Optimization of the Preparation Process of Fair-Faced Concrete Incorporating Recycled Aggregates

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Abstract: Recycling construction wastes as aggregates to replace natural sources to produce concrete has attracted the attention of many researchers and is necessary for sustainable development. The water content of recycled coarse aggregate (RCA) and the concrete mixing approach in preparing fair-faced concrete incorporating recycled aggregates (FCRA) were optimized in this study. The results showed that the slump flow of FCRA exceeds 600 mm and that the 28-d compressive strength reaches approximately 40 MPa, which can meet the requirements of Chinese standards. Compared with concrete prepared with absolute dry RCA and with saturated surface dry RCA, the concrete prepared with semidry RCA better maintains its workability. The adverse effect on the compressive strength of concrete is weakened, which helps improve the structural performance of the ITZ of recycled aggregate concrete (RC). The concrete mixing approach has a significant influence on the physical and mechanical properties of FCRA. Compared with the ordinary mixing method, the 28-d strength of the concrete obtained by the cement stone wrapping approach is increased by 13.33%, and the surface pore area is reduced by 42.6%. Cement stone wrapping in two-stage mixing greatly improves the concrete performance, effectively satisfying the requirements for FCRA.

Keywords: Recycled coarse aggregates; Preparation process; Fair-faced concrete; Workability; Mechanical properties; Interfacial transition zone; Two-stage mixing approach

1 Introduction

With the continuous advancement of urban modernization, many existing concrete structures will be transformed or demolished, resulting in a large amount of concrete waste. The recycling of concrete waste is an urgent problem to be solved, which is conducive to the sustainable development of the environment and resources. At present, the overall utilization rate of concrete waste concrete in various countries is not satisfactory. The main disposal methods of building waste are stacking and landfilling, which seriously pollute the environment[1]. The use of recycled aggregate (RA) from construction and demolition waste is a promising solution to these serious problems that also helps to reduce the cost of coarse aggregates[2-5]. In concrete, coarse aggregate accounts for a major volume of concrete. Recycled coarse aggregate (RCA) will be an ideal option to reduce the amount of concrete waste going into landfills. A. Arun proposed that recycled coarse aggregate (RCA) will be an ideal option to reduce the amount of concrete waste going into landfills since coarse aggregate accounts for a major volume of concrete[6]. However, the quality of RA from construction and demolition waste may not be as good as that of natural aggregate (NA). The poor properties of RA present some difficulties in controlling the physical and mechanical properties of recycled aggregate concrete (RC)[7-9]. The major problem associated with RCA is its high water absorption due to the high porosity of the residual cement mortar attached at the initial natural coarse aggregate (NCA). The absorption kinetics are strongly affected by the size and configuration of the attached cement mortar[10]. The water absorption content ranges from 3% to 13% depending on whether the attached cement mortar comes from low- or high-strength concrete[11-13]. To reduce the abovementioned adverse effects of RA, different mixing processes have been conducted to improve the physical and mechanical properties of RC[14]. V. W. Y Tam proposed the two-stage mixing approach to improve the quality of RC[15]. M. Eckert optimized the two-stage mixing approach, and a staged mixing method based on aggregate water absorption over time was developed to regulate the interfacial transition zone (ITZ) water flow[11]. To further strengthen the ITZ structure in RC, an optimized triple mixing (OTM) method was developed with supplementary cementitious materials[16].

In recent years, domestic and foreign architects, represented by the Japanese architect *Tadao Ando*, began to use fair-faced concrete (FFC). After pouring, vibrating and demoulding, the surface of FFC is relatively dense, its colour is uniform, and there are no obvious defects. Because of these remarkable visual properties, FFC is used as not only exterior wall materials but also structural materials, which saves considerable material and time costs. In the era of a low-carbon economy, the application of FFC is conducive to the realization of low carbon usage in the construction industry[17]. China has issued several technical standards related to FFC, such as “Technical specification for fair-faced concrete construction” JGJ 169-2009[18], “Technical specification for post-cast fair-faced concrete” T/CECS814-2021[19] and “Technical specification for application of fair faced concrete” DB32/T 4184-2021[20]. The above specifications stipulate the workability and mechanical properties of FFC and recommend qualitative and quantitative testing methods for the apparent properties of the FFC surface. M. Wu quantitatively investigated the effects of aggregate and mineral admixtures on the workability, compressive strength and decoration effect of FFC and obtained an optimal mix proportion[21]. E. Neto analysed the efficiency of FFC surface protection against graffiti paints. The following three cases were considered: (i) FFC without protection before and after the application of graffiti paint, (ii) FFC with protection before and after the application of graffiti paint and (iii) FFC after graffiti paint removal[22]. Considering that FFC used in coastal areas is vulnerable to erosion, H. Chang studied the comprehensive resistance of fair-faced concrete in marine environments. The results showed that the selection of FFC used in coastal subway stations should consider sulphate corrosion, which can lead to significant deterioration of the surface decorative effect[23].

The abovementioned studies, however, were mainly focused on the high porosity of RA, the improvement effect of the mixing approach on RC and the properties of FCC without RA; the adoption of RA in the preparation of FCC has not been thoroughly discussed, apart from a few exceptions[24, 25]. The authors previously investigated the mix proportion optimization and apparent performance of FFC with recycled aggregates (FCRA)[26] but did not consider the effect of the water content of RA and the mixing approach on the properties of FCRA.

The aim of this paper is to optimize the preparation process of FCRA. Based on the existing mix proportion of FCRA[26], the workability, mechanical properties, and ITZ of FCRA prepared with different RCA water contents and mixing approaches were tested. Through comparative analysis, the optimal water content of RCA and the optimal mixing approach for preparing FCRA were finally obtained, which can provide a technical reference for the promotion and industrial production of FCRA in the future.

2 Materials and Methods

2.1 Materials

The cement used was Type 42.5 ordinary Portland cement according to Chinese Standard GB175. The mineral admixtures used were Grade I fly ash according to Chinese Standard GB/T 1596-2017 and Grade S95 slag powder according to Chinese Standard GB/T 18046-2017. The fine aggregate used was ordinary river sand, which met the requirements of Chinese Standard GB/T 14684-2011, with a fineness modulus of 2.4, an apparent density of 2640 kg/m^3, a mud content of 1.06%, and a certain degree of unevenness. The superplasticizer was a polycarboxylic acid high-performance superplasticizer (PCA-I, 30% reduction rate) produced by Jiangsu Subote New Material Co., Ltd., and the water was tap water. The coarse aggregate used was 5~20 mm RCA. The basic properties are shown in Table 1.

Table 1. Properties of RCA

Size	Apparent density /(kg/m^3)	Water absorption /%	Micro powder content /%	Crushing index /%
5~20 mm	2510	7.0	1.8	17.9

2.2 Methods

The author investigated the optimal mix proportion of FCRA using orthogonal arrays and the Taguchi method[26]. Orthogonal array testing is an effective method for maximizing the test coverage while minimizing the number of test cases[27]. In the present study, the water binder ratio, sand ratio, and amount of cementitious material were selected as key mix proportion parameters. The orthogonal array $L_9(3^4)$ was adopted, and nine experimental tests were performed covering different combinations of these factors, as shown in Table 2. The slump expansion, compressive strength and apparent properties measured by digital image processing technology were tested. Range analysis and variance analysis of the orthogonal test were performed following the procedure described by Xu[27, 28]. The results of range analysis show the effect of selected factors on the properties of FCRA. A high value of corresponding to a certain factor (e.g., sand ratio) means that this factor has a relatively strong effect on the concrete properties. The F value is a key parameter of variance analysis that shows the significance of each factor on the concrete properties. If the obtained F value is equal to or higher than the critical F value at defined levels of significance, the given factor has a significant effect on the properties of FCRA.

