RS and NCA, the sand ratio is determined to be 38%; the amount of water-reducing agent is 1.2% of the total amount of cementitious material and the mixing water amount is adjusted, based on the slump of the concrete mixture of 160–170 mm. The test mix ratio is displayed in Table 5.

Table 5. Test mix ratio of recycled concrete.

Number	Aggregate Combination	Cement /(kg/m^3)	RP		Coarse Aggregate/(kg/m^3)	Fine Aggregate/(kg/m^3)	Water Reducing Agent /(kg/m^3)
			Substitution Rate/%	Consumption /(kg/m^3)			
d-1	NCA + RS	320.0	20.0	80.0	1136.0	696.0	4.8
3-1	PSRCA + PSRFA	320.0	20.0	80.0	1136.0	696.0	4.8
f-1	SCRCA + SCRFA	320.0	20.0	80.0	1136.0	696.0	4.8

The preparation and performance tests of concrete are carried out according to the Chinese national standards: “standard for test methods of performance of ordinary concrete mixture” (GB/T 50080-2016), and “standard for test methods of physical and mechanical properties of concrete” (GB/T 50081-2019). The aggregate interface transition zone of concrete is observed and analyzed.

The specific experimental operations are as follows:

Water consumption test: The slump test is performed on the mixed concrete. The water consumption when the slump is controlled at 160–170 mm is the water required for the test.

Strength test: Use the concrete that has been mixed; the slump meets the requirements to prepare a cube test block of 100 mm × 100 mm × 100 mm. After curing it to the specified age, use a pressure testing machine to test at a rate of 0.3 MPa/s.

Aggregate transition zone analysis: After crushing different aggregate combinations and the cube test blocks, take the broken cube test blocks, observe the fracture interface, and explore the fracture factors of the cube test blocks.

3. Results and Discussion

3.1. Research on the Performance of Construction Solid Waste Treatment Products

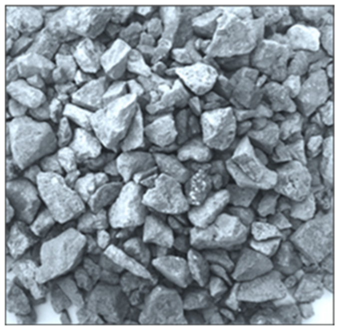
3.1.1. Performance Analysis of Coarse Aggregate

The main physical properties of SCRCA and PSRCA are displayed in Table 6, and the appearance and particle size distribution are displayed in Figure 2.

Table 6. Physical properties of coarse aggregates in different treatments.

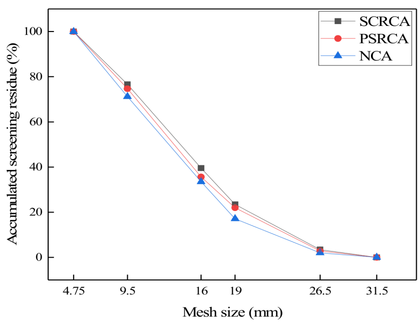
Type	Fine Powder Content/%	Clay Lump/%	Water Absorption/%		Content of Needle Like Particles/%	Crushing Index/%	Apparent Density/(kg/m^3)	Porosity/%	Moisture Content/%
			1 h	24 h					
SCRCA	1.9	0.6	2.3	3.7	6	18	2430	44	0.29
PSRCA	1.1	0.2	1.7	2.3	4	15	2470	44	0.21

(**a**) SCRCA



(**b**) PSRCA

(**c**) NCA



(**d**) Particle size distribution

Figure 2. Particle size distribution and appearance of the RCA with different treatment methods.

