Article

Study on Mechanical and Shrinkage Properties of High Belite Sulphoaluminate Cement-Based Green Recycled Aggregate Concrete

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Abstract: Green recycled aggregate concrete (RAC) with high strength and low shrinkage is prepared based on recycled coarse aggregate produced by the particle-shaping and aggregate-strengthening method and green low-carbon new cement. This not only effectively alleviates the shortage of natural resources, but also improves the performance of recycled aggregate concrete, which is of great significance for multi-channel resource utilization of construction waste. In this study, three kinds of recycled coarse aggregates (RCA), including simple crushing recycled coarse aggregate (JD-RCA), one-time particle-shaping recycled coarse aggregate (KL-RCA) and two-time particle-shaping recycled coarse aggregate (EKL-RCA), were prepared from the preparation technology of recycled aggregate, and high belite sulphoaluminate cement with excellent performance was used. The effects of aggregate quality, aggregate replacement ratio, and cementitious material content on mechanical properties and shrinkage properties of green recycled aggregate concrete were studied in comparison with ordinary Portland cement-based recycled aggregate concrete. The testing results show that the particle-shaping method can effectively improve the aggregate quality. The compressive strength and dry shrinkage performance of recycled aggregate concrete made of particle-shaped aggregate are only a little different from those of natural aggregate concrete, and even the performance of recycled aggregate is better than that of natural aggregate concrete under the condition of a low replacement ratio of recycled aggregate. In addition, high belite sulphoaluminate cement-based recycled aggregate concrete (HBRAC) not only has early strength and rapid hardening, but also has excellent drying shrinkage resistance, and its shrinkage rate can be reduced to more than 75% compared with ordinary Portland cement-based recycled aggregate concrete (OPRAC).

Keywords: recycled aggregate concrete; particle-shaping method; high belite sulphoaluminate cement; mechanical properties; shrinkage properties

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1. Introduction

In recent years, the rapid development of the global economy has led to the rapid rise of the construction industry, but its rapid development inevitably faces many problems such as construction waste pollution and over-exploitation of natural aggregate. How to properly deal with these problems has become an important topic in today's social research [1–5]. With the protection of environment and the strengthening of the consciousness of social sustainable development, the application of recycled concrete has become an important development direction of construction waste recycling [6–10].

How to reuse recycled coarse aggregate (RCA) in concrete is an important subject in the research of recycled aggregate concrete (RAC), which promotes the rapid development

of reinforced preparation technology of RCA. This technology can improve the inferior properties of RCA, such as roughness, porosity, high water absorption, and high crushing index. It treats construction waste after a series of processes and re-use it as building materials [11–15]. At present, RCA is mainly strengthened by physical and chemical methods. Physical strengthening requires grinding the RCA by various mechanical methods, and directly removes inferior parts [16–18]. Chemical strengthening consists of pre-treatment of RCA by various slurry pouring and soaking, and indirectly makes up for the inferior part [19–23]. The particle-shaping method used in this paper is a new technology that can effectively grind the old mortar and cement paste attached to the surface of RCA by using the repeated impact and mutual friction between RCAs under the high-speed movement of line speed (the speed of the fixed axis of the vertical rotating impeller in circular motion at any point of the recycled aggregate) ≥ 80 m/s and can effectively strengthen RCA [24].

Mechanical properties are important properties in the research of recycled concrete. The mechanical properties of RAC increase with the improvement of the quality of RCA and decrease with the increase of the replacement ratio of RCA. It is an important research direction to analyze the properties of RAC from the aspects of the quality and replacement ratio of RCA [25–29]. Ismail et al. used hydrochloric acid and calcium silicate solution to strengthen recycled coarse aggregate and found that the strength of recycled concrete prepared by it was also greatly improved [30]. Limbachiya et al. studied the change of compressive strength of recycled aggregate concrete under different aggregate replacement ratios and found that when the replacement ratio is over 30%, the compressive strength decreases obviously with the increase of the replacement ratio [31].

Because of the low elastic modulus, high porosity, and many micro-cracks of RCA, the shrinkage deformation of RAC prepared by RCA is larger than that of ordinary concrete, which brings great restrictions to the application of RAC. At present, many scholars choose high-quality RCA and add mineral admixtures and admixtures to reduce the shrinkage deformation of RAC [32–36]. Domingo et al. found that the shrinkage of concrete with 100% recycled coarse aggregate increased by about 70% compared with ordinary concrete [37]. Kou et al.'s research on mineral admixtures found that the addition of fly ash, ground blast furnace slag, and metakaolin makes the drying shrinkage of RAC larger, while the addition of fly ash and ground slag makes the drying shrinkage of recycled concrete smaller [38]. He et al. found that the addition of shrinkage-reducing admixture can significantly reduce the shrinkage deformation of recycled concrete [39].