Table 2. Experimental arrangement based on the Taguchi method

Tests	Factors			
	Water binder ratio (A)	Sand ratio (B)	Cementitious material content (C)	Error (D)
T1	0.24	46%	450 kg/m^3	1
T2	0.24	49%	500 kg/m^3	2
T3	0.24	52%	550 kg/m^3	3
T4	0.27	46%	500 kg/m^3	2
T5	0.27	49%	550 kg/m^3	3
T6	0.27	52%	450 kg/m^3	1
T7	0.30	46%	550 kg/m^3	3
T8	0.30	49%	450 kg/m^3	1
T9	0.30	52%	500 kg/m^3	2

Based on the above range analysis and variance analysis results, the optimal combination of the workability, mechanical performance and apparent properties can be selected. The obtained key parameters were as follows: a water binder ratio of 0.27, sand ratio of 0.46, and binder material proportion of 500 kg/m^3 (including 20% fly ash and 20% slag powder). Due to its high water absorption, RCA was preconditioned to reach the saturated surface-dried content, and the additional water absorbed by RCA could not be ignored[29-32]. However, this part of the additional water was not included in the calculation of the effective water binder ratio for each mixture, which is shown in Table 3 in the form of additional water.

Table 3. Optimal mix proportion of FCRA (kg/m^3)

Cement	Fly ash	Slag powder	Water	Additional water	Sand	RCA	Superplasticizer	Water (All)
300	100	100	135	57	724	850	5	192

2.2.1 RCA water content

Keeping the net water binder ratio, sand ratio and binder material contents unchanged, one control group of NCA and three test groups of RCA with different water contents were prepared, including dry (0% water), semidry (50% moisture content) and saturated surface dry (100% moisture content) RCA. The images are shown in Figure 1.

(a) Dry (b) Semidry (c) Saturated surface dry

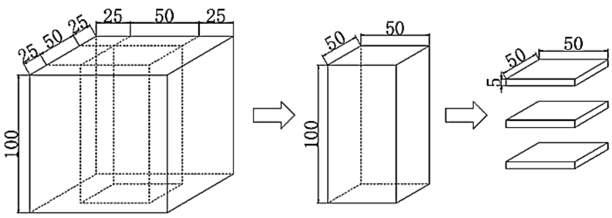
Figure 1. RCA with different water contents

The control group was designated NC (natural aggregate concrete), and the experimental groups (100% replacing NCA) with different moisture contents were designated RC-1, RC-2, and RC-3 (from dry to saturated surface dry). Based on Table 3, a total of four groups of specific mix proportions are shown in Table 4.

Table 4. Mix proportions of concrete (kg/m^3)

Group	Cement	Fly ash	Slag powder	Water	Additional Water	Sand	NCA	RCA	Superplasticizer
NC	300	100	100	135	0	724	850	0	5
RC-1	300	100	100	135	60	724	0	850	5
RC-2	300	100	100	135	30	724	0	850	5
RC-3	300	100	100	135	0	724	0	850	5

According to the mix proportion in Table 4, NC and RC group concrete was prepared. Then, the slump flow of each group of concrete at 0 min, 20 min, 40 min and 60 min was tested. In addition, 100 mm×100 mm×100 mm concrete cubes were made according to Chinese Standard GB/T 50081-2019 "Test methods for concrete physical and mechanical properties"[33] to test the mechanical properties. Microhardness samples (50 mm×50 mm×5 mm) were prepared following the steps shown in Figure 2. The surfaces to be tested after slicing were preground and polished with 320-mesh, 800-mesh and 1200-mesh sandpaper in the order of increasing particle size, and the obtained samples were used to test the microhardness of the concrete ITZ. Then, the prepared specimens were selected for SEM analysis, and the microappearance of the ITZ was analysed in detail.



(a) Schematic illustration

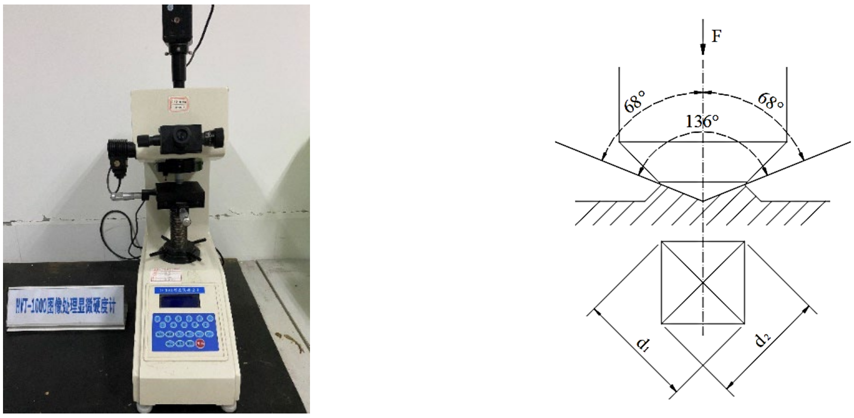
(b) Grinding and polishing machine (c) Test sample

Figure 2. Microhardness sample preparation process

The microhardness of the ITZ was tested by an HV-1000 Vickers indenter, as shown in Figure 3. The calculation formula of the Vickers hardness value is shown in Eq. (1).

$$HV = \frac{F}{S} = 0.1891\frac{F}{d^2} \quad (1)$$

where HV is the Vickers hardness value (N/mm^2); F is the pressure value adopted for the test (N); S is the area of the cross indentation (mm^2); and d is the average length of two diagonal lines (d_1 and d_2) of indentations (mm).



(a) HV-1000 Vickers indenter (b) Schematic illustration of the pyramid indenter

Figure 3. Vickers indenter and testing principles

2.2.2 Mixing approach

The normal concrete mixing procedure used was a one-stage mixing approach in which all water and other materials are mixed in one stage. Both coarse and fine aggregates and cementitious materials were added to the mixer at the same time for dry mixing. Then, water and superplasticizer were added after 60 seconds, and wet mixing was continued to obtain the concrete mixture. This approach is easy and convenient to use and requires only a short time. Considering the particularity of RCA, it was proposed that the performance of FCRA could be improved by changing the concrete mixing approach.

In this paper, a group prepared by the one-stage mixing approach was set as the control group, and three experimental groups of the two-stage mixing approach were prepared with differences in the specific feeding sequences and mixing times. The two groups of two-stage mixing approaches, which wrap the cement stone and cement sand, were also termed the cement stone wrapping approach and the cement sand wrapping approach, respectively. The detailed steps are shown in Figure 4.