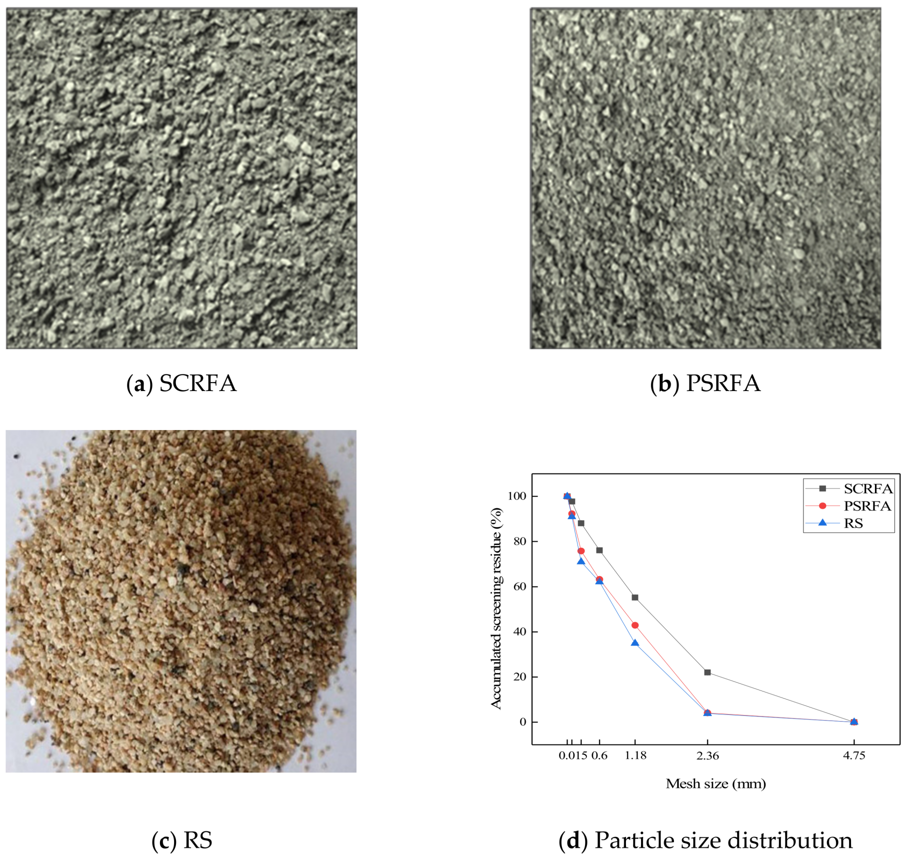
It can be observed from Table 6 that the performance of PSRCA is effectively improved after SCRCA is processed by particle-shaping. Compared with SCRCA, the powder content, mud content, 1 h water absorption rate, 24 h water absorption rate, needle-like particle content, and crushing index of PSRCA are reduced by 42.1%, 66.7%, 26.1%, 37.8%, 33.3%, and 16.7%, respectively. The apparent density has increased by 1.6%. The performance index of PSRCA is slightly lower than that of I class RCA, other indexes are upgraded from II class to I class, and its particle size distribution is also closer to NCA. Combining the coarse aggregate images of different processing states in Figure 2, it can be observed that this is caused by the removal of the mortar attached to the PSRCA surface after being processed by the particle-shaping equipment [30–32]. In addition, it can be observed from the particle size distribution diagram that after the particle-shaping treatment, the cement paste on the surface of the SCRCA is peeled off and the sharp edges and corners are polished, which reduces the proportion of large-size aggregates in the PSRCA.

3.1.2. Performance Analysis of Fine Aggregate

The main physical properties of the two RFAs after simple-crushing and particle-shaping are displayed in Table 7, and the appearance and particle size distribution are displayed in Figure 3.

Table 7. Physical properties of fine aggregate in different processing methods.

Type	Fine Powder Content/%	Clay Lump/%	Crushing Index/%	Water Requirement Ratio/%	Strength Ratio/%	Apparent Density /(kg/m^3)	Bulk Density /(kg/m^3)	Porosity/%	Moisture Content/%
SCRFA	1.8	1.4	24	1.31	0.96	2360	1380	44	0.19
PSRFA	3.2	0.8	22	1.27	0.87	2440	1333	42	0.12



(**a**) SCRFA (**b**) PSRFA

(**c**) RS (**d**) Particle size distribution

Figure 3. Particle size distribution and appearance of RFA with different treatment methods.