It is a new idea to use new cement to improve the strength of RAC and reduce the shrinkage deformation of RAC. High belite sulphoaluminate cement is a new green inorganic nonmetallic cementing material developed based on of traditional Portland cement and sulphoaluminate cement [40–45]. Compared with ordinary Portland cement, this kind of cement has a lower firing temperature and most of its raw materials are industrial solid wastes, which not only have less carbon dioxide emissions, but also reuse solid wastes based on cost saving. This outstanding feature is in line with the concept of green development of man and nature in China. In addition, cement also has the advantages of high early strength, stable development of late strength, low alkali corrosion resistance, strong drying shrinkage resistance, and good appearance of cement in comprehensive properties, which provide favorable conditions for the preparation of green RAC.

In this paper, the 45 groups of experimental proportions were designed to prepare green RAC with RCA after simple crushing and particle-shaping treatment as main raw materials and high belite sulphoaluminate cement as basic cementitious material. The effects of cementitious material content, physical quality, and the replacement ratio of aggregate on mechanical properties and drying shrinkage properties were systematically studied and compared with OPRAC to show the advantages of HBRAC.

2. Experimental Program

2.1. Raw Materials

The 42.5R high belite sulphoaluminate cement (HBSAC) produced by China Tangshan Polar Bear Building Materials Co., Ltd. (Tangshan, China) was used in this study, which is fired from industrial solid waste, and its chemical composition and mineral composition are shown in Table 1. Ordinary Portland cement (OPC) produced by Shandong Mountain Aluminum Cement Corp., Ltd. (Qingdao, China) and its chemical composition and mineral composition are shown in Table 2. Grade II river sand produced in Pingdu, China, as a natural fine aggregate, has good gradation, and its performance index is shown in Table 3. Granite crushed stone produced in Qingdao, China, as natural coarse aggregate, has good gradation, and its performance index is shown in Table 4. The test methods of performance indexes in Tables 3 and 4 refer to the Standard for Technical requirements and Test Method of Sand and Crushed Stone for Ordinary Concrete (JGJ 52-2006, China). The recycled coarse aggregate (RCA) includes the following: simple crushing recycled coarse aggregate (JD-RCA), one-time particle-shaping recycled coarse aggregate (KL-RCA), and two-time particle-shaping recycled coarse aggregate (EKL-RCA); ordinary tap water in Qingdao, China; and the polycarboxylic acid superplasticizer with a water-reducing rate of 30%, which is provided by Qingdao Qingjian New Materials Co., Ltd. (Qingdao, China).

Table 1. Chemical compositions and mineral compositions of HBSAC (%).

Chemical Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	TiO ₂	Loss on Ignition
	45.34	12.56	20.78	2.32	3.04	13.67	0.68	0.38
Mineral Composition	C ₄ A ₃ $\bar{S}$		β -C ₂ S		C ₄ A _{2.85} Fe _{1.5} $\bar{S}$		C $\bar{S}$	C _m
	35.77		36.05		8.07		14.05	1.01

Table 2. Chemical compositions and mineral compositions of OPC (%).

Chemical Composition	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	SO ₃	TiO ₂	Loss on Ignition
	62.73	17.8	6.38	5.83	1.94	2.98	0.52	0.38
Mineral Composition	C ₃ S		C ₂ S		C ₃ A		C ₄ AF	
	50.25		23.31		7.17		13.55	

Table 3. Performance indexes of natural fine aggregate.

Fineness Module	Specifications	Bulk Density (kg/m ³)	Apparent Density (kg/m ³)	Void Ratio/%	Micro Powder Content/%	Mud Content/%	Crushing Index/%
2.6	Medium sand II class	1450	2600	40	1.1	0.7	12.5

Table 4. Performance indexes 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)
1.6	0.45	4.25	11.9	1458	2480

2.2. Preparation Procedures of RCA

Simple crushing recycled coarse aggregate (JD-RCA), one-time particle-shaping recycled coarse aggregate (KL-RCA), and two-time particle-shaping recycled coarse aggregate (EKL-RCA) were prepared by using a jaw crusher and particle-shaping machine. The appearance and working principle of the particle-shaping equipment are shown in Figure 1a,b,

respectively. The shaping equipment is equipped with a vertical shaft-rotating impeller in the host system. When working, raw materials enter the machine from the upper inlet, a part of the raw materials enter from the middle, accelerate, and are thrown out at high speed due to centrifugal action, while another part of materials enter from the left and right sides and collide with the materials thrown out by the impeller to achieve the purpose of shaping. Therefore, the equipment has the advantages of low wear and energy consumption, small size, simple operation, and green production requirements, and has been put into practical engineering application. The preparation procedures of three types of RCA are shown in Figure 2. The performance index of RCA is shown in Table 5, and its test method refers to Recycled Coarse Aggregate for Concrete (GB/T 25177-2010, China). Table 6 shows the comparison of particle gradation between recycled coarse aggregate and natural coarse aggregate.