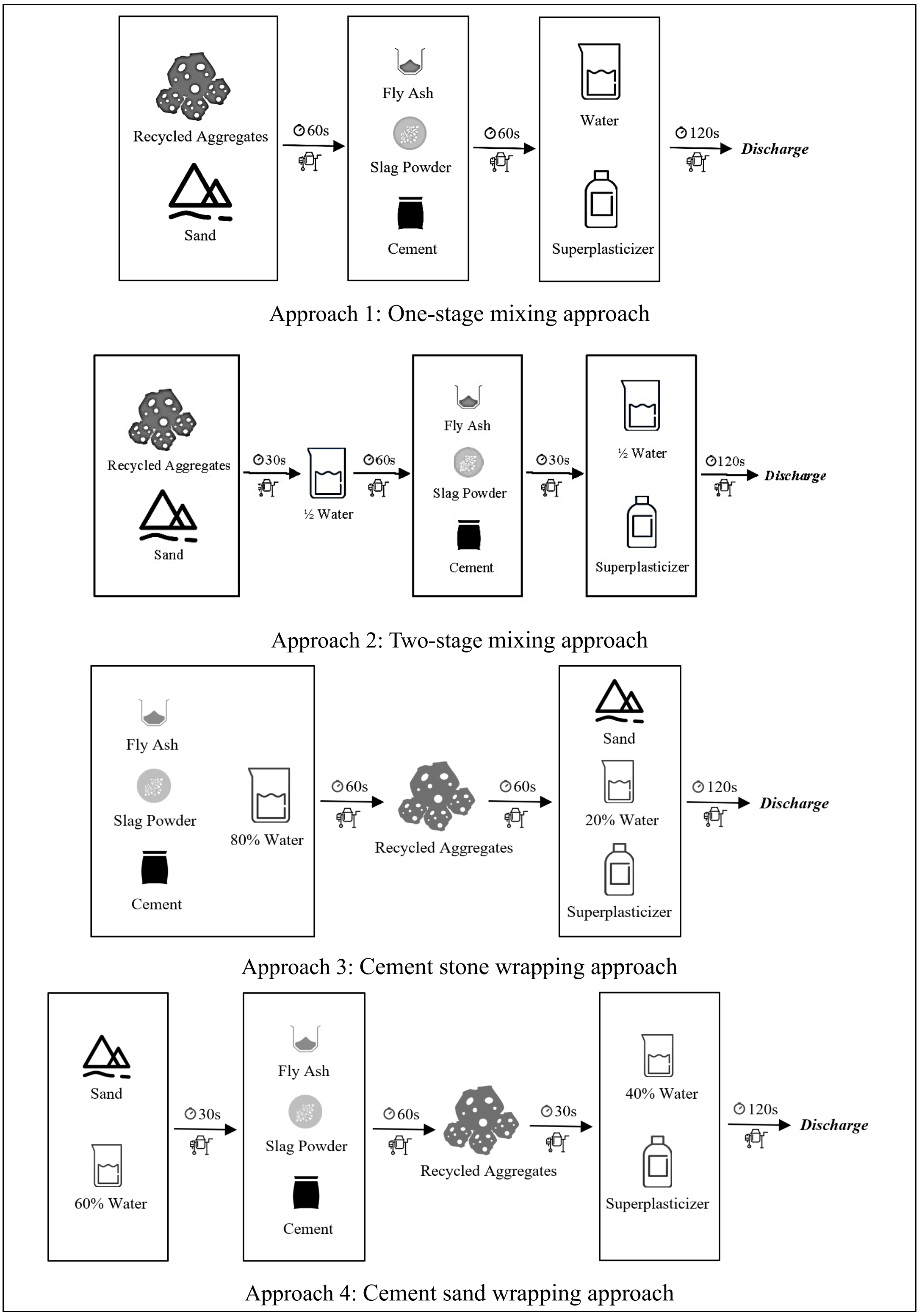


Figure 4. Concrete mixing approaches

The control group of approach 1 was the one-stage mixing approach, and the experimental groups of the two-stage mixing approach adopted three approaches: the two-stage mixing approach (Approach 2), the cement stone wrapping approach (Approach 3) and the cement sand wrapping approach (Approach 4). The aggregates used, including RCA and sand, are all in a dry state. The key point was that mixing water was added in two stages. Previous studies have shown that the mixing water applied in the first stage is usually 50%-75% of the total water[34, 35]. On the one hand, water will not be consumed by the residual cement paste on the surface of recycled aggregate. On the other hand, water forms a thin layer of cement paste with a low water-binder ratio on the surface of aggregate, thus improving the interface transition zone[36]. To ensure that the cement paste can be evenly mixed and can wrap around the surface of the aggregate, the mixing water applied in the first stage was determined through exploratory experiments.

For the two-stage mixing approach, half of the water was added for mixing to wet the aggregates in the first stage and form a thin layer of cement mortar on the aggregate surfaces, and then, the remaining water was added in the second stage to complete the final mixing step. For the cement stone wrapping approach, the mixing steps were as follows: cementitious material and 80% of the water were first added and mixed to obtain cement, and then, RCA was added to the machine for mixing. Finally, sand, the remaining 20% of water and part of the superplasticizer were mixed to obtain the concrete mixture. For the cement sand wrapping approach, the mixing steps were different. Sand, 60% of the mixing water and superplasticizer were added first, and then, cementitious materials were added to form cement mortar. Next, RCA and the remaining 40% of water were added and fully mixed to obtain the concrete mixture.

After completing the steps above, the workability, mechanical properties and apparent properties of FCRA were evaluated, and finally, the effects of different mixing approaches on the performance of FCRA at the same mix proportion were obtained.

2.2.3 Testing the apparent properties

According to the recommendations in Chinese standard “Technical specification for fair-faced concrete construction” JGJ 169-2009[18], the surface chromatic aberration of FFC is evaluated at a distance of 5 m from the wall. The surface bubbles are measured by a ruler, which is not only subjective but also time-consuming and laborious. To reflect the chromatic aberration and bubble area of the concrete surface more objectively, FFC specimens with a size of 400 mm×200 mm×50 mm were poured. Based on the Chinese standard "Technical specification for application of fair faced concrete" DB32/T 4184-2021[20], the apparent properties of FFC were quantitatively characterized by digital image processing technology. The FFC specimen was placed under the same lighting conditions, and photos were taken with a digital camera perpendicular to the surface of the test piece at the same height, as shown in Figure 5. The collected digital image was imported into Image-Pro Plus software for grey processing, and the corresponding image grey standard deviation was obtained. The image grey standard deviation was calculated according to the grey value and grey level mean value of each pixel of the collected image, which is a parameter reflecting the chromatic aberration of the image and represents the dispersion degree of the target data. The automatic measurement function in Image-Pro Plus software was used to count the pore area on the FFC surface in the binary diagram.