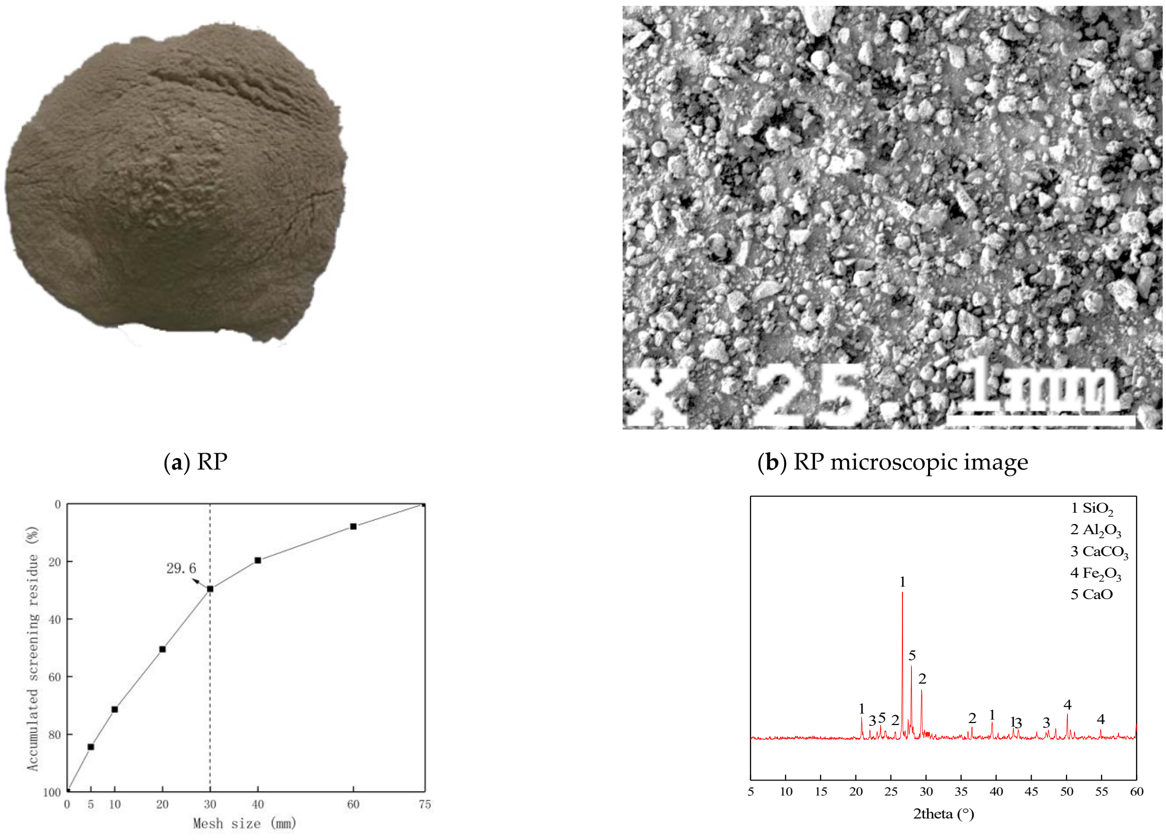
It can be observed from Table 7 that PSRFA has a greater performance improvement than SCRFA after processing by particle-shaping technology. Among them, the clay content, porosity, crushing index, and water demand ratio decreased by 42.9%, 8.3%, 3.1%, and 9.4%, respectively; The fine powder content, apparent density and bulk density increased by 77.8%, 3.4% and 3.4%, respectively. Except for the crushing index and the strength ratio, all the basic performance indexes of the PSRFA meet the I class RFA standard. However, it is worth noting that the increase in the content of fine powder in the PSRFA is relatively large. This is because, after being processed by the particle shaping equipment, the edges and corners of the fine aggregate and the impurities doped in it are crushed; the content of fine powder has increased, but it still meets use standards. In addition, in conjunction with the fine aggregate images and particle size distribution of different processing states in Figure 3, it can be observed that the particle size distribution of SCRFA is not uniform. The particle size of PSRFA is relatively uniform, the particles are relatively smooth, the particle size is small, and the particle size distribution is the same as RS. This shows that when SCRFA is processed by particle-shaping technology, the cement stone on the surface of the SCRFA is also effectively removed, which improves the quality of the SCRFA [33].

3.1.3. Performance Analysis of RP

The chemical composition analysis of the RP produced during aggregate processing is displayed in Table 8, and the appearance morphology, microscopic image, particle size distribution, and XRD diffraction pattern are displayed in Figure 4.

Table 8. Chemical composition analysis of RP (%).

Type	CaO	CO_2	Al_2O_3	SO_3	SiO_2	Fe_2O_3	MgO	K_2O	Na_2O	LOSS	Moisture Content/%
RP	13.31	14.87	14.57	0.52	45.24	4.30	1.66	3.74	1.50	0.29	0.11