Figure 1. Particle-shaping strengthening equipment and working principle: (a) equipment appearance and (b) working principle. Note: ① raw material, ② air inlet port, ③ dust collector, ④ induced draft fan, ⑤ air outlet port, ⑥ granular plastic regenerated aggregate, and ⑦ recycled powder.

Figure 2. Preparation procedures of three kinds of RCA.

Table 5. Performance indexes of three kinds of RCA.

Projects	Recycled Coarse Aggregates for Trials		
	EKL-RCA	KL-RCA	JD-RCA
Grain Gradation	Qualified	Qualified	Qualified
Powder Content/%	0.7	0.9	2.2
Water Absorption/%	1.6	2.4	3.5
Content of Needle-Like Particles/%	1.0	4.0	7.0
Impurity Content/%	0.2	0.5	0.9
Ruggedness/%	3.9	4.9	9.8
Crushing Index/%	9.0	14.0	17.0
Apparent Density/(kg/m ³)	2475	2470	2436
Void ratio/%	43.0	46.0	48.0

Table 6. Comparison of aggregate particle gradation.

Aggregate Category	Nominal Diameter/mm	Accumulated Retained Percentage/%							
		The Side Length of the Square Hole Screen/mm							
		0	4.75	9.50	16.0	19.0	26.5	31.5	37.5
Natural coarse aggregate	5–31.5	99.9	97.1	63.5	28.4	15.2	1.9	0.3	0
EKL-RCA	5–31.5	99.9	97.8	62.7	28.1	15.8	2.0	0.3	0
KL-RCA	5–31.5	99.8	98.8	74.6	35.5	21.9	2.3	0.4	0
JD-RCA	5–31.5	99.7	99.2	76.6	39.6	23.3	3.2	0.5	0

As can be seen from Table 5, compared with JD-RCA, the properties of RCA after particle-shaping process, such as micro-powder content, water absorption, needle-like particle content, sundries content, firmness, and the crushing index, are significantly improved, which confirms the effectiveness of preparing high-quality RCA by the particle-shaping method.

2.3. Design of Experiment

In total, 39 mix proportion ratios were designed in this experiment, and three variables were set: aggregate quality (JD-RCA, KL-RCA, and EKL-RCA), aggregate replacement ratio (0, 25%, 50%, 75%, and 100%), and cement cementitious material content (300 kg/m³, 400 kg/m³, and 500 kg/m³). The purpose of setting cement cementitious material content as a variable is to prepare recycled concrete with different strength grades. According to “Test Method for Performance of Ordinary Concrete Mixture” (China GB/T50080-2016), the water consumption of concrete is determined by controlling slump in the range of 160–200 mm, which aims to meet the working performance requirements of practical projects. The detailed mixing proportions of concrete are shown in Table 7.

Table 7. Mixing proportions of concrete (kg/m³).

Item No.	Cement Content	Recycled Coarse Aggregate			Natural Coarse Aggregate	Natural Fine Aggregate	Water Reducer	Water Consumption
		Type	Replacement Ratio (%)	Content				
N1	300	-	0	0	1166	714	3.6	150.0
N2	300	EKL-RCA	25	291.5	874.5	714	3.6	150.9
N3	300	EKL-RCA	50	583	583	714	3.6	153.2
N4	300	EKL-RCA	75	874.5	291.5	714	3.6	152.6
N5	300	EKL-RCA	100	1166	0	714	3.6	157.9
N6	300	KL-RCA	25	291.5	874.5	714	3.6	154.2
N7	300	KL-RCA	50	583	583	714	3.6	154.9
N8	300	KL-RCA	75	874.5	291.5	714	3.6	155.3
N9	300	KL-RCA	100	1166	0	714	3.6	161.2
N10	300	JD-RCA	25	291.5	874.5	714	3.6	154.2
N11	300	JD-RCA	50	583	583	714	3.6	159.4
N12	300	JD-RCA	75	874.5	291.5	714	3.6	164.3
N13	300	JD-RCA	100	1166	0	714	3.6	167.2
N14	400	-	0	0	1136	696	4.8	152.2
N15	400	EKL-RCA	25	284	852	696	4.8	153.3
N16	400	EKL-RCA	50	568	568	696	4.8	152.6
N17	400	EKL-RCA	75	852	284	696	4.8	160.3
N18	400	EKL-RCA	100	1136	0	696	4.8	159.6
N19	400	KL-RCA	25	284	852	696	4.8	153.3
N20	400	KL-RCA	50	568	568	696	4.8	158.6
N21	400	KL-RCA	75	852	284	696	4.8	159.9
N22	400	KL-RCA	100	1136	0	696	4.8	163.8
N23	400	JD-RCA	25	284	852	696	4.8	157.8
N24	400	JD-RCA	50	568	568	696	4.8	161.2
N25	400	JD-RCA	75	852	284	696	4.8	165.2
N26	400	JD-RCA	100	1136	0	696	4.8	169.6
N27	500	-	0	0	1106	678	6.0	154.3
N28	500	EKL-RCA	25	276.5	829.5	678	6.0	155.6
N29	500	EKL-RCA	50	553	553	678	6.0	155.5
N30	500	EKL-RCA	75	829.5	276.5	678	6.0	156.9
N31	500	EKL-RCA	100	1106	0	678	6.0	161.3
N32	500	KL-RCA	25	276.5	829.5	678	6.0	156.3
N33	500	KL-RCA	50	553	553	678	6.0	163.5
N34	500	KL-RCA	75	829.5	276.5	678	6.0	162.3
N35	500	KL-RCA	100	1106	0	678	6.0	165.8
N36	500	JD-RCA	25	276.5	829.5	678	6.0	159.9
N37	500	JD-RCA	50	553	553	678	6.0	163.6
N38	500	JD-RCA	75	829.5	276.5	678	6.0	167.1
N39	500	JD-RCA	100	1106	0	678	6.0	171.5

