

Research Article

Preparation, Performance Test, and Microstructure of Composite Modified Reinforced Concrete

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To investigate whether the compound modification means which mixes modified Polyvinyl chloride (PVC) aggregate and polypropylene fiber in concrete could gain “positive hybrid effect” and cope with more sophisticated engineering circumstances, four groups of test specimens were prepared: concrete doped with unmodified PVC aggregate, concrete doped with modified PVC aggregate, concrete doped with unmodified PVC aggregate and polypropylene fiber, and concrete doped with modified PVC aggregate and polypropylene fiber. The fiber content is 0.9 kg/m^3 , the modified solution content is 1 mol/L NaOH, and the replacement amount of PVC fine aggregate in replacement sand is 0%, 5%, 10%, 20%, and 30%. Mechanical property and durability tests were carried out to compare and analyze the measured compressive strength, splitting tensile strength, flexural tensile strength, water absorption rate, and impact failure energy. Moreover, scanning electron microscopy and XRD diffraction were used to analyze micromorphology and crystal structure of concrete. The test results demonstrate that as the content of PVC aggregate increases, the compressive strength, splitting tensile strength, and flexural tensile strength of the concrete decrease significantly, while the brittleness is improved. Meanwhile, the water absorption rate increases and the impact resistance shows an approximately linear increase trend. Under the same content of PVC aggregate, the most effective way to improve compressive strength is to use modified PVC aggregate. The rapid decrease of compressive strength caused by PVC aggregate can be effectively delayed by doping polypropylene fiber and modified PVC aggregate. Adding polypropylene fiber or using the modified PVC aggregate can improve the brittleness, tensile strength, flexural tensile strength, and impact resistance, but they have different modification and reinforcement effects. The concrete prepared by doping polypropylene fiber and modified PVC aggregate has better performance in tensile strength, flexural tensile strength, brittleness, and impact resistance, and the water absorption and the compressive strength of the concrete are enhanced compared with the normal group. Therefore, composite modified reinforced concrete doped with modified PVC aggregate-polypropylene fiber has broad application prospects.

1. Introduction

In the past one century since the invention of Portland cement in 1824, concrete is the most commonly used construction material. Concrete has the advantages of abundant raw material sources, simple process, low production cost, fire resistance, high strength, strong adaptability, convenient application, etc. However, it also has the disadvantages of heavy dead weight, low tensile and flexural tensile strength, large internal pores, and poor impact resistance. The existing studies of concrete mainly focus on

enhancing the comprehensive properties of green and high-performance concrete, such as durability, high strength, and high workability, rather than a single property [1].

Meanwhile, the global waste plastic pollution is serious. It is simple and environmentally friendly to replace concrete aggregates with plastics such as polyethylene terephthalate (PET) and PVC, which can improve the brittleness and enhance the impact resistance. However, as the mixing amount of plastic increases, the strength decreases and the water absorption increases [2–5], and adding a single material to enhance the performance of concrete can no longer

meet engineering requirements. Scholars have carried out many studies on these issues.

Mohammed et al. [3] used PVC aggregates with different particle sizes obtained from crushed PVC boards to replace sand or stone in concrete, which significantly decrease the slump of concrete and improved the brittleness. When replacing sand with PVC aggregate, the decrease rate of compressive strength and splitting tensile strength is much lower than that when replacing stone. Meanwhile, the water absorption is significantly lower. In their study, the raw materials were obtained through two times of crushing, and the crushing process was complicated and energy-consuming. It is more meaningful to use recycled plastic particles made from recycled waste plastics. Kou et al. [6] used recycled PVC pipe particles and expanded clay to make non-load-bearing lightweight concrete, which has the good properties of low density, high ductility, low shrinkage, and high resistance to chloride ion permeability. Haghghatnejad et al. [7] studied the performance of concrete by replacing sand with the same volume of PVC aggregates under different curing conditions, and they believed that the incorporation of PVC aggregates could decrease the mechanical properties of concrete. Al-Tayeb et al. [8] used vehicle waste plastics as replacement aggregates, finding that the impact resistance significantly improved with the increase of the mixing amount under low-speed impact load. Saxena et al. [9] shredded PET bottles to replace natural coarse and fine aggregates in concrete. Although the concrete had poor compressive strength, as the amount of PET plastic increased, the impact resistance and the energy absorption capacity were improved. Hu et al. [10] replaced the natural fine aggregate with the well-graded regenerated PVC particles and added it to the concrete. With the increase of the replacement amount, the strength and unloading elastic modulus decrease, while the ductility and energy absorption ability are enhanced. Compared with their previous study [3], Mohammed et al. [11] replaced concrete sand with crushed PVC and added silica fume as reinforcement material, finding that PVC particles and cement paste were well bonded. However, the UPV value decreased obviously with the increase of the mixing amount. Alenogines et al. [12] used PVC aggregates mixed with cement and sand to produce a Paver. The results showed that using the new mixture of 1:2:3 (cement + sand + PVC aggregate) is moderately acceptable regarding appearance and it is highly acceptable regarding cost. Hu S et al. [13] added crushed large-diameter PVC particles into concrete. With the increase of mixing amount, the brittleness, ductility, and energy absorption capacity of concrete are enhanced. However, in order to ensure engineering strength, the replacement amount of PVC coarse aggregate should not exceed 20%. Estabraq et al. [14] added 1% and 3% of PVC powder to asphalt concrete. The experimental results show that PVC powder can decrease the rutting depth of asphalt and effectively improve the durability of asphalt pavement. By comprehensively analyzing the study results, we found that the strength of plastic modified concrete decreased significantly and the water absorption increased because of the sidewall effect in the interfacial transition zone between

cement and plastic aggregate and poor bonding effect [3–10]. Therefore, experiments should be carried out to examine whether the modification method of replacing sand in concrete with recycled PVC particles with a particle size of about 1 mm can cause similar changes in strength, brittleness, and impact resistance.

In recent years, considering the decreasing strength and the increasing water absorption of concrete caused by adding plastic particles, the modification of plastics surface by chemical or physical methods has become a study hotspot. Choi et al. [15] added PET plastic particles to a mixer rotating at low speed under high-temperature heating and then added granulated blast furnace slag powder. The plastic particles were approximately spherical, and the surface was coated with a layer of slag powder. The fine aggregate was replaced with modified PET concrete, and the slump of the modified PET concrete increased with the increase of plastic replacement rate. Compared with the experimental results of Albano et al. [16], although the elastic modulus, compressive strength, and splitting tensile strength of the modified PET concrete decreased with the increase of the aggregate replacement rate, the reduction rate was significantly lower than that of ordinary PET concrete. Kan and Demirboğa [17] heated the Expandable Polystyrene (EPS) particles and reduced the volume by 20 times. Although the surface of the modified EPS particles cannot react with the cement matrix, it can improve the performance of EPS concrete, meet the requirements for the strength of non-load-bearing lightweight concrete, and improve the frost resistance of plastic concrete. In order to improve the interface adhesion between plastic particles and the cement matrix, Naik et al. [18] used water, bleach, and bleach + sodium hydroxide solution to treat high-density polyethylene (PE) plastic. Although the treatment results were unsatisfactory, a new idea for modified plastic concrete was provided. Wang et al. [19] used silane coupling agents to realize the interface chemical bonding between organic materials and inorganic materials and used silane coupling agents with different concentrations to treat ABS/PC plastic particles. They found that silane coupling agents can improve the mechanical properties of ABS/PC concrete, and the improvement effect is more obvious with the increase of the plastic content; Jokar et al. [20, 21] treated the rubber particles with 1 mol/L NaOH solution and found that the compressive strength, tensile strength, and flexural strength were significantly improved after the modified treatment. The larger the rubber particles, the better the strength improvement effect after modification. Based on the studies, we believe that physical or chemical modification of plastic particles can significantly enhance various properties. In addition, many scholars added polypropylene fibers to improve the mechanical and impact resistance of concrete. For example, Grdic et al. [22] found that adding polypropylene fibers can improve the tensile strength of concrete but has little influence on compressive strength. Nili et al. [23] found that adding polypropylene fibers can also improve the dynamic mechanical properties of concrete under impact loads. Luo et al. [24] studied the influence of polypropylene fibers with different length-diameter ratios on the properties of concrete