(**a**) RP

(**b**) RP microscopic image

(**c**) Particle size distribution

(**d**) XRD diffraction pattern of RP

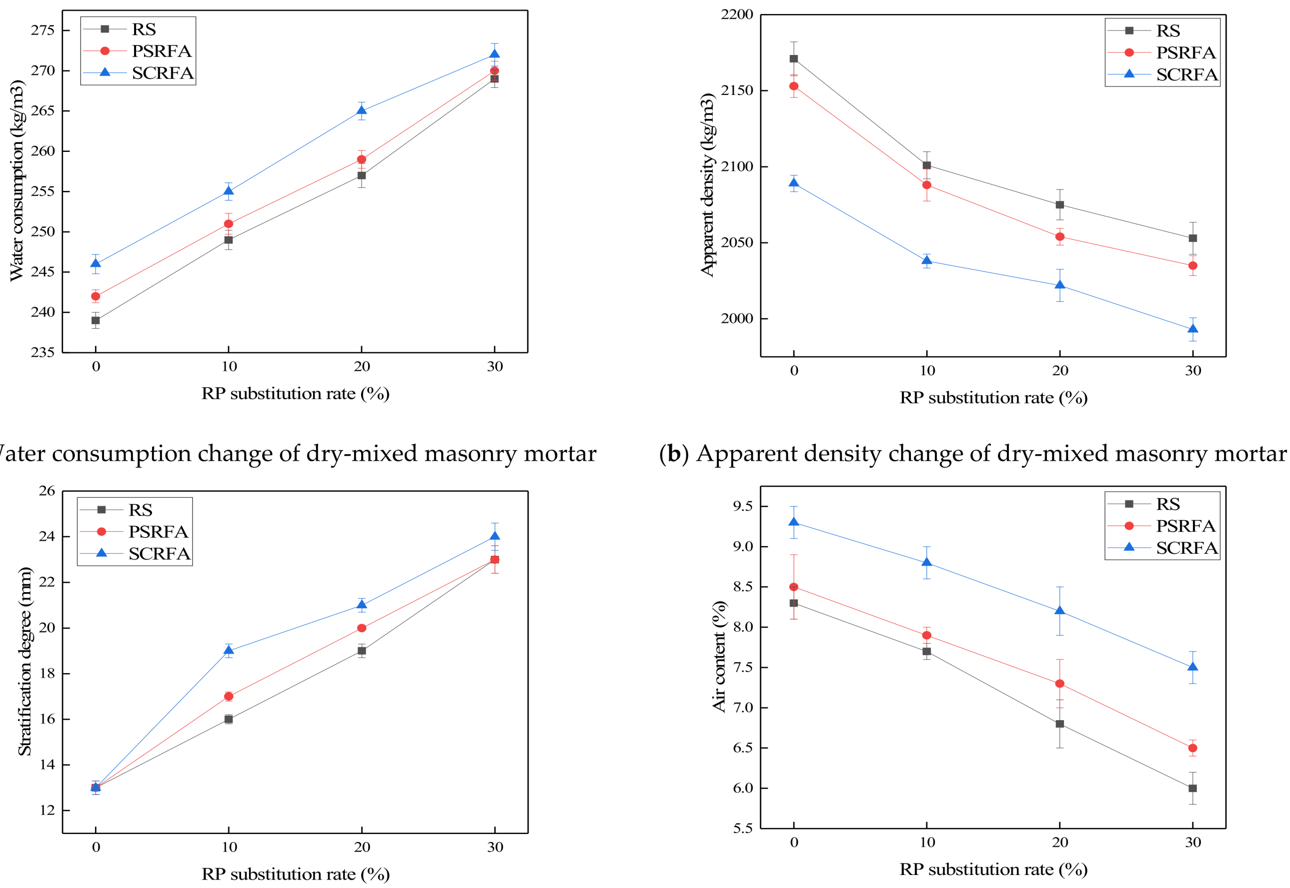
Figure 4. RP appearance, microscopic image, particle size distribution, and XRD pattern.

From Table 8 and Figure 4, it is known that the diffraction peaks of calcium silicate and calcium aluminate have not been found in the XRD diffraction pattern. This indicates that the proportion of cement particles in the RP is less. Most of the cement particles are hydrated calcium silicate and calcium aluminate gel, and the hydration product $Ca(OH)_2$ has also been carbonized. The most important mineral component of RP is SiO_2, followed by Al_2O_3 and other mineral components with hydration activity, which can be used as mineral admixtures [24–29]. In addition, from the microscopic image and particle size distribution in Figure 4, it can be observed that the shape of the RP is mostly irregular geometrically, the surface is relatively rough, but the particles are very small, and the 30-micron sieve margin is only 29.6%, which meets class I RP requirements.

3.2. Research on the Performance of Dry-Mixed Masonry Mortar

3.2.1. Basic Performance

When the consistency of the dry-mixed masonry mortar is the same, as the RP substitution rate increases, the water consumption, apparent density, stratification degree, and air content of the dry-mixed mortar change as displayed in Figure 5.



(**a**)Water consumption change of dry-mixed masonry mortar (**b**) Apparent density change of dry-mixed masonry mortar

(**c**) Stratification degree of dry-mixed masonry mortar (**d**) Air content change of dry-mixed masonry mortar

Figure 5. Basic properties of dry-mixed masonry mortar.

It can be observed from Figure 5 that, compared with RS dry-mixed masonry mortar, SCRFA dry-mixed masonry mortar and PSRFA dry-mixed masonry mortar have higher water consumption, stratification, and air content, and the apparent density is relatively reduced. The performance degree of dry-mixed masonry mortar prepared by SCRFA is quite different from that of dry-mixed masonry mortar prepared by PSRFA and RS, while PSRFA dry-mixed masonry mortar and RS dry-mixed masonry mortar are closer in various properties. This is because the SCRFA is attached with some "porous cement paste" on the surface and has micro-cracks, which makes its water absorption increase, increasing the water consumption of mortar, while increasing water consumption reduces the water holding capacity of mortar. However, with the increase of water consumption, the water holding capacity of mortar decreases and the stratification degree increases. Moreover, the composition of SCRFA is complex, the density of each component is different, the filling effect is poor, and it is easy to delaminate, which further leads to the increase of air content and the decrease of apparent density [33,34]. After the particle-shaping technology, the cement stone and edges on the surface of SCRFA are polished and removed. The cement stone adhesion on the surface of the PSRCA is less, and the overall shape of the PSRCA is more rounded; it can effectively play a "ball effect" and "filling effect" between coarse aggregates, reduce the water consumption and stratification degree of mortar, and improve the water holding capacity and apparent density.