3. Experimental Methods

3.1. Compressive Strength

According to the Test Method for Physical and Mechanical Properties of Concrete (GB/T 50081-2019, China), the compressive strength of concrete is tested for 1 day, 3 day, 7 day, and 28 day, respectively, by using 100 mm × 100 mm × 100 mm cube test specimens and carrying out standard curing.

3.2. Shrinkage Test

The method for drying shrinkage performance of green recycled aggregate concrete (RAC) is carried out according to the Standard for Test Methods for Long-Term Performance and Durability of Ordinary Concrete (GB/T 50082-2009, China). The cuboid specimens of 100 mm × 100 mm × 515 mm were put into a constant temperature and humidity chamber with temperature of 20 ± 2 °C and relative humidity of 60% ± 5% immediately after curing.

for 1 d. The initial length was recorded, and the shrinkage changes were measured at intervals of 1 d, 3 d, 7 d, 28 d, 45 d, 60 d, 90 d, 120 d, 150 d, and 180 d, respectively.

High belite sulphoaluminate cement has micro-expansion and crack resistance, which can make the shrinkage change of green RAC smaller. Therefore, a new fixed vertical shrinkage dilatometer was used in the test. The appearance and working principle of the equipment are shown in Figure 3a,b. The advantage of this equipment is that the four-claw anchoring iron plate is embedded in the bottom of the test block to ensure the integration with the equipment and prevent the experimental error caused by the loosening of the two. In addition, the internal twist screw is embedded at the top of the test specimens, which can install a fixed small platform to contact with the dial indicator point and surface, so as to avoid the shift of the position of the embedded probe in the concrete molding process or the loose drop of the probe in the concrete formwork removal process, and thus indirectly improve the data accuracy.

Figure 3. Concrete shrinkage dilatometer: ① dilatometer, ② fixed small platform, ③ internal twist screw, ④ test block, and ⑤ fixed small platform. (a) Equipment appearance and (b) working principle.

The shrinkage rate of green RAC is calculated according to the following formula:

$$\varepsilon_{st} = \frac{L_0 - L_t}{L_b} \quad (1)$$

where ε_{st} refers to the shrinkage rate of concrete specimen t (d), L_0 refers to the initial length reading (mm), L_t refers to the measurement reading (mm) at test piece t (d), and L_b refers to the gauge distance (mm) of the specimen.

3.3. Microstructural Characterization

A scanning electron microscope (FEG-SEM, JSM 7500f, Jeol, Tokyo, Japan) was used to observe the microstructure of high belite sulphoaluminate cement paste under different multiples, including void and crack structure, and compared with ordinary Portland cement paste.

4. Results and Discussion

4.1. Effect of RCA Quality and the Replacement Ratio on Mechanical Properties of HBRAC

Figure 4 shows the effect of RCA quality and the replacement ratio on concrete compressive strength under different cementitious material content.

Figure 4. Effect of RCA quality and the replacement ratio on compressive strength of HBRAC: (a) cementitious material content 300 kg/m^3 , (b) cementitious material content 400 kg/m^3 , and (c) cementitious material content 500 kg/m^3 .