and found that adding polypropylene fibers can decrease the slump of the concrete despite the length-diameter ratio. The concrete added with polypropylene fine fibers has early strength. Compared with the normal concrete and the change laws of compressive resistance, flexural tensile strength and splitting tensile strength are different. However, the compressive resistance, flexural tensile strength, and splitting tensile strength of polypropylene fine fiber concrete increase first and then decrease with the increase of the length-diameter ratio of the fiber. Factors such as shrinkage reduction effects, slump loss, and economy should be considered when determining the optimal doping amount of polypropylene fine fibers. The optimal doping amount of polypropylene fine fibers is 0.9 kg/m^3 . Song et al. [25] carried out relevant experiments and found that the addition of polypropylene fibers can improve the splitting tensile strength, flexural strength, compressive strength, and impact resistance of concrete, and the plastic shrinkage cracks of concrete can be suppressed at the early stage. Choi and Yuan [26] concluded that adding polypropylene fiber and glass fiber could enhance the split tensile strength, but the compressive strength of concrete was not improved. The toughness of concrete was improved. Xu et al. [27] studied the volumetric content and length-diameter ratio of polypropylene fibers. Compared with ordinary concrete, the failure mode of polypropylene fiber concrete is ductile failure, which significantly improves the compressive toughness and postpeak ductility of concrete. However, it has little effect on peak strength, elastic modulus, and plastic strain, and polypropylene fiber content has more significant effects than length-diameter ratio. In addition, in order to more significantly improve the performance of concrete, composite material modification reinforced concrete has become a study hotspot. Xie et al. [28] found the combination of rubber and silica fume exhibited excellent coupling effects on the fracture performance of steel-fiber recycled aggregate concrete, and the best combination is to use 5% rubber and 10% silicon powder content. Mohammed et al. [11] used PVC fine aggregate crushed twice and added silica fume as concrete reinforcement material, finding that PVC particles and cement paste were well bonded; Yang et al. [29] studied the preparation of high-performance concrete by mixing polyvinyl alcohol fiber, imitation steel fiber, and expansion agent, thereby improving the strength, crack resistance and impermeability of concrete. Wang et al. [30] found that adding polypropylene fiber or fine rubber aggregate can improve the fracture energy of concrete. Adding the two materials has a “positive hybrid effect,” significantly increasing overall fracture toughness and reducing brittleness. Although there have been many studies focusing on the use of composite materials modified reinforced concrete, relatively few studies further combine with NaOH to treat material surface.

To sum up, the current study of modified reinforced concrete has transformed from adding a single type of material to multiple types of materials. This is because the “positive hybrid effect” obtained by multiple types of composite modified reinforced concrete can cope with more complex engineering environment [28–30].

Therefore, this study used the triple modification and reinforcement technique of PVC particles modified with NaOH and polypropylene fibers to improve the impact resistance of concrete, so that the rapid decrease of strength and the increase of water absorption caused by PVC aggregate can be delayed. Various properties and microstructures of composite modified reinforced concrete were studied by carrying out cube compression test, split tensile test, flexural test, water absorption test, steel wheel wear test, drop hammer impact test, and SEM and XRD tests, expecting to provide reference for mechanism study and engineering application of modified PVC aggregate-polypropylene fiber composite modified reinforced concrete.

2. Test Part

2.1. Materials. In this study, the cement is P.042.5 Portland cement produced by Anhui Huainan Conch Cement Plant, which complies with the GB175-2018 specification; the fine aggregate is natural Huai River medium sand with a maximum particle size of 4.75 mm and a fineness modulus of 2.68, which conforms to GB/T14684-2011 specification; the coarse aggregate is 4.75–19 mm continuous graded granite crushed stone, which conforms to GB/T14685-2011 specification; the water used in this study is tap water in the laboratory; the modified solution is NaOH standard solution with the concentration of 1 mol/L manufactured by Guangzhou Kyle Chemical Company; PVC aggregate is recycled PVC particles with a particle size of 1 mm and a density of 1.4 g/cm^3 , shown in Figure 1(a). Modified PVC aggregate was immersed in a modified solution for 24 h and then rinsed with water to pH = 7. The modification process is described in Figure 1(b); Figure 1(c) shows the bundled monofilament polypropylene fibers used in the test. The relevant physical performance indicators are listed in Table 1.

2.2. Concrete Specimen Preparation. With C30 ordinary concrete as the standard, the mix proportion was designed in accordance with the provisions of JGJ55-2011, and the water-cement ratio was 0.48. The river sand was replaced with equal volume of PVC aggregate, and the admixture method was used to add 0.9 kg/m^3 polypropylene fiber to the concrete. Therefore, 4 groups of concrete with 18 mixing ratios were designed. The mixing proportions and unit weight are shown in Table 2.

In the following table, NC indicates the normal concrete, RC indicates the reinforced concrete, and, for RC-X-Y-Z, X indicates whether the PVC aggregate replacing the river sand is modified or not, where 1 represents modified and 0 represents unmodified; Y represents whether the fiber is added, where 1 means the fiber has been added, and 0 indicates that the fiber is not added; Z indicates the amount of PVC aggregate added. For example, 5 indicates that 5% of the river sand was replaced with equal volume of PVC aggregate. The weight is the unit weight of six $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ cube specimens.

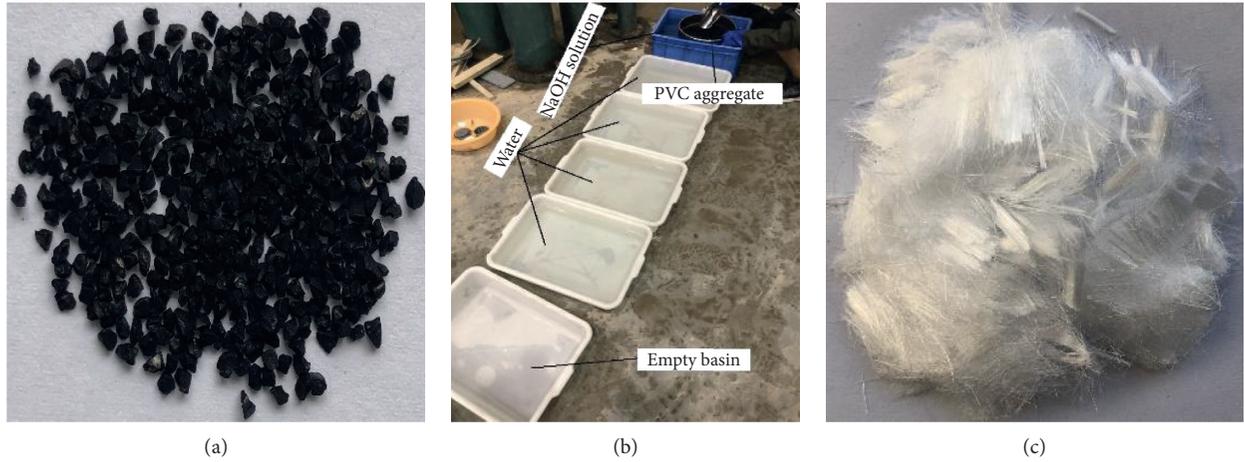


FIGURE 1: Modification process of PVC aggregate and polypropylene fiber used in test. (a) PVC aggregate. (b) Modified treatment process. (c) Polypropylene fiber.