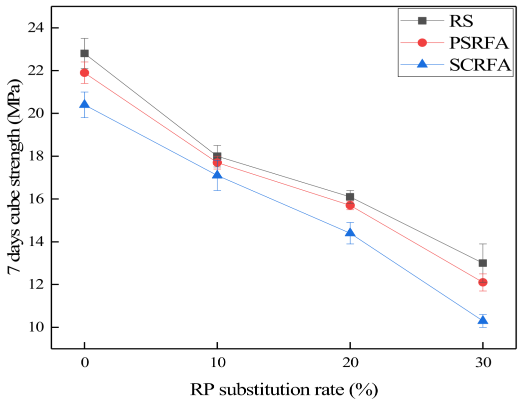
In addition, further analysis of Figure 5 shows that in dry-mixed masonry mortar prepared with different fine aggregates, with the increase of RP substitution rate, the water consumption and stratification degree increase linearly, while the apparent density and air content decrease gradually. This is due to the relatively loose RP, poor geometry and gradation, and a large number of connected pores in the particles, so that the dry-mixed masonry mortar can still absorb part of the water after the mixing is completed [27,28]. To meet the consistency requirements of dry-mixed masonry mortar, after the RP replacement rate increases, the amount of mixing water must increase. However, with the increase of water consumption, the water holding capacity of mortar decreases, and the fineness of RP is small; the density of each component is uneven. With the increase of the RP substitution rate, the low-density powder will float up in the process of vibration, which makes the stratification degree of dry-mixed masonry mortar increase and the apparent density decrease. In addition, RP also contains large quantities of SiO_2, Al_2O_3, and Cao, and its chemical composition is similar to that of fly ash. Therefore, RP has certain pozzolanic activity, which can have filling and activity effects [29]. This will reduce the existing space of bubbles in the mortar and air content.

In the same RP replacement rate, the performance of the RS dry-mixed masonry mortar is higher than the PSRFA and SCRFA dry-mixed masonry mortars; this is also determined by the nature of fine aggregate itself. RS has a smooth and round surface, and its water absorption is small. Most of the water in the mortar mixture is mixed with cement to form a lubricating cement paste, which, together with the rounded RS, improve the performance of dry-mixed masonry mortar. However, SCRFA has high water absorption due to a large amount of cement stone attached to its surface and micro-cracks. To ensure the required consistency, the water consumption will increase, and the increase of water consumption will further reduce the water-binder ratio, negatively effecting the performance of dry mixed masonry mortar. After particle-shaping, the cement stone on the surface of PSRFA is polished, and the particle shape is also optimized. The basic properties of PSRFA are far superior to SCRFA and close to RS. Therefore, the performance of dry-mixed masonry mortar mixed with PSRFA is close to that of RS dry-mixed masonry mortar, and it is better than that of SCRFA dry-mixed masonry mortar.

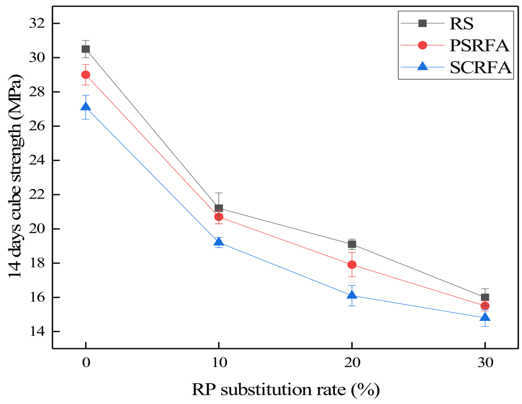
In summary, the replacement rate of RP and the type of fine aggregate are important factors that affect the basic performance of dry-mixed masonry mortar. The use of different RFA treatments will have different effects on the performance of dry-mixed masonry mortar. Among them, the performance of PSRFA is better than SCRFA; as the content of RP increases, the water consumption of dry-mixed masonry mortar and the stratification degree increase, while the apparent density and air content decrease. However, when the replacement rate of RP is within 20%, it can meet the requirements of actual engineering.

3.2.2. Mechanical Properties

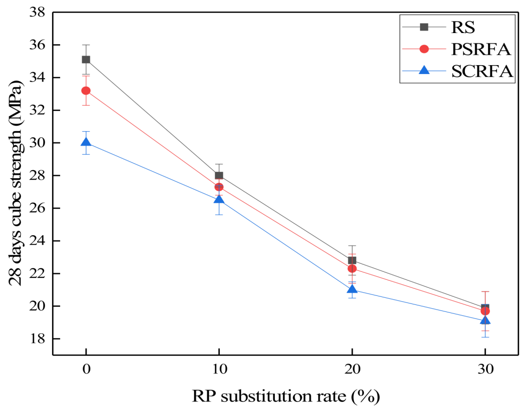
The curve of the cube compressive strength of dry-mixed masonry mortar specimens with different aggregate types and curing ages is displayed in Figure 6, with the increase of RP replacement rate.