It can be seen from Figure 4 that there are obvious differences in the effect of RCAs with different qualities on 28-day compressive strength of HBRAC, and the difference is most obvious when the replacement ratio of RCAs is 100%. Specifically, compared with the strength of high belite sulphoaluminate cement-based recycled concrete with simple crushed recycled coarse aggregate (JD-HBRAC), the average strength growth rate of high belite sulphoaluminate cement-based recycled concrete with one-time particle-shaping recycled coarse aggregate (KL-HBRAC) is 11.4%, and that of high belite sulphoaluminate cement-based recycled concrete with two-time particle-shaping recycled coarse aggregate (EKL-HBRAC) is 18.5%. The main reasons are likely to be that more internal micro-cracks of JD-RCA in the support of concrete skeleton effect are much worse, and the surface of the aggregate contains large water absorption of the old mortar and other impurities, resulting in increased water consumption of concrete and decreased compressive strength. KL-RCA is a kind of aggregate with better performance, which is made of JD-RCA by grinding all kinds of impurities and prominent edges and corners on the surface of aggregate with the particle-shaping machine, and the grain surface changes from rough to smooth, and the grain shape changes from irregular to spherical. The improvement of aggregate performance not only reduces the weak layer of new and old interface in concrete, but also greatly reduces the demand of concrete for water consumption and improves the overall compressive strength of concrete. The performance of EKL-RCA is more stable than that of KL-RCA. The most important point is to polish and remove the aggregate containing mortar and irregular water chestnut, which still exists in the first particle shaping, so that the

aggregate tends to be more spherical and effectively reduces the content of flaky aggregate. Therefore, the compressive strength of JD-HBRAC is the worst, the compressive strength of EKL-HBRAC is the best, and the compressive strength of KL-HBRAC is in between.

It can also be seen from Figure 4 that there is a high linear correlation between the 28d compressive strength of the HBRAC and the RAC replacement ratio; that is, the compressive strength of HBRAC decreases with the increase of RAC replacement ratio, but the strength decrease range of concrete is different with the increase of the RAC replacement ratio, which has a great relationship with the quality of RCA. Specifically, compared with NA-HBNC, the compressive strength of JD-HBRAC, KL-HBRAC, and EKL-HBRAC varies with the replacement ratios of 25%, 50%, 75%, and 100%, and the average strength reduction rates respectively decrease by the following percentages: 5.1%, 10.0%, 12.8%, and 17.9%; 0.3%, 5.0%, 6.5%, and 8.6%; and -2.3% , 1.8%, 3.4%, and 2.9%. According to the data, the average strength reduction rate of JD-HBRAC can reach about 18.0%, and the compressive strength decreases obviously after the replacement ratio of JD-RCA is higher than 25%. Therefore, it can be ensured that the compressive strength of HBRAC and JD-RCA is only suitable for replacing natural aggregate with low content, and the best replacement ratio is 25%. The average strength reduction rate of RCA after particle-shaping treatment is obviously lower and even lower than 3.5% after two-time particle shaping. It is worth noting that when the replacement ratio of RCA by two-time particle shaping is 25%, the compressive strength of HBRAC prepared by replacing the natural aggregate is even higher than that of natural aggregate concrete, which is because the performance of aggregate after two-time particle shaping is more stable, the shape is closer to spherical, the surface-hardened mortar is removed more fully, the aggregate gradation is more reasonable, and the combination effect with cement paste is better, so the concrete prepared by HBRAC can achieve a higher strength.

4.2. Effect of Cementitious Material Content on Mechanical Properties of HBRAC

Figure 5 shows the effect of cementitious material content on the compressive strength of RAC.

It can be seen from Figure 5 that the cementitious material content keeps a high consistency with the strength growth law, and the cementitious material content has a great influence on the mechanical properties of HBRAC, and the strength growth rate can reach about 35%. When the replacement ratio of RCA is 100%, the cementitious material content is increased from 300 kg/m^3 to 400 kg/m^3 , and the compressive strength of JP-HBRAC, KL-HBRAC, and EKL-HBRAC is increased by 11.5 MPa, 12.7 MPa and 11.9 MPa, respectively, and the strength growth rates are 38.6%, 35.4%, and 32.9%, respectively. The increase of compressive strength is because the more cementitious materials are used, more hydration products are obtained by reacting with water, and there is a better combination effect with aggregate, so that the structure of HBRAC is denser; thus, it significantly improves the mechanical properties of HBRAC. In addition, the strength growth rate of HBRAC with different quality aggregates is different. The strength growth rate of JP-HBRAC is the largest, KL-HBRAC is the second, and EKL-HBRAC is the smallest. This is because, on the one hand, high belite sulfoaluminate cement has the effect of rapid setting and hardening; it can accelerate the hydration process of cement, and form a large amount of ettringite in the early stage. The accumulation of ettringite itself and the volume increase in the reaction process, that is, the micro-expansion performance, not only fill the internal voids of RCA, but also improve the interface weak layer to a certain extent in a short time. On the other hand, compared with ordinary Portland cement, the gel types in this cement are more aluminum glue, which can enhance the bonding strength to the interface zone of RCA during the reaction process. Therefore, with the increase of the cementitious material content, the more ettringite and aluminum glue produced, the better the effect of improving the void and interface structure of low-quality RCA with more internal voids, and the higher the strength growth rate.

Figure 5. Effect of cementitious material content on compressive strength of RAC: (a) JD-HBRAC, (b) KL-HBRAC, and (c) EKL-HBRAC.