TABLE 1: Physical properties of polypropylene fiber.

Aspect ratio	Length (mm)	Diameter	Density	Elastic modulus (GPa)	Tensile strength	Water absorption
237	9	38 μm	0.91 g/cm^3	4.5	≥ 458 MPa	<0.1%

TABLE 2: Concrete mix proportions and unit weight.

Large group	Specimen	Sand (kg/m^3)	PVC aggregate (kg/m^3)	Polypropylene fiber (kg/m^3)	Unit weight (kg/m^3)	
					Theoretical	Hardened
RC-0-0-Z	RC-0-0-0 (NC)	701	0.0	0.0	2400.0	2375.6
	RC-0-0-5	665.9	20.4	0.0	2385.4	2334.3
	RC-0-0-10	630.9	40.7	0.0	2370.7	2300.9
	RC-0-0-20	560.8	81.4	0.0	2341.4	2248.7
	RC-0-0-30	490.7	122.2	0.0	2312.1	2233.2
RC-0-1-Z	RC-0-1-0	701	0.0	0.9	2400.9	2371.6
	RC-0-1-5	665.9	20.4	0.9	2386.3	2328.7
	RC-0-1-10	630.9	40.7	0.9	2371.6	2302.1
	RC-0-1-20	560.8	81.4	0.9	2342.3	2253.7
	RC-0-1-30	490.7	122.2	0.9	2313.0	2235.6
RC-1-0-Z	RC-1-0-5	665.9	20.4	0.0	2385.3	2332.1
	RC-1-0-10	630.9	40.7	0.0	2370.5	2290.9
	RC-1-0-20	560.8	81.4	0.0	2341.0	2249.7
	RC-1-0-30	490.7	122.2	0.0	2311.5	2235.3
RC-1-1-Z	RC-1-1-5	665.9	20.4	0.9	2386.2	2318.9
	RC-1-1-10	630.9	40.7	0.9	2371.4	2294.1
	RC-1-1-20	560.8	81.4	0.9	2341.9	2254.9
	RC-1-1-30	490.7	122.2	0.9	2312.4	2235.1

As for the concrete mix proportion, the contents of cement, crushed stone, and water are $437.5 \text{ kg}/\text{m}^3$, $1051.5 \text{ kg}/\text{m}^3$, and $210 \text{ kg}/\text{m}^3$, respectively. For the 18 kinds of concrete with different mix proportions, six $100 \text{ mm} \times 100 \text{ mm} \times 100 \text{ mm}$ cube test pieces, three $100 \text{ mm} \times 100 \text{ mm} \times 400 \text{ mm}$ prism test pieces, and three cylindrical test pieces with a diameter of 150 mm and a height of 65 mm were prepared for every kind. A group consists of 3 test pieces, and the average of the three test pieces is taken as the final test result of a set of test pieces.

The preparation process of the test piece is as follows: First, river sand, cement, and fiber were poured into the mixer for dry mixing for 3 minutes. Second, PVC aggregate and crushed stone were added and mixed for 2 minutes. Third, water was added to the mixer and mixed for 2 minutes. Fourth, the mixed concrete was poured to a mold, vibrated, and molded on a shaking table. The test pieces were placed for 24 hours, and the mold was removed. Finally, the test pieces were numbered and cured in the standard concrete curing room for 28 days for testing.

2.3. Test Instruments and Methods

2.3.1. Test of Compressive Strength, Splitting Tensile Strength, and Flexural Strength. According to GB/T50081-2019, Suns WAW-2000 universal testing machine in Figure 2(a) was used to test the compressive strength of the cube test piece at a loading rate of 0.5 MPa/s. As shown in Figure 2(b), a block was placed above and below the test piece, and the tensile strength of the cube test piece was tested at a loading rate of 0.05 MPa/s. The Suns WAW-2000 universal testing machine equipped with four-point bending fixture shown in Figure 2(c) was employed to test the flexural tensile strength of the prism test pieces at a loading rate of 0.05 MPa/s.

2.3.2. Water Absorption Test. Since the test method for concrete water absorption in ASTM C1585-13 is complex, according to the provisions of GB/T50081-2019 and JG/T266-2011, a simple water absorption test was designed, as shown in Figure 3(a). Before the test, the pieces were placed in an electric blast drying box for 24 hours, and the temperature was maintained at $(105 \pm 5)^\circ\text{C}$. After the test pieces were cooled to room temperature, the weight after drying was determined; two steel bars with a diameter of 10 mm were placed in the water tank to underlay the concrete test piece, and water was added to 30 mm higher than the top surface of the test piece and kept for 3 d. The test piece was taken from the water, and the water on the surface was removed with a damp cloth. The test piece was weighed immediately using the electronic balance shown in Figure 3(b). The final water absorption rate formula is as follows:

$$W_a = \frac{m_s - m_d}{m_d} \times 100\%, \quad (1)$$

where W_a is the weight water absorption rate (%) of the test piece, accurate to 0.1; m_d is the weight of the dry test piece (g); m_s is the weight of the saturated test piece (g).

2.3.3. Drop Hammer Impact Test. According to ACI544, the drop hammer impact test device was prepared, as shown in Figure 4(a). Before the test, the cylindrical test piece was placed in the lower rigid baffle and fixed with the paper baffle around the test piece. The force-transmitting steel ball with a diameter of 63.5 mm was put in the positioning ring and the infrared induction counter was started; the cylinder steel hammer with a diameter of 70 mm, a height of 126 mm, and weight of 4.5 kg was pulled with a wire rope to 457 mm, and the force-transmitting steel ball was impacted; when an initial crack occurred as shown in Figure 4(b), the paper baffle was removed; when the test specimen cracked and contacted with any three of the four rigid baffles, the test specimen was completely destroyed; the number displayed by the counter was recorded as the number of impacts N . In order to avoid the impact of air resistance and friction between the steel hammer and the sleeve, combined with the kinetic energy theorem, an optimized formula was obtained to calculate the impact failure energy E of the test specimen:

$$E = N \frac{mv^2}{2}, \quad (2)$$

$$\text{where, } v = \sqrt{2(0.9g)h}.$$

E is the impact failure energy (J); N is the number of impacts in failure; m is 4.5 kg; g is 9.81 m/s^2 ; h is 457 mm; the coefficient was set to 0.9 to avoid the impact of air resistance and the friction between the hammer and the steel hammer during the impact process [8, 31].

2.3.4. SEM and XRD Tests. In the SEM test, the scanning electron beams were used to excite various physical signals from the sample surface to modulate the imaging, so as to obtain the microscopic three-dimensional topography of the sample. The concrete in the core area of the compression test specimen was cut into thin slices with a size of about $6 \text{ mm} \times 6 \text{ mm} \times 4 \text{ mm}$. After drying, Supra 55 scanning electron microscope manufactured by Zeiss, Germany, was employed to study its microstructure. The XRD test was carried out to identify the crystal microstructure. The shape of the diffraction peak can reflect the information of the crystal microstructure. The relative content of the crystal compositions was determined according to the size of the diffraction peak. The concrete in the core area of the compression test specimen was ground into powder and dried. The scanning angle range was $5\text{--}90^\circ$. D8 Advance X-ray diffractometer produced by Bruker, Germany, was used to study the crystal structure of the concrete.

3. Results and Discussion

3.1. Compressive Strength and Compressive Strength Ratio. The 28 d compressive strength and compressive strength ratio of different groups of concrete and the standard deviation of test results are shown in Figure 5. The compressive strength ratio refers to the ratio of the actual compressive strength of the test piece to the compressive strength of the reference group.

As can be seen from Figure 5, in the four groups, as the content of PVC aggregate increased, the compressive strength decreased significantly, and the decline rate was smaller. The normal concrete compressive strength was 47.88 MPa. Compared with other data, it can be found that, with the increase of the amount of PVC, the decline rate of PVC aggregate concrete (RC-0-0-Z) was the fastest, and the largest decline rate was up to 48.08%. According to the microstructure diagram in Figure 6, the continuous decrease in strength was caused by the poor adhesion and loose porosity at the interface transition zone between cement and PVC aggregate because of boundary effect after the addition of PVC aggregate to concrete [32]. The compressive strength of the double-doped polypropylene fibers and unmodified PVC aggregate concrete (RC-0-1-Z) decreased slowly compared with that of the RC-0-0-Z test piece, and the decline rate was about 3–4%. As the content of PVC aggregate increased, the reduction of the compressive strength by the polypropylene fiber was slowed down [33]. According to the microstructure diagram in Figure 7, because the

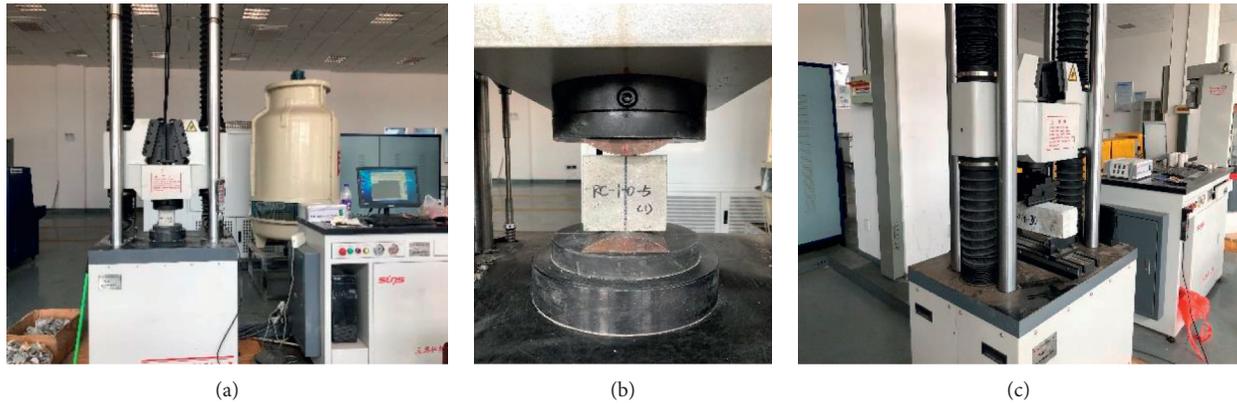


FIGURE 2: Basic static mechanical test. (a) Universal testing machine. (b) Splitting tensile fixture. (c) Four-point flexural tensile fixture.

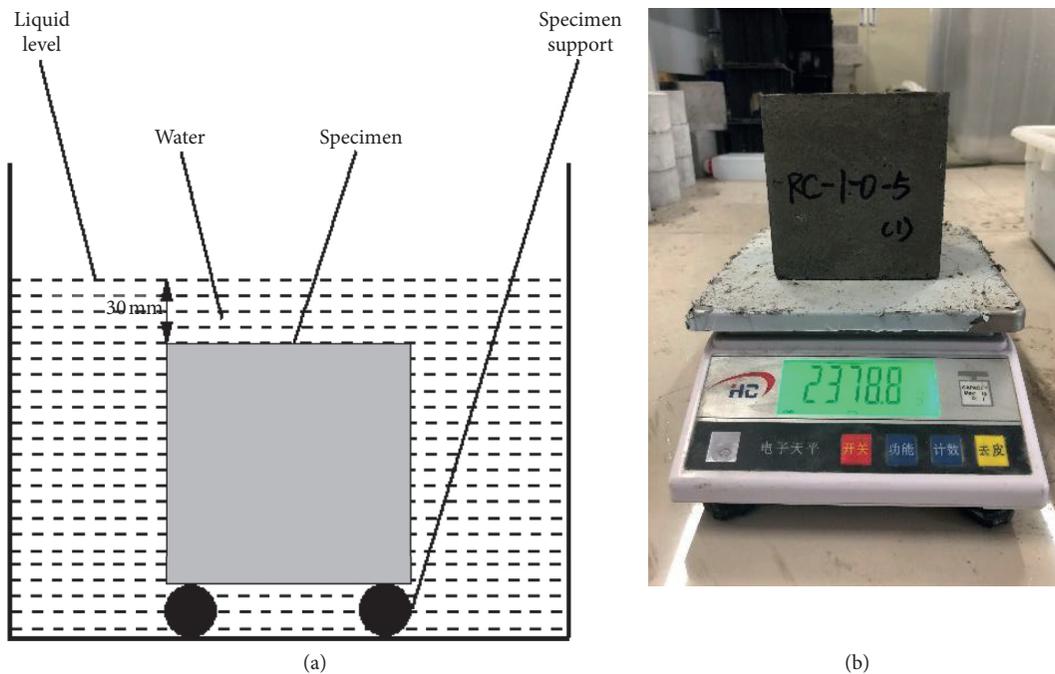


FIGURE 3: Water absorption test. (a) Self-made water absorption test device. (b) Electronic balance.

polypropylene fiber affected the compactness of concrete, the bonding performance of aggregate and cement slurry was weakened, but the strength decreased slowly due to the small amount of addition.

The compressive strength of the modified PVC aggregate concrete (RC-1-0-Z) was significantly improved compared to RC-0-0-Z test specimens by about 8–12%. As more PVC aggregate was added, the modified PVC aggregate enhanced the compressive strength more significantly. Zinc stearate was used in most of PVC production as a heat stabilizer [34]. Soaking in NaOH solution can not only remove the dust on the surface of PVC aggregate but also react with zinc stearate to generate sodium stearate, which is soluble in water and can be washed away with water. Therefore, the surface of the PVC aggregate is rough, hydrophilic groups are added, and cement hydrate was generated on the surface. Moreover, the

compactness of the interface transition zone was improved. Figure 8 shows the microstructure of the surface of the PVC aggregate before and after modification in concrete.

The compressive strength of double-doped polypropylene fiber and modified PVC aggregate concrete (RC-1-1-Z) decreased by 5% compared with that of RC-1-0-Z test piece and was between RC-0-1-Z and RC-1-0-Z test pieces. When the content was 30%, the compressive strength was only 27.11 MPa, which did not reach the design strength. Moreover, these composite modification methods can significantly delay the decrease of strength caused by adding PVC aggregate, and the strength reduction rate was the slowest. This is caused by the poor adhesion between fiber and cement slurry. However, there are many factors influencing the composite modification reinforcement effect. The compressive strength does not simply increase or decrease, and the change is unstable. However, the

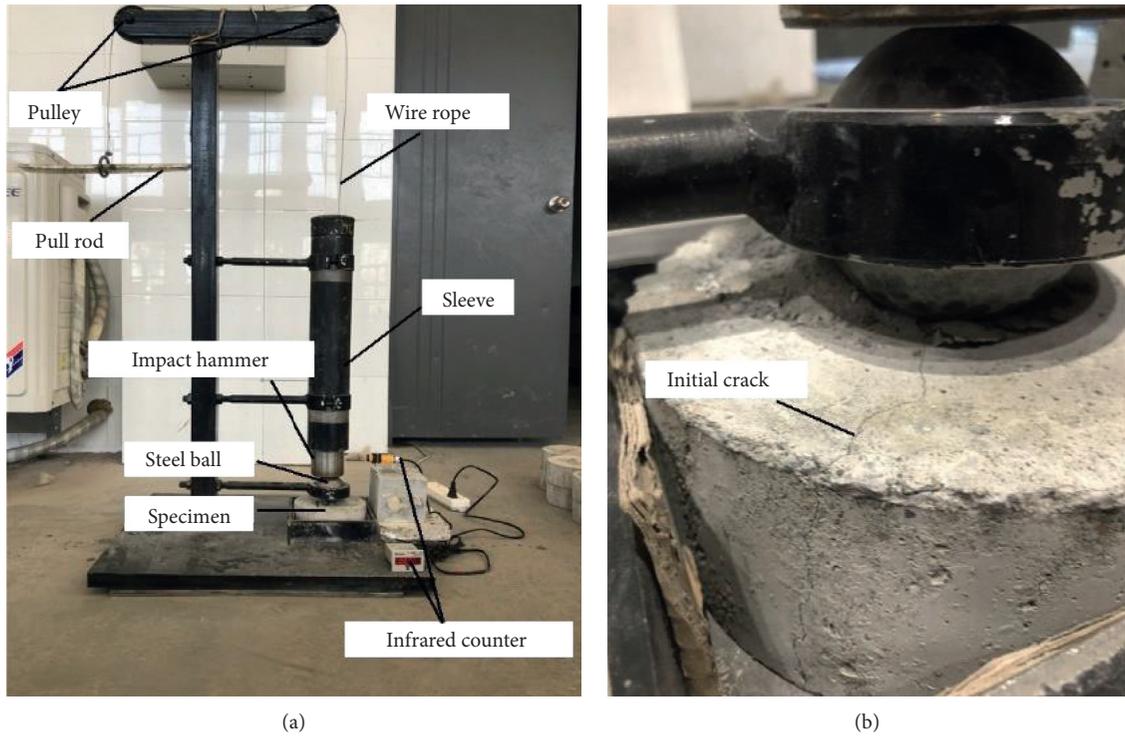


FIGURE 4: Impact test. (a) Self-made impact test device. (b) Initial crack.

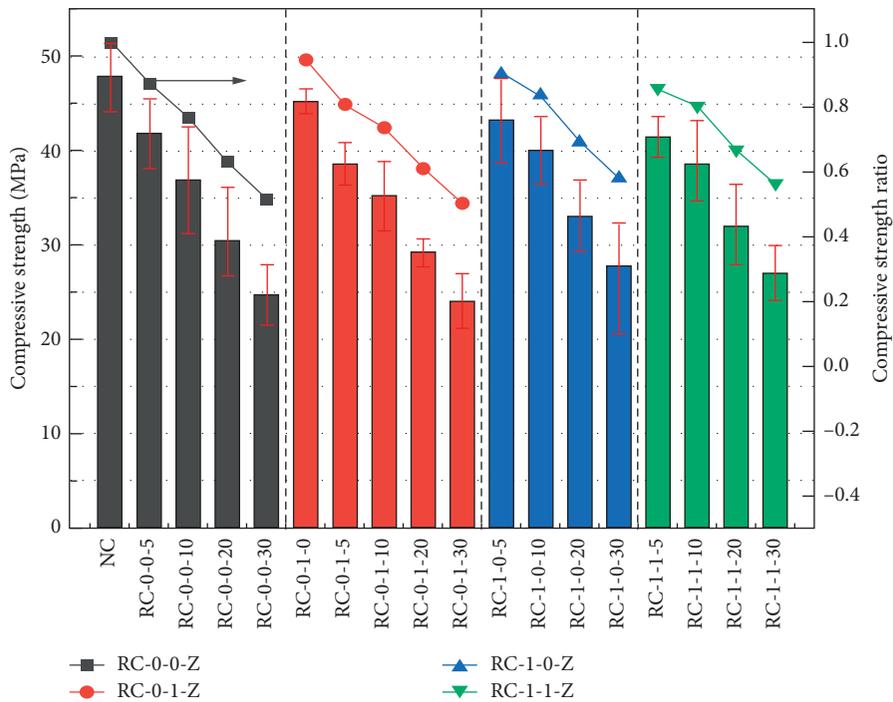


FIGURE 5: 28 d compressive strength and compressive strength ratio.

change rate does not exceed 25% [30]. The failure modes of different concrete are shown in Figure 9. The amount of PVC aggregate increased, and there were fewer macro penetration fracture surfaces on the test piece, indicating that the brittleness of the concrete was improved. With the same amount of PVC

aggregate, adding polypropylene fiber or using the modified PVC aggregate can reduce the macro penetration fracture surface and improve the brittleness of the test piece. Adding PVC particles as an elastic-like material to the concrete can improve the resistance to compressive deformation; during the

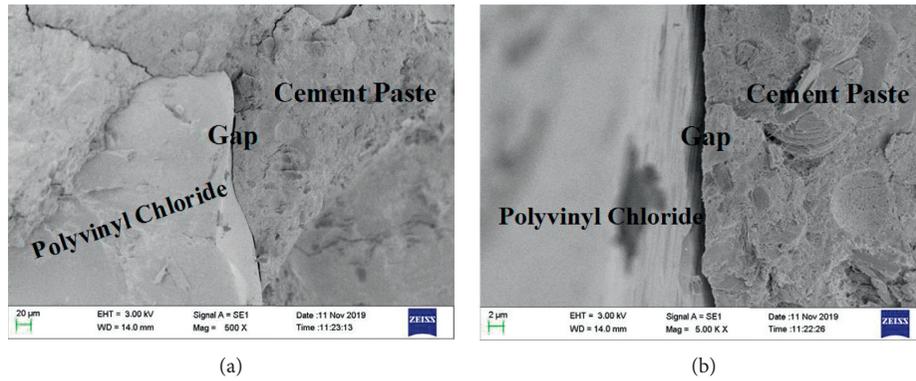


FIGURE 6: Microstructure of RC-0-0-30 at different magnification. (a) 500x. (b) 5.00kx.

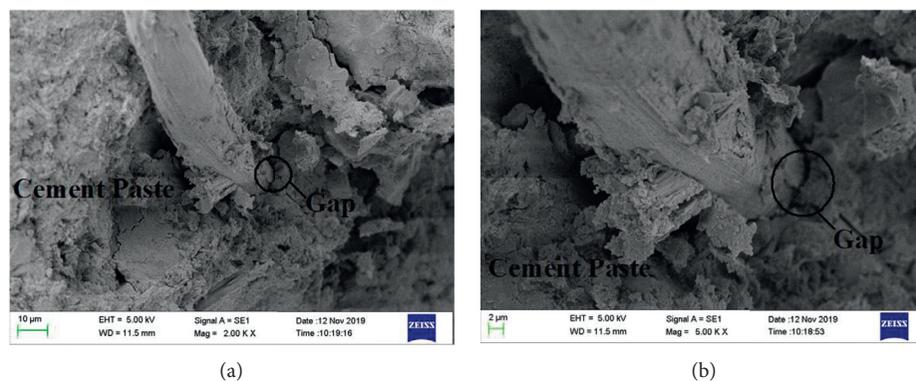


FIGURE 7: Microstructure of RC-0-1-30 at different magnification. (a) 2.00kx. (b) 5.00kx.

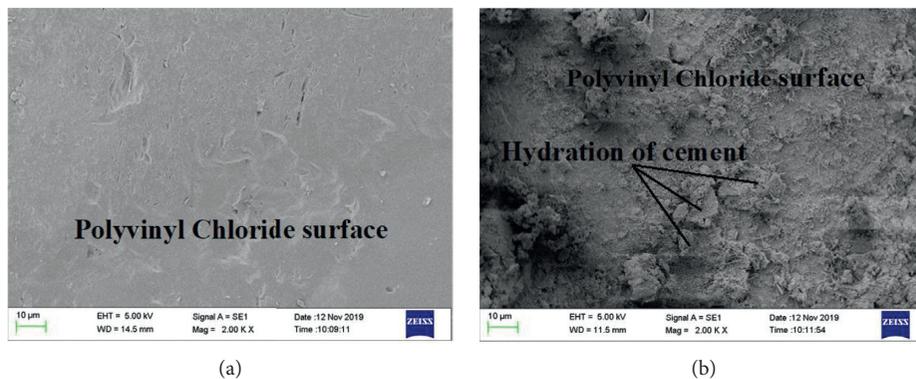


FIGURE 8: Microstructure of PVC aggregate surface before and after modification in concrete. (a) Unmodified surface. (b) Modified surface.

failure process of polypropylene fiber, the sliding friction between the aggregate and the slurry interface consumed more energy. After NaOH modification, the surface of PVC aggregate became rough, and the hydrophilic group was increased. Cement hydrate was formed on the surface, and the compactness of the interfacial transition zone was improved, thus reducing the fracture surface.

3.2. Splitting Tensile Strength and Flexural Tensile Strength. The 28 d splitting tensile strength and flexural tensile strength of different groups of concrete are shown in Figure 10.

Through comparison, we can find that the splitting tensile strength and flexural strength show similar trends in the four groups. As the content of PVC aggregate increased, both the splitting tensile strength and the flexural tensile strength of the concrete decreased significantly, and the decrease rate of the flexural tensile strength was greater. Both modified and unmodified PVC aggregates have poor bonding effect with the interface transition zone of the concrete because of the boundary effect. Meanwhile, the failure mechanism of splitting tensile strength and fracture resistance is different. Splitting tensile strength is the ultimate uniformly distributed tensile stress on the vertical

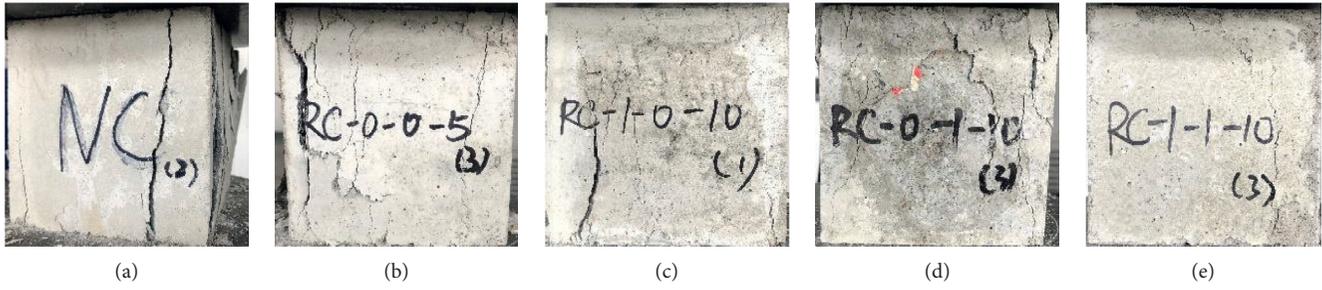


FIGURE 9: Typical failure forms of concrete. (a) NC. (b) RC-0-0-5. (c) RC-1-0-10. (d) RC-0-1-10. (e) RC-1-1-10.

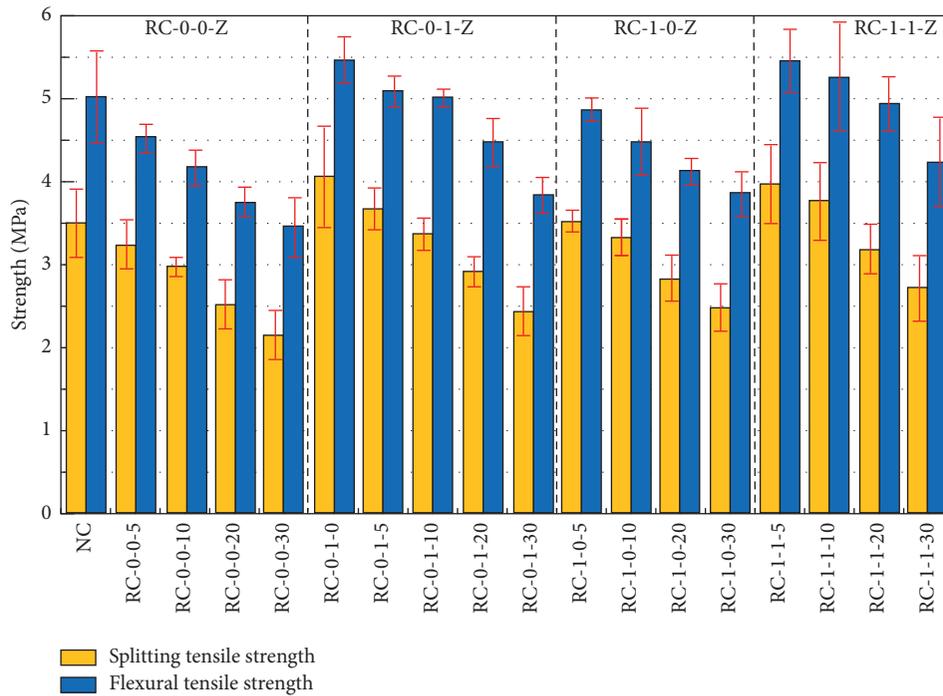


FIGURE 10: 28 d splitting tensile strength and flexural tensile strength.

plane in the middle of the cube specimen, while fracture resistance is the flexural failure due to bending moment, which is the continuous tensile stress on the surface of the beam specimen. Therefore, the decline rate of the flexural tensile strength is large.

With the same content of PVC aggregate, adding polypropylene fibers to the concrete or using modified PVC aggregate can improve its tensile strength and flexural tensile strength. However, the addition of polypropylene fibers has a better effect, and the increase rate of the flexural tensile strength (10–20%) is higher than that of splitting tensile strength (12–16%). During the failure process of polypropylene fiber, the sliding friction with the aggregate and the slurry interface consumes more energy. Tens of millions of polypropylene fibers are mixed into concrete, which overlap and affect each other, forming a random support system in the concrete. The splitting tensile strength and flexural failure mainly occur on the surface, thus enhancing the strength. The surface of PVC aggregate becomes rough after NaOH modification. There are more hydrophilic groups, and cement hydrates are generated

on the surface. Moreover, the compactness of the interface transition zone was improved. The increase rate of splitting tensile strength (8–15%) is higher than that of flexural tensile strength (7–11%). According to the XRD analysis in Figure 11, there is still residual NaOH in the modified PVC aggregate concrete, and modification treatment cannot change the internal molecular structure of PVC. This may be because the strength increase after the modification treatment is not obvious [20, 21].

The double-doped polypropylene fiber and modified PVC aggregate concrete shows the best composite reinforcement effect of tensile strength and flexural tensile strength. Compared with RC-0-0-Z, the increase rate of flexural tensile strength (26–31%) is slightly higher than that of splitting tensile strength (22–26%). There are many factors influencing the reinforcement effect of composite modification. However, the change rate does not exceed 10% [30].

Based on the change law of static mechanics and brittleness performance, the composite modification method of

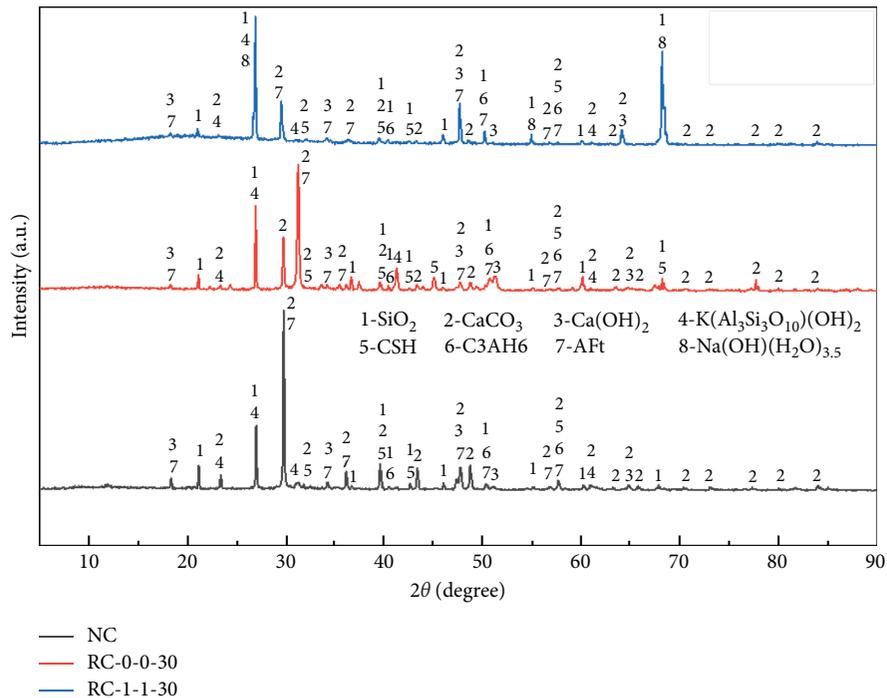


FIGURE 11: XRD diffraction peak results.

adding polypropylene fiber and modified PVC aggregate can effectively improve the brittleness of concrete. However, in order to meet the minimum requirements for the strength of concrete in engineering, the amount of PVC should not be greater than 20%, which provides an effective method for preparation of concrete with low brittleness and future environmental governance [3, 4].

3.3. Water Absorption Rate. Water is the main cause of concrete failure. Harmful ions usually enter the concrete through waste, damaging the structure and reducing durability. Therefore, controlling the entry of water is one of the main measures to improve the durability of concrete, which can be characterized by water absorption [35]. The water absorption of different groups of concrete is shown in Figure 12.

Through comparison, in the four groups, with the increase of the content of PVC aggregate, the water absorption rate of concrete generally increased. Both modified and unmodified PVC aggregates have poor bonding effect with the interface transition zone of the concrete because of the boundary effect. However, the water absorption test is influenced by factors, and the results may have some errors; with the same content of PVC aggregate, when polypropylene fibers were added, the water absorption of concrete increased slightly (2–4%). This is because adding polypropylene fibers to concrete can influence the compactness of concrete and weaken bond performance of aggregate and cement slurry. However, the amount of addition was small, and the increase effect was not obvious; when modified PVC aggregate was used, the water absorption rate of concrete was significantly reduced (4–9%). The surface of PVC

aggregate became rough after NaOH modification. Hydrophilic groups were added, and cement hydrates were generated on the surface, which improved the compactness of the interface transition and reduced the water migration speed in the concrete.

By comparing double-doped polypropylene fibers and modified PVC aggregates with RC-0-0-Z, the water absorption of concrete decreased (5–7%). However, when the PVC content was 5%, its water absorption increased by 0.6% due to the slight increase in water absorption after adding polypropylene fibers. However, the results are unstable, and there are many factors influencing the composite modification reinforcement effect.

3.4. Impact Failure Energy. The impact failure energy and impact failure energy ratios of concrete in different groups are shown in Figure 13. The impact failure energy ratio is the ratio of the actual impact failure energy of the test piece to the impact failure energy of the baseline group. It is necessary to use concrete with strong impact resistance and energy absorbing capacity in military protection, airport pavement, deep roadway support, and so forth [36, 37].

Through comparison, we found that the impact failure energy of the normal concrete is 380.89 J. In the four groups, as the amount of PVC aggregate increased, the impact failure energy of the concrete shows an approximately straight upward trend, and the maximum impact energy is 3636.88 J (RC-1-1-30). This is because the recycled PVC plastic has good elasticity and low shock wave impedance. Under the action of the impact load, the PVC particles have a large deformation. This process has an unloading and sparse effect on the shock wave, which consumes the impact energy of the

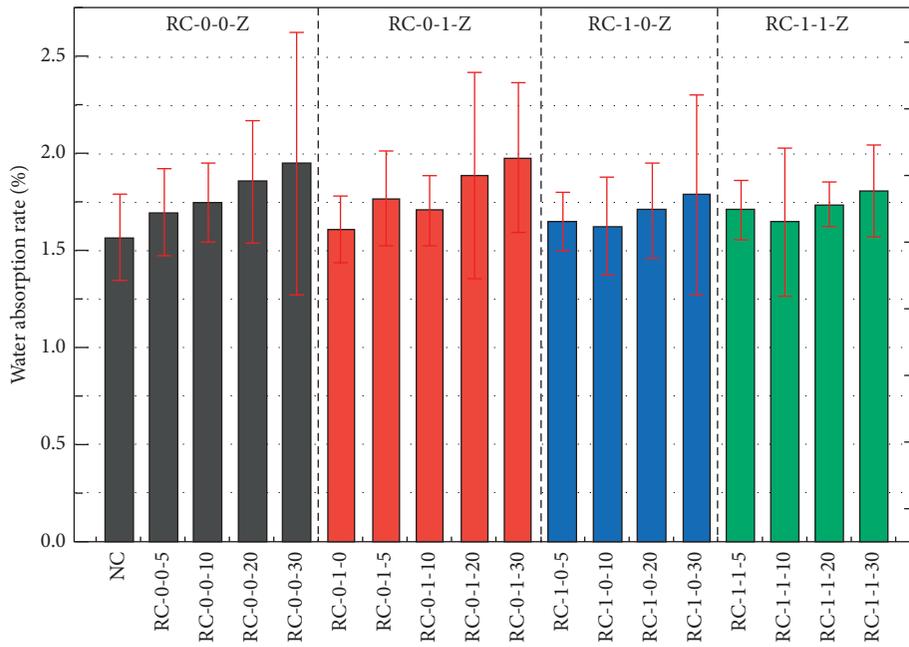


FIGURE 12: Water absorption rate.

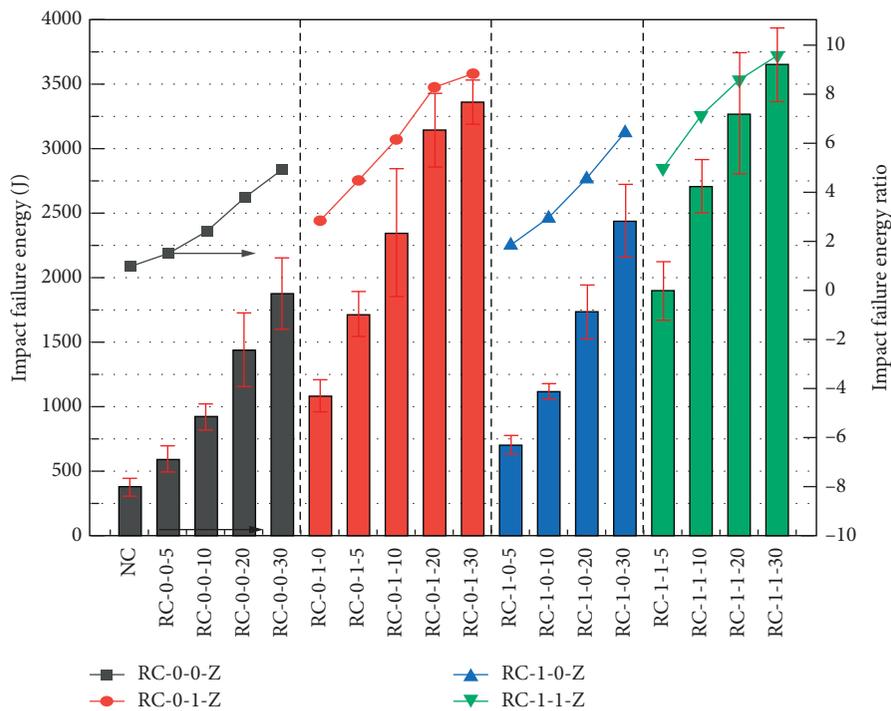


FIGURE 13: Impact failure energy and impact failure energy ratio.

drop hammer. In addition, during the development stage of micro cracks in the concrete, the PVC particles have large deformation, and the stress at the tip of the crack is relieved, which avoids stress concentration and delays crack propagation.

With the same amount of PVC aggregate, adding polypropylene fibers can significantly increase the impact failure energy of concrete (79–189%). The increase in the amount of polypropylene fibers can weaken the

reinforcement effect. This is because the fibers have good impact resistance. Moreover, the polypropylene fibers in the concrete overlap and connect with each other and form a random support system in the concrete. Under the action of impact load, micro cracks tend to occur in the concrete, and the crack generation direction is random; when the micro cracks propagate and contact with the fiber, the load is transmitted to the fiber bridging the crack, and the frictional peeling and pulling of the fibers consume friction energy;

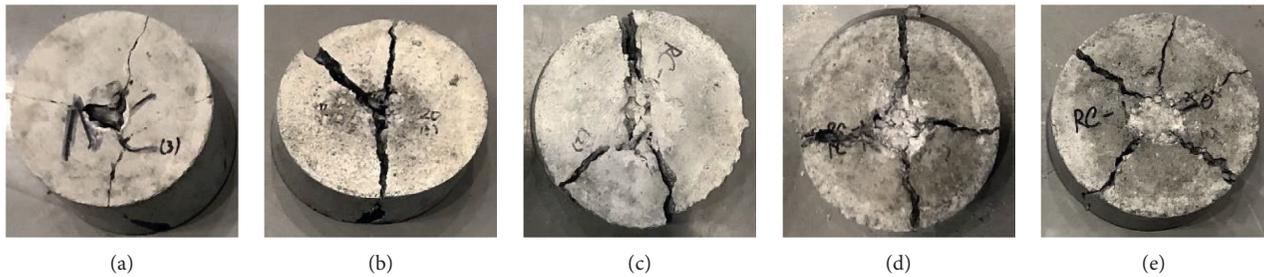


FIGURE 14: Typical drop hammer impact failure forms of concrete. (a) NC. (b) RC-0-0-20. (c) RC-1-0-20. (d) RC-0-1-20. (e) RC-1-1-20.

when the modified PVC aggregate is used, the impact energy of the concrete is increased (18–30%). This is because the surface of the PVC aggregate becomes rough after NaOH modification treatment, and the hydrophilic groups are added. Cement hydrates are formed on the surface, and the compactness of the interface transition zone is improved. The impact wave energy is transmitted to the surface of the PVC particles, and the PVC particles have better energy absorption performance.

Based on the comparison between the impact failure energy of double-doped polypropylene fiber and modified PVC aggregate concrete and RC-0-0-Z, the impact failure energy increased significantly (95–218%). This is because the impact failure energy of the composite modified concrete was enhanced. However, there are many factors influencing the modification and reinforcement effect, which is not simple number superposition. The change does not exceed 15%. The failure impact energy of concrete test piece is positively correlated with the number of specimen failure blocks; the test results are verified by Figure 14 [9].

4. Conclusions

This study thoroughly studied the properties and micro structure of PVC-polypropylene fiber composite modified reinforced concrete. The following conclusions are drawn:

- (1) The compressive strength of concrete decreases significantly with the increase of the amount of PVC aggregate. With the same content of PVC aggregate, the most effective way to improve the compressive strength is to use modified PVC aggregate. Adding polypropylene fiber and modified PVC aggregate is the most effective way to delay the rapid decrease of compressive strength caused by PVC aggregate. After adding polypropylene fibers, the compressive strength decreases slightly. No matter what kind of PVC aggregate concrete is used, when the addition amount of PVC aggregate is above 30%, its compressive strength does not reach the designed strength.
- (2) The brittleness of the concrete is improved with the increase of PVC aggregate content. With the same content of PVC aggregate, adding polypropylene fiber or modified PVC aggregate can improve the brittleness. Double mixing of polypropylene fiber

and modified PVC aggregate has the best effect of improving the brittleness.

- (3) The splitting tensile strength and flexural tensile strength of concrete show similar change trends. With the increase of the amount of PVC aggregate, the splitting tensile strength and flexural tensile strength of concrete are significantly reduced, and the flexural tensile strength has greater decrease rate. With the same content of PVC aggregate, adding polypropylene fibers to the concrete or using modified PVC aggregates can improve the tensile strength and flexural tensile strength, but adding polypropylene fibers has better effect. Adding polypropylene fibers and modified PVC aggregates can enhance the tensile strength and the flexural tensile strength most significantly.
- (4) The water absorption rate of concrete generally increases with the increase of the amount of PVC aggregate. With the same content of PVC aggregate, when polypropylene fibers are added, the water absorption rate of the concrete increases slightly; when the modified PVC is used, the water absorption rate decreases significantly. The water absorption rate of the concrete added with polypropylene fiber and modified PVC aggregate decreases slightly.
- (5) The impact resistance of concrete is positively related to the impact failure energy. As the amount of PVC aggregate increases, the impact failure energy of concrete increases approximately linearly. When the same amount of PVC aggregate is added, adding polypropylene fibers can enhance the impact failure energy of concrete. The reinforcing effect of polypropylene fiber is weakened as the mixing amount increases. When the modified PVC aggregate is used, the impact failure energy of concrete is increased, but the increase rate is much lower than the modification and reinforcement effect of fibers. The impact failure energy of concrete added with polypropylene fibers and modified PVC aggregate increases significantly, and the reinforcement effect of the impact resistance is the best.

Based on the above conclusions, the composite modification method of adding modified PVC aggregate and polypropylene fiber can enhance the splitting tensile strength, flexural tensile strength, and impact resistance of

concrete and has obvious advantages. Although the corresponding compressive strength and low water absorption have not achieved the effect of composite modification, the compressive strength and water absorption can basically meet engineering requirements. After comprehensively analyzing the advantages and disadvantages of each performance, this study proposes adding less than 20% volume PVC aggregate, 1 mol/L NaOH modification solution, and 0.9 kg/m³ polypropylene fiber to prepare C30 concrete with low brittleness, good impact resistance, and lower water absorption.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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