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Effect of Composite Impregnation on Properties of Recycled Coarse Aggregate and Recycled Aggregate Concrete

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Abstract: To improve the properties of recycled aggregate concrete, single and composite impregnation treatments were carried out on recycled coarse aggregates with sodium silicate solution, silane slurry, and polyvinyl alcohol solution. The effects of the three chemical modifiers and different impregnation methods on the apparent density, water absorption, and crushing index of recycled coarse aggregates, as well as the basic properties of recycled aggregate concrete, were investigated. Additionally, the microstructure of the surface of recycled coarse aggregate and the interior of recycled aggregate concrete were analyzed by scanning electron microscopy. The experimental results show that the water absorption of recycled coarse aggregate soaked in polyvinyl alcohol solution decreases most significantly, reaching 64.56%. Only the combination of sodium silicate and silane impregnation produces a positive compounding effect, with a significant increase in the apparent density and a significant reduction in the crushing index of the recycled coarse aggregate. Compared with untreated concrete, the slump, compressive strength, splitting tensile strength, and flexural strength of recycled aggregate concrete prepared by sodium silicate and silane composite impregnation are increased by 9.8%, 26.53%, 21.70%, and 14.72%, respectively. The microstructure analysis shows that the composite impregnation treatment of sodium silicate and silane is most conducive to filling the cracks and holes on the surface of recycled coarse aggregate, which makes the interfacial transition zone of recycled aggregate concrete more compact and the structure more stable.

Keywords: recycled aggregate concrete; strengthening aggregate; chemical modifiers; composite impregnation; mechanical property

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1. Introduction

In recent years, a considerable amount of waste has been generated in construction and transformation processes, which has adverse effects on the ecological environment and urban and rural landscape [1]. At the same time, in the process of engineering construction, the consumption of natural sand and stone has increased. To protect natural resources and deal with discarded construction waste, the reuse of construction waste has become a key topic in the field of concrete research internationally, which has attracted the attention of experts and scholars from around the world [2]. Recycling construction waste, crushing, cleaning, and screening into a recycled coarse aggregate (RCA) can not only save natural resources and reduce environmental pollution, but also reduce the cost of aggregate used in construction projects. The direct use of recycled aggregate to prepare concrete will significantly reduce the working performance, mechanical properties, and durability of concrete [3]. The causes of performance defects of recycled aggregate concrete are analyzed in many aspects. From a macro perspective, the physical and mechanical properties of recycled aggregate decrease because of a large number of edges and angles of recycled aggregate particles and initial cracks in the rough surface of hardened cement mortar attached to the surface, such as a decrease in surface density, an increase in water absorption, an increase in crushing index, and an increase in water content [4]. From the microscopic point of view, first of all, there is an old interfacial transition zone (ITZ) between the mortar and the natural aggregate; the porosity of this area is 10% higher than the mortar matrix, and there are many directional arrangements of $Ca(OH)_2$, so the old ITZ is relatively weak [5]. Second, in the mixing process of recycled aggregate concrete, the recycled aggregate will form a more complex ITZ with the new mortar. Due to the adsorption of a large amount of water on the surface of the recycled aggregate, the local water-cement ratio of recycled aggregate concrete is high, increasing pores in the ITZ, resulting in a weaker, new ITZ [6]. To improve the utilization rate of RCA, scholars worldwide have found that strengthening the aggregate is an effective and feasible method.

Contemporary aggregate strengthening methods focus on removing old mortar from the surface of the aggregate, strengthening old mortar, and restructuring the composition of the aggregate, utilizing a variety of physical, chemical, and biological methods. Pedro et al. [7] employed particle-shaping technology to maximize stripping mortar while ensuring the integrity of RCA, thereby enhancing the performance of concrete. Lippiatt et al. [8] used microwave heat treatment of waste concrete to improve the quality of RCA and the recovery of cement by allowing a better separation of aggregate and mortar after impact fracture. Compared with the microwave treatment, the electrical pulses resulted in the higher separation of aggregate and mortar, lower energy consumption, and greater retention of the integrity of the aggregate [9]. Çakır et al. [10] found that the durability of concrete prepared with 60% RCA through the optimized ball mill method was generally higher than that of untreated RCA. Mondal et al. [11] studied the bio–deposition treatment of RCA and found that the $CaCO_3$ generated was on the surface and crevices of the RCA, thereby reducing the water absorption of the RCA and enhancing its surface tension. Tam et al. [12] used three acid solutions to remove the mortar from the RCA surface, effectively reducing the water absorption of the RCA while leaving the alkalinity of the aggregate unaffected. Pavlu et al. [13,14] showed that crystal admixtures could fill the pores in recycled masonry aggregate, thereby improving the mechanical properties and durability of recycled masonry concrete. Spaeth et al. [15] used a polymer impregnation treatment to significantly reduce the water absorption of RCA and improve its resistance to cracking. Christodoulou [16] et al. suggest that silane is a kind of porous liner hydrophobic resin, where the alkoxy (CH_3O) in the molecule contains silicon–oxygen bonds that will bond to the silicate on the RCA surface and the residual organic alkyl (CH_3) will protrude from the pores and be hydrophobic. Park et al. [17] found that sodium silicate reacted with cement hydration product $Ca(OH)_2$ to form C–S–H gel ($Ca–SiO_2$) to fill the pores on the outer surface of RCA, improving the pore structure and surface microcracks. C–S–H gel has the same material properties as concrete and can bond perfectly with new mortar without delaminating the impregnation layer. Bui et al. [18] treated RCA using sodium silicate soaking and a silica fume surface coating to increase compressive strength by 33–50% and tensile strength by 33–41% over untreated concrete. Alqarni et al. [19] studied cement slurry, sodium silicate impregnation, and Los Angeles wear simulation to treat RCA and applied it to high-performance concrete, effectively reducing the water absorption of RCA and improving the performance of concrete. Kou et al. [20] tried to use different concentrations of polyvinyl alcohol (PVA) solution to soak the RCA and found that PVA molecules filled the pores attached to the hardened cement slurry, which made the structure of the RCA denser, reduced the porosity, and greatly reduced the water absorption rate of the aggregate. Pretreatment of RCA with PVA solution can improve the compressive strength of concrete and effectively resist sulfate attack [21]. Xu et al. [22] found that the optimum impregnation time, as well as solution concentration, could be determined using sodium silicate solution, silane slurry, and PVA solution for the RCA impregnation treatment. Most scholars have studied the chemical impregnation RCA in a single solution, but there is still a lack of studies on composite impregnation RCA. In addition, adding fiber [23] to recycled coarse aggregate concrete and adjusting the water–cement ratio [24] can effectively improve the performance of concrete.

Based on the research status of the above scholars, this study selected sodium silicate, silane, and PVA as three kinds of chemical strengthening agents to strengthen the impregnation treatment of RCA, and studied the physical properties of RCA and the basic mechanical properties of recycled aggregate concrete under the single and composite impregnation of these three chemical strengthening agents and analyzed the microstructure of RCA surface and recycled aggregate concrete by scanning electron microscopy.