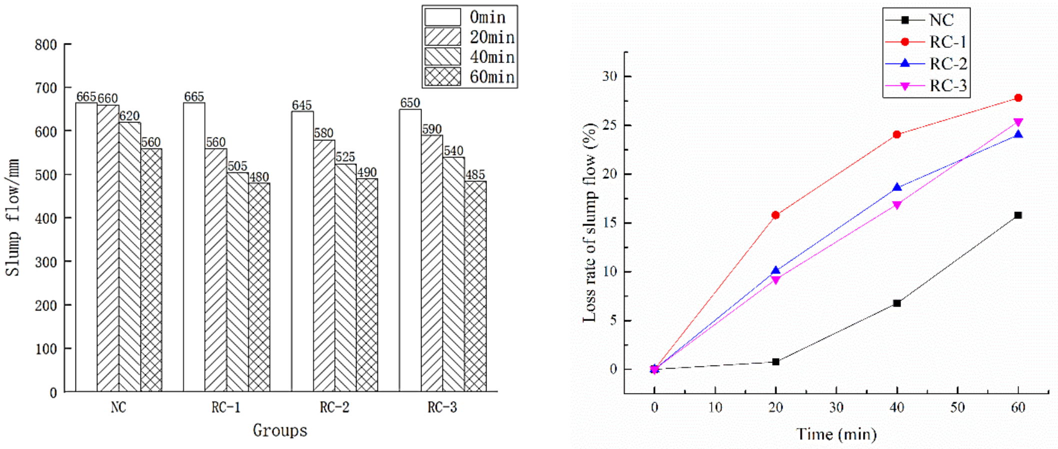
Figure 5. Image acquisition device

3 Results and Discussion

3.1 Effect of the moisture content of RCA on concrete performance

3.1.1 Workability

The slump flow of the control group and three experimental groups was tested over time, and the loss rate of the slump flow of each group of concrete was calculated according to the change in slump flow, as shown in Figure 6. According to the Chinese standard "Technical specification for post-cast fair-faced concrete" T/CECS814-2021[19], the recommended slump flow value of FFC is 600± 50 mm. During the construction of the Wuchang high-speed railway station in China, the slump flow requirement for FFC was 700±50 mm[17]. M. Wu divided FFC into three classes by slump flow value: (i) SF1, with a slump flow requirement of 550-655 mm; (ii) SF2, with a slump flow requirement of 660-755 mm; and (iii) SF3, with a slump flow requirement of 760-850 mm. The optimized mix proportion was applied successfully in the second lining of the 1200-m Nan Kunshan tunnel in China[21]. Obviously, the workability of all the prepared FFC samples, whether NCA or RCA was used, can meet construction requirements. The slump flow of FCRA is basically the same as that of NC, which is more than 600 mm. However, the slump flow losses of each group of concrete are different. The 60-min slump loss of FCRA made with NCA is only 15.5%, while the 60-min slump losses of FCRA made with dry, semidry and saturated surface dry RCA are 27.8%, 24.0% and 25.4%, respectively.



(a) Variation in slump flow with time (b) Loss rate of slump flow

Figure 6. Effect of the moisture content of coarse aggregate on workability

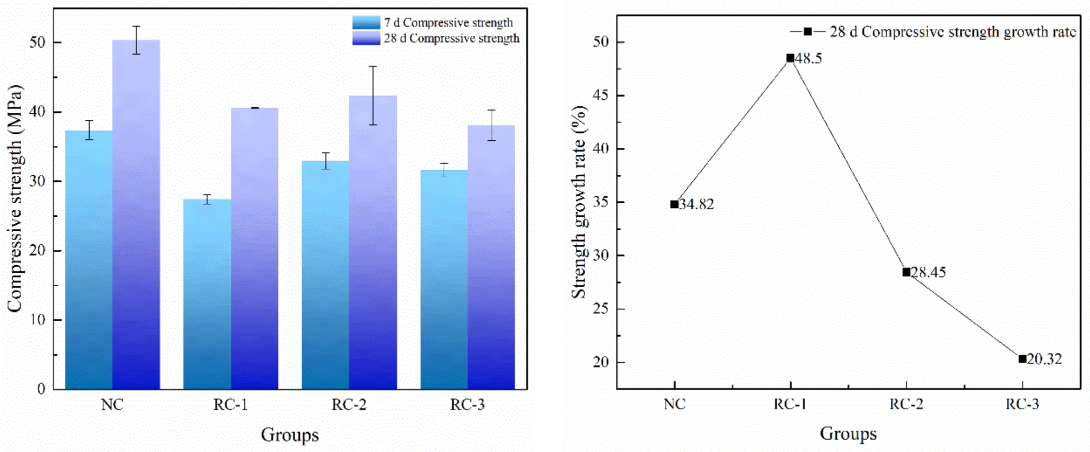
Studies have shown that the surface state, composition, incorporation ratio and mixing sequence of recycled aggregate affect the efficiency of superplasticizers[37, 38]. RCA has been proven to be an effective chemical sorbent for many ions. The mechanism can be attributed to the porous media characteristics of RCA, in which cases the ions may have complexed in the aggregates and/or may have precipitated on the pore surface of RCA[39, 40]. As shown in Figure 6, the slump flow loss rate of concrete made of NCA (NC Group) was significantly less than that of concrete made of RCA (RC Group). This can be explained by the fact that the surface of NCA is relatively smooth and the water absorption of the aggregate itself is low. Therefore, the mortar can fully exploit its fluidity and maintain excellent workability after a period of time. RCA has a rough surface and high water absorption. Therefore, the free water and superplasticizer in the concrete mixture are continuously absorbed by the RCA over a period of time. Moreover, part of the mortar fills the pores on the surface of the RCA, thus increasing the slump flow loss rate of the mixture over time.

Previous works[41] have shown that water exchange between recycled aggregate and fresh cement paste is more complex than that generally considered. Water can get into or out of the RCA, depending on the initial moisture history[42]. Comparing the 60-min slump flow loss rates of the three experimental groups reveals that the slump flow loss of the RC-1 group was the largest, followed by that of the RC-3 group, and the loss of the RC-2 group was the smallest. This was because the initial water content of the RCA of the RC-1 group was 0%, and its early water absorption rate was large, making its slump flow loss larger than that of the RC-2 group. For the RC-3 group, the saturated surface dry RCA underwent water transmission with the concrete mixture; thus, the concentration of effective superplasticizer in the mixture was reduced, and the slump flow loss rate of the mixture was increased.

Therefore, compared with the dry and saturated surface dry RCA, the semidry RCA was more conducive to maintaining the workability of the concrete mixture.

3.1.2 Mechanical properties

The compressive strength of the four concrete groups was tested after 7 d and 28 d, and the compressive strength growth rate of each group was calculated according to the compressive strength. The test results are shown in Figure 7. According to the Chinese standard “Technical specification for fair-faced concrete construction” JGJ 169-2009[18], the compressive strength grade of FFC should not be lower than C25. According to another Chinese standard, “Technical specification for post-cast fair-faced concrete” T/CECS814-2021[19], the 28-d compressive strength of C30 grade FFC should not be lower than 38.2 MPa. Obviously, all the prepared RC groups can meet the strength requirement of grade C25. Moreover, RC-1 and RC-2 can meet the strength requirement of grade C30. For the RC-3 group, the 28-d compressive strength is 38.1 MPa, which is very close to the requirements of grade C30.



(a) Compressive strength (b) 28-d compressive strength growth rate

Figure 7. Mechanical properties of FFC with NCA and RCA

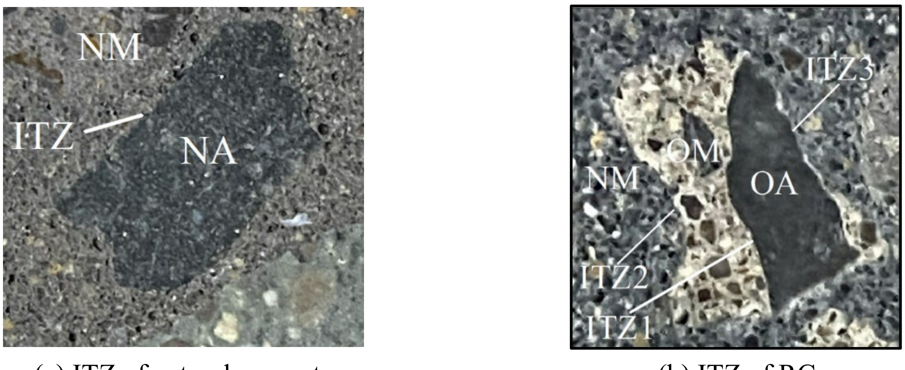
Figure 7 shows that both the 7-d and 28-d compressive strength values of the NC group were higher than those of the RC group at the same net water binder ratio. Previous works[43] have shown that using RA negatively affects the compressive strength, with strength development in concrete mixtures decreasing as the RA content increases for up to 120 days of curing. The old mortar attached to its surface and the microcracks after crushing made the performance of RCA far worse than that of NCA.