(**a**) 7d compressive strength of dry-mixed masonry mortar



(**b**) 14d compressive strength of dry-mixed masonry mortar



(**c**) 28 d compressive strength of dry-mixed masonry mortar

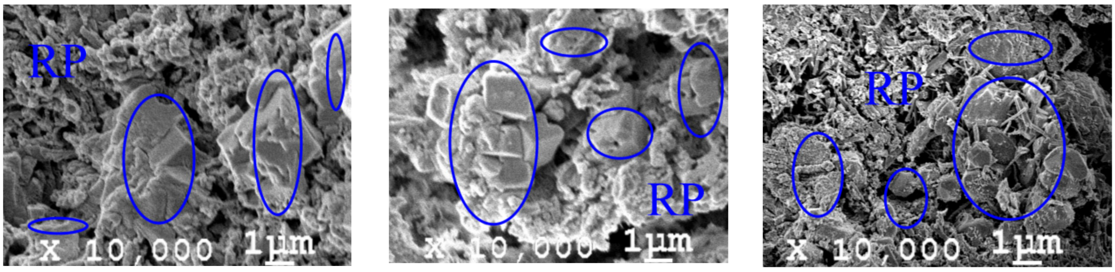
Figure 6. Compressive strength of fully recycled dry-mixed mortar.

It can be observed from Figure 6 that, under different curing ages, with the increase of the RP substitution rate, the strength of dry-mixed masonry mortar prepared with different fine aggregates decreases continuously. This is mainly because, with the increase of the RP substitution rate, the amount of cement, hydration products, and strength decrease [29]. In addition, the strength of PSRFA dry-mixed masonry mortar and SCRFA dry-mixed masonry mortar is lower than that of RS dry-mixed masonry mortar. However, the cube compressive strength of PSRFA dry-mixed masonry mortar at each age is close to that of RS dry-mixed masonry mortar, and the largest difference is only 5.4% at the age of 28 days. Under the same RP substitution rate, the strength of the RS dry-mixed masonry mortar > the PSRFA and SCRFA dry-mixed masonry mortar strengths. This is mainly due to the difference in the water absorption of the fine aggregate and the shape of the fine aggregate particles. SCRFA has high water absorption and poor particle shape, which increases water consumption and reduces the compactness of hydration products of cement paste [34]. After PSRFA undergoes particle shaping treatment, the particle shape is optimized, the water absorption rate is also reduced, and the basic properties are close to RS, which reduces the water-binder ratio of the mortar and makes the structure of the mortar hydration product compact.

In conclusion, for dry-mixed masonry mortar, the increase of RP content and RFA with low treatment degrees will reduce its compressive strength. However, according to the division of compressive strength in the "technical specification for production and application of dry-mixed masonry mortar" (DG/T J08-502A-2000), when the RP content is less than 20%, the dry-mixed masonry mortar with strength grade M20 can be prepared, which can fully meet the application requirements of actual engineering. Among them, when the RP substitution rate is 20%, it can not only reduce the cement consumption to the greatest extent but also meet the practical application; so, the maximum RP substitution rate is 20%.

3.2.3. Micro Analysis of Dry-Mixed Masonry Mortar

For curing to 28 days, the RP replacement rate is 20%, and the dry-mixed masonry mortar of different fine aggregates is used for microscopic observation of hydration products. The microscopic image is displayed in Figure 7.



(**a**) RS (**b**) PSRFA (**c**) SCRFA

Figure 7. Hydration products of mortar.

It can be observed from Figure 7 that no CH crystals were detected in the three groups of samples, but all the unhydrated RP particles were observed. The number of unhydrated RP particles in the three groups of samples, in descending order, is SCRFA dry-mixed masonry mortar, PSRFA dry-mixed masonry mortar, and RS dry-mixed masonry mortar. This is mainly because RP has similar hydration activity to fly ash [27,28]. It can be secondarily hydrated with CH to form a gel to provide strength for the sample, but the amount of CH produced by the cement′s own hydration is not enough to support the consumption of the RP's complete secondary hydration, so there will be some RP particles in the sample. In addition, the compactness of RS dry-mixed masonry mortar is similar to that of PSRFA dry-mixed masonry mortar, while the compactness of SCRFA dry-mixed masonry mortar is lower. This is due to the physical defects of the SCRFA and PSRFA themselves, so that the water consumption of dry-mixed masonry mortar prepared by SCRFA and PSRFA will increase when the consistency is 70–80 mm. The increase in water consumption will lead to an increase in the water-binder ratio, which will reduce the compactness of the mortar hydration product. However, because the performance of PSRFA is similar to RS, the water consumption of PSRFA dry-mixed mortar and RS dry-mixed mortar are also similar, and the water-binder ratio of the mortar is not much different. Therefore, the compactness of PSRFA dry-mixed masonry mortar is similar to that of RS dry-mixed masonry mortar. This is consistent with the above-mentioned performance analysis and effectively verifies its validity.