2. Materials and Methods

2.1. Materials

The test was carried out with ordinary P·O32.5 Portland cement, fine aggregates of machine-made sand, and natural river sand with a fineness modulus of 2.5, and city tap water for mixing. The RCA was obtained from laboratory waste concrete specimens with an initial strength of C30, which were crushed and sieved to obtain RCA with a particle size of 5–31 mm, the interface schematic and grading curves of which are shown in Figures 1 and 2. The natural coarse aggregate (NCA) was made from well-graded crushed stone. The strength decreased as the aggregate replacement rate increased, and the compressive strength and splitting tensile strength were in a relatively flat growth range at a 25% to 50% replacement rate. Therefore, an RCA substitution rate of 25% was chosen for the preparation of the specimens in this study [3].

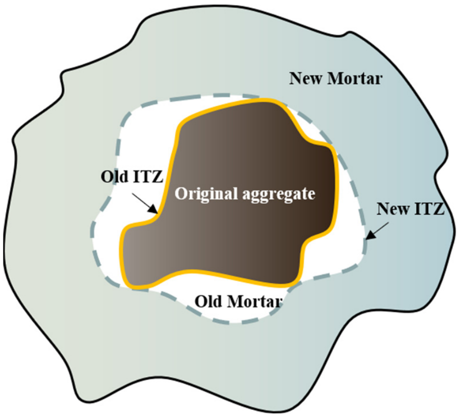


Figure 1. Interfaces of RCA.

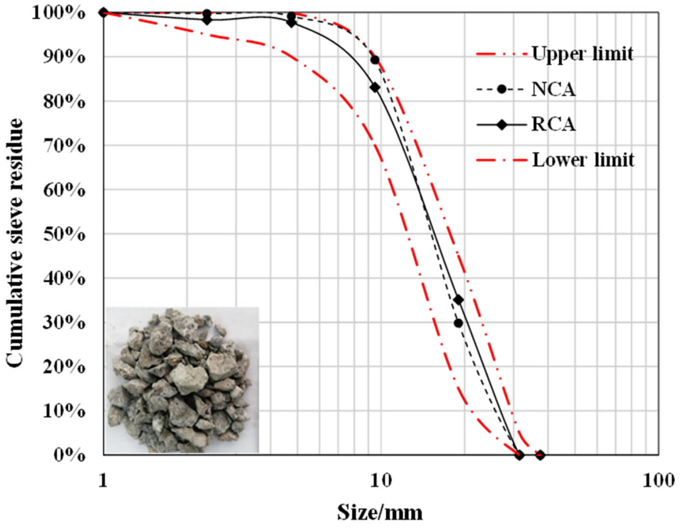


Figure 2. Gradation curve of concrete.

2.2. Impregnation Treatment Methods

According to the research conclusion in [20,22], in this test, three chemical reinforcing agents, a 5% mass fraction sodium silicate solution, an 8% silane slurry, and a 10% PVA solution, were used for the single and compound impregnation of RCA. The impregnation treatment options are shown in Table 1. Single impregnation refers to the impregnation of RCA with a single chemical strengthening agent. S1 was impregnated with sodium silicate solution for 1 h, S2 with silane slurry for 24 h, and P1 with PVA solution for 24 h. After the end of impregnation, the aggregate was dried in a TY/HWHHS–225L–type constant temperature and humidity test chamber (20 °C, 50% relative humidity) manufactured by Shanghai Tingyi Instrument and Equipment Factory and dried until the mass difference after 24 h was less than 1% and then removed. Compound impregnation means using another chemical strengthening reagent to impregnate the treatment RCA again after the end of a single impregnation. S1S2 was impregnated with sodium silicate solution for 1 h and dried, then impregnated with silane slurry for 24 h. S1P1 was impregnated with sodium silicate solution for 1 h and dried, then placed in PVA solution for 24 h. S2P1 was impregnated with silane slurry for 24 h and dried, then placed in PVA solution for 24 h. The microscopic mechanism of the strengthening scheme is shown in Figure 3.

Table 1. Impregnation treatment scheme.

Sample NO	Strengthening Method	Strengthening Type
R0	RCA	Untreated
S1	Sodium silicate solution	Single impregnation
S2	Silane slurry	
P1	PVA solution	
S1S2	Sodium silicate solution + silane slurry	Compound impregnation
S1P1	Sodium silicate solution + PVA solution	
S2P1	Silane slurry + PVA solution	

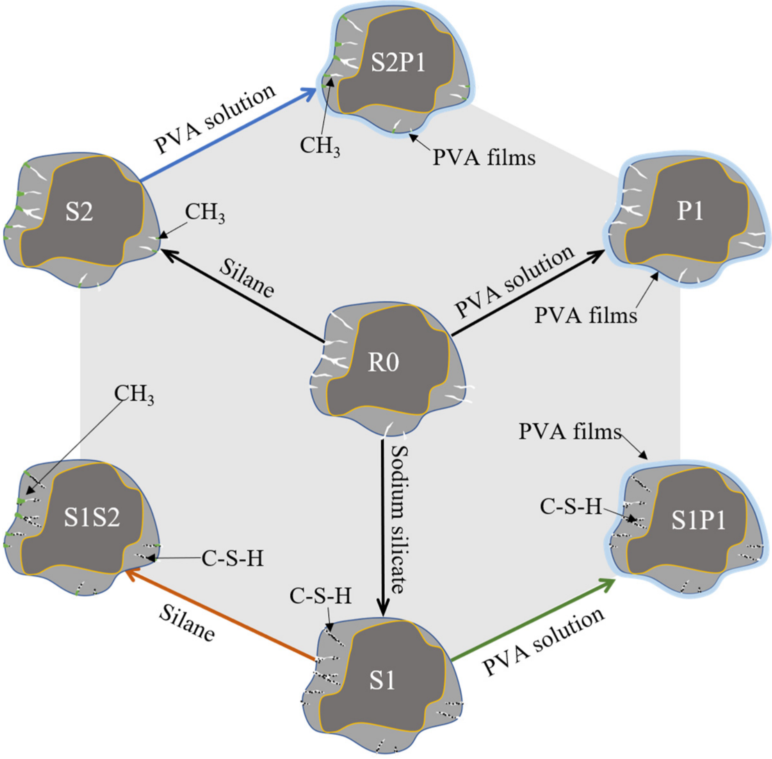


Figure 3. The strengthening principle.

2.3. Preparation of Concrete

To explore the basic mechanical properties of RCA under different treatment schemes, the concrete test block was prepared with the concrete mix ratio shown in Table 2. The concrete design strength was C30. Six cube specimens of 100 mm × 100 mm × 100 mm were prepared in each group for compressive strength and splitting tensile strength tests, and three prism specimens of 100 mm × 100 mm × 400 mm for flexural strength tests. The process of preparing the concrete is shown in Figure 4.

Table 2. Mix ratios of concrete (kg/m^3).