The test results of the three RC groups showed that the moisture content of RCA has a certain influence on its strength. The 7-d and 28-d compressive strengths of the RC-2 group were higher than those of the RC-1 and RC-3 groups. Compared with that of the RC-1 group, the 7-d compressive strength of the RC-2 group increased by 20%. According to M. El-Hawary[44], RCA can act as a medium for supplementary water due to its high water absorption. For the RC-2 group, the use of semidry RCA can provide internal curing for cement paste and reduce the local water binder ratio around aggregate. For the RC-1 group, the free water in the concrete mixture increased because its additional water volume was the largest, which increased the effective water binder ratio of the concrete, resulting in concrete strength that was lower than that of the other two RC groups. Because the RCA adopted in the RC-3 group is saturated and surface dry, the water absorbed in the coarse aggregate penetrated its surface during the hardening process of the concrete, which increased the local water binder ratio of the concrete and reduced its strength.

Figure 7(b) shows that the strength growth rate of the RC-2 group is in line with that of NC. RC-1 has the lowest 7-d compressive strength, but its 28-d compressive strength growth rate is the largest, which shows that when additional water is added, there is a large amount of additional water in the early-age concrete that is not absorbed or utilized, increasing its effective water binder ratio. With increasing strength, this part of the additional water is absorbed and utilized, which increases the growth rate of the 28-d compressive strength of this group of concrete. The RC-3 group had the lowest 28-d compressive strength growth rate because its effective water binder ratio was less than that of the RC-1 group without adding additional water, so its 7-d compressive strength was greater than that of the RC-1 group. However, in the process of concrete curing, part of the water in the saturated surface dry aggregate moves outward, increasing the local water binder ratio and affecting the increase in strength.

3.1.3 Microstructural analysis

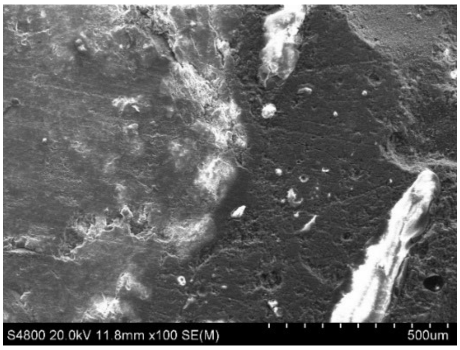
The ITZ is the interface between coarse aggregates and hardened cement mortar and is formed in three stages: mixing, early hydration and hardening. The ITZ is a loose porous structure with a large extent of $Ca(OH)_2$ enrichment and orientation[45]. It is a weak link in the concrete structure, and concrete damage often occurs here. Therefore, the structural performance of the ITZ has a significant impact on the mechanical properties of concrete. Compared with natural concrete with only one ITZ, recycled concrete has multiple ITZs due to the presence of RCA[46], as shown in Figure 8, which shows three main ITZs: the first is ITZ 1 between the old aggregate (OA) of RCA itself and the old mortar (OM) attached to its surface; the second is ITZ 2 between old mortar (OM) and the new mortar (NM) on the surface of RCA; and the third is ITZ 3 between old aggregate (OA) and the new mortar (NM) of RCA.

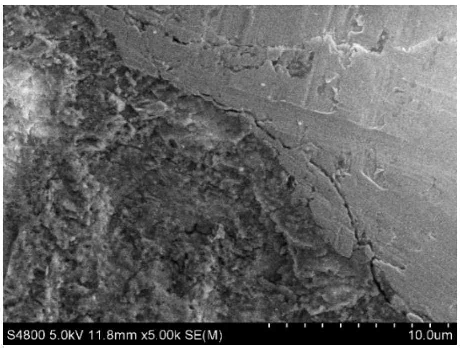


(a) ITZ of natural concrete (b) ITZ of RC

Figure 8. Comparison of concrete interfacial structures

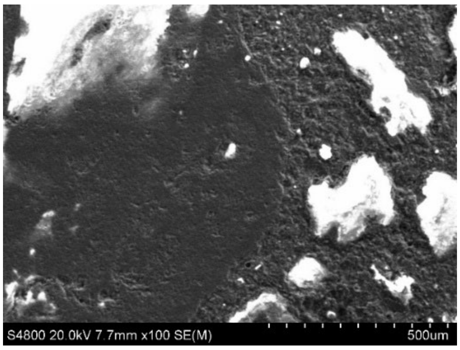
To further study and analyse the microstructure and properties of the ITZ of FCRA, the micromorphology of the interface between the aggregate and cement paste of NC and RC was analysed by SEM. As shown in Figures 9(a) and 9(b), the ITZ of NC has a relatively compact, uniform structure, tight adhesion between the mortar and aggregate and relatively few surface pores. The three different ITZ micromorphologies of RC in Figure 10 show that the structures of ITZ 1 and ITZ 3, which are the ITZs between the aggregate and mortar, are relatively loose, with many pores and some microcracks; the ITZ structure between the new mortar and old mortar is relatively compact, and there are few pores.



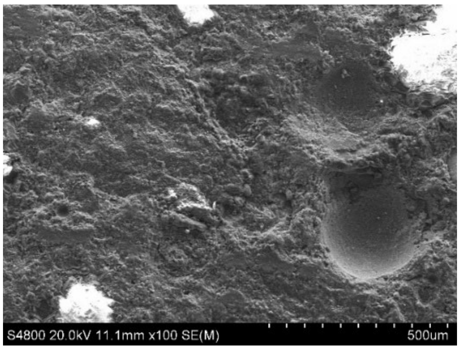


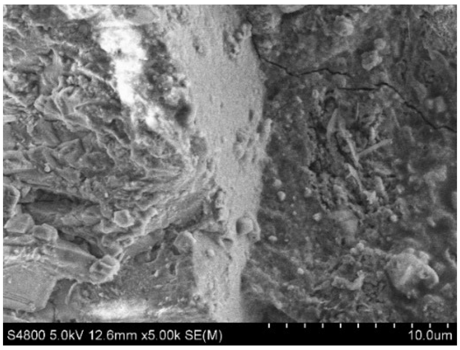
(a) NC (100X) (b) NC (5000X)

Figure 9. ITZ micromorphology of NC

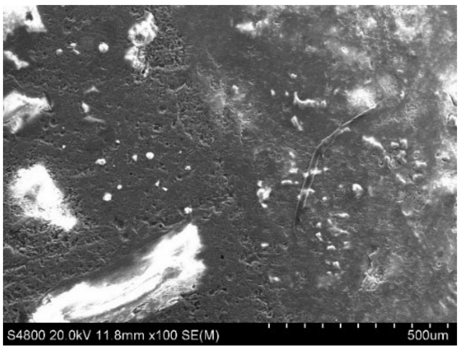


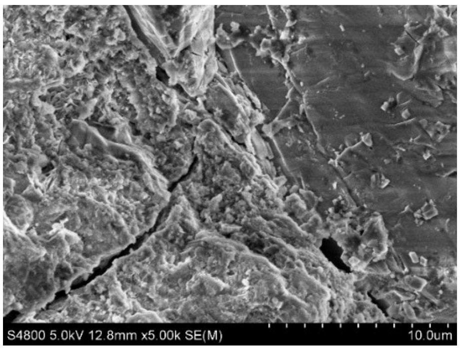
(a) RC-ITZ1 (100X) (b) RC-ITZ1 (5000X)





(c) RC-ITZ2 (100X) (d) RC-ITZ2 (5000X)