3.3. Concrete Performance Research

3.3.1. Work Performance

After the concrete slump test, the water consumption when the slump reaches 160–170 mm is the water consumption for the working performance of the concrete. The water consumption for the working performance of the concrete with three different aggregate combinations is demonstrated in Figure 8.

It can be observed from Figure 8 that the water consumption of the three aggregate combinations rises sequentially, with SCRCA and SCRFA concrete having the largest water consumption, PSRCA and PSRFA concrete in the middle, and NCA and RS concrete the least. Among them, the water consumption of SCRCA and SCRFA concrete is 10 kg/m^3 higher than that of PSRCA and PSRFA concrete, and 13 kg/m^3 higher than that of NCA and RS concrete. This is mainly caused by the physical defects of the aggregate itself. The "old mortar" attached to the surface of the aggregate and internal micro-cracks will increase its water absorption, increasing concrete water consumption [35,36]. After the aggregate combination of PSRCA and RSRFA is processed by particle shaping, the old mortar and corners on the surface of SCRCA and SCRFA are removed, which improves the quality of the aggregate and makes its basic performance close to NCA and RS; the work performance of concrete is also improved [37].

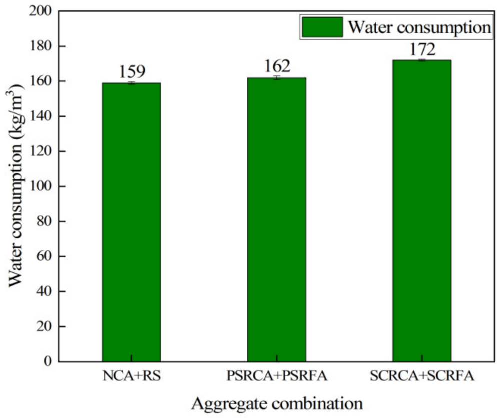


Figure 8. Water consumption of fully recycled concrete.

3.3.2. Mechanical Properties

The mechanical properties of the concrete with three aggregate combinations after standard curing to different ages are displayed in Figure 9.

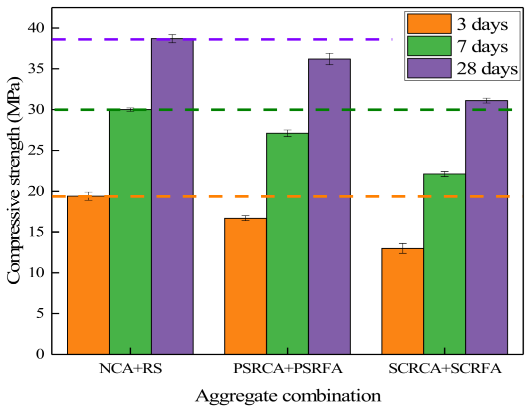
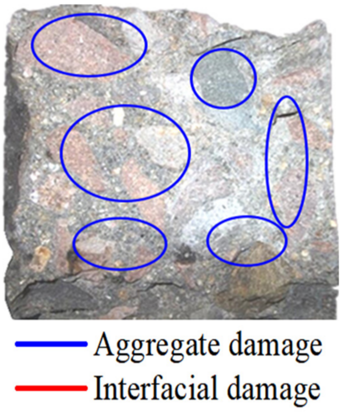


Figure 9. Compressive strength of concrete at different ages.

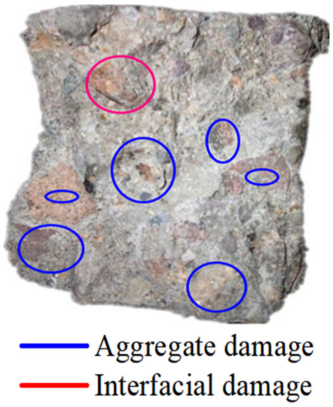
It can be observed from Figure 9 that due to the properties of aggregate, the compressive strength of SCRCA and SCRFA concrete and PSRCA and PSRFA concrete is lower than that of NCA and RS concrete. This is because the water consumption of SCRCA and SCRFA concrete and PSRCA and PSRFA concrete is higher than that of NCA and RS concrete, the compactness is lower, and they contain micro-cracks that are easily damaged [38]. However, the strength of each age of PSRCA and PSRFA concrete is similar to that of NCA and RS concrete, while the strength of each age of SCRCA and SCRFA concrete is quite different from that of NCA and RS concrete. The 3 day compressive strength of NCA and RS concrete is close to the 7 day compressive strength of SCRCA and SCRFA concrete, and the 7 day compressive strength of NCA and RS concrete is close to the 28 day compressive strength of SCRCA and SCRFA concrete. This is because there are numerous old cement stones and mortars on the surface of SCRCA and SCRFA, which makes the interface transition zone very weak and easily damaged after they are prepared into concrete [38]. After PSRCA and PSRFA are processed by particle-shaping, the cement stone and mortar on the surface have been removed. In the concrete prepared using PSRCA and PSRFA, the interface transition zone of aggregate has been strengthened to a certain extent, compared with that of SCRCA and SCRFA concrete. This is similar to the research conclusion of H.K.A. Al-Bayati [39].