Cement	Water	Coarse Aggregate		Fine Aggregate		Admixture		Water Reducing Agent
		NCA	RCA	Machine–Made Sand	Sand	Fly Ash	Mineral Powder	
220	160	787.5	262.5	370	455	57	104	7.4

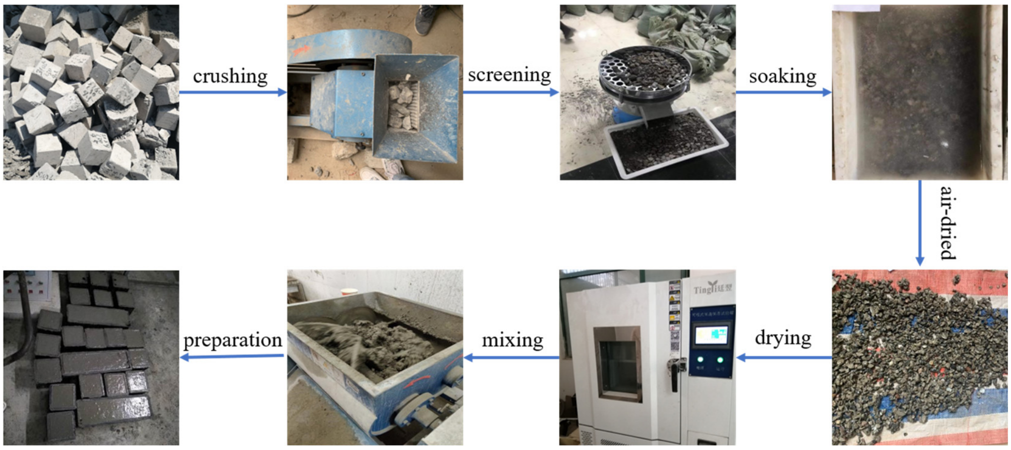


Figure 4. Preparation of concrete.

2.4. Physical Properties Test of RCA

According to the JGJ 52–2006 standard for technical requirements and test method of sand and crushed stone (or gravel) for ordinary concrete [25], the RCA at the end of impregnation was taken out and dried at room temperature to measure its apparent density, water absorption, and crushing index. The physical index test of the RCA is shown in Figure 5a–c. Three samples were tested in each group and the average value was calculated.

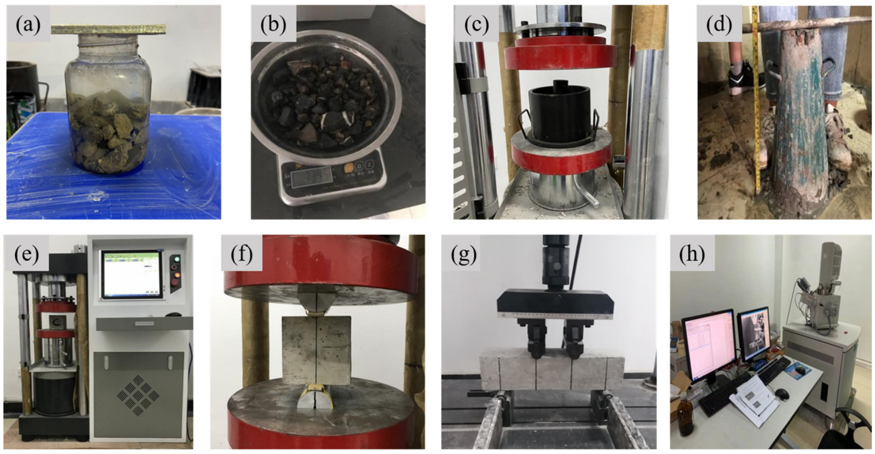


Figure 5. Testing and equipment: (**a**) apparent density; (**b**) water absorption; (**c**) crushing index; (**d**) slump; (**e**) compressive strength; (**f**) splitting tensile strength; (**g**) flexural strength; and (**h**) scanning electron microscopy.

2.5. Concrete Slump and Mechanical Properties Test

The slump of fresh concrete in each group was tested according to the GB/T50080–2002 standard for testing the performance of ordinary fresh concrete [26]; according to the GB/T50081–2019 standard test methods for concrete physical and mechanical properties [27], the specimens were taken out for basic mechanical tests after standard maintenance for 28 days. The concrete slump and mechanical property tests are shown in Figure 5d–g. Three samples were tested in each group and the average value was calculated.

The compressive strength test was carried out using a DYE–2000S microcomputer servo pressure tester (manufactured by Cangzhou Zhulong Engineering Instrument Co., Ltd., Cangzhou City, China) to load the cubic specimen at 0.3 MPa/s, increasing the load until the specimen was destabilized and destroyed, and the data were recorded.

The splitting tensile strength test was carried out using a DYE–2000S microcomputer servo pressure tester to load the test block at 0.3 MPa/s. The center line of the cubic test block was checked for alignment with the center lines of the two half–cylinder mat blocks before loading. As the tester was loaded, the force was transferred to the mat strips; eventually, the test block was broken from the middle and destroyed, and the data were recorded.

Flexural strength tests were performed using a CBT1105–D–type microcomputer–controlled electronic pressure tester (manufactured by MTS SYSTEMS (CHINA) Co., Ltd., Beijing, China) on the rhombus body test block at 0.05 MPa/s speed for loading, then loaded to the bending failure, and the data were recorded.