4.3. Comparison of Mechanical Properties between HBRAC and OPRAC

Figure 6 shows the comparison of compressive strength of high belite sulphoaluminate cement-based recycled aggregate concrete (HBRAC) and ordinary Portland cement-based recycled aggregate concrete (OPRAC) at different ages with different cementitious material content when the replacement ratio of three kinds of RCA is 100%.

It can be seen from Figure 6a that the compressive strength of JD-HBRAC, KL-HBRAC, and EKL-HBRAC in 1 d reaches 73.8%, 73.9%, and 79.8% of the 28 d compressive strength, respectively, the 28 d compressive strength values are 29.8 MPa, 34.1 MPa, and 36.2 MPa, respectively, and the 150 d compressive strength can reach 38.9 MPa, 43.3 MPa, and 45.4 MPa, respectively. The compressive strength of JD-OPRAC, KL-OPRAC, and EKL-OPRAC at 1 d is 30.6%, 29.7%, and 33.1% of the 28 d compressive strength, it is 27.8 MPa, 33.7 MPa, and 34.4 MPa at 28 d, and it is 35.6 MPa, 40.2 MPa, and 43.9 MPa at 150 d, respectively. Comparing the data of the two groups, it can be seen that HBRAC has fast hardening performance in the early stage, and the compressive strength of 1 d can reach more than 70% in 28 d, which is much higher than OPRAC. At 28 d and 150 d of age, HBRAC still maintained high intensity and was slightly higher than OPRAC. This is due to the rapid reaction between sulphoaluminate and gypsum in the early stage, which produces a large amount of aluminum gum and gel, and quickly combines with RCA to form a whole to achieve short-term improvement of concrete strength. In the later stage, the interlaced bonding of ettringite with gel and aluminum glue not only enhances the encapsulation force of aggregate and improves the compactness of concrete, but also changes its internal structure and makes it more compact and firmer as a whole. Therefore,

HBRAC not only has early strength and quick hardening, but also can maintain a higher strength value in the middle and late stages.

Figure 6. Comparison of compressive strength of HBRAC and OPRAC at different ages: (a) cementitious material content 300 kg/m³, (b) cementitious material content 400 kg/m³, and (c) cementitious material content 500 kg/m³.

It can be seen from Figure 6 that the 150-day compressive strength of HBRAC is 2.6 MPa, 3.9 MPa, and 6.0 MPa higher than that of OPRAC on average when the cementitious material content varies from 300 kg/m³, 400 kg/m³, and 500 kg/m³, respectively. It can be seen that with the increase of cementitious materials, the greater the difference of compressive strength between the two kinds of cement concrete and the greater the advantage of HBRAC, which shows that the more cement particles in HBRAC, the better the combination of gel and aggregate formed after hydration reaction, and the denser the structure, the easier it is to form a gap with OPRAC in compressive strength.

4.4. Effect of RCA Quality and the Replacement Ratio on Shrinkage Performance of HBRAC

Figure 7 shows the effect of RCA quality and the replacement ratio on drying shrinkage of RAC under different cementitious material contents. In the figure, NA represents natural aggregate concrete; JD-50%, KL-50%, and EKL-50% respectively represent simple crushed recycled concrete, one-time particle-shaped recycled concrete, and two-time particle-shaped recycled concrete with an aggregate replacement ratio of 50%. JD-100%, KL-100%, and EKL-100% respectively represent simple crushed recycled concrete, one-time particle-shaped recycled concrete, and two-time particle-shaped recycled concrete with an aggregate replacement ratio of 100%.

Figure 7. Effect of RCA quality and the replacement ratio on drying shrinkage of HBRAC: (a) cementitious material content 300 kg/m^3 , (b) cementitious material content 400 kg/m^3 , and (c) cementitious material content 500 kg/m^3 .

As can be seen from Figure 7, with the improvement of RCA quality, the shrinkage rate of HBRAC decreases. The shrinkage of EKL-HBRAC is the smallest, KL-HBRAC is the second, and JD-HBRAC is the largest and obviously higher than KL-HBRAC and EKL-HBRAC. This is due to the fact that there are still a large number of slurries with high water absorption on the surface of JD-RCA, and the elastic modulus of the aggregate that can inhibit shrinkage is low. However, one-time particle shaping can remove the old interface of aggregate old mortar, improve the overall elastic modulus, and greatly narrow the performance gap with natural aggregate. Two-time particle shaping can consolidate or even improve the aggregate performance, and the shrinkage performance can even be compared with that of natural aggregate, which further shows that the particle-shaping method has significant advantages in improving the shrinkage performance of RAC.