3.3.3. Interface Analysis of Concrete Failure Mode

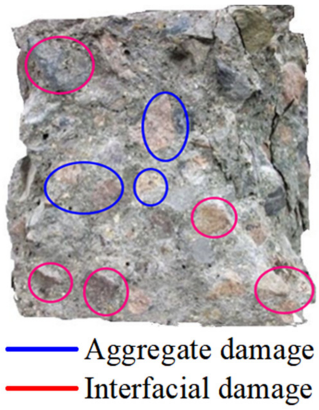
Take the 28 day age concrete test blocks with different aggregate combinations after the mechanical performance test, observe the broken interface, and explore the interface failure form. The specific image is demonstrated in Figure 10.



(**a**) NCA + RS



(**b**) PSRCA + PSRFA



(**c**) SCRCA + SCRFA

Figure 10. Fracture interface of concrete block.

It can be observed from Figure 10 that the failure modes of the NCA and RS concrete test blocks are failures caused by the crushing of the NCA, and no interface failure between the NCA and the cement paste has been found. The failure section of the concrete test block prepared by SCRCA and SCRFA mostly occurred at the interface between the new and old mortar; most of the SCRCA remained intact without being crushed, and it did not play the role of skeleton support. However, the proportion of PSRCA crushing failure in the concrete test blocks prepared by PSRCA and PSRFA is larger than that of SCRCA and SCRFA concrete, and there is only a small amount of interface failure. This is consistent with the conclusion of the mechanical performance test. Namely: NCA and RS concrete strength > PSRCA and PSRFA, and SCRCA and SCRFA concrete strengths; the strength of NCA and RS concrete and the strength of PSRCA and RSRFA concrete are close to and far higher than the strength of SCRCA and SCRFA concrete.

4. Conclusions

In this paper, construction solid waste is prepared into different types of recycled coarse/fine aggregates through different treatment methods. The dry-mixed masonry mortar and concrete were prepared using 100% recycled coarse/fine aggregate and part by-product RP and compared with the dry-mixed masonry mortar and concrete prepared by using natural coarse/fine aggregate. By studying its basic and mechanical properties and microstructure, the following conclusions are drawn.

(1) After particle shaping, the performance of PSRCA and PSRFA is close to the basic performance of NCA and RS and is much higher than that of SCRCA and SCRFA.
(2) As the replacement rate of RP increases, the performance indicators of dry-mixed masonry mortar gradually decrease. To ensure the application of products in actual projects, the maximum replacement rate of RP should not be greater than 20%.
(3) When the RP replacement rate is 20%, the performance of the product can not only meet the requirements of use, but also reduce the amount of cement to the greatest extent, and realize the comprehensive utilization of waste resources, energy savings, and emission reduction.
(4) In the concrete prepared with different aggregate combinations, the failure mode of SCRCA and DCRFA concrete mainly damage the interface between the old and the new mortar, and the aggregate cannot play the role of skeleton support. The damage morphology of the concrete prepared by the PSRCA and PSRFA treated by

the particle-shaping technology is the same as that of the NCA and RS concrete, and the damage is mainly caused by the crushing of the aggregate.

(5) In follow-up research, we can further study the influence of different types of aggregates on the performance of concrete, such as NCA and PSRFA, NCA and SCRFA, PSRCA and RS, PSRCA and SCRFA, etc.

Author Contributions: Data curation, Y.G. and S.Z.; Formal analysis, Z.H. and Z.K.; Investigation, Q.L. and J.L.; Methodology, Z.H. and Y.G.; Resources, Z.K. Y.G. and G.C.; Software, Z.K.; Writing—original draft, Z.H.; Writing—review & editing, Q.L. and D.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number 51878366, 51808310, 51978353, and 52078261, the Natural Science Foundation of Shandong Province, China, grant number ZR2019PEE007 and ZR2020ME036, and the Qingdao Science and Technology Demonstration and Guidance Project (20-3-4-10-nsh).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Since the experiment was completed with the support of Qingdao Agricultural University, the data used to support the results of this study are available from the responsible person and the author upon request.

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

Abbreviations

Abbreviations	Long Noun
RCA	recycled coarse aggregate
RFA	recycled fine aggregate
RP	recycled powder
SFRFA	steel fiber reinforced recycled fine aggregate
SCRFA	simple-crushed fine aggregate
SCRCA	simple-crushed coarse aggregate
PSRFA	particle-shaping fine aggregate
PSRCA	particle-shaping coarse aggregate
NCA	natural aggregate
RS	river sand

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