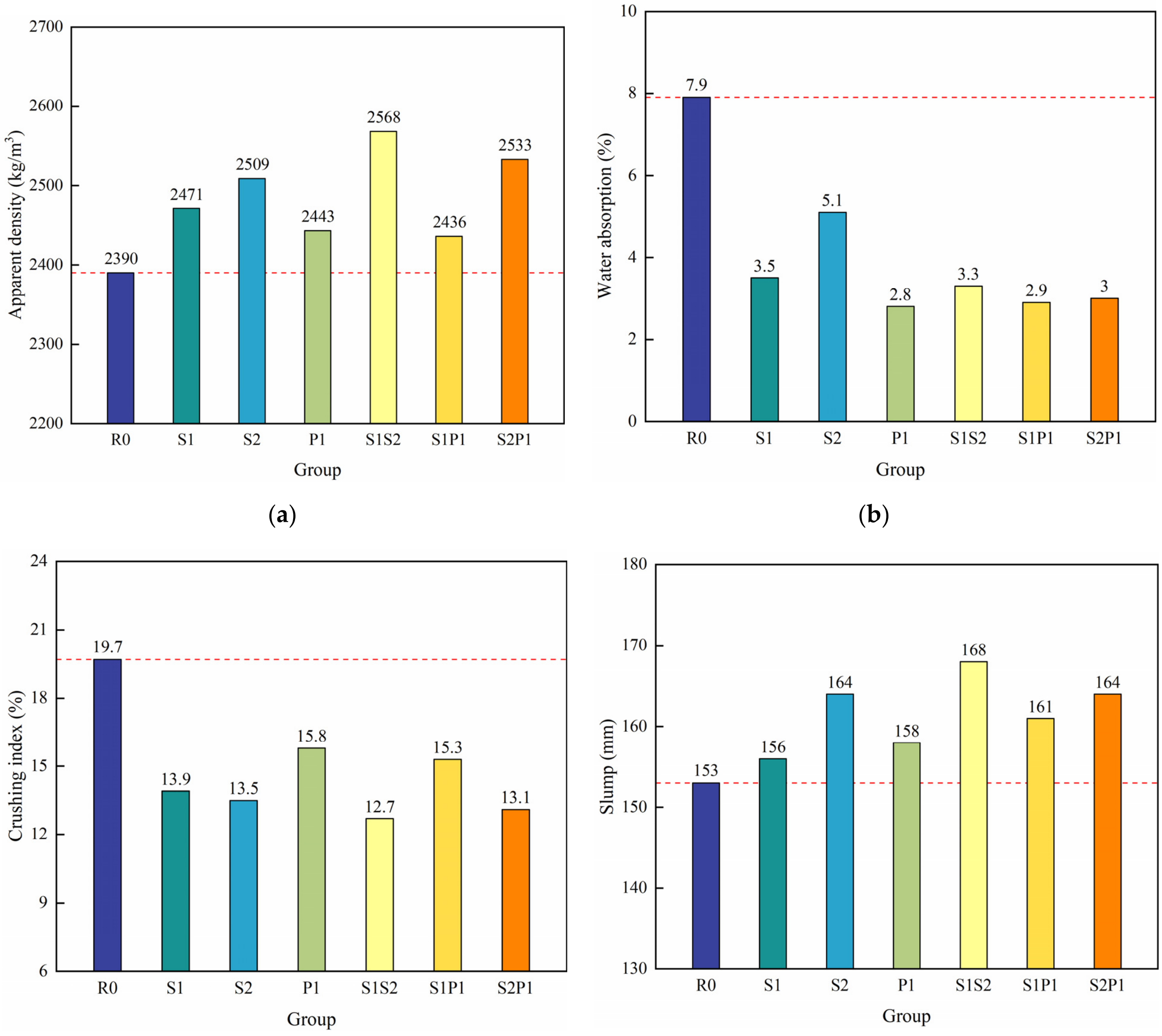
2.6. Microstructure Performance Test

The RCA after strengthening treatment and the specimens after splitting tensile strength test were sampled and dried. The samples were observed by scanning electron microscopy using Shanghai Liepu company's Casi EVO18 model, as shown in Figure 5h.

3. Results and Discussion

3.1. Physical Properties of RCA and Slump

The measurement results of the apparent density, water absorption, and crushing index of RCA are shown in Figure 6, and the grade standard is presented in Table 3. Figure 6a shows that the apparent density of RCA after strengthening was higher than that of RCA without strengthening, and the apparent densities of S1, S2, P1, S1S2, S1P1, and S2P1 increased by 3.39%, 4.98%, 2.22%, 7.45%, 1.92%, and 5.98%, respectively, compared with R0. The apparent densities of S1, S2, S1S2, and S2P1 were significantly increased to meet the Class I standard. From Figure 6b, it can be seen that the water absorption rate of RCA after strengthening was reduced, and the water absorption rates of S1, S2, P1, S1S2, S1P1, and S2P1 were reduced by 55.70%, 35.44%, 64.56%, 58.23%, 63.29%, and 62.03%, respectively, compared with R0. Among them, P1, S1P1, and S2P1 had significantly lower water absorption rates and met the Class I standard; S2 had a slightly lower water absorption rate, but did not meet the Class II standard. The higher water absorption of S2 compared with the other treated samples is due to the organic alkyl groups produced by the silane accumulating in the cracks and pores of the RCA, but not completely closing the pores and filling the cracks. After the PVA impregnation treatment of RCA, the water absorption rate is significantly reduced because the hydrophobic film formed by PVA on the outer surface of the aggregate effectively isolates water molecules. Figure 6c shows that the crushing indexes of the strengthened RCA were lower than those of the unstrengthened RCA, and the crushing indexes of S1, S2, P1, S1S2, S1P1, and S2P1 were reduced by 29.44%, 31.47%, 19.80%, 35.53%, 22.34%, and 33.50% compared with R0, respectively, but they all failed to meet the Class I standard. Combined with the apparent density, water absorption, and crushing index of RCA in each group, it can be seen that the composite impregnation treatment of sodium silicate and silane had the most prominent improvement effect on the physical index of RCA.



(**a**) (**b**)

(**c**) (**d**)

Figure 6. Physical properties of RCA: (**a**) apparent density; (**b**) water absorption; (**c**) crushing index; and (**d**) slump.

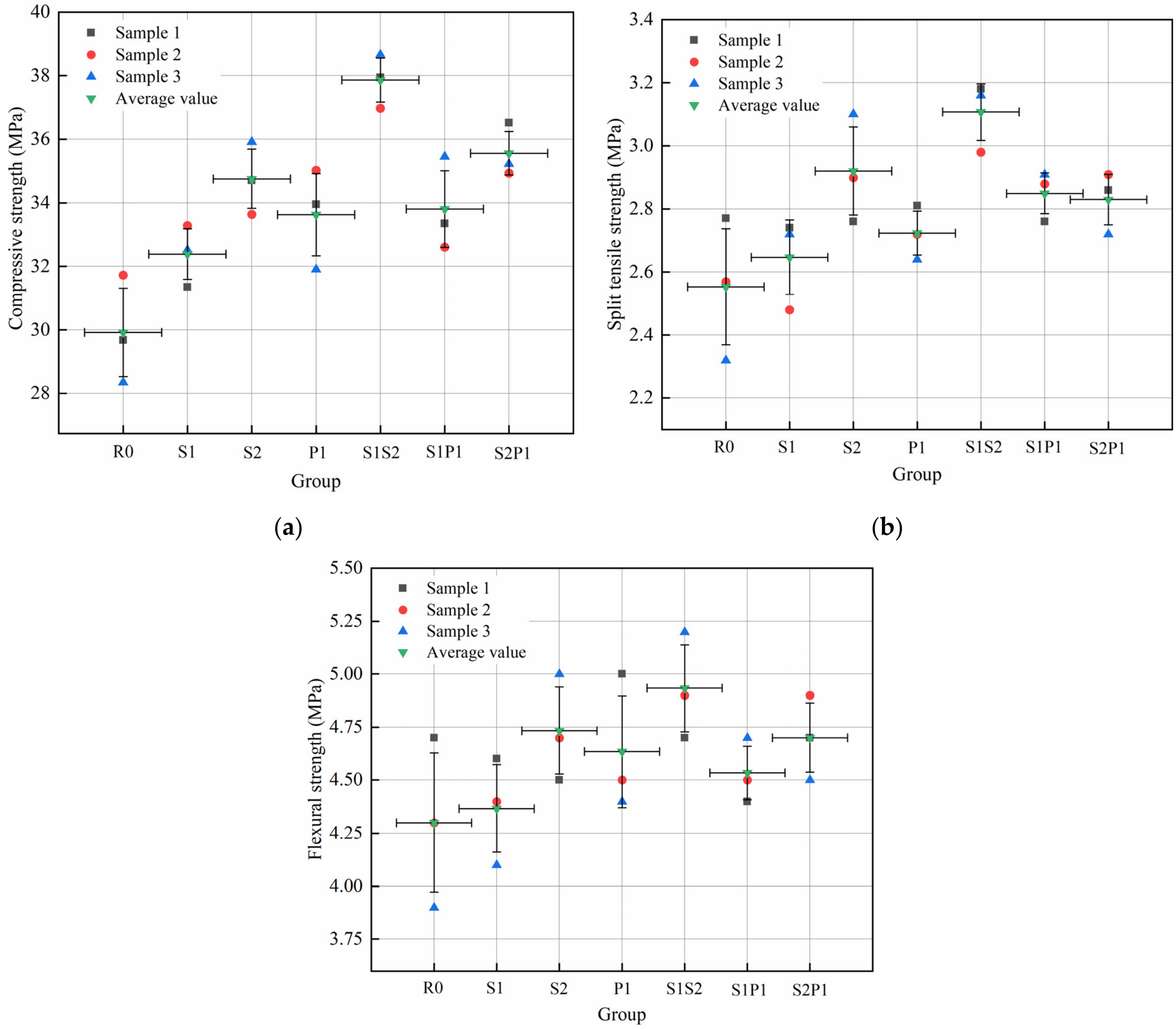
Table 3. Physical performance grade of RCA.