From Figure 7, it also can be seen that the replacement ratio of RCA has no less influence on the drying shrinkage performance of green concrete than the quality of RCA. The contraction values of JD-HBRAC and KL-HBRAC increased with the increase of the replacement ratio. This is because the higher the replacement ratio of RCA with a high water absorption rate, the more water the concrete needs to meet the slump of the project; that is, the water-binder ratio increases, which leads to more and more capillary channels formed by continuous water evaporation in concrete, and the negative pressure value in the holes becomes larger, which increases the drying shrinkage of concrete. For EKL-HBRAC, the shrinkage of EKL-HBRAC is smaller than that of natural concrete when the replacement ratio is 50%, and there is little difference between EKL-HBRAC and natural concrete when the replacement ratio is 100%. This is because the secondary shaping of EKL-RCA can

not only greatly reduce the content of the needle-flake aggregate, but also can peel off the surface mortar with high water absorption and make the particle shape of aggregate tend to be spherical, and the aggregate gradation is better, which greatly improves the shrinkage performance of RAC prepared by EKL-RCA.

4.5. Effect of Cementitious Material Content on the Shrinkage Performance of HBRAC

Figure 8 shows the effect of cementitious material content on the drying shrinkage performance of HBRAC under different RCA quality. In the figure, 50%–300 kg/m³, 50%–400 kg/m³, and 50%–500 kg/m³ refer to recycled concrete with cementitious materials of 300 kg/m³, 400 kg/m³, and 500 kg/m³, respectively, on the premise that the aggregate replacement ratio is 50%. The values of 100%–300 kg/m³, 100%–400 kg/m³, and 100%–500 kg/m³ refer to recycled concrete with cementitious materials of 300 kg/m³, 400 kg/m³, and 500 kg/m³, respectively, on the premise that the aggregate replacement ratio is 100%.

Figure 8. Effect of cementitious material content on the drying shrinkage performance of RAC: (a) JD-HBRAC, (b) KL-HBRAC, and (c) EKL-HBRAC.

It can be seen from Figure 8 that the cementitious material content has obvious influence on the shrinkage performance of green concrete. With the increase of cementitious material content, the shrinkage rate increases. Specifically, compared with 300 kg/m³ of cementitious material, the 180-day shrinkage of HBRAC with 400 kg/m³ of cementitious material increased by about 17.6%–20.1%, and that of HBRAC with 500 kg/m³ of cementitious material increased by about 32.7%–37.6%. The analysis of the above data shows that it is caused by the joint action of the two aspects. On the one hand, regarding the cement cementitious material as a flexible material of cementitious bonding, the greater its content,

the stronger its flexible effect and the greater its absolute shrinkage. On the other hand, regarding aggregate as a rigid material, the less its content, the weaker its rigid shrinkage inhibition ability.

4.6. Comparison of the Shrinkage Performance between HBRAC and OPRAC

Figure 9 shows the comparison of the drying shrinkage performance of high belite sulphoaluminate cement-based recycled aggregate concrete (HBRAC) and ordinary Portland cement-based recycled aggregate concrete (OPRAC) at different ages with different cementitious material content when the replacement ratio of the three kinds of RCA is 100%.

Figure 9. Comparison of drying shrinkage performance of HBRAC and OPRAC at different ages: (a) cementitious material content 300 kg/m^3 , (b) cementitious material content 400 kg/m^3 , (c) and cementitious material content 500 kg/m^3 .

As can be seen from Figure 9a, the 180-day shrinkage values of JD-OPRAC, KL-OPRAC, and EKL-OPRAC are 566.2×10^{-6} , 606.8×10^{-6} , and 726.1×10^{-6} , respectively, while the 180 d shrinkage values of JD-HBRAC, KL-HBRAC, and EKL-HBRAC are 129.2×10^{-6} , 147.7×10^{-6} , and 178.2×10^{-6} , respectively. Compared with OPRAC, the drying shrinkage is reduced by 77.2%, 75.7%, and 75.5%, respectively. In addition, the shrinkage curve of HBRAC at 45 d is basically flat, and its shrinkage rate accounted for 80.0%–84.4% of the 180 d shrinkage rate, while the shrinkage curve of OPRAC tends to be flat at 60 d, and its shrinkage rate accounted for 80.0%–84.8% of the 180 d shrinkage rate. It can be seen that the drying shrinkage of HBRAC not only increases slowly, but also is far lower than that of OPRAC, which has excellent anti-drying shrinkage ability and ensures that the shrinkage can be reduced to more than 75%. This is due to the shrinkage compensation of ettringite produced by hydration of anhydrous calcium sulfate in high

belite sulphoaluminate cement, which makes the cement slurry dense, reduces the number of micro-cracks, and improves the overall volume stability of concrete. At the same time, it not only shows that the influence of cement varieties on the shrinkage performance of RAC is far greater than the cementitious material content, aggregate quality, and replacement ratio, but also proves the effectiveness of high belite sulphoaluminate cement in reducing the shrinkage of RAC.