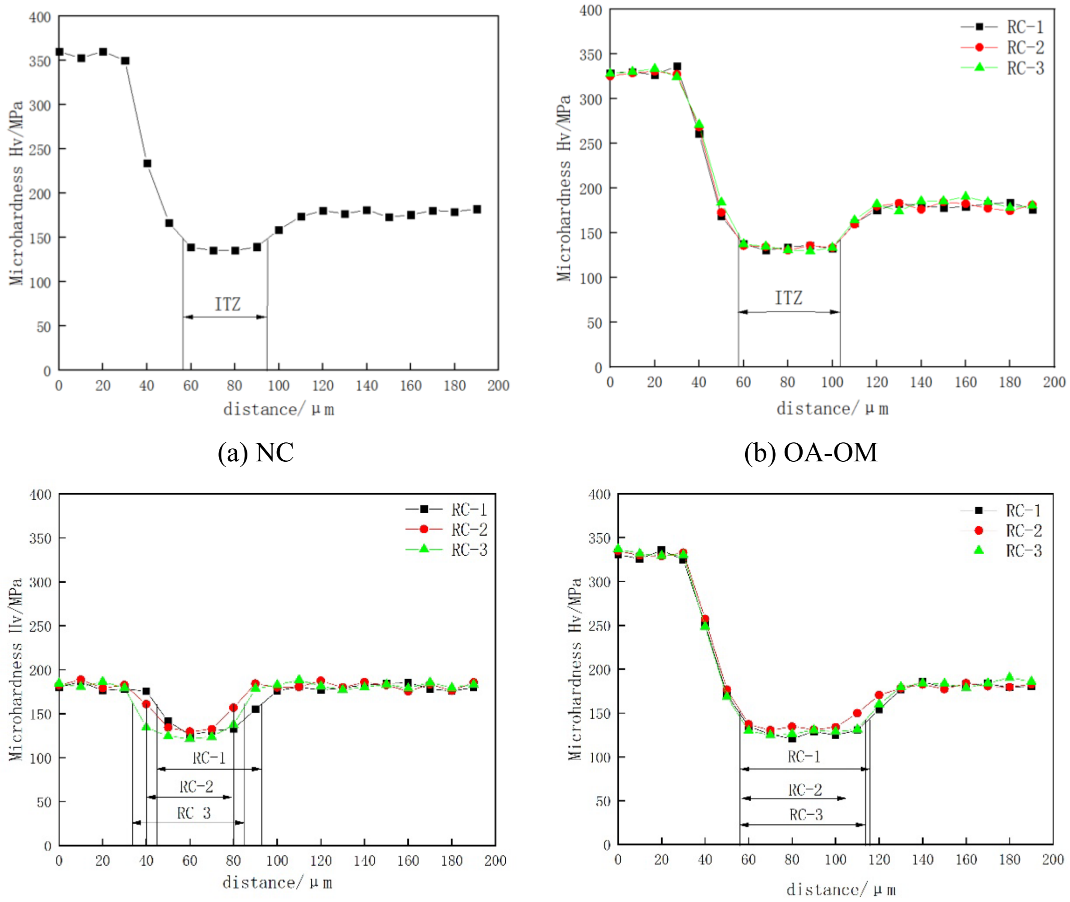
(e) RC-ITZ3 (100X) (f) RC-ITZ3 (5000X)

Figure 10. ITZ micromorphologies of RC

As mentioned above, RC groups have multiple ITZs, in which ITZ1 and ITZ3 are both formed by cement paste and NCA. Previous studies[36, 47, 48] have shown that the ITZ formed by cement paste and NCA has the following microstructures: (i) high water-binder ratio and porosity, (ii) high contents of hydration products (CH and AFt), and (iii) orientation growth of CH. ITZ2 is formed by old mortar and new mortar (NM), and its microstructure can be described by a transition ring, which can be divided into three layers[49]. The first layer is a diffusion layer formed by the active ions in the fresh cement paste, such as Na^+, K^+, SO_4^{2-}, Al^{3+}, Ca^{2+}, and Si^{4+}, diffusing into the old cement mortar through a water film. This layer is located on the side of the old cement mortar. The second layer is a strong-effect layer and is the enrichment area of hydration products, voids and the water film. This layer has a significant effect on the properties of ITZ2. The water absorption and water supply effect of RAC can reduce the orientation of CH crystals and the Ca/Si ratio of C-S-H, avoiding the enrichment of the water film and thus improving the microstructure of the strong-effect layer to a certain extent. The third layer is a weak-effect layer, the structure of which is similar to that of the fresh cement mortar. This layer has little effect on the properties of ITZ2.

To further verify the effect of the water content of RAC on the ITZ properties, a microhardness test is carried out on the natural concrete interface and the three RC interfaces prepared with RCA containing different water contents, as shown in Figure 11. The old aggregate-old mortar (OA-OM) interface, old mortar-new mortar (OM-OM) interface and old aggregate-new mortar (OA-NM) interface of the RC group are compared. As mentioned before, the ITZ usually has the following characteristics: a high water/binder ratio, a high content of $Ca(OH)_2$ with an oriented arrangement and poor mechanical properties[49]. The point 80 μm to the left of the ITZ was herein set as the origin of coordinates, and the interval between every two adjacent indents was 10 μm. Since the micromechanical properties of the ITZ will undergo abrupt changes compared with those of the cement matrix and aggregate, the distance between the two ends of the microhardness curve where abrupt changes occur was adopted as the length of the ITZ.

Some scholars have used the microhardness test to study the properties of the ITZ. The measured width of the ITZ was found to vary according to the aggregates used and the service conditions. The available data showed that the ITZ width of NC was approximately 30-50 μm, while the ITZ width of RAC (including OA-OM and OM-NM) was approximately 30-80 μm[50-52]. In the present study, the measured ITZ length of NC was approximately 40 μm, OA-OM was approximately 45 μm, OM-NM was approximately 40-50 μm, and OA-NM was approximately 50-60 μm, which is consistent with the previous studies. By using microhardness testing, Gao[51] systemically investigated the modification effects on RC prepared with nano-SiO_2 and CO_2 cured RCA subjected to an aggressive ionic environment. The results showed that the width of OA-OM-ITZ was smaller than that of concrete prepared from simple crushed RCA before and after ion erosion. Cl^- and SO_4^{2-} erosion caused the width of each ITZ to decrease.



(a) NC (b) OA-OM

(c) OM-NM (d) OA-NM

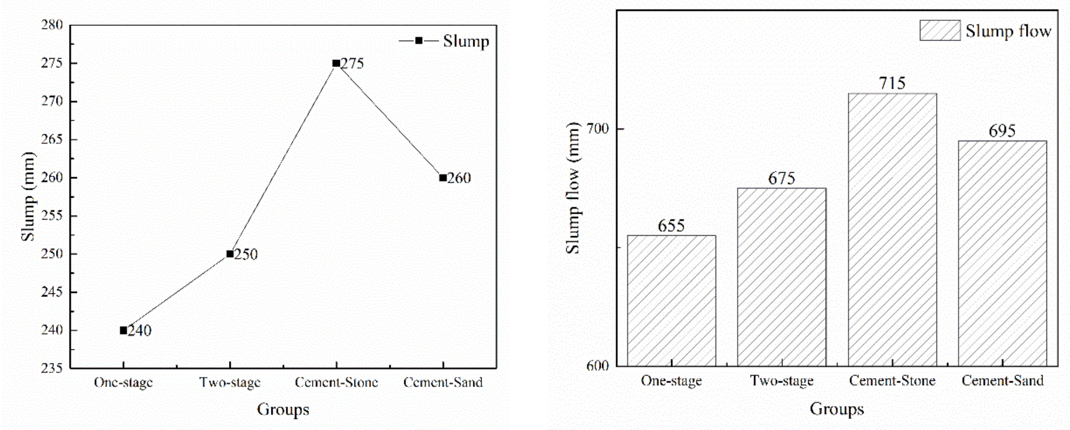
Figure 11. Effect of moisture content on the microhardness of the ITZ

Figure 11 shows that the water content of RCA has a great impact on the old mortar-new mortar (OM-NM) interface and the old aggregate-new mortar (OA-NM) interface but has little impact on the old aggregate-old mortar (OA-OM) interface. This is because the OA-OM interface is the interface between the old aggregate and the old mortar of the RCA itself, which has been completely set and solidified before pouring the concrete, so the different water contents of the RCA have little effect. For the OM-NM interface and OA-NM interface, the ITZ thickness of the RC-2 group is the smallest, and the average microhardness is higher than that of the other two groups, indicating that semidry RCA is conducive to improving the structural properties of the ITZ of recycled concrete. Compared with the concrete prepared with semidry RCA and saturated surface dry RCA, the concrete prepared with absolutely dry RCA has more free water in its cement mortar, but the aggregate has high water absorption in the early stage, accompanied by water absorption by the coarse aggregate and the evaporation of water, resulting in the formation of a transition zone with low cement density and high porosity between the coarse aggregate and cement mortar. A large amount of free water exists in the coarse aggregate in the saturated surface dry RCA. In the process of concrete curing, the water in the coarse aggregate penetrates the aggregate surface, which increases the effective water binder ratio in the ITZ and reduces its structural performance.

3.2 Effect of mixing approaches on concrete performance

3.2.1 Workability

The slump and slump flow of FCRA prepared with different mixing approaches were tested, and the test results are shown in Figure 12.



(a) Slump (b) Slump flow

Figure 12. Effect of mixing approaches on concrete workability

There are relatively few studies on the effect of different mixing processes on the workability of recycled concrete. The existing studies usually control the slump of concrete to be approximately 75 mm[15, 34]. As shown in Figure 12, compared with the one-stage mixing approach, the two-stage mixing approaches can improve the workability of FCRA to a certain extent, and the lifting effect on concrete slump and slump flow is in the order cement stone wrapping approach > cement sand wrapping approach > two-stage mixing approach.

There is little difference between the workabilities obtained with the two-stage mixing approach and the one-stage mixing approach. The main difference between the two approaches is the stage in which mixing water is added. A one-stage mixing approach effectively reduced the absorption of the water reducing agent added later by RCA by adding half of the water to wet the aggregates before adding cementitious material and water reducing agent, fully exploiting the effect of the water reducing agent and increasing the fluidity of the concrete. The cement stone wrapping approach first mixed cementitious materials with part of the water to form a cement paste with a relatively high water binder ratio and then added RCA to the cement paste for mixing so that the cement paste could wrap around the RCA, and part of the cement paste could be embedded into the pores on the surface of the RCA to form relatively smooth coarse aggregate. This approach not only improved the fluidity of the mixture but also reduced the absorption of the later coarse aggregate and greatly improved the workability of the concrete mixture. For the cement sand wrapping approach, part of the water added in the early stage was used for the mixing of fine aggregate and cementitious material. Therefore, after RCA was added, the wetted and stirred fine aggregate and cementitious material could fill the large pores on the surface of RCA. Compared with that of the cement stone wrapping approach, the improvement in the rough surface of RCA and reduction in the absorption of water and water reducing agent by the coarse aggregate in the later stage were relatively weak, but the concrete workability was greatly improved compared to that of the one-stage mixing approach.

3.2.2 Mechanical properties

The compressive strengths of concrete prepared with different mixing approaches were tested at 7 d and 28 d, and the results shown in Figure 13 were obtained.

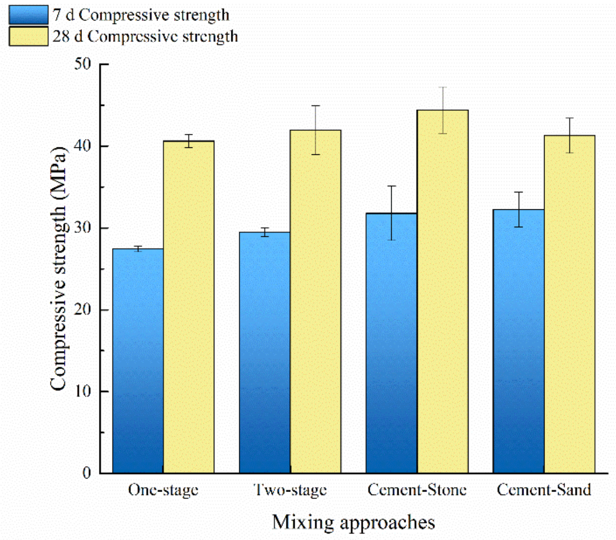
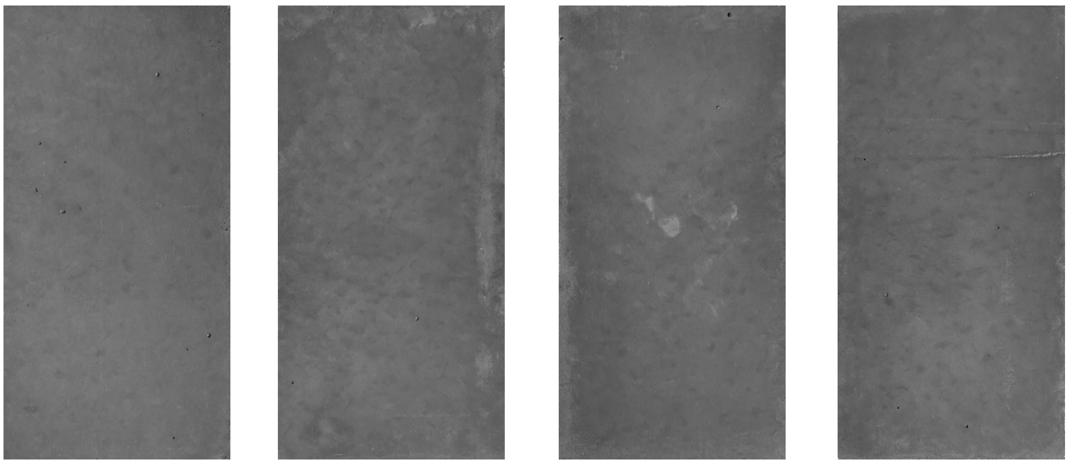


Figure 13. Effect of mixing approaches on concrete mechanical properties

V. W. Y Tam reviewed the compressive strengths and percentages of improvement of RC prepared using a two-stage mixing approach. Compared with those of RC prepared using a one-stage mixing approach, the improvement percentages of the 7-d and 28-d compressive strengths were located in two intervals, [0.73%, 12.96%] and [0.47%, 19.50%], respectively[53], which is consistent with the results of this article. Comparing the 7-d and 28-d compressive strengths of recycled concrete prepared with different mixing approaches showed that the cement stone wrapping approach improved the 28-d compressive strength of concrete the most. Compared with the one-stage mixing approach, the cement stone wrapping approach improved the 28-d compressive strength of concrete by 13.33%, while the two-stage mixing approach and cement sand wrapping approach produced increases of 7.12% and 5.39%, respectively. For the 7-d compressive strength, the cement sand wrapping approach produced the greatest increase, reaching 12.29%, and the two-stage mixing approach and cement stone wrapping approach achieved increases of 2.61% and 10.69%, respectively. This is because the cement stone wrapping approach wrapped RCA with cement paste to form a relatively dense cement slurry shell on its surface, which made the bond between coarse aggregate and mortar more compact, improved the performance of the concrete ITZ, and improved the strength of concrete to a certain extent. The two-stage mixing approach increased the bonding force between the cementitious material and the aggregate to a certain extent by prewetting the RCA and fine aggregate. However, because the amount of water added was much higher than the water absorption of the aggregate itself, a water slurry shell with a high water cement ratio formed on the surface of the aggregate. The improvement in the mechanical properties of concrete was not as good as that achieved with the cement stone wrapping approach. The cement sand wrapping approach mixed some water with the fine aggregate first and then added cementitious materials to make the cement particles disperse more fully, which was conducive to increasing the strength of concrete. However, it formed a mortar with a low water cement ratio, which made it slightly dry when it wrapped around the surface of coarse aggregate, and the enhancement effect of the ITZ and interfacial adhesion was not as good as that achieved with the cement stone wrapping approach. In conclusion, by changing the feeding sequence, the two-stage mixing approach promoted the dispersion of cement particles in the mixture, made the cement hydration more complete, and improved the interface structure and compressive strength of the concrete.

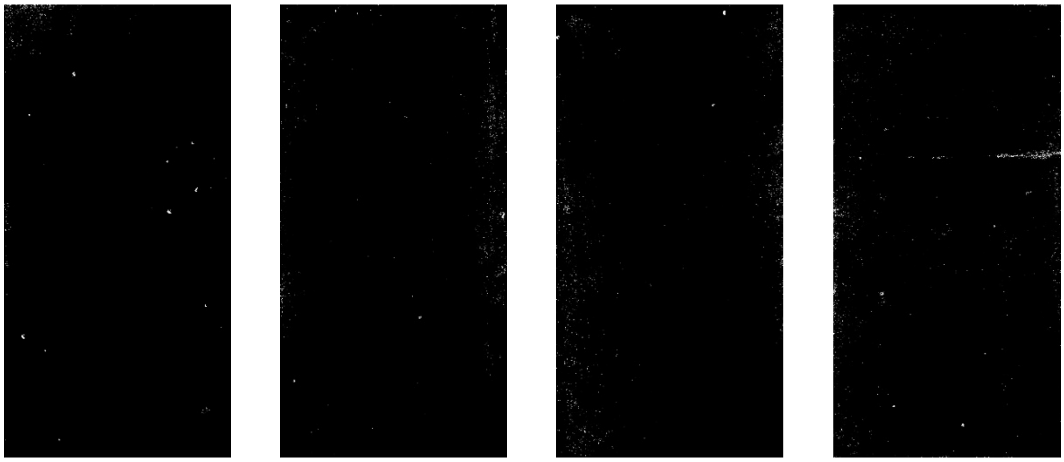
3.2.3 Apparent properties

Surface images of FCRA prepared with different mixing approaches were collected and are shown in Figure 14. The size of the specimen shown in each image is 400 mm × 200 mm. Then, the obtained images were converted into a binary diagram by Image-Pro Plus software, as shown in Figure 15.



(a) One-stage mixing (b) Two-stage mixing (c) Cement stone wrapping approach (d) Cement sand wrapping approach

Figure 14. Surface images of concrete prepared with different mixing approaches



(a) One-stage mixing (b) Two-stage mixing (c) Cement stone wrapping approach (d) Cement sand wrapping approach

Figure 15. Binary diagram of the surface of concrete prepared with different mixing approaches

Based on the above collected images and the transformed binary map, the surface grey standard deviation and surface pore area of the surface of concrete prepared with different mixing approaches were obtained, as shown in Table 5.

Table 5. Grey standard deviation and pore area of the surface of concrete prepared with different mixing approaches

Test	One-stage mixing	Two-stage mixing	Cement stone wrapping approach	Cement sand wrapping approach
Grey standard deviation	12.36	14.69	13.05	13.13
Surface pore area/mm^2	18.15	15.34	10.42	13.50

In the process of concrete mixing, air entrainment will lead to the formation of bubbles in the fresh concrete. Due to the density difference between bubbles and fresh concrete, bubbles will rise under the action of buoyancy. In the rising process, the rising speed of bubbles is affected by their buoyancy and friction force. The magnitude of friction is related to the viscosity of concrete and the rising speed of bubbles[54]. The force on bubbles can be analysed by the Navier Stokes equation, which is used to describe the force on spherical particles in fluids[55]. According to the force equation of spherical particles in hydrodynamics, the rising speed of the bubble (V) is shown in Eq. (2) [56].

$$V = \frac{2}{9}\frac{(\rho_f-\rho_b)}{\eta} gR^2 \quad (2)$$

where ρ_f is the bubble density, kg/m^3; ρ_b is the concrete density, kg/m^3; η is the dynamic viscosity of bubbles, N·s/m^2; g is the acceleration of gravity, m/s^2; and R is the bubble radius, m.

Table 5 shows that the different mixing approaches had little effect on the surface colour difference of concrete, but the two-stage mixing approach reduced the generation of pores on the concrete surface. This is because the colour of the concrete surface mainly reflects the cement paste wrapped around the aggregate in the concrete mixture. For a cementitious material with a given composition and content, the colour difference of the surface will not be too large, although the cementitious material can be more completely dispersed in the concrete mixture through the two-stage mixing approach. However, its influence on the colour of the concrete surface is relatively small.

The pores on the concrete surface are mainly due to air entrainment and other factors during concrete mixing. According to Eq. (2), whether the bubbles in the concrete can be discharged depends on the rising speed of the bubbles and the distance to the surface. The rising speed of bubbles is related to the concrete density, dynamic viscosity and bubble radius. The water binder ratio, sand ratio and cementitious material content will affect the density and dynamic viscosity of concrete. Due to the density difference between bubbles and fresh concrete, some bubbles will move to the concrete surface to form pores. Therefore, through the two-stage mixing approach, all the raw materials in the concrete can be dispersed more evenly, reducing the generation of bubbles in the concrete and thus reducing the pore area on the concrete surface.

4 Conclusion

(1) In this experiment, the effects of different RCA water contents on the time-lapse loss of concrete slump flow, 7-d and 28-d compressive strengths and microhardness value of the ITZ were compared and analysed. The water content of RCA has a certain influence on the physical and mechanical properties of FCRA. The slump flow of FCRA is basically the same as that of reference concrete made with natural aggregate, which is more than 600 mm. However, the 60 min slump losses of FCRA made with dry, semidry and saturated surface dry RCA are 27.8%, 24.0% and 25.4%, respectively. The compressive strength of FCRA is much lower than that of the reference concrete. FCRA with semidry RCA has the highest 28-d strength, and the strength growth rate is close to that of the reference concrete. Microscopic test results show that the water content of RCA has a notable impact on the old mortar-new mortar interface and the old aggregate-new mortar interface but has little impact on the old aggregate-old mortar interface. Concrete prepared with semidry RCA performs better than concrete prepared with dry or saturated surface dry RCA. The mechanism of improvement can be attributed to the migration and evaporation of free water in cement mortar and RCA.

(2) Using different mixing approaches, there were certain differences in the performance of FCRA. The two-stage mixing approach improved the workability, mechanical properties and apparent properties of concrete to a certain extent. The cement stone wrapping approach greatly improved the fluidity of the concrete mixture and the structural properties of the ITZ. Compared with that achieved with the ordinary mixing method, the 28-d strength of the concrete obtained by the cement stone wrapping approach increased by 13.33%, and the surface pore area was reduced by 42.6%. This research optimizes the preparation of FCRA, provides a good foundation for the future widespread use of FCRA, and promotes environmentally sustainable development.

CRediT authorship contribution statement

Wangxin Li: Writing – original draft, Visualization, Investigation. **Tao Jiang:** Methodology, Investigation, Formal analysis. **Ruoyu Jin:** Conceptualization, Methodology. **Yidong Xu:** Conceptualization, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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