Physical Property	Class I	Class II	Class III
Apparent density (kg/m^3)	>2450	>2350	>2250
Water absorption (%)	<3	<5	<8
Crushing index (%)	<12	<20	<30

Slump is a quantitative index that directly reflects the working performance of concrete, and the slump test results of each group of recycled aggregate concrete are shown in Figure 6d. Compared with R0, the slump values of S1, S2, P1, S1S2, S1P1, and S2P1 increased by 1.96%, 7.19%, 3.27%, 9.80%, 5.23%, and 7.19%, respectively. Among them, the composite impregnation of sodium silicate and silane exhibited the best improvement on the slump, which could be increased to 168 mm. It can be seen from Figure 6b that the chemical strengthening agent could effectively reduce the water absorption of RCA; thus, under the same amount of mixing water, the slump of recycled aggregate concrete after strengthening treatment was higher. Moreover, the chemical strengthening agent treatment made up for the surface defects of aggregate, making the aggregate surface smoother, reducing the friction between concrete slurry and the outer surface of RCA, further improving the workability of recycled aggregate concrete and increasing the slump [28].

3.2. Basic Mechanical Properties of Recycled Aggregate Concrete

The test results of compressive strength, splitting tensile strength, and flexural strength of concrete samples in each group are shown in Figure 7. There are many pores and micro-cracks in RCA after secondary crushing, resulting in the transition zone of the RCA interface being different from the transition zone of slurry and aggregate bonding surface formed by ordinary concrete materials, and its structure is more complex. The action of external force is more likely to produce crack tip stress concentration phenomena, with crack propagation throughout, resulting in a lower R0 compressive strength, splitting tensile strength, and flexural strength than ordinary concrete [29].



(**a**) (**b**)

(**c**)

Figure 7. Mechanical properties of recycled aggregate concrete: (**a**) compressive strength; (**b**) splitting tensile strength; and (**c**) flexural strength.

Figure 7a shows that the compressive strengths of S1, S2, P1, S1S2, S1P1, and S2P1 increased by 8.25%, 16.17%, 12.40%, 26.53%, 12.99%, and 18.85% compared with R0, respectively. It can be seen that the composite impregnation of sodium silicate and silane is the most favorable to improving the compressive strength of RCA, whereas the single impregnation and composite impregnation of sodium silicate and PVA are not obvious. It can be seen from Figure 7b that the splitting tensile strengths of S1, S2, P1, S1S2, S1P1, and S2P1 increased by 3.68%, 14.38%, 6.66%, 21.70%, 11.63%, and 10.85% compared with R0, respectively. It can be seen that the single silane impregnation and the composite impregnation of sodium silicate and silane had the greatest impact on improving the splitting tensile strength of RCA. It can be seen from Figure 7c that the flexural strengths of S1, S2, P1, S1S2, S1P1, and S2P1 increased by 1.56%, 10.07%, 7.74%, 14.72%, 5.42%, and 9.30% compared with R0, respectively, and the enhancement effect of group S1S2 was the best. For the basic mechanical properties of recycled aggregate concrete specimens treated with different impregnation methods, single impregnation and composite impregnation can improve the basic mechanical properties of recycled aggregate concrete, and the cubic compressive strength, splitting tensile strength, and flexural strength of recycled aggregate concrete treated by sodium silicate and silane composite impregnation are significantly increased.

The initial defects of recycled aggregate concrete specimens lead to considerable discreteness of the basic mechanical property test results. Figure 7 shows the standard deviations of compressive, splitting tensile, and flexural strength of recycled aggregate concrete under different strengthening treatments. The standard deviation of recycled aggregate concrete strength after the strengthening treatment was lower than that for R0. It can be seen that the treatment of a chemical strengthening agent exerted an obvious improvement effect on the discreteness of the basic mechanical test results of concrete, especially in the splitting tensile strength test.

3.3. The Enhancement Coefficients

According to the basic mechanical test results, the enhancement coefficients of cubic compressive strength, splitting tensile strength, and flexural strength of recycled aggregate concrete specimens could be calculated. The calculation formula is shown in Equation (1).

$$\alpha_i = \frac{f_i}{f_{i0}}, (i = 1, 2, 3) \tag{1}$$

where α_i represents the enhancement coefficient of recycled aggregate concrete specimens, f_i represents the strength of recycled aggregate concrete specimens after strengthening, f_{i0} represents the strength of recycled aggregate concrete specimens without strengthening, and 1, 2, and 3 represent the cube compressive strength, splitting tensile strength, and flexural strength of specimens, respectively.

According to Equation (1), when $\alpha_i > 1.0$, the impregnation strengthening treatment can enhance the basic mechanical properties of recycled aggregate concrete. When $\alpha_i < 1.0$, the impregnation strengthening treatment will weaken the basic mechanical properties of recycled aggregate concrete. The strength test results and the enhancement coefficient are shown in Table 4.

Table 4. Mechanical properties and enhancement coefficient.

Sample NO	Compressive Strength/MPa	α_1	Split Tensile Strength/MPa	α_2	Flexural Strength/MPa	α_3
R0	29.920	1.000	2.553	1.000	4.300	1.000
S1	32.387	1.082	2.647	1.037	4.367	1.016
S2	34.757	1.162	2.920	1.144	4.733	1.101
P1	33.630	1.124	2.723	1.067	4.633	1.077
S1S2	37.857	1.265	3.107	1.217	4.933	1.147
S1P1	33.807	1.130	2.850	1.116	4.533	1.054
S2P1	35.560	1.189	2.830	1.108	4.700	1.093

Analysis of the data in Table 4 shows that the α values for each group of specimens are greater than 1.0, meaning that the impregnation strengthening treatment is effective in improving the basic mechanical properties of recycled aggregate concrete.

The compound effect coefficient of the chemical intensifier can be analyzed by the composite effect coefficient of the three chemical enhancers. The formula for calculating the compound effect coefficient is shown in Equation (2).

$$\beta_i = \frac{\alpha_{j,k}}{\alpha_j \alpha_k}, (i, j, k = 1, 2, 3, j \neq k) \tag{2}$$

where β_i is the composite effect coefficient, $\alpha_{j,k}$ is the enhancement coefficient of specimens S1S2, S1P1, and S2P1 treated by composite impregnation, and α_j and α_k are the enhancement coefficients of specimens S1, S2, and P1 treated by single impregnation. When $\beta_i > 1.0$, it indicates that the composite impregnation treatment produces a positive composite effect, and when $\beta_i < 1.0$, it indicates that the composite impregnation treatment produces a negative composite effect.