4.7. Microstructural Analysis

Drying shrinkage is the shrinkage deformation caused by water loss in the inner void of concrete, which results in the generation of dry shrinkage cracks. In order to study the effect of high belite sulphoaluminate cement and ordinary Portland cement on the dry shrinkage of concrete, the micro-morphology of hydration products of the two kinds of cement at an early stage and 28 d of age were analyzed by SEM under 1000 times, as shown in Figure 10.

Figure 10. SEM images of HBSAC cement paste and OPC cement paste at 1 day and 28 days of age: (a) HBSAC 1 d, (b) HBSAC 28 d, (c) OPC 3 d, and (d) OPC 28 d.

From Figure 10a,b, it can be seen that only small voids exist in HBSAC cement paste structure after hydration for 1 d, which is due to the fact that fine needle-like or coarse needle-like ettringite is wrapped by a large number of flocculent gels, so that the voids can be filled, and the paste structure is denser and only fine cracks appear after hydration for 28 d. As can be seen from Figure 10c,d, there are a lot of deep and large voids in the structure of OPC cement paste after hydration for 3 d, because the early hydration reaction of OPC cement is slow, and the hydration products are mainly lamellar calcium hydroxide and flocculent C-S-H gel, and the voids in the structure of OPC cement paste have not been well filled. After hydration for 28 d, there are still obvious macrovoids in the structure of OPC cement paste. Therefore, HBSAC cement has a fast hydration reaction, dense

paste structure, and few cracks, which can resist drying shrinkage caused by water loss, while OPC cement has slow strength growth and more voids in paste, which increases the number of water loss channels and capillary voids, resulting in the poor drying shrinkage performance of concrete. This proves the effectiveness of preparing recycled concrete with high belite sulphaaluminate cement to improve its shrinkage performance from microscopic aspects.

5. Conclusions

In this study, high-quality recycled coarse aggregate was prepared by recycled aggregate preparation technology and used in recycled aggregate concrete together with high belite sulphaaluminate cement with excellent performance. The effects of the recycled coarse aggregate quality, the replacement ratio of recycled coarse aggregate, and the amount of cement cementitious material on the mechanical properties and shrinkage properties of recycled aggregate concrete were analyzed and compared with those of ordinary Portland cement-based recycled aggregate concrete, and the main conclusions are as follows:

- (1) Compared with the simple crushing strengthening process of recycled aggregate, the particle-shaping and strengthening technology significantly improves the performance indexes of recycled coarse aggregate, and the performance of two-time particle-shaping aggregate is better than that of one-time particle-shaping aggregate, which further proves the effectiveness of preparing high-quality recycled coarse aggregate by particle-shaping method.
- (2) Recycled concrete prepared from recycled coarse aggregate with particle shaping can keep high compressive strength. Compared with natural aggregate concrete, the compressive strength of JD-HBRAC can be reduced by about 18.0%, while the compressive strength of KL-HBRAC and EKL-HBRAC can be reduced significantly; even the compressive strength of EKL-HBRAC can be reduced to less than 3.5%. In addition, the cementitious material content has a great influence on the compressive strength of recycled concrete. With the increase of the cementitious material content, the strength growth rate can reach about 35%.
- (3) The drying shrinkage of recycled concrete prepared by particle-shaped recycled coarse aggregate is obviously lower than that of JD-HBRAC, and even the shrinkage of EKL-HBRAC is comparable to that of natural concrete under the condition of a low replacement rate of recycled aggregate. In addition, the cementitious material content also has a greater influence on the drying shrinkage of recycled concrete. Compared with the cementitious material content of 300 kg/m³, the 180 d shrinkage of HBRAC with the cementitious material content of 400 kg/m³ and 500 kg/m³ increased by about 17.6%~20.1% and 32.7%~37.6%, respectively.
- (4) Compared with ordinary Portland cement-based recycled aggregate concrete, high belite sulphaaluminate cement-based recycled aggregate concrete not only has early strength and quick hardening, but also keeps higher compressive strength in the middle and late stages, and has excellent drying shrinkage resistance, which can ensure that the shrinkage rate can be reduced to more than 75%.

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Abbreviations

RCA	recycled coarse aggregate
JD-RCA	simple crushing recycled coarse aggregate
KL-RCA	one-time particle-shaping recycled coarse aggregate
EKL-RCA	two-time particle-shaping recycled coarse aggregate
HBSAC	high belite sulphoaluminate cement
OPC	ordinary Portland cement
RAC	recycled aggregate concrete
HBRAC	high belite sulphoaluminate cement-based recycled aggregate concrete
OPRAC	ordinary Portland cement-based recycled aggregate concrete
JD-HBRAC	high belite sulphoaluminate cement-based recycled concrete with simple crushed recycled coarse aggregate
KL-HBRAC	high belite sulphoaluminate cement-based recycled concrete with one-time particle-shaping recycled coarse aggregate
EKL-HBRAC	high belite sulphoaluminate cement-based recycled concrete with two-time particle-shaping recycled coarse aggregate

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