Table 5 is the composite effect coefficient of the cubic compressive strength, splitting tensile strength, and flexural strength of recycled aggregate concrete specimens after composite impregnation treatment. It can be seen from Table 5 that the basic mechanical properties of recycled aggregate concrete specimens formed a composite effect after composite impregnation with different strengthening agents. Only the β values of the cubic compressive strength, splitting tensile strength, and flexural strength of group S1S2 were greater than 1.0, indicating that the composite impregnation of sodium silicate and silane had a positive composite effect, which effectively improved the basic mechanical properties of recycled aggregate concrete specimens. The β value of the splitting tensile strength of group S1P1 was 1.009, which showed that the composite impregnation of sodium silicate and PVA only had a positive composite effect on the splitting tensile strength, which effectively improved it. The β values of cubic compressive strength and flexural strength were less than 1.0. The β values of cubic compressive strength, splitting tensile strength, and flexural strength of group S2P1 were less than 1.0, indicating that the composite impregnation of silane and PVA only had a negative composite effect, which could not significantly improve the basic mechanical properties of recycled aggregate concrete.

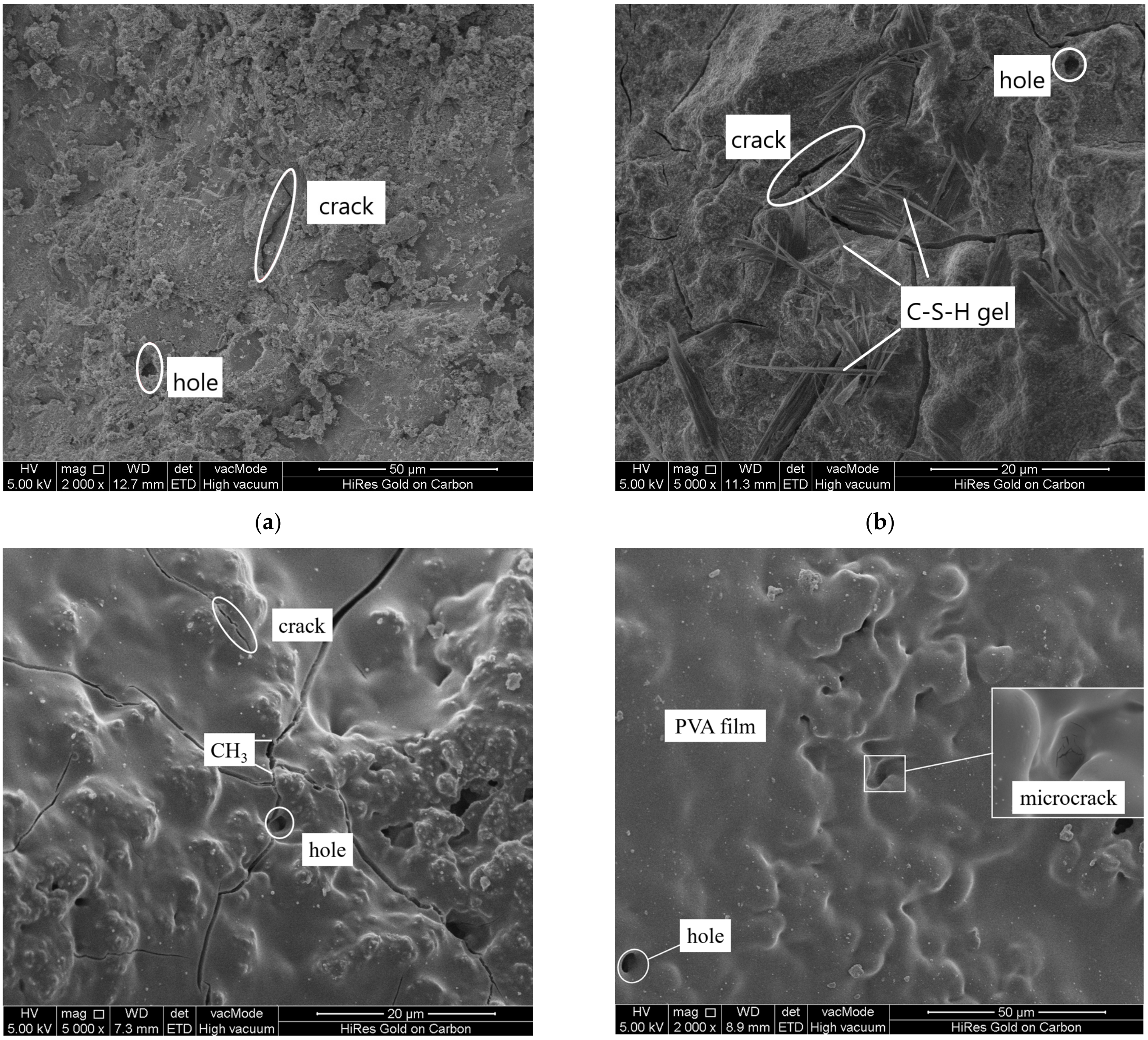
Table 5. Composite effect coefficient of recycled aggregate concrete after composite impregnation.

Sample NO	β_1	β_2	β_3
S1S2	1.006	1.026	1.025
S1P1	0.929	1.009	0.963
S2P1	0.910	0.908	0.922

4. Micro–Analysis of RCA and Recycled Aggregate Concrete

4.1. Surface Microstructure of RCA

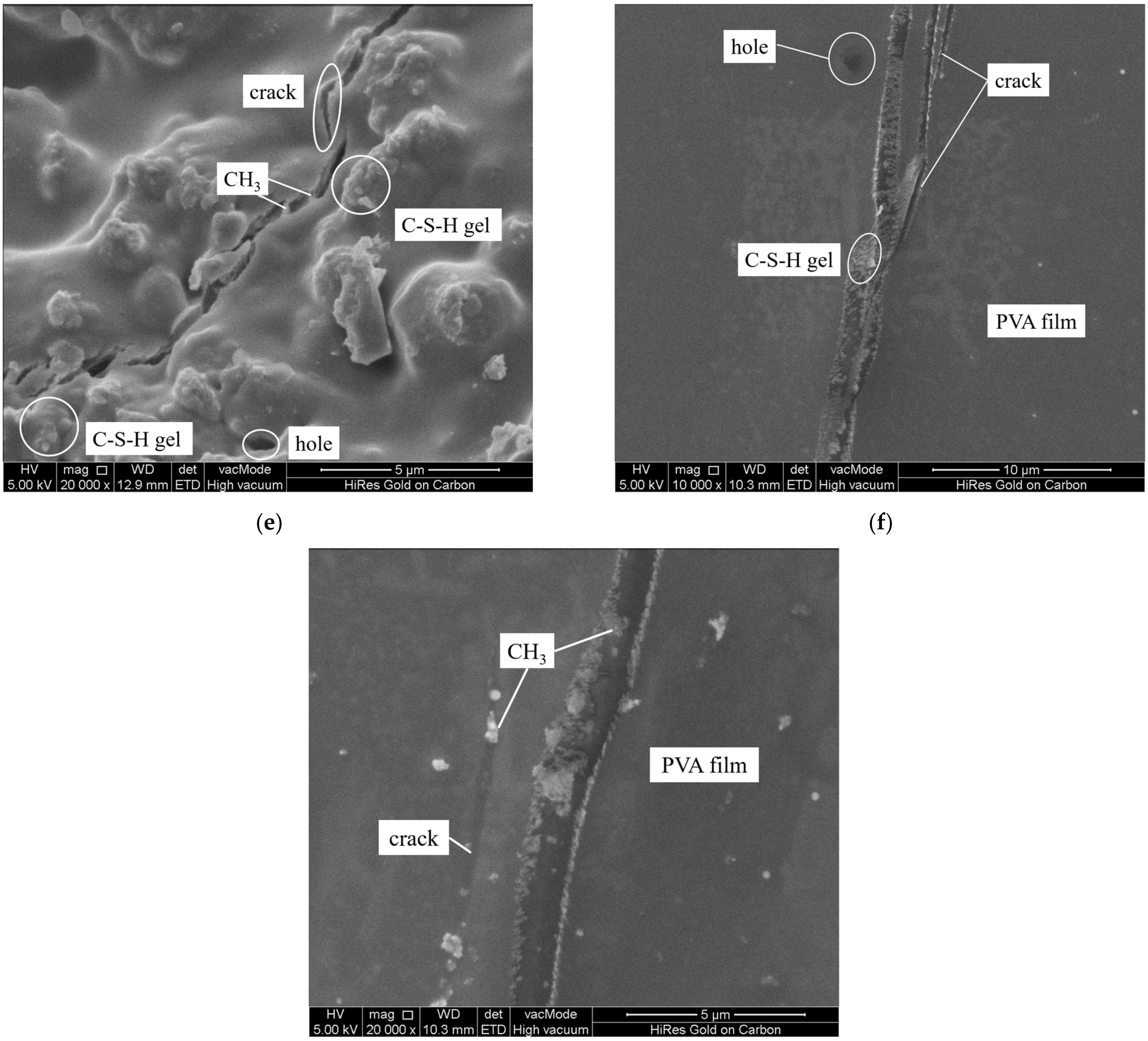
Figure 8 shows the scanning electron microscopy images of the outer surface of the RCA after different strengthening methods. It can be seen that the outer surface of the R0 aggregate is covered with many pieces of old mortar, which are rough and uneven, with many cracks and holes. The outer surface of S1 aggregate is smoother than that of R0 because many strip–shaped gel particles of C–S–H formed by the reaction of sodium silicate with the cement hydration product $Ca(OH)_2$ in the old mortar on the aggregate surface bridge and interpose between cracks to fill the cracks. The accumulation effect of hydrophobic organic alkyl groups in the cracks and pores on the outer surface of the S2 aggregate is obvious, which effectively improves the loose and porous condition of the aggregate surface. The outer surface of the P1 aggregate is covered with a layer of PVA film, which makes its surface very smooth, although the PVA film does not repair the internal micro–cracks better. The flexible network structure generated by the C–S–H gel aggregates on the outer surface of the S1S2 aggregate and forms a fine hoop effect, which makes the surface more compact. The CH_3 accumulation formed by the reaction of silane and cement mortar is wrapped with a layer of resin products, which further refines and seals the pores of the RCA. There are many strip junctions in the cracks on the outer surface of S1P1 aggregate, interspersed in the cracks to form a network structure to create a bridge, and the outer surface is very smooth because of the coverage of PVA film. However, sodium silicate filled the cracks and pores and PVA film only covered the surface, and there was no effective bonding between the two. There are many granular materials accumulated in the cracks of S2P1, which are formed by the tight combination of organic alkyl groups formed by silane, and the film formed by PVA covers the surface of the aggregate to make the surface of the aggregate smooth. It can be seen that the surface of RCA treated by silane single impregnation, sodium silicate, and silane composite impregnation has the closest stacking structure and the best repair effect on holes and cracks.



(**a**) (**b**)

(**c**) (**d**)

Figure 8. *Cont.*



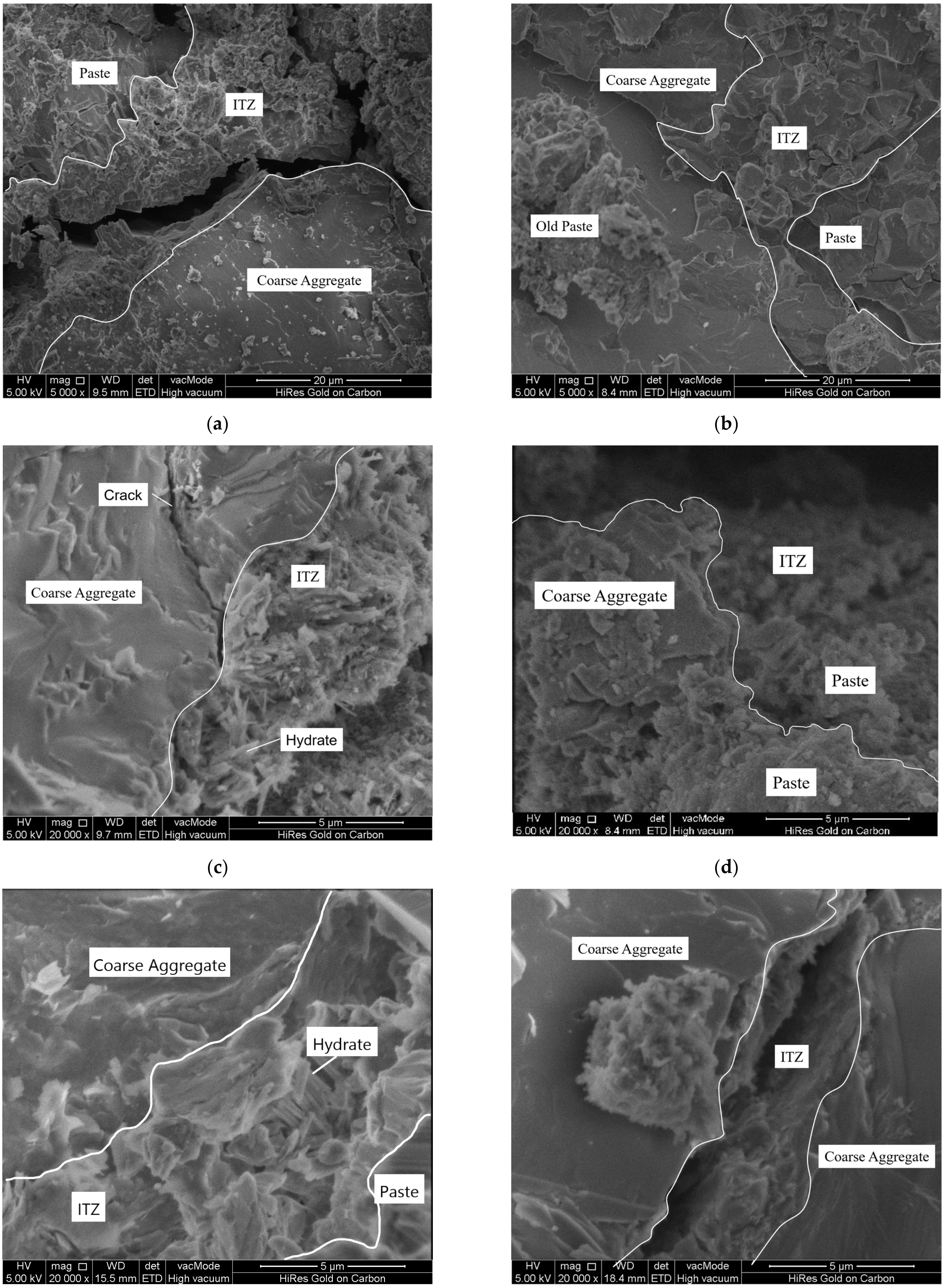
(**e**) (**f**)

(**g**)

Figure 8. Micromorphology of the outer surface of RCA after different strengthening methods: (**a**) R0; (**b**) S1; (**c**) S2; (**d**) P1; (**e**) S1S2; (**f**) S1P1; and (**g**) S2P1.

4.2. Analysis of the Internal Microstructure of Recycled Aggregate Concrete

Figure 9 shows the microstructure of the ITZ of recycled aggregate concrete treated by different strengthening methods. It can be seen from Figure 9 that the ITZ of R0 is loose and there are many penetrating cracks. The boundary between new and old mortars is obvious, and the hydration products are rare.

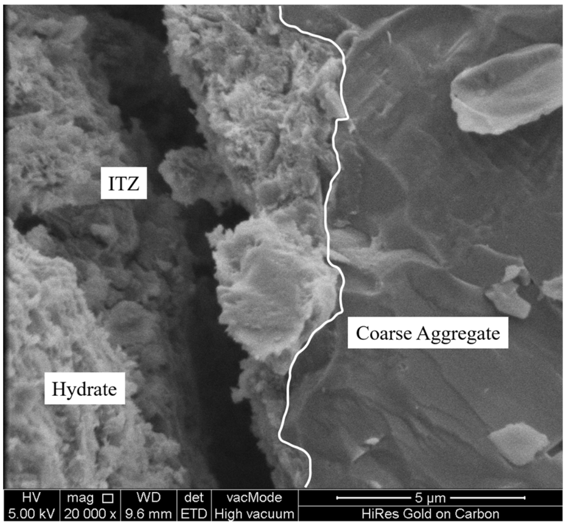


(**a**) (**b**)

(**c**) (**d**)

(**e**) (**f**)

Figure 9. *Cont.*



(**g**)

Figure 9. Micromorphology of interfacial transition zone of recycled aggregate concrete treated by different strengthening methods: (**a**) R0; (**b**) S1; (**c**) S2; (**d**) P1; (**e**) S1S2; (**f**) S1P1; and (**g**) S2P1.

S1 has a clear boundary between the new and old mortars, but there is no obvious crack in the ITZ. This is because when the RCA makes contact with the cement mortar, the hydrolysis products of sodium silicate on the aggregate surface and in the pores can react with Ca^{2+} and Al^{3+} in the hydration products of cement to generate calcium silicate hydrate and calcium aluminate hydrate, thus accelerating the hydration and setting of cement [30]. The ITZ of S2 was filled with abundant hydration products, and the surface of the old mortar was covered with an obvious organic alkyl layer, which enhanced the structural compactness. The hydration products in the ITZ of P1 are less, the cracks are obvious, and the interface is loose, which is due to the formation of the hydrophobic film on the aggregate surface by PVA. Although PVA repairs the holes and cracks on the surface, it blocks full contact between the RCA and cement mortar, and PVA itself reacts less with cement mortar. Therefore, the bonding of ITZ is weak, resulting in little enhancement of the basic mechanical properties.

S1S2 has no obvious boundary between the new and old mortars, and the hydration products are rich and exhibit tendentious accumulation, which makes the ITZ tight. The C–S–H gel generated by the reaction of sodium silicate with the cement hydration product $Ca(OH)_2$ in the new mortar can be interspersed in ITZ so that the ITZ structure is quite stable, and there is a covalent bond between the bond product atoms of silane and silicate on the aggregate surface so that its fracture consumes a lot of energy. Therefore, the positive composite effect is produced in the S1S2 group, and the improvement of its basic mechanical properties is the most obvious. The S1P1 interface junction is smooth, as the PVA is wrapped around the surface of the RCA so that the hydrolysis products of the sodium silicate are not in full contact with the cement mortar, therefore the hydration products at the ITZ of the recycled aggregate concrete are needle–like, interspersed, and in small quantities, which is not sufficient to fill the cracks, resulting in the basic mechanical properties not being effectively improved. A large amount of CH_3 generated by the reaction between silane and cement mortar on the aggregate surface is accumulated in the transition zone of the S2P1 interface, which has a filling effect on the voids and cracks, and silane and PVA will form a protective film on the aggregate surface, but the bonding between the two is not tight, so the corresponding negative composite effect will be generated, which makes the improvement of the basic mechanical properties weak. Based on the above analysis, it can be seen that the composite impregnation treatment of sodium silicate and silane has abundant hydration products in the transition zone of the RAC interface, with tight adhesion and stable structure, which has obvious advantages in improving the basic mechanical properties of recycled aggregate concrete.

5. Conclusions

This paper studied single and composite impregnation of RCA with sodium silicate, silane, and PVA solution chemical reinforcement. The physical properties and slump of modified RCA were measured. The modified recycled aggregate concrete was tested for compressive strength, splitting tensile strength, and flexural strength. Scanning electron microscopy images were used to observe the surface of the modified aggregate and the ITZ of the concrete. The following conclusions were reached:

(1) Composite impregnation treatment can comprehensively improve the physical properties of RCA and show higher stability. Among them, the composite impregnation treatment of sodium silicate and silane has the best repair effect on the cracks and holes on the surface of RCA, and the increase of apparent density and the decrease of the crushing index is the most obvious. Using PVA solution single impregnation, sodium silicate, and PVA composite impregnation treatment, the surface of RCA formed a hydrophobic membrane to isolate water molecules, which improved the water absorption of RCA best.

(2) All composite impregnation schemes can effectively improve the working performance of recycled aggregate concrete, in which the composite impregnation of sodium silicate and silane can increase the slump of fresh recycled aggregate concrete slurry by 9.8%.

(3) After impregnation strengthening treatment, the enhancement coefficient of basic mechanical properties of each specimen is greater than 1.0, which shows that three chemical strengthening agents and different impregnation treatments can effectively improve the basic mechanical properties of recycled aggregate concrete. According to the composite effect coefficient, only the composite impregnation of sodium silicate and silane can produce a positive composite effect, which can effectively improve the basic mechanical properties of recycled aggregate concrete specimens. The cubic compressive strength, split tensile strength, and flexural strength are improved by 26.53%, 21.70%, and 14.72%, respectively. The analysis results of the standard deviation of the strength of recycled aggregate concrete show that the treatment of three chemical strengthening agents and different treatment methods have a certain improvement effect on the strong dispersion of recycled aggregate concrete.

(4) According to the analysis of scanning electron microscopy images, the ITZ of recycled aggregate concrete with sodium silicate and silane composite impregnation has rich hydration products and compact accumulation, and the interfacial strengthening and toughening effects are the most obvious. The strengthening effect of sodium silicate and PVA and silane and PVA composite impregnation treatment is not obvious because the hydrophobic film formed by PVA is covered on the surface of aggregate so that the hydrolysis product of sodium silicate and the residual alkoxy group of silane cannot fully contact with cement mortar, and the interface hydration is less and the structure is loose. Compared with single impregnation, the proper composite impregnation scheme can better repair the original defects of RCA and form a denser ITZ, thus improving the mechanical properties of recycled aggregate concrete